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Infrastructure as social, technical, and environmental systems to advance climate risk governance

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By

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Abstract

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The Anthropocene epoch's highly coupled human-natural systems and unprecedented rates of change call for a paradigm shift in environmental planning to help us move from threshold-based to transformational and inclusive process-based policies. In the context of the climate change crisis, there is a very short time window to shift from short-term, single sector, and reactive practices; to policies that aim to change the fundamental attributes of socioeconomic and socioenvironmental systems in anticipation of climate change effects. Process-based policies require us to iteratively address the conditions and systems at the root cause of vulnerabilities, encouraging more systemic, integrated, and deliberately inclusive approaches. We argue that governance and spatial analysis tools can leverage this paradigm shift by better tracing the connection between decision-making power and landscape processes. Drawing from political ecology, disaster risk reduction, and complexity sciences, we hypothesize scale mismatch between policy and expected impacts from climate change to infrastructure systems results in maladaptation. Through two case studies, this dissertation explores in-depth climate risk management gaps in the transportation fuel and airport infrastructure systems. By framing the transportation fuel system (TFS) and airports as sociotechnical and socioenvironmental systems, we develop an approach that recognizes the interconnectedness, dynamic, and multiscalar challenges of networked infrastructure climate risk management. We set important next steps to enhance climate adaptation governance of complex systems.

Chapter 1 introduces the background of this research together with key concepts and methods helping the reader navigate the different sections of the dissertation. Chapter 2 sets the theoretical baseline of this research by questioning the influence of critical infrastructure institutional framing of criticality metrics; how it aligns or misaligns with infrastructure resilience policy goals; what gaps are uncovered by these misalignments; and what solutions can be harnessed to address this misalignment based on disaster risk reduction and complexity science theories. Chapter 3 presents the TFS case study, showing how this infrastructure can be framed as a social, technical, and environmental system; and based on this framework, what can be learned from the contemporary TFS vulnerability to climate change that will help improve future TFS resilience and avoid maladaptation. Chapter 4 presents the airport case study and provides a method to identify how climate adaptation practices can emerge through current airport regulatory structures; as well as the barriers and pathways for airport climate

adaptation governance. Chapter 5 combines geographical and topological concepts of space to model exposure of sociotechnical networks using empirical data of the TFS, airports, and coastal flooding projections in California. It provides applied examples of how to measure the links between climate-induced landscape hazards, infrastructure systems, and social entities with decision-making power; and how these interlinks identify new stakeholders, new roles, and new forms of collaboration for effective climate adaptation governance.

Infrastructure systems enrich this research by providing a much needed lens to advance our knowledge on the networked nature of environmental challenges and vulnerabilities; going further than the simple co-occurrence of hazards and physical assets. Using qualitative methods (stakeholder interviews, policy review, and content analysis) and quantitative methods (Geographic Information Science and network science), infrastructure is modeled not only as technology and hardware, but as organizational and institutional networks tied together through ownership and operational jurisdiction, as well as through constitutive and operational policies. Our approach to infrastructure climate risk governance focuses on the ability of sociotechnical systems to transform adaptively from one configuration to another in anticipation of potential disturbances or shocks. Stakeholders of climate risk, and their institutions, are framed as emergent properties of complex systems, where connectivity patterns between social entities can be identified, studied, and eventually modified for improved system function and resilience. Looking at infrastructure as sociotechnical systems helps link decision-making entities and physical infrastructure across time, landscape processes, and space to optimize the scale of climate adaptation and resilience actions. It also allows expansion of ways in which infrastructure climate adaptation stakeholders can be identified and targeted for collaborative and inclusive decision-making, providing avenues for operationalizing different dimensions of environmental justice.

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AR5: IPCC's Fifth Assessment Report (2013 for the physical science assessment and 2014 for the climate impact, vulnerabilities, and adaptation assessment)

AR6: IPCC's Sixth Assessment Report (2021 for the physical science assessment and 2022 for the climate impact, vulnerabilities, and adaptation assessment)

ARCCA: Alliance for Regional Collaboratives for Climate Adaptation

C4CCA: California's Fourth Climate Change Assessment (2018)

CASP: California Aviation System

CI: Critical infrastructure

DRR: Disaster risk reduction

ESGs: environmental, social, governance (corporate due diligence)

FAA: Federal Aviation Administration

GHG: greenhouse gas

GIS: Geographic Information Science

GS: Glide slope (airport navigational aid equipment)

IPCC: Intergovernmental Panel for Climate Change

ITSP: Interregional Transportation Strategic Plan

LLCA: Low-lying coastal airports

NAS: National Airspace System

PAPI: Precision Approach Path Indicator (airport navigational aid equipment)

PCCPs: Potential climate-cognizant policies

ROWs: Rights-of-way

SDGs: Sustainable Development Goals

TFS: Transportation fuel System

UNISDR: United Nations International Strategy for Disaster Risk Reduction

Chapter 1. General Introduction

1.1. Background and problem statement

1.1.1. A paradigm shift to understand highly coupled human-natural systems and unprecedented rates of change

The dynamic links between decision-making power and landscape processes are ill-defined. In the context of climate risk, this results in inappropriate and ineffective governance systems, where the scales in which climate impacts are projected to occur do not match the scales of decision-making process resulting in maladaptation. A major shortcoming of our inability to link decision-making to landscape processes associated with climate-induced hazards is that we lack understanding of stakeholders involved to collectively design and implement adaptation and resilience strategies. Throughout this research governance and spatial analysis are explored as tools through which these links can be mapped and monitored to improve network-level, collective, and inclusive outcomes for climate adaptation and resilience. Based on political ecology, disaster risk reduction, and complexity sciences theories, we set important next steps to move from threshold-based to transformational and inclusive process-based policies. These policies are needed to shift from short-term, single-sector, and reactive practices, to iteratively address the conditions and systems at the root cause of vulnerabilities, encouraging mode systemic, integrated, and deliberatively inclusive approaches.

The beginning of the 21st century has been marked with the discovery that massive human-generated planetary change has brought us to a new geologic epoch called the Anthropocene. Starting somewhere between the spread of agriculture, the Columbian Imperialism, the Industrial Revolution, and the mid-20th century acceleration of population growth[1], this new epoch is functionally and stratigraphically different from the Holocene. It's distinct geochemical signatures are observed in sediments and ice showing elevated levels of a combination of fly ash, plastics, metals, and pesticides[2]. Accelerated rates of species extinction and invasion also mark global biotic changes, where the human footprint on terrestrial biosphere (ice-free land) has increased from 5%[2] in the 1700's to 58% in 2013[3]. At the atmospheric level, Antarctic ice cores show evidence of unprecedented rates of carbon dioxide emission resulting in anthropogenic changes of planetary surface energy balance and consequential average surface temperature increases. Between the 1850-1900 and the 2010-2019 periods, total human-caused global surface temperature increase is estimated to 1.07°C[4], warming the climate at a rate that is unprecedented in the last 2000 years and setting the stage of our current climate change crisis.

Beyond the planetary emergency discourse accompanying this new epoch, the Anthropocene highlights two important concepts that call for significant paradigm shifts in environmental planning: highly coupled human-natural systems and unprecedented rates of change.

Landscape processes such as atmospheric, geologic, hydrologic, and biologic transformations of the landscape, deemed as "natural systems", are evermore determined by anthropogenic activities. This challenges dualistic paradigms of nature-society that have shaped many disciplines over time[5], resulting in compartmentalized perceptions of landscape and human systems. The Anthropocene calls for new paradigms to better understand tightly coupled nature-society systems which many environmental fields have started to respond to in the 21st century. In the field of disaster risk, it has brought forth ecological frameworks to help define adaptation and resilience goals for society, as well as socially critical perspectives of these concepts based on the "de-naturalization" of problems issuing from environmental hazards.

The unprecedented rates of change that define the Anthropocene add the idea of non-linear behavior marked by volatility and unpredictability. Previously known stability thresholds are challenged by tipping points, or regime shifts, that break path-dependence by reinstating new positive feedback loops and chain reactions moving systems from one trajectory to another. The Anthropocene has required new paradigms able to break from single states of equilibrium and incremental change. Efforts to understand dynamic equilibrium, propagation of cascades, and interconnectivity have also been developing in many environmental fields, notably through the incorporation of complexity sciences. Adaptative governance also emerged in the last two decades to face the complexities and uncertainties associated with accelerated environmental change and management of social-ecological systems. The Anthropocene has also shed light on the unreliability of the past to predict the future, especially when it involves using climate baselines for managerial or strategic decision-making. In the science-policy interface, the combination of highly coupled human-natural systems and unprecedented change, point to the need to move from threshold-based to process-based policies.

1.1.2. Understating the links between decision-making and landscape-processes to address the climate adaptation gap

Adaptation response has been accelerating in the last couple of decades according to the latest Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC)[6]. Adaptation knowledge is in demand in public and private sectors and there is an increasing number of policy and legal frameworks dedicated to climate adaptation world-wide. Adaptation responses include hard engineering interventions ranging to nature-based solutions; disaster risk management; institutional capacity building; relocating settlements; material and design interventions on built infrastructure; fostering social safety networks; and a combination of these measures and others over-time. However, there is a gap between the current state of adaptation and the adaptation needed to address climate impacts observed across sectors and regions.

While cities increasingly develop adaptation plans, few of these plans have been implemented and fewer still are being co-developed and implemented encompassing the diverse range of stakeholders, notably those that are historically marginalized, or remain opportunistically hidden. Furthermore, observed adaptation is dominated by small incremental, reactive changes to usual practices, often after extreme weather events, while evidence of transformative adaptation is limited. The latest IPCC report indicates that the greatest gaps between policy design and implementation lie in the integration of justice concerns into adaptation action and addressing complex interconnected risks. Evidence of maladaptation is increasing in some sectors and regions, underlining how inappropriate responses to climate change create long-term locked-in vulnerability, exposure, and risks that are difficult and costly to reverse. This exacerbates existing inequalities and impedes achievement of the Sustainable Development Goals (SDGs) while increasing adaptation needs and shrinking the window for solutions[7]. Maladaptation can be reduced by integrating and flexible governance mechanisms that account for long-term goals. It requires using principles of recognitional, procedural and distributional justice in decision-making, responsibly evaluation who is regarded as vulnerable and at risk; who is part of decision-making; who is paying; and who is benefiting from adaptation measures.

Across sectors and regions, there is recent realization that the most significant determinants of adaptation barriers stem from financial, institutional, and policy constraints. In this context, further investigating governance issues of critical infrastructure adaptation by developing methods to map the links between decision-making and landscape processes related to climate-induced hazards is pertinent to address the climate adaptation gap.

1.2. Key Concepts

1.2.1. Climate risk, adaptation, and governance in the context of political ecology

The main concepts discussed in this dissertation are explained below and, unless specified, reflect definitions from the most recent international policy documents from the Intergovernmental Panel for Climate Change (IPCC) [4,8] and the United Nations International Strategy for Disaster Risk Reduction (UNISDR) [9]. Most of these terminologies, notably adaptation and resilience, are polysemous, semantically elusive, and highly disputed in academia[10]. Political ecology and related fields, such as cultural geography and human ecology, which critically reflect on relationships between nature and culture, notably that between human communities and environmental shocks, have highly contested the technocratic approach of these terms [11]. Especially the dangers of seamlessly incorporating concepts from evolutionary biology to fields with strong cultural and social praxis, and of these concepts uncontested normative quality for prescribing public policy [1]. Although a

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[1] Normative qualities of adaptation, and notably resilience, have been highly critiqued as a form of governing and exerting power "for achieving the subjugation of bodies and control of populations" according to Michel Foucault's biopower theory[11]. Biopower theories advanced in disaster risk reduction research that denounces the pervasive use of power onto population under "extraordinary" disaster risk conditions and climate security to execute forced

conceptual analysis of adaptation or resilience is not the focus of this dissertation, with the definition of key concepts of this research, we intend to highlight the relevance of political ecology insights on these terminologies to advance our capacity to address wicked socioenvironmental problems. These insights include a distinction between incremental and transformational adaptation as well as better addressing issues of environmental justice and maladaptation.

Socioenvironmental or socio-ecological refers to the tightly linked bio-geo-physical and social systems. Drawn from socio-ecological systems (SES) theory, the terms associates social and institutional actors to systems ecology[18].

Sociotechnical refers to the tightly coupled physical and technological artifacts and human, or organizational systems. It looks at technology as physical assets (like pipelines, transportation networks, supply chains, navigation systems) which are both society shaping and shaped by society (like users, organizations, regulatory institutions, and other stakeholders)[19]. The sociotechnical framework acknowledges that fixed technical infrastructure and the underlying human organizational networks are sub-components of the same large-scale complex system[20]. The social and human component of technical systems are studies in this research as an often forgotten, however key element to manage climate risk.

Climate risk arises from the dynamic interactions between climate-induced hazards, exposure and vulnerability of affected human or ecological systems. Climate risk is managed through two main strategies: climate mitigation which acts on the cause of climate change (reduction of greenhouse gas emission), and climate adaptation which acts on the unavoidable effect of climate change (reduction of vulnerability). Climate risk can also arise due to human responses to climate change, such as maladaptation. The concept of maladaptation arises in recent policy documents questioning adaptation as a status quo normative prospect of adaptation, pointing to limits where assets and stakeholders fail to be secured from intolerable risk.

Hazard is the potential occurrence of any natural or anthropogenic event that may cause loss of life, injury, or other health impacts, as well as damage and loss to infrastructure, livelihoods, service provisions, and environmental resources. *Climate-induced hazards* are those conditioned or triggered by weather and climatic phenomena such as storms, floods, landslides, wildfires, heat-waves, droughts, etc. The identification and description of climate-induced hazards are based on scientific knowledge of landscape processes. Mapping climate-induced hazards relies largely on our technological capacity for modeling physical, chemical, biological processes, and their interaction with landscape systems

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migration and reduce people's agency [12,13]. Although not directly addressed in this research, biopower theories have underlined links between knowledge, government power, and governing tactics and how they can perversely reproduce the problems of technocratic, liberal, and utilitarian decision-making rendering individuals and societies vulnerable in the first place[14–17].

(atmospheric, hydrologic, geologic, ecologic, and anthropogenic). It is often measured based on spatiotemporal occurrence and magnitude patterns. In this dissertation we use coastal flooding hazard as an applied example of climate -induced hazards, which is measured based on recurrence intervals, flood extent, and flow, depth. The latest IPCC report identifies specific types of climate-induced hazards, called “climatic impact drivers”, that cause impact to society and ecosystems. Increase of overall coastal hazards (relative sea level and coastal floods), and increase of heavy precipitation and pluvial flooding are among the most widespread and high-confidence climatic impact drivers of this century[4].

Exposure is here defined as the spatial co-occurrence, overlay, or intersection of climate-induced hazards with people, infrastructure, livelihoods, ecosystems, natural resources, and other assets.

Vulnerability here refers to the propensity or predisposition of being adversely impacted by climate-induced hazards. Vulnerability is a subjective component of climate risk since it is intrinsic and idiosyncratic to each system, individual, or location. Methods to assess vulnerability have greatly evolved through time and are widely distinct among research communities and across societies and geographies. It encompasses the sensitivity to hazards and the capacity to cope and adapt to harm, and has historically been used to understand the disproportionate suffering of marginalized stakeholders[21,22]. In disaster risk theory, the vulnerability paradigm is a precursor to the concept of environmental justice, which has only recently been incorporated in climate adaptation policy[2].

Wicked mess describes the unstructured, unbounded, and dynamic nature of society’s problems as well as the deep interconnectedness between them all[30]. It stems from the planners and designers Horst Rittel and Melvin Webber’s[31] concept of “wicked problem” as well as from Russel Ackoff’s[32] term “messes”, which criticized the framing of social and environmental problems as tame, static, and compartmentalized. This term is further explored in chapter 3.

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[2] We call the “vulnerability paradigm” the emergence of social attribution to disaster risk reduction which has been considered one of the antecedent fields of political ecology in three important phases: The vulnerability paradigm, in western environmental sciences, has been traced to Gilbert F. White in the 1930-1940’s “human adjustment” approach to flood management[23], later landmarked with the 1970’s and 1980’s efforts to take the “naturalness” out of natural disasters[24,25], and finally mainstreamed in the 1990’s and early 2000’s with the pressure and release vulnerability model from the human ecology school in the U.S[26–29]. Gilbert White worked with flooding hazards and describes adjustment (a proxy to adaptation), as the human process of occupying or living in an area which results in the transformation of the initial landscape. White highlights behavioral and social-centric solutions to flooding in the U.S. such as emergency warning and evacuation, structural changes in transportation and buildings, changing land use to reduce vulnerability, and insurance.

Resilience describes the ability to maintain essential function, identity, and structure, but also the capacity to transform after a disturbance; that in this study focuses on the climate change crisis. Resilience concepts have been growing in policies in the last two decades and valuably highlight the complex, open, path-dependent dynamics of coupled socio-environmental systems[33]. Resilience and adaptation are interrelated where adaptative capacity enhances resilience, and resilient systems are capable to cope with, adapt to, and shape change. This concept is further discussed in chapter 2.

Adaptation is key to reducing exposure and vulnerability to climate change. In human systems, it is the process of adjustment to actual or projected effects of climate change by mitigating harm or benefiting from opportunities. Adaptation options aim to reduce risk to human and natural systems but cannot present all impacts and are not a substitute for climate risk mitigation (as in reducing GHG emissions). Adaptation can be anticipatory or reactive and ranges from incremental to transformational qualities. Incremental adaptation is often characterized by short-term, single-sector, non-inclusive, and reactive change to usual practices, often after the occurrence of an extreme weather event. Transformational adaptation is a response to the generalized critique of existing adaptation practices that have been framed as inadequate, uncoordinated, and unjust. It aims to change fundamental attributes of socio-economic and socioenvironmental systems (e.g., energy, land use, urban, infrastructure) in anticipation of climate change effects that require not only technological and economic transitions but significant shifts in most aspects of society. It underlines the limits of the “climate-proofing” mind-set, which addresses “end-point vulnerability” (most visible symptoms of past socioenvironmental development patterns) to highlight deliberate and fundamental system changes that achieve more just and equitable adaptation outcomes[34]. Transformational adaptation seeks to address the “starting point vulnerability”, or the conditions, and systems at the root causes of vulnerabilities, encouraging more systemic, integrated, and deliberately inclusive approaches. Key to transformational adaptation lies in better understanding complex, compound, and cascading risk as well as deliberative and effective incorporation of environmental equity and justice values.

Maladaptation is when policy and practices aiming to avoid or reduce climate risk adversely increases the vulnerability of the targeted system, sectors, or social groups[35]. Maladaptation can also refer to spillover effects of adaptation actions that have an adverse effect on other systems, sectors, or social groups. Some examples include the externalities of infrastructure hardening and climate-proofing such as increased GHG emissions, environmental encroachment, or life-threatening residual risk from levee breaches. Maladaptation has been associated to two mechanisms (1) as challenges escalate and cascade adaptive capacity tends to exhaust, (2) adaptation is effective at a local scale but maladaptive at a global scale[36]. These maladaptation mechanisms are also common to issues of critical infrastructure failure and governance scale mismatch (further developed in sections 1.2.3.).

Environmental justice in its broadest sense fights injustice with respect to environmental conditions[37]. Environmental justice embeds climate justice and is a twin concept of energy justice. Although developed through a long history of movements for pluralistic and democratic societies, this concept gained strength in environmental fields with the intergenerational justice concept embedded in the Brundtland report of 1987, and the sustainability premise. Environmental justice has had a direct influence on the development of climate justice and the growing ethical and moral concerns for the inverse distribution of climate risk and climate responsibility, i.e., those who contribute the least to the cause of climate change pay the most for its effects[38,39]. Environmental justice in climate policy documents is often addressed in three normative dimensions: distributive, procedural, and recognition. In the case of climate risk, the first is concerned with the fair distribution of costs and benefits of climate mitigation and adaptation; the second addresses the fairness, legitimacy of decision-making process focusing on who decides and participates; and the third refers to the fair consideration of diverse values, cultures, and perspectives. Recognition justice is a prerequisite for distributive and procedural justice. Environmental justice, which has recently received greater attention in environmental and climate policy [40], is a core value of climate risk management and is most useful as a pragmatic goal rather than an absolute concept since the complete elimination of injustice is unattainable. However, it enforced transparency, accountability, and negotiated trade-offs to maximize gains and minimize losses. Environmental justice underlines the importance of multi-stakeholder and collaborative governance processes for addressing wicked socioenvironmental problems as will be developed in chapters 3-5.

Governance is largely viewed as an institutional, organizational, or social function that orchestrates decision-making and behavior towards collectively desirable outcomes. Science-policy research has pointed to environmental governance as a powerful tool to address wicked, complex, and collective-action problems such as climate change[40–45]. In this research we are interested in the interactions between institutions and decision-makers (or stakeholders) of climate risk governance. Institutions are viewed as the collection of rights, rules, principles, and decision-making procedures steering social practices, setting roles to participants in these practices and guiding interactions among them[46]. Social entities that compose the institutional systems may self-organize and give rise to coordinated and adaptive behavior even in the absence of a central authority. In this research we argue that stakeholders of climate risk, and their institutions can be understood as emergent properties of complex systems[46–48], where connectivity patterns between social entities can be identified, studied, and eventually modified for improved system function. This brings forth the possibility of improving our understanding and improving the effectiveness of current governance system for climate risk reduction, notably given scale mismatch issues inherent to landscape systems and infrastructure networks. Concepts of complex systems applied to governance and policy will be further developed in chapters 2 and 5.

1.2.2. The problem of scale mismatch

Many problems encountered by societies managing natural resources or hazards arise because of a mismatch between the scale of governance and the scale of landscape processes [43,48–50]. Scale is a central issue for effective governance that refers to a specific spatial or temporal boundary where a phenomenon is recognized. Such boundaries may be natural (watersheds, biomes, geomorphological landforms); administrative (county, state, national); socioecological (land tenure, land use types); and sociotechnical (metropolitan transportation regions; power distribution regions). Adaptation related to flood hazards for example, have greatly developed by promoting transboundary governance systems that consider geomorphologic and hydrographic scales [49,51–54]. These scales best describe for example, how flood management decision-making results in effective outcomes at the catchment, delta, or coastal scale, and their geomorphologic time processes.

Given the networked nature of infrastructure we study in this dissertation, we develop a technical, social, and environmental framework to similarly address issues of temporal and spatial scale adequacy of infrastructure policy. This framework is inspired by the natural resources management field which often tackles planning and policy decision-making issues at a jurisdictional or political scale that does not correspond to the scale of the natural resource or hazard at hand [18,55]. This framework also draws from critical infrastructure resilience research which looks at infrastructure networks as interdependent complex systems with multilevel boundaries, notably the technical, the social, and the environmental [56,57]. In this research we specifically hypothesize on a mismatch between infrastructure policy temporal and spatial scales and the scale of expected impacts from climate change to these infrastructure systems. Scale mismatch problems are studied for two types of infrastructure systems: the transportation fuel system (TFS) (chapter 3 and 5) and airports (chapters 4 and 5).

1.2.3. A focus on infrastructure networks and movement: transportation fuel and airport infrastructure systems

In this dissertation we apply climate governance analysis to infrastructure systems, focusing on the transportation fuel and airport sectors (Figure 1). Both sectors are represented as complex, multiscalar, and critical infrastructure systems which we rely on for movement changing our relationship with space. They are both critical for the supply of vital goods and services. At the crux of the climate change crisis, both systems are challenged by energy transition and heightened risk from climate-induced hazards. Climate impact to any of these systems present significant cascading and compounding risks in view of their networked structure and their functional dependence on hazardous materials (notably fuel). Both present a complex social network of entities behind decision-making processes that are not well understood and can be enhanced for the effectiveness of adaptation and resilience at the collective scale.

The transportation fuel and airport infrastructure systems also present very distinct features which have important implications for climate governance challenges and the choice of methods applied to study them. The first functions as a supply chain for fuel commodity and the second as a transportation mode of people and goods. In the context of climate risk, the contemporary transportation fuel infrastructure planning is fundamentally challenged by the strategic decommission of fossil fuels and transition into renewable and clean energy. The sector has a very strong decentralized and private policy stakeholder community, characterized by fragmented sectoral-level coordination and governance. Airport infrastructure planning is challenged by long-term adaptation coupled with energy transition. The sector has strong centralized regulatory frameworks and higher involvement of public stakeholders characterized by a more cohesive sectoral coordination.

Infrastructure systems provide a much needed lens to advance our knowledge on the networked nature of environmental challenges and vulnerabilities, which goes beyond the co-occurrence of hazards and physical assets. As arteries of our society, climate resilience of critical infrastructure networks is key to better understand and manage cascading and compound risks. Assessing energy supply chain and airport infrastructure given their similarities and differences, allows us to explore in-depth climate resilience and adaptation gaps of complex and coupled sociotechnical and socioenvironmental systems. In this dissertation we hope to develop and apply frameworks that better address scale mismatch by modeling infrastructure not only as technology and hardware, but as organizational and institutional networks tied together through ownership and operational jurisdiction, as well as through constitutive and operational policies. We propose an approach to infrastructure climate risk governance that focuses on the ability of sociotechnical systems to transform from one configuration to another in response to disturbances or shocks. Looking at infrastructure as sociotechnical systems help link decision-making entities and physical infrastructure across time, landscape processes, and space to optimize the scale of climate adaptation and resilience actions. It also allows to expand ways in which infrastructure adaptation stakeholders can be identified and targeted for collaborative decision-making.

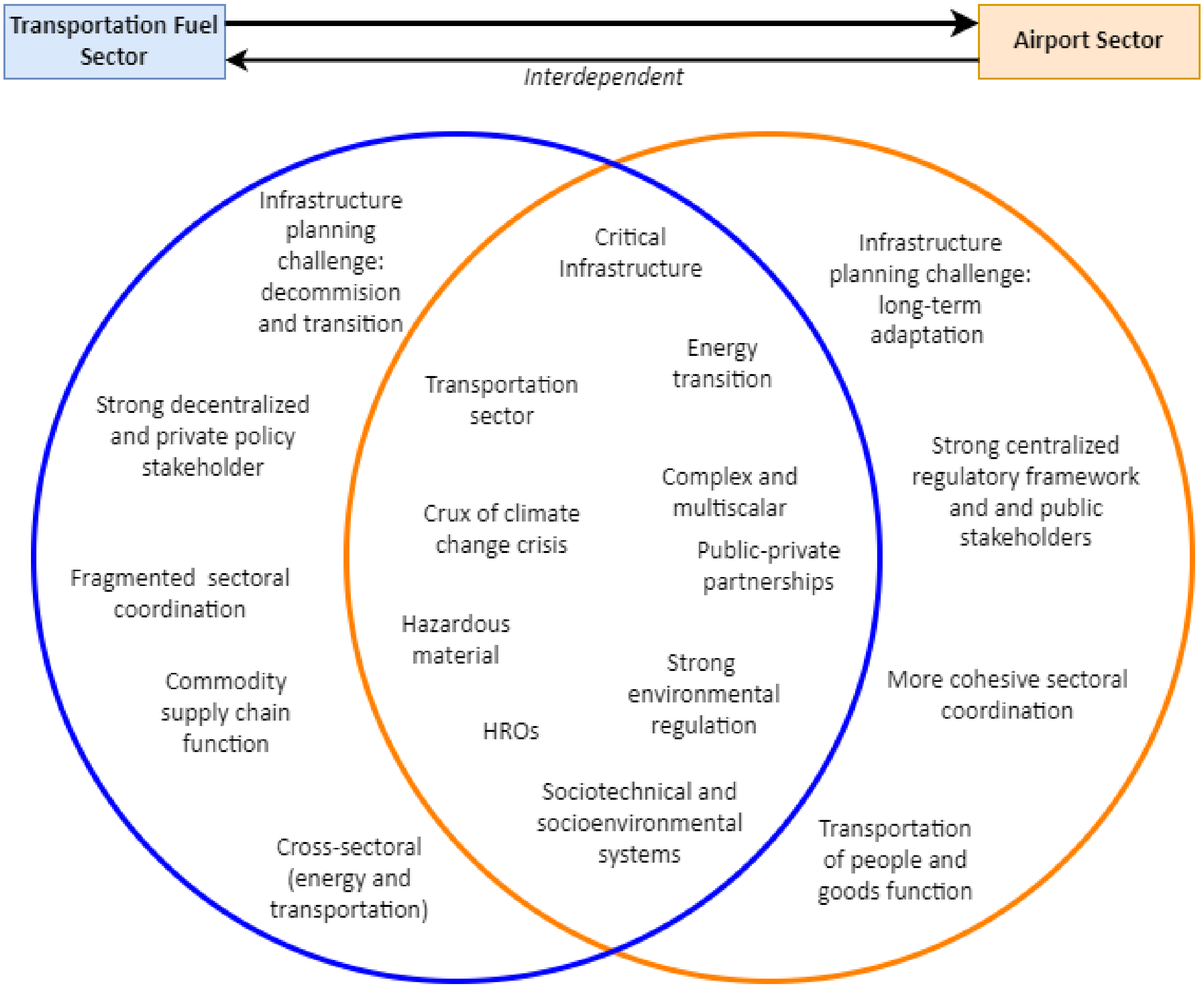

Figure 1. Similarities and disparities between the transportation fuel sector and with implication for climate risk governance

1.3. Key Methods

Case studies are the guiding method[58] of this dissertation used to provide in-depth exploration from multiple perspectives of the complexity and uniqueness of two critical infrastructure systems in the context of climate risk. We apply a set of qualitative and quantitative methods to our collection of case studies which start from a theoretical framework drawn on political ecology, disaster risk reduction, and complexity sciences. We hope that the rich depiction of insights interpreted in each case study hold insights to why policies of climate adaptation and resilience have or have not worked in the past. The cross-generalization of both case-studies applied in the theoretical framework (chapter2) and the empirical application of sociotechnical networks helps identify the significant gap of scale mismatch of the TFS (chapter 3) and airports (chapter 4), together with methods to advance our understanding of the links between decision-making power and landscape processes (chapter 5), that have equal significance in other networked infrastructures.

We apply five major qualitative and quantitative methods to the TFS and airport case studies: formal content analysis; policy review (airport case study only); semi-structured interviews of stakeholders within the transportation fuel and airport sectors; Geographic Information Science (GIS) to build infrastructure models and assess coastal flooding exposure; and network science to build social networks and assess results. The complementarity of these mixed methods is described in Figure 2. Within each case study, iterative cycles of stakeholder interviews and data processing (GIS, policy review, or network analysis) were needed throughout different phases of the study (scope determination, data processing, result interpretation). Software used to apply qualitative methods include Mind Meister to build the mind maps which helped synthesize and publish the policy review data; Dedoose for the content analysis of the policy review and the interviews; and Zoom Meetings for the interviews with airport case study stakeholders. For the application of the quantitative methods ArcGIS was used for the coastal flood exposure analysis and to to build infrastructure GIS models. Gephi and Python (NetworkX package) were used for assessing social networks. For figure development and finalization, we used Adobe Illustrator, Microsoft Excel, and Draw io-desktop.

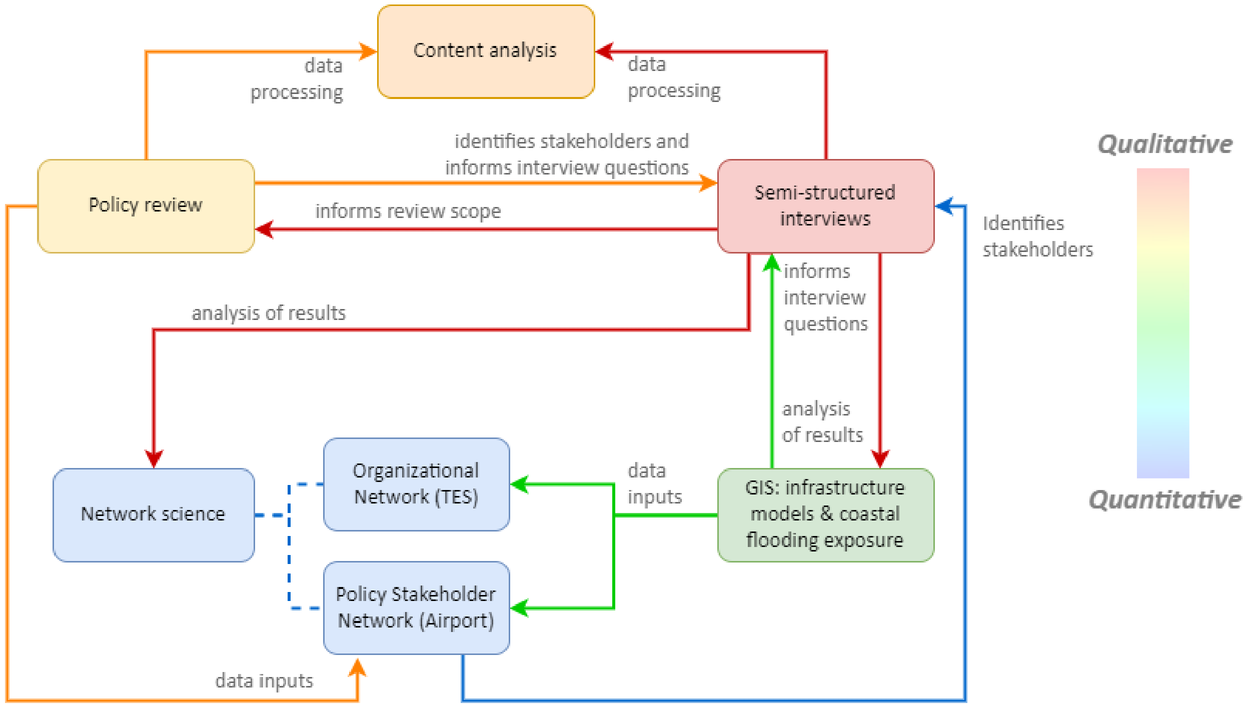

Figure 2. Complementary integration of qualitative and quantitative methods applied to two case studies (TFS and airports)

1.3.1. Stakeholder interviews, content analysis, and policy review

(a) *Formal content analysis*

Content analysis is a mixed methods approach to document data that seek to code or quantify content in terms of predetermined categories or themes in a systemic and replicable manner[59]. We apply formal content analysis[60] to extract data from stakeholder interview transcripts, applied in the TFS case study; and from policy documents, applied to the airport case study. The content analysis starts with the research question for each case study and the preparatory work necessary for the anticipation of methods and data sources available for answering the questions. The second step was collecting data that actively informs the research questions and organizing the data in a repository for analysis. The data analysis consists in the observation and discernment of patterns within and regularities among the data collected that help determine a coding scheme (process for categorization of data). The categorization here seeks to cluster similar or comparable codes into groups that help answer the research questions and deepen the analysis. Once the data has been fully categorized and coded the interrelation between the codes and themes is assessed: i.e., how categories co-occur and how one or more categories might influence the others.

A formal content analysis undergoes a sampling technique, and the definition of a clear data unit, unit of analysis, and a coding scheme. Our sampling techniques for the TFS were based on "snowballing" stakeholder engagement and interviews. Stakeholders of the TFS represent organizations that own and operate key transportation fuel assets (refineries, terminals, pipeline, etc.); organizations that heavily depend on transportation fuel commodity (power and water infrastructure); and organizations that regulate key transportation assets and their interdependencies. The data unit for the TFS is one interview transcript. Our sampling technique for the airports was based on a policy review in the nexus of climate change adaptation guidelines and industry safety and environmental regulation (see section 1.3.1.c and Appendix B). The airport data unit is one policy document. The unit of analysis consists of *themes* which are constructed before the content analysis based on the research question and further developed based on themes that emerge from the interview transcripts or policy review data.

Our coding scheme for the TFS case study is detailed in the interview questions in Appendix A, with further information in Appendix E of Radke et al (2018). Content analysis data from the interviews was used to conceptualize and build California's transportation fuel sector GIS model (Appendix A of Radke et al 2018), but also to provide insights on the vulnerability of this sector in relation to climate risk developed in chapter 3.

Our coding scheme for the airport case study is detailed in section 4.3.2 with publicly available raw data[3]. Content analysis data from the policy review was used to build the social network analysis of airport policy stakeholders in chapter 5.

(b) Stakeholder interviews

Stakeholder identification and interview is a key method used to generate data through the application of content analysis for both the TFS and airport studies. Stakeholders are defined as "all those individual actors and parties, organized groups and professions, and institutions that have bearing on the behavior of the organization as revealed in its policies and actions on the environment […]It is any party that both affects and is affected by an organization and its policies" [61]. Within the different methods for defining stakeholders, we are using (1) a *positional approach*, that identifies stakeholders that occupy formal positions in a decision-making structure (jurisdictional ownership or operation over assets and policy-making structure; and (2) a *social participation* approach that identifies stakeholders participating in policy-related issues such as membership on committees, and attendance in industry meetings and policy driven conferences. This approach is deficient where it does not integrate informal stakeholders, or those who have high leverage and influence in decision-making structures of these infrastructure assets like opinion influences, lobbyists, or civil society organizations.

Most of the stakeholder interaction involved map-elicitation, where projected climate exposure-scenarios are overlayed with TFS or airport infrastructure assets. The results are used in semi-structured interviews for which the questions are available in Appendix A.

For the TFS case study, we conducted 21 semi-structured interviews covering 18 different organizations, and 36 sectoral experts and officials; held between January 2017 and December 2017 in the context of the technical report for California's Fourth Climate Change Assessment (C4CCA). The data gathered in this process helped conceptualize and build California's fuel sector in a GIS (applied in chapter 5) as well as gather insights on its unique features and vulnerabilities to climate change (developed in chapter 3 and 5). For methodological details on the TFS stakeholder interview data collection and processing please refer to Appendix E of the 2018 technical report for C4CCA titled "Assessing Extreme Weather-Related Vulnerability and Identifying Resilience Options for California's Interdependent Transportation Fuel Sector"[62].

For the airport case study, a total of 13 semi-structured interviews were held between September 2020 and August 2021, involving six different organizations and 21 airport experts and officials. In a first instance to better comprehend airport regulation at the

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[3] https://www.sciencedirect.com/science/article/pii/S0959652621042840?dgcid=author#appsec1

national level, our interviews were directed towards FAA airport policy, airport environmental management, airport design, airport engineering experts, and FAA consulting agencies with published material on airport climate adaptation. At a second level our interviews targeted Caltrans Aeronautics airport planners; and airport officials responsible for planning, airport engineering, and environmental management from SFO, OAK, and SAN. Our second-level interviews were anchored in the coastal flood exposure results. For further information on the semi-structured interview design, data gathering, and data processing please refer to the technical report for the University of California (UC) Institution of Transportation Studies (ITS) titled "Airport Climate Adaptation Governance: actors, rules, and enablers of resilient infrastructure in California".

(c) Policy review

A systemic policy review was developed for the airport case study to generate data through the application of formal content analysis. Considering the sparsity of academic literature in airport adaptation [63–66], this study reviews overarching literature in adaptation governance, but focuses on airport adaptation policy "gray literature". Gray literature includes multilevel government publications, report literature from aviation organizations, international and national policy guidelines, protocols, standards, and state legislative documents influencing airport climate adaptation (California Senate Bills, Assembly Bills, and Executive Orders).

This review assesses policy from a spatial and temporal perspective. Policy timelines help assess the incorporation of adaptation and resilience goals through time. This issue is especially important for policies that embed scheduled or unscheduled updates (i.e., the IPCC reports scheduled for update every 5-6 years; or the California's Environmental Quality Act amendments, respectively). From a spatial perspective, this review crosses international, national, and state-level policies and guidelines at the interface of climate adaptation scholarship and the airport industry. The temporal and spatial structure of this review helps contextualize the evolution of airport adaptation policies within global, national, and state level climate change agenda, which is necessary to identify trends, barriers, and opportunities for airport climate adaptation governance.

More than 300 policy and planning documents where reviewed, including the systemic review of 129 national airport policies from the Federal Aviation Administration (FAA) and 87 legislative documents from California. For more information on the policy review data please refer to Appendix B.

1.3.2. Integration of geographical and topological space

Dominant methods that identify societies' vulnerability to natural hazards are location-based [67], which means they target economic, social, health, environmental, engineering, and other aspects that describe the propensity to damage of elements that are directly exposed to a specific hazard (spatial co-occurrence). Location-based risk assessments focus on two risk mitigative alternatives: land-use planning and structural design regulations such as building codes. Prevalence of location-based methods resulted in over-reliance of spatial overlay or intersection of hazard and exposed elements, which undermines our understanding of network exposure and vulnerability, i.e., elements that are not in hazardous areas but are prone to suffer damage due to their inherent interconnectedness to social, technical, environmental elements directly exposed. Here we combine geographical and topological concepts of space to model exposure of the infrastructure system to climate-induced hazards to understand how interconnectivity between decision-making entities (sociotechnical networks) can advance climate risk governance.

GIS is needed to understand spatial-temporal landscape processes related to climate change. In this research we apply GIS to coastal flood hazards and to assess the exposure of technical assets using the overlay technique. Coastal flood hazard is measured based on the projected flood depth and extent of sea level projections combined with extreme storm surge events. The flooding models used were developed for C4CCA [62] where the projections for 2020 to 2040 and 2080 to 2100 periods are used against GIS data models of current TFS and airport physical infrastructure. Detailed information on projected coastal flood data, infrastructure geospatial modeling, and data processing is available in sections 5.2.2, 5.2.3, and 5.2.4 respectively.

Network science is used theoretically in chapter 2 to discuss dominant methods used to measure infrastructure network criticality and is applied in chapter 5 to understand topological connectivity between infrastructure assets and social entities with formal decision-making power over infrastructure assets. Based on GIS and policy data we build two types of social networks: organizational networks for the TFS and stakeholder policy networks for airports. For the organizational and stakeholder policy networks we assess their topological structure and the roles of the nodes within the network. The main goal of the social network analysis is to provide a framework helping link decision-making power to technical assets (sociotechnical networks) and how they relate to climate risk (socioenvironmental interlinks). Key network metrics applied include centrality metrics, and community detection, further developed in section 5.2.1.

1.4. Research goal and dissertation structure

Given the paradigm shift needed to understand highly-coupled human-natural systems and unprecedented rates of change we propose two case studies to better understand the links between decision-making and landscape processes to address the climate adaptation gap. Our approach frames two sets of critical infrastructure, the TFS and airports, as technical, social, and environmental systems to improve our understanding and effectiveness of current governance system for climate risk reduction. This framework is pertinent to address temporal and spatial scale mismatch issues inherent to landscape systems and infrastructure networks. From a science-policy standpoint, our goal is to provide in-depth information about the vulnerabilities of these two sectors, while also developing insights on how to benchmark, monitor and improve climate-cognizant policy taking into consideration collaborative governance.

The goal of this research is better understanding links between decision-making power and landscape processes related to climate hazards to advance complex systems governance. The structure of the dissertation is presented in Figure 3.

To achieve this goal, each chapter is composed of specific research questions:

- Chapter 2 sets the theoretical baseline of the dissertation by questioning the influence of CI institutional framework on criticality metrics, and how does this align or misalign with CI policy resilience goals; what gaps are uncovered by these misalignments; and what solutions can be harnessed to address this misalignment based on DRR and complexity sciences theories.
- Chapter 3 presents our case study on the TFS showing how it can be framed as a social, technical, and environmental system; and based on this framework, what can be learned from the contemporary TFS vulnerability to climate change that will help improve future TFS resilience and avoid maladaptation.
- Chapter 4 presents our case study on the airport infrastructure system and provides a method to identify how climate adaptation practices can emerge through current airport regulatory structures; and what are the barriers and pathways for airport adaptation governance.
- Chapter 5 combines geographical and topological concepts of space to model exposure of sociotechnical networks to climate risk using empirical data of the TFS, airports, and coastal flooding projections. It provides applied examples of how to measure the links between climate-induced landscape hazards, infrastructure systems, and social entities with decision-making power; how these interlinks identify new roles and forms of collaboration for TFS and airport climate adaptation governance stakeholders.

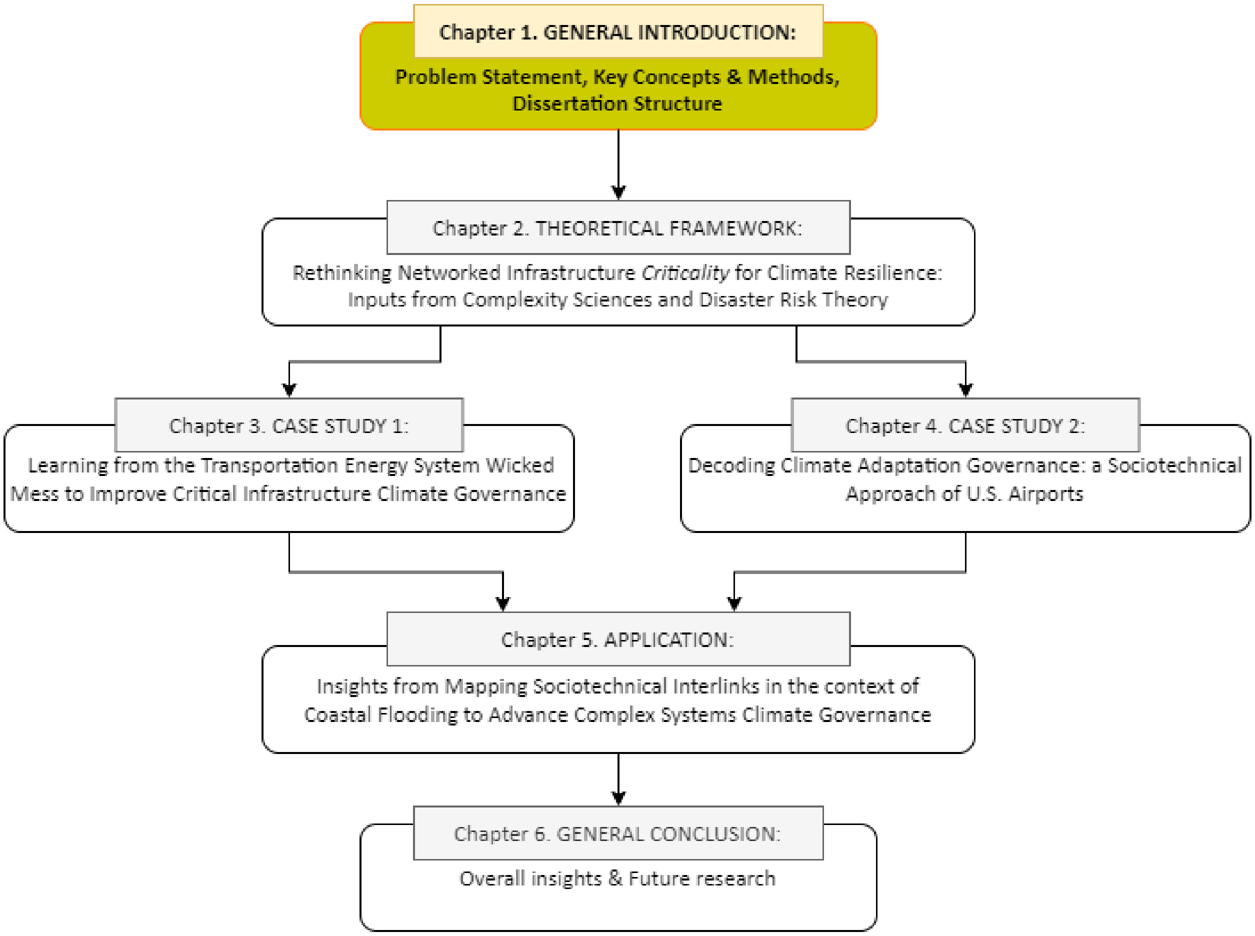
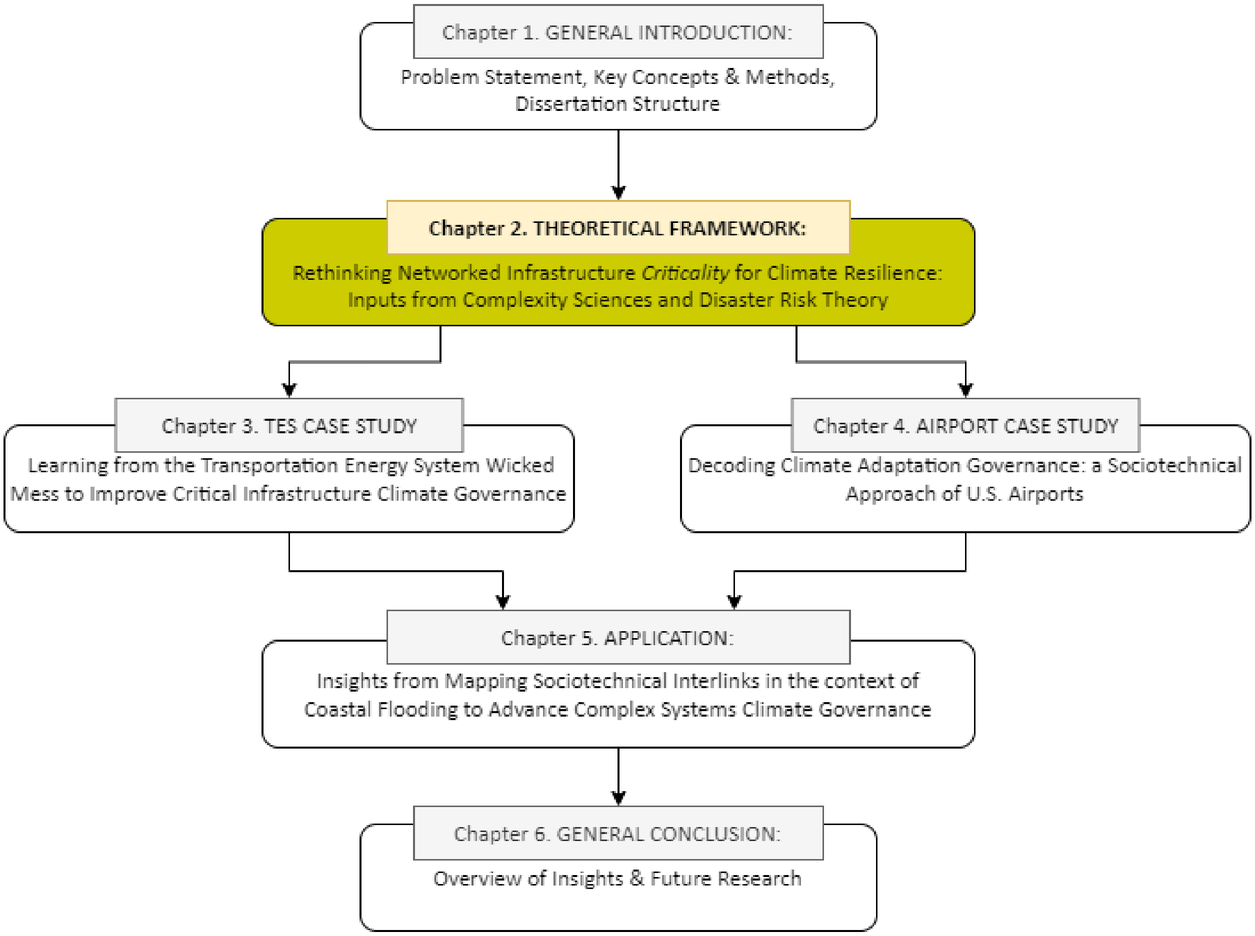


Figure 3. Structure of the dissertation

Chapter 2. Rethinking Infrastructure Network *Criticality* for Climate Resilience: Inputs from Complexity Sciences and Disaster Risk Theory



2.1. Introduction: The Institutional Legacy of Critical Infrastructures (CI)

Infrastructure criticality is intricate to modern cities metabolisms which owe their urbanization processes to innovations in water, energy, food supply, sanitation, transport systems, communication, security, safety, and other services. Debilitating effects from disruption of these utilities makes it easy to understand why they are considered the “Achilles’ heel of urbanized societies” [68]. The institutionalization of critical infrastructure (CI) and the characterization of their criticality has historically been powered by national order and security concerns. Notably, governments around the world growing terrorism threat concern, in the mid 1990’s, institutionalized CI risk management and governance amidst a security crisis [69–72].

In the U.S., the first official definition of CI dates from a 1996, Executive Order 13010, signed two years after the Oklahoma City bombing, establishing the President’s Commission on Critical Infrastructure Protection. Central governmental guidelines on CI protection came from the National Plan for Critical Infrastructure and originated from Presidential Decision Directive 63. After the 2001, 9/11 terrorist act, Executive Order 13228 established the Department of Homeland Security (DHS)[73] with responsibilities to protect a list of CI sectors. Similarly, in Europe, the development of CI policies followed the Madrid and London bombings (March 2004 and July 2005 respectively), originated the European Program for CI Protection in 2005 [74].

In the U.S., CI planning documents borrow CI definition from the Homeland Security Act of 2002:

> “critical infrastructure includes systems and assets whether physical or virtual, so vital to the US that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters”

Social studies of technology and disaster risk have well examined the legacies and issues of top-down infrastructure development and institutional standardization of CI, as from the first half of the 20th century [50,50,75–77]. Historical definitions of “vital systems security”, developed by military strategists and intelligence economists, rose throughout the 20th century interwar offensive airpower and derived tactics of strategic bombing, nuclear risk, and protection of “critical targets” [78]. This modern awareness of infrastructure criticality, formerly designed for ‘emergency states of exception’ [79], has been criticized to enable mechanisms of political administration to exert extraordinary executive powers. The advent of CI protection and the use of the resilience concept within U.S. security policies has also been critiqued as an excuse for the intense privatization of public utilities at the end of the 1970’s [80]. One other example is the transfer, in the early 2000’s, of regulatory power from the civil sectors of CI to the DHS agency, whose risk management strategies “ignore(s) the boundaries between military threat of terrorist attack and civil contingencies such as natural disasters” [81].

While the institutionalization of CI in the US triggered nation-wide investigations on CI asset design for robustness and reliability, the science of integrating those assets into a whole interacting network with systemic behavior parameters was considered fragmented at the turn of the 21st century [82]. Network science re-emerged then in multiple disciplines as a promising method that allows the abstraction of global behavior from complex systems [83–85] and it was concomitantly integrated into national security research to understand CI connectivity, dynamics, and graph-based risk assessment, including quantitative approaches to criticality.

The institutional roots and historical legacy of infrastructure criticality concepts lead us to question the influence of the CI institutional framework on criticality metrics, its impact on infrastructure modeling and how it is aligned with CI resilience goals. These questions also point to CI resilience gaps which derive from siloed disciplinary approaches to infrastructure system resilience and a technocentric approaches to infrastructure risk management, i.e.: driven by top-down securitization interests and protective measures overfocused on technical dimensions of CI and the hardening of central assets.

Technocentric approaches have also been critiqued in disaster risk reduction (DRR) theories and associated with hazard-centric risk management. These undermine intrinsic vulnerabilities and the interconnectedness of underlying sociotechnical and socioecological problems of disasters. Developed to counter hazard-centric technological fixes in DRR, the vulnerability paradigm is being integrated into CI protection policies, to expand to and strive for CI resilience policies since the turn of the 21st century [86–88]. Dialectic approaches to risk considering both hazard and vulnerability determinants, as well as the hybrid technical and social dimension of infrastructure systems, are key for addressing CI climate resilience. These approaches, rooted on theories of social construct of risk, are incipient in the current paradigm shift of CI as sociotechnical and socioecological systems, and as necessary to investigate their criticality from qualitative and quantitative perspectives.

Considering the historical legacy of CI as a military defense issue and institutional concepts of CI we raise the question on how the concept of criticality responds to current expectations of CI climate resilience policies. In other words:

- **What is the influence of the CI institutional framework on criticality metrics, and how does this align or misalign with CI resilience goals?**
- **What gaps are uncovered by these misalignments?**
- **Based on DRR, CI and complexity sciences literature, what inputs can be harnessed to address this misalignment?**

In section 2.2 we present common metrics derived from network science used to define criticality of network infrastructure from a quantitative perspective. We explain how "local" and "global" parameters allow fundamental assessments of CI network vulnerability and resilience but are highly sensitive to the function and spatial boundaries of the infrastructure network under study. We argue that the omission of this sensitivity at a conceptual level reinforces misalignments between infrastructure criticality definitions and CI climate resilience goals. In section 2.3 we highlight contributions from complexity sciences and disaster risk theory to address current conceptual gaps of CI climate resilience related to loose definitions of CI function and spatial boundaries. We explore how the definition of CI function is relevant within complexity sciences as it is a variable in the definition of ecological resilience, however, whereas ecological function is more easily translatable to socioecological systems, translating stability and collapse in terms of sociotechnical system is ambiguous. We end section 2.3 by visiting root theories of social construct of risk and the vulnerability paradigm in DRR which have high potential to better explore sociotechnical and socioecological functions of CI. In section 2.4 we illustrate the embryonic ingression of CI resilience goals in DRR and climate change policies in the U.S. These policies highlight future directions and current challenges related to CI risk governance and shared risk. We argue that there is a latent potential for theories of social construct of risk and ecological resilience to address the misalignment between criticality metrics for infrastructure networks and CI resilience goals that contribute to collective and collaborative risk governance.

2.2. Infrastructure Network Criticality Quantification and Lingering Conceptual Gaps

Quantitative and spatial concepts of infrastructure criticality in the U.S. dates at least from the first half of the 20th Century. Graph theory and systems engineering were then applied to measure high profile utility system vulnerability and criticality such as in the energy sector [89] and the oil industry [90,91]. Understanding the criticality of interconnected networks, is directly related to our ability to model their mutually dependent properties [92]. CI interdependence describes a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other, i.e., when two infrastructures depend on each other for the supply of vital services or commodities [70]. Within complexity sciences, network science, was applied to model connectivity and capture the dependencies and interdependencies of infrastructures from a spatial perspective [93–97]. Coinciding with the latest revolutions in information technology and the emergence of “big data” [98,99], network science was used as a tool for extracting explanatory and predictive power of spatial phenomena both from geospatial and topological perspectives [100]. Mathematically, this studies the relationship between elements named nodes, and their interconnections named links which together form discrete structures that are also referred to as graphs [101].

Complexity sciences have helped identify universal parameters of network criticality, which derive from the relationship between network structure (topology or connectivity) and network dynamics (flow of goods and/or services). These parameters are commonly subdivided in local and global. Local parameters pertain to characterizing the smallest units of the network, i.e., nodes and links; while global parameters describe full network characteristics such as its topological structure, giant connected component, or diameter (developed below).

Node or link criticality (local parameter) can often be attributed to CI failure cascade size through load redistribution, or contagion models; while network topology (global parameter) is used to inform network accessibility, path availability and CI disruption propagation dynamics. Local and global parameters are complementary and are frequently used in conjunction to properly assess CI network structural and dynamical organization [94,95,102–104].

2.2.1. Centrality Metrics and Local Parameters to Quantify Criticality

Local parameters, such as centrality metrics, assist in the observation that the removal of certain critical nodes or links aids rapid degradation of the network function [105]. While centrality metrics were originally applied in social sciences and social physics gravity models in the 1930s and 1940s [106,107], they have become key in CI protection plans. These metrics calculate the position, influence and overall importance of a node or link in relation to the full topological structure to which they belong and enable a ranking process of assets. Many different centrality formulas have been developed based on graph theory [108,109]. The two most common metrics rely on calculating the number of links attributed to each node such as degree and eigenvector centrality; and shortest paths calculations such as betweenness and closeness centrality [110,111]. A critical node failure for example, would increase the load or contagion on neighboring nodes which might exceed their robustness, cause their failure, and possibly trigger a cascading failure [104,112,113]. Centrality metrics are also applied in post-failure scenario to measure network infrastructure recovery process and how to maximize the restoration of network functionality. Centrality-based metrics have been mostly applied for single transportation infrastructure networks and have been recently tested to identify efficient recovery strategies for multimodal transportation networks. Percolation thresholds and phase transitions measure topological effects from disabling specific network elements to measure CI robustness and resilience [93].

2.2.2. Topological Structure and Global Parameters to Model Critical Infrastructure Networks

Global parameters such as topological structures are essential to understand the way in which nodes and links are interrelated and arranged and how their sequencing can facilitate or impede the transmission of CI information, goods, services, etc. Global metrics can be as simple as the network diameter (maximum length among all shortest paths) and or as complex as universal parameters that help the identification of probability distributions of nodes and links and emergence proprieties. The giant connected component of a CI network is commonly used to assess the functionality of the network. The most relevant theoretical models used to describe real world networks are small world and scale-free networks.

Small world networks, or the Watts and Strogatz model [114], have two important unique characteristics: short average paths and short diameter with a high clustering coefficient, or a high ratio between the number of existing links and maximum number of possible links in a graph. Small world models illustrate the key role of shortcuts in network; especially in relation to the dynamics of communication or contagion spread. Watts and

Strogatz provide empirical evidence of emergence of small world patterns in a series of real-world networks such as neural networks, film actors collaborative networks, and in CI such as the U.S. power grid. Electrical power grids are typically the only physical infrastructure network that have shown to fit the small world parameters, mostly because their optimization is tightly related to providing shortest distances between power generation, stations, substations, and the consumer [108].

Most CI and social networks follow scale-free properties [114,115]. Scale-free network models, conceived by Barabasi and Albert[114], present a highly heterogenous degree distribution forming a power law. This degree distribution indicates that most real-world networks, such as CI, are the result of a simple organizing principle like the law of increasing returns, or what Barabasi and Albert named preferential attachment. This principle states that new links are not randomly connected to exiting nodes, there is a higher likelihood that they are linked to high degree nodes, reinforcing the existence of hubs or clustered critical nodes and topological heterogeneity. Small world networks have a power law degree distribution, but scale-free networks typically present even smaller diameters and high clustering coefficients. The internet's hardware and the World Wide Web (software) [116]; the US railway and interstate highway system with Chicago as the major hub [108]; the global airline network (Molly and Reed in [93]); social network based on mobile phone data (Lambiotte et. al. 2008 in [93]), and transnational corporation ownership networks [117] all fit scale free network models.

These empirical applications of small world and scale free models near the turn of the 21st century, allowed the development of fundamental theories of CI network vulnerability and resilience with relation to random failures and targeted attacks [85,93]. More generally within DRR and CI climate adaptation, network models and criticality metrics pushed the development of methods that evaluate indirect exposure to climate hazards as opposed to purely direct exposure (topological vs. geographical proximity to hazards) [118–122].

2.2.3. Lingering Conceptual Gaps: Omissions of Network Function and Spatial Boundaries

The 21st century's re-emergence of network science found empirical strength in the engineered protection and military securitization of CI. Knowledge of topological structure is the baseline for interconnectivity modeling as it allows for the quantification of node criticality of specific physical assets as a guiding principle for protection policies [69,108]. Protection decision-making is fundamentally based on network interdiction simulations that identify worst case interdiction scenarios [94,95]. U.S. CI protection plans are technocentric, which means they focus prioritizing hardening of central nodes or hubs (physical assets) that provide higher return in terms of decreasing the consequences of failure to the entire system in a cost-benefit analysis [123]. However, it is important to underline that criticality quantification varies immensely based on how a facility or infrastructure network function is characterized and too, based on where the spatial boundaries of the system are drawn. Very often CI functionality is modeled based on connectivity properties such as centrality metrics and giant connected component, but challenges to incorporate spatial constraints to these properties remain (Table 1). Furthermore, in most CI literature, the relationships between current metrics of criticality and institutional definitions of CI functions are rarely addressed.

Better incorporating geospatial constraints to purely topological structures is a well know gap in network science, especially in studies of real-world networks, where the length of edges is relevant and will have significant effects on the network structure [93]. Nevertheless, the acknowledgement of border effects on criticality results are rare. Some examples of local and global parameters deployed in network science to quantify criticality of infrastructure networks are presented below in Table 1 together with notes, if any, on spatial boundary effects on these metrics.

Table 1. Examples of graph-based criticality metrics for CI networks

Reference	CI type	Criticality approach	Global/Local parameters	Notes on Spatial Constraints and Boundary Effects
Gao et al. (2011)	Interdependent CI or network of networks (theoretical)	System robustness	Global (giant connected component size, critical percolation threshold for first and second order transitions of cascading failures).	Recognizes gaps from the lack of incorporating spatial constraints of real-world networks. No notes on spatial or system boundaries.
Gorman et al. (2004)	Information networks	Critical nodes, network survivability	Global (Small World Hierarchy) & Local (nodal hierarchy based on accessibility index).	Recognizes drawbacks from border effect on nodal hierarchy results.
Grubesic et al. (2008)	CI network (theoretical review)	Facility importance and network operability	Global (average length of shortest path, gamma index) & Local (node accessibility/ degree centrality).	Recognizes issues of evaluating node or arc criticality in an aspatial manner and independently of network dynamical organization. No notes on spatial or system boundaries.
Holmgren (2006)	Electric power delivery networks	Network vulnerability	Global (clustering coefficient, average path length, Small world and Scale-free sensitivity to attacks).	Recognizes the shortcomings of not incorporating spatial aspects of the network.
Kasmalkar et al. (2020)	Road network	Traffic resilience	Local (metric reach of a road segment within a service radius).	Includes spatial components such as network density. No notes on spatial or system boundaries.
Matisziw,	Internet	Network	Local (origin-destination path	No notes on spatial or

Murray, and Grubesic (2009)	backbone	vulnerability	availability).	system boundaries.
Nuss et al. 2016	Supply-chain networks	Resource criticality and important actors	Local (node degree, closeness and betweenness centrality).	No notes on spatial or system boundaries.
Yadav et al., (2020)	Urban rail systems	Infrastructure node criticality, network resilience and robustness	Global (giant connected component size, average shortest path length, greedy algorithm) & Local (node betweenness, degree and eigenvector centrality).	Verifies the need to incorporate spatial constraints to real world networks resilience metrics.
Zio and Sansavini (2011)	Power transmission network	Component criticality for cascading failures	Global (cascade propagation and size) & Local (node degree, closeness, betweenness and informational centrality).	No notes on spatial or system boundaries.

While these metrics revolutionized our ability to quantify criticality of infrastructure networks, their application in real world CI systems illustrate conceptual gaps of CI resilience related to loose definitions of system functions and spatial boundaries. Some of the gaps in CI functionality assessments can be related to the difficulties of assessing CI network dynamic data (flow and usage, i.e., CI services and/or goods) which is less studied due to data accessibility issues and computational complexity.

Considering that one of the goals of complexity sciences is understanding the connections between system functions and topology [18], it is counterproductive to CI resilience that criticality concepts are ill defined. In other words, explicitly articulating CI functions and boundaries is a necessary step to reexamine criticality based on CI services, which is urgent in the context of changing climate landscapes. We argue that failure to properly assess CI network functions and spatial boundaries prior to assessing criticality through multiple local or global parameters, can cause misalignments between CI resilience goals and societal utility of CI, i.e., CI services.

In section 2.3 we highlight conceptual contributions from ecological resilience which frame CI as complex adaptive systems with panarchical cycles of stability and change; then we underline latent contributions from disaster risk theory with special attention to the vulnerability paradigm to better understand shared risk and qualify CI societal functions.

2.3. Covering Conceptual Gaps of CI Climate Resilience Bridging Complexity Sciences and Disaster Risk theory

2.3.1. Inputs from Ecological Resilience: CI as Complex Adaptive Systems

Complex system theories are the backbone to conceptual and quantitative definitions of resilience. Although resilience as a development goal gained momentum at of the turn of the 21st century [130], it stems from *resilio*, which is a Latin term for "bounce", and has been historically used in the sense of rebounding [131]. The scientific foundations of the resilience concept which is applied to DRR have originated in engineering (mid-17th Century), biology (1950's), and ecology fields (1970's). The term resilience has been traced to 1858, used by engineer William Rankine used it to describe the quality of steel beams. Resilient steel beams present both rigidity (robustness) and ability to deform under pressure (ductility) to survive the application of force [132]. These origins explain why traditional "engineering resilience" emphasizes robustness, rapidity, and speedy return to a previous stable state [133] within CI literature. Studies that adopt sociotechnical and socioecological framework of CI, aspire to ecological resilience, especially in the realm of DRR and climate risk management where there are tight couplings between socioecological systems and sociotechnical transitions [19,56,86,132,134–138]. "Ecological resilience", originating in the middle of the 20th century fields of biology and ecology, challenges the adequacy of equilibria, or "stable state" (i.e. homeostasis) to describe the wellbeing of complex adaptive systems [33] which are inherently adaptive and evolutionary [139].

The advent of resilience in complex systems theory has been traced to the biologist Ludwig von Bertalanffy, originator of the open systems theory in which mathematically describes an organism's growth [132,140]. Different from closed systems, which are stability-and conservation-centered such as the laws of thermodynamics, open systems are holistic and evolutionary, and better suited to describe living organisms. Bertalanffy characterizes an organism as a complex organization and integration of physiological functions in which the whole determines the character and function of its parts [141], de-emphasizing reductionist approaches to life sciences.

Ecologist Crawford S. Holling is responsible for mainstreaming the modern usage of resilience concept in his seminal 1973 publication "Resilience and Stability of Ecological Systems". Interested in the survival of ecological systems, Holling coins "ecological resilience", which challenges the stable-centered and equilibria theories of mature organisms or ecosystems by including the possibility of multiple stable states, non-linear causation, feedback, and self-organization.

Therefore, the idea of resilience being purely related to our capacity to absorb shocks and change while maintaining structure and function incorporates aspects of transformability and adaptation [33]. Ecological resilience draws attention to the paradox of consistency and change for survival, and has henceforth been incorporated in many fields such as psychology, social research, sustainability sciences, and notably human ecology, DRR, and climate change adaptation [29,132].

Understanding these conceptual roots and their evolution is especially relevant for tracing gaps in CI climate resilience. It is not difficult therefore to understand why the operationalization of ecological resilience has been prominent in socioecological systems studies [18,142].

Despite the epistemological divergence of "engineering resilience" and "ecological resilience", these concepts are ontologically complementary in what concerns the paradigm shift from techno-centric and hazard-centric approaches of CI protection to sociotechnical and socioecological approaches of CI resilience. This paradigm shift implies that resilient CI, within its social, ecological, and technological dimensions, process or contain information more and more effectively reflecting the ability to respond to environmental stimuli through self-organization, learning and reasoning; and through a dynamic balance of creative and conservative cross-scale cycles [18,33]. The advent of ecological resilience for CI climate risk management therefore demands process-based and iterative management policies, capable of incorporating what Holling calls "panarchical" cycles of stasis and change (syntropic or entropic change). Panarchical cycles are not necessarily sequential, fixed, or single cycles; but nested within each other with the ability of interacting across different spatial and temporal scales [33,139]. In 2001 Holling himself expanded the scope of resilience to "human-natural systems"—i.e., socioecological systems—using it as a heuristic, non-linear approach to understanding adaptive cycles in the human-natural interface [81].

Finally, complexity sciences have been most relevant to the socioecological aspect of CI systems as they harness empirical evidence from biology and ecology fields. The challenge remains in translating the concepts of function from ecosystems and ecology perspectives to the social or sociotechnical perspective. What is considered as a cycle of stasis and a cycle of entropic or syntropic change for a sociotechnical or socioecological system can present conflicting rationales and rises questions of "whose system" is being considered [134]. Again, this brings questions of stakeholder engagement and collaborative governance to the forefront of complex system resilience goals. Notably in the case of CI it raises the question: "critical for whom?" [143]. Some argue that keeping such concepts vague serves a useful purpose to give space for the development of the scientific community in the emerging field of complex systems without getting stuck in semantics [18]. Others have questioned the usefulness of the Considering the historical and quantitative issues tied to the institutionalization of CI, the vagueness in the definition of function is not only a passive space for reflection, but it flags the need for active, iterative and critical examinations of what is being assumed as critical; notably in in the context of DRR and climate risk management, where resilience has become a status quo policy goal in the last two decades [144] and assumed as a desirable outcome.

2.3.2. Inputs from Disaster Risk theory and Social Construct of Risk to Qualify CI Functions

Failure of massive international infrastructure investments in jump-starting economic development have already justified criticism of infrastructure as being purely grandiose technical and physical capital as understood in the 1960s and 1970's [76]. Concomitantly, the emergence of sociotechnical theories in safety science (systems engineering) and social science approaches of organizational behavior [61,72,145–147] and of science and technology in the 1970's and 1980's [148,149] helped frame infrastructure beyond hardware. As sociotechnical systems, infrastructures represent complex interactions between humans, organizations, institutions, and technology [138]. The relevance of sociotechnical frameworks for resilience studies has been highlighted as a powerful approach in engineering systems for "joint optimization" to cope with uncertainties of disturbances under "un-designed" and "non-linear relationships" between human and technical factors [150]. Amir and Kant [138] harness further contributions from science and technology studies by emphasizing the "transformability" character of sociotechnical resilience through informal relations, sociomaterial structures and anticipatory practices. These are considered as key mechanisms of resilience that enable "sociotechnical systems to shift from one configuration to another in response to shock and disruption".

The view of infrastructure as sociotechnical systems developed our understanding of modern and systemic vulnerabilities derived from the inseparableness of technology, society, and nature [75]. Our knowledge of these systemic vulnerabilities, of infrastructure influence on planetary carbon metabolism, and of global environmental change issues, was incorporated in the international policy agenda with milestone guidelines from the United Nations (UN) and the Intergovernmental Panel on Climate Change (IPCC) between the late 1970s and late 1980s. Concomitantly, in social sciences the pivotal concepts of "tight couplings" and "risk society" were being produced, respectively, by Charles Perrow in 1984 and by Ulrich Beck in 1986. Fundamentally from similar scholarships, these terms are rarely associated in CI literature, but were clearly described new forms of risk as a consequence of heightened interdependencies and modern society while pointing to important contributions to CI risk management [151,152].

"Tight couplings" is the term used to characterize interactions within infrastructure systems and between infrastructure and human systems with processes that happen very fast and cannot be isolated in case of failure. Tight couplings lead to unavoidable system failures. Often used in safety and reliability and system engineering disciplines, "tightly coupled systems" refers to complex interactions "of unfamiliar sequences, and either not visible or not immediately comprehensible" [153]. Perrow's organizational theory of the production of risk, describes unexpected failures, or "normal accidents" of technological systems that can quickly lead to catastrophic risk. This path between "seamless accidents" and catastrophic risk is characteristic of higher interdependencies between society and technology through infrastructure systems and sociopolitical contexts of organizations [70,135,154]. Although not commonly explored in CI literature, Perrow's sociotechnical perspective on modern risk also contributes to the identification of populations with no power in the decision of their exposure to hazards. This population is also referred as "third" and "fourth-level victims" of modern catastrophes such as innocent bystanders or future generations that are exposed to far reaching effects of technological hazards but excluded from discussions that affect them. As opposed to "first" and "second level victims", such as operators of the system and users or suppliers of the system respectively, they do not choose to participate in the system but still share the risk. This concept of shared risk also brings therefore, stakeholder engagement [155,156], collaborative governance [157,158], and ethical issues such as questions of fair exchange of risk [159], to the forefront of CI climate resilience problems.

From the socio-cultural perspective, Beck's "risk society" presents a theory of "man-made" risk as "unintended consequence of modernity" [160]. Beck also argued that the novelty of contemporary risk is in the scale of spatial distribution and in the ability to affect multiple generations [161]. "Risk society" corroborates with theories of social production of risk which emphasize the intrinsic characteristic of risk, originating within society itself [28,162]. This intrinsic characteristic of risk has been theorized and applied in (DRR) as the vulnerability paradigm [23,25,27,163–165]. It has been noted that the advent of the vulnerability paradigm in DRR in the 1980's, relates to the social construct of risk; the authors add it also corroborates the sociotechnical approach of CI resilience.

Hellström [86] highlights the relevance of the vulnerability paradigm to assess the recursive progression of vulnerability in CI. The DRR's classic "pressure-and-release" (PAR) vulnerability model, first published in 1994 by Wisner et al.[26], was designed to identify the progression of vulnerability looking through the links of "root causes" and "dynamic pressures" that create "fragile livelihoods" or "unsafe location conditions" which, when intersected in time and space with hazards, provide a chain of explanation to disaster risk. By understating the links that feed into dynamic pressures of vulnerability we can also develop methods to "reverse-engineer" the process and introduce coping or resilience capacities and "release the pressures". PAR functions as process-tracing inquiry system to understand risk by emphasizing the vulnerability component, thus expanding on socioeconomic, ideological, cultural, political, and historical processes.

The relevance of the PAR model is emphasized by the sociotechnical system framework Hellström applies to information communication technology networks. The vulnerability paradigm demonstrates the shortcomings of technocratic approach to risk. Likewise, traditional CI protection focuses on facing hazards with war-like strategies, such as engineering-centered guidelines for "infrastructure defense" developed under the International Decade for Natural Disaster Reduction [166]. Issues of overemphasizing hardening or structural measures have been thoroughly critiqued within the vulnerability paradigm as they fix on infrastructure "hardware" and containment of hazards with reactive command-and-control strategies [163]. Taken in isolation, these tecno-and hazard-centric approaches have been proven to: (1) function as "band-aid" solutions that fail to understand the dynamic pressures and roots causes of disasters [26]; and (2) become very disconnected from everyday development practices thus counter-productive to holistic disaster planning and increase quality of life overall [167–169]. Furthermore, focus on infrastructure hardware, or "technical" dimensions, has resulted, sometimes tragically, on an overreliance on design and building standards for implementing resilience strategies in multiple sectors. This overreliance, especially in the case of long-lived and capital intensive infrastructure investment, is no longer considered as a reasonable assumption in engineering and architecture practices that are compelled to plan in view of deep climate uncertainties [170,171].

CI resilience studies informed by complex adaptive systems theory point to the of gap of properly addressing the “panarchical” nature of CI systems collapse and its social, ecological, and technological interlinks. Pescaroli and Alexander[136] explain that the interconnectedness and interdependence of CI significantly increases the potential for cascading failures, but they build on promoting the investigation of CI vulnerability pathways to better understand cascading disasters root causes and unpredictability (similar to the PAR vulnerability model). These vulnerability pathways, beyond the physical infrastructure fragilities, address cross-scale vulnerabilities rising from CI services ambivalent relationship with socioecological systems, i.e., providing resource and damage simultaneously. There is a clear distinction between what is narrowly defined as a sequence of events with linear cause effect relationships, and the “toppling domino” effect of CI cascading failure and “panarchical collapses”. Pescaroli and Alexander suggest a paradigm shift necessary to interpret CI complex adaptive systems where interdependencies and interlinks represent local and global dynamics that together form panarchical cycles. When a cascading event is triggered, it progresses through unresolved vulnerabilities concentrated in these interdependencies. The “alignment” of unsolved vulnerabilities will result in non-linear amplification of disaster impacts through complex social, ecological and technological chains creating panarchical collapses. Corroborating with the vulnerability paradigm, this calls for a shift from hazard-centric triggered cascade pathway inquiries to vulnerability cascade pathway inquiries. The emphasis here is on understanding “worst case amplification scenarios” instead of “worst case scenarios based on initial triggers”.

In section 2.4 we illustrate the ingression of CI resilience in DRR and climate change policies at the international and U.S. levels, with special focus on California’s climate change impact assessment system and pioneering infrastructure climate adaptation standards and regulations.

2.4. Resilience Ingression in DRR & Climate Change Policies in the U.S. and its Implication for Future CI Research

Rinaldi et al.[70] bridged ecological resilience theories and CI resilience, defining both as “complex collections of interacting components in which change often occurs as a result of learning processes; that is, they are complex adaptive systems”. From this bridge, Rinaldi et al pioneered fundamental concepts of CI interdependence which have been widely used in infrastructure network engineering and spatial models. After the turn of the 21st century, the concept of resilience, originating in systems theory and ecology in the 1950s and 1970s, becomes the premise for DRR, climate change adaptation and CI science-policy guidelines. Nevertheless, the alignment of ecological resilience discourse with CI network risk management and the vulnerability paradigm is still under way. In this section, we provide a brief description on how CI resilience goals emerged in international, U.S. and regional policies within climate adaptation, DRR and CI planning documents. We specifically underline the recent preoccupation with cascading failure of CI as well as cascading risk due to CI exposure to climate disasters in DRR and climate change documents. This coincides with the incorporation of ecological resilience to infrastructure risk management. Two important challenges and future trajectories for CI resilience can be inferred from these policies studies: creating and reinforcing climate-cognizant infrastructure design and standards, and collective organizational challenges of regional or large-scale infrastructure systems governance to address climate adaptation within collaborative frameworks.

At the international level, it was not until the 2005-2015 UN Hyogo Framework Action that resilience, based on persistence (robustness and reliability), preparedness (learning capacity and redundancy), adaptability (being flexible) and transformability (being innovative) [172], was officially incorporated in DRR policy guidelines [168,173]. The relevance of understanding cascading risk or "sequential effects", through social and spatial scales was only officially addressed in the current U.N. Sendai Framework priorities for action [9]. This latest international policy guideline for DRR also explicitly addresses, for the first-time, complex supply chains as drivers of vulnerability (I.6. p.10) and identifies resilience of new or existing "critical infrastructure" and "critical facilities" as a priority at national and local scales (IV.30. c., and 33.c). The criticality of CI here is inferred as "life-saving and essential services" during and after disasters such as water, transportation, telecommunications educational and health facilities. Within climate risk management in international policy, the IPCC only targeted CI interdependencies and cascading failures as key resilience challenges for the first time in the Fifth Assessment Reports (AR5) [174].

At the U.S. level, the establishment of climate science-policy guidelines for infrastructure adaptation is centralized in the National Climate Change Assessments (NCA), first published in 2000 [175], and which is charged with interpreting global climate risk at the U.S. scale and reporting it to the Executive and Legislative powers. In the early 2000's climate change science started to slowly penetrate national security agenda in the U.S. Military intelligence reports, to dismiss uncertainties of the climate change "scientific debate" over the potential consequences of extreme weather on food, water and energy security [176]; and in which famously acknowledging climate change as "threat multiplier" to underlying geopolitical instabilities due to natural hazards or natural resource accessibility issues [177]. This military recognition of climate change as a security threat inspired metaphorical descriptions of U.S. mitigation and adaptive efforts as "war against climate change", which, some argue, represented a milestone in the communication of urgency and risk of climate resilience [178].

At the regional level, California's Climate Change Assessment (CCA) was the first state-level guideline to iteratively downscale climate models, improving their accuracy and promoting state-relevant infrastructure adaptation policies in the U.S. Nevertheless, it was not until 2009, at the second NCA and California's CCA that the focus by both was with climate mitigation (emissions reduction) and with adaptation policies, including infrastructure-sector-specific strategies [179,180]. The main outcome of California's 2nd CCA was the 2009 Climate Adaptation Strategy that supported new climate adaptation laws, notably Assembly Bill AB-1482: Climate Adaptation Strategy introduced on February 27, 2015 and establishing the Strategic Growth Council leadership to continually update the state's climate adaptation strategy, aligning it with California's Five-Year Infrastructure Plan in coordination with other agencies. Later, California AB-2800 “Climate Change: Infrastructure Planning”, approved September 24, 2016, was introduced which required California state agencies to incorporate current and future climate change impacts specifically when planning, designing, building, operating, maintaining, and investing in state infrastructure. The advent of the resilience discourse in DRR and climate risk international policies has only recently trickled down to national and local infrastructure resilience policies. In other words, the incorporation of climate risk into infrastructure planning is novel and the institutional alignment of DRR, climate risk management and CI resilience is embryonic. Nevertheless, policies such as AB2800 are pioneering where they promote “climate-safe infrastructure” guidelines which simultaneously address issues of climate mitigation and adaptation emphasizing social equity discourse, and governance as a major enabler of resilient infrastructure [181].

From the CI planning perspective, DHS’s association of resilience to security of CI was one of the main changes of the theoretical discourse of the latest National Infrastructure Protection Plan from 2013, a contrast to the former version that focused narrowly on infrastructure protection. The resilience concept is conceived as the “ability to prepare and adapt to changing conditions and withstand and recover rapidly from disruptions […] Resilient infrastructure assets, systems and networks must also be robust, agile and adaptable.”[73]. Although this integration mostly focuses on technical domain infrastructure systems, addressing physical and cyber aspects of CI, it benchmarks increasing influence of ecological resilience within CI management and planning [88,182–187]. Furthermore, sociotechnical dimensions of CI are integrated in this latest national policy through the reinforcement of collaborative platforms referred as the “National Partnership Structure”. Notably promoting public-private sector and cross-sector coordinating structures for government agencies and private sector operators and owners across jurisdictions and administrative boundaries. Yet, in light of recent disasters and updates on climate change risk, assessments of CI resilience challenges demonstrate limitations of current governance structures to find balance between prescriptive and voluntary collaborative mechanisms for effective partnerships [188,189]. The effectiveness of these CI partnerships and their complex governance structures remains obscure. Further research of these governance structures through organizational and policy network analysis [190–192] would contribute to our understanding of CI sociotechnical interlinks as well as network level CI stakeholders which should strive to include Perrow’s third-level victims.

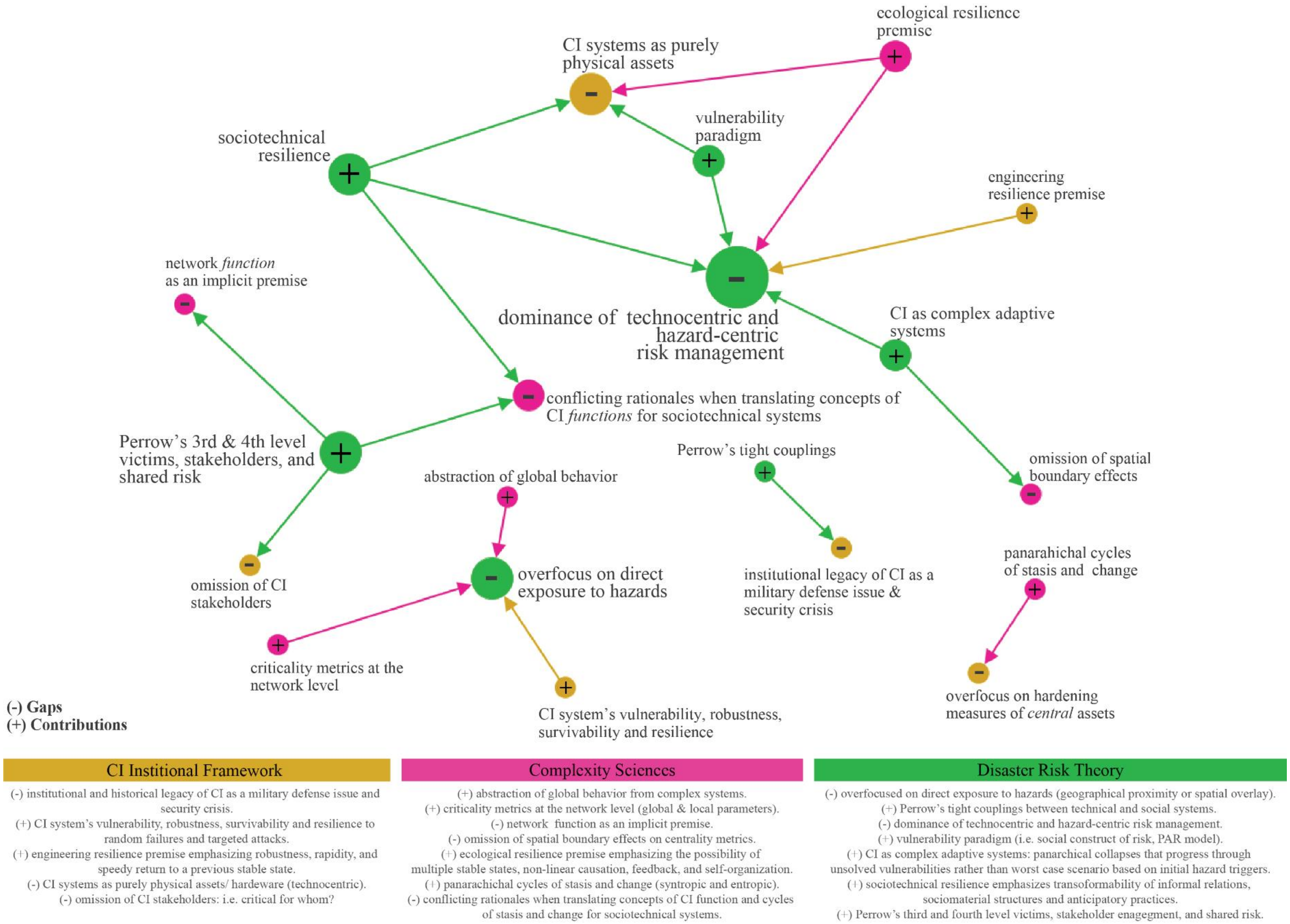
2.5. Conclusion and Discussion

Considering the substantial research that flags the militarized legacy of infrastructure planning and its counter-productive effects on DRR, we lack understanding of how this conceptual approach has informed quantitative assessments of infrastructure criticality. The relationships between institutional CI definitions and current metrics of criticality are rarely addressed, in other words consensus of criticality is assumed and this assumption is visible in quantitative assessments, where explicit discussions of infrastructure network functionality and spatial boundaries are rare or non-existent. Therefore, despite considerable progress in our ability to model and quantitatively assess network level criticality through local (i.e., centrality metrics) and global network parameters (i.e., cascading thresholds, giant connected component), functions of CI networks are often implicit premises, and the effects of spatial boundaries is omitted. Investigating how the institutional legacy informs these assumptions is an important next step to realign criticality metrics to CI resilience goals, especially in the context of climate change risk. This realignment responds to current policy premises of ecological resilience for CI, viewing them as complex adaptive systems, with social, ecological, and technological dimensions.

When modeling CI, we call for a reexamination of infrastructure networks functions and spatial boundaries to harness our conceptual advancements on CI resilience within disaster risk theory and complexity sciences. Figure 4 presents a summary of the gaps from different literature bodies covered in this chapter as well as their complementary contributions to the paradigm shift defining CI as sociotechnical and socioecological systems for climate resilience.

Rethinking infrastructure network criticality through an ecological resilience lens provide insights to prevent maladaptation and to proactively address climate change lock-in issues [52,56]. Climate lock-in mechanisms stem from our reliance on hydrocarbon-dependent infrastructures are well researched and established, but they are also embedded in the amplification of vulnerabilities due to CI exposure to climate threats. With consideration of the militarization, securitization, techno-and hazard-centric critique of CI, some argue that the resilience premise is necessary to ultimately re-invent our relationship with vital infrastructures [77,193]. This new relationship could rise with the recognition of co-benefits from green infrastructures and ecosystem services [194,195]; the evidence of increased efficient, effective, and equitable use of natural resources through decentralization and short lead times of alternative energy infrastructure [80,196,197], and the emancipation of grass-roots infrastructural stewardship [198].

Most common applications of ecological resilience within socioecological systems apply graph theory to ecosystem conservation or socioecological sustainability. Some examples are studies that enhance conservation management through governance networks [199–204] and transition management for sustainable natural resource regimes [51,199,205–207]. Fewer examples apply concepts of ecological resilience and graph theory to DRR and climate change risk management, some of these have developed pioneering methods to: improve collaborative governance for climate adaptation [43]; and incorporate social network analysis to improve flood risk management [49,53], wildfire risk management [208,209]; and model organizational networks to improve situational awareness for disaster response and emergency management [210–212]. The dominating risk assessment framework in DRR focuses on direct exposure, or calculating risk based on spatial overlay of people, goods, and hazard. The bridge between DRR and complexity sciences still has much room to improve our understanding of indirect exposure and vulnerability from a systems perspective i.e., better assessing elements that are not in hazardous areas but still prone to suffer damage due to their inherent interconnectedness to complex socioecological and sociotechnical systems, which are in turn, directly exposed. Even though this concept of indirect exposure



CI Institional Framework

(-) institutional and historical legacy of CI as a military defense issue and security crisis.
(+) CI system's vulnerability, robustness, survivability and resilience to random failures and targeted attacks.
(+) engineering resilience premise emphasizing robustness, rapidity, and speedy return to a previous stable state.
(-) CI systems as purely physical assets/ hardeware (technocentric).
(-) omission of CI stakeholders: i.e. critical for whom?

Complexity Sciences

(+) abstraction of global behavior from complex systems.
(+) criticality metrics at the network level (global & local parameters).
(-) network function as an implicit premise.
(-) omission of spatial boundary effects on centrality metrics.
(+) ecological resilience premise emphasizing the possibility of multiple stable states, non-linear causation, feedback, and self-organization.
(+) panarachichal cycles of stasis and change (syntropic and entropic).
(-) conflicting rationales when translating concepts of CI function and cycles of stasis and change for sociotechnical systems.

Disaster Risk Theory

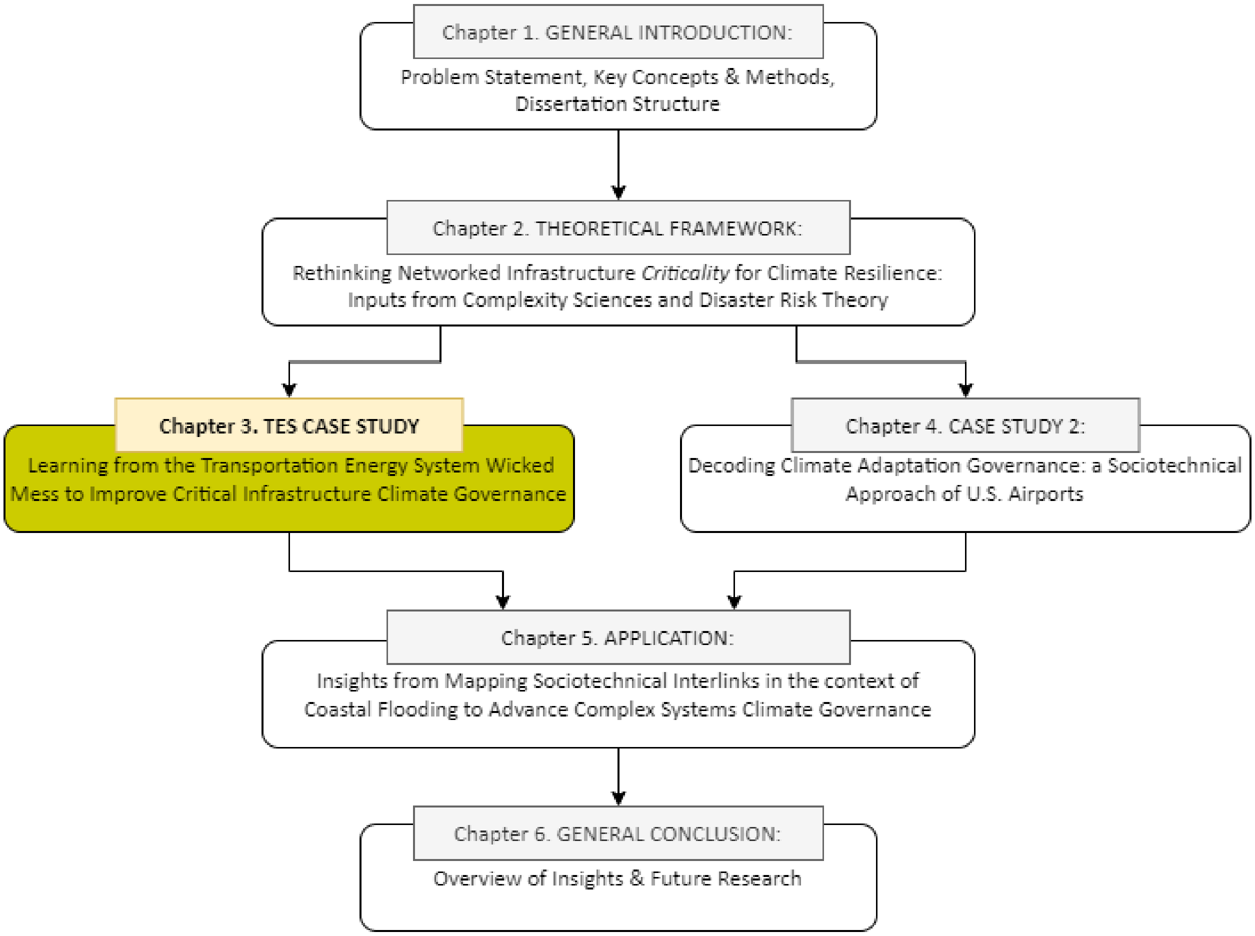
(-) overfocused on direct exposure to hazards (geographical proximity or spatial overlay).
(+) Perrow's tight couplings between technical and social systems.
(-) dominance of technocentric and hazard-centric risk management.
(+) vulnerability paradigm (i.e. social construct of risk, PAR model).
(+) CI as complex adaptive systems: panarchical collapses that progress through unsolved vulnerabilities rather than worst case scenario based on initial hazard triggers.
(+) sociotechnical resilience emphasizes transoformability of informal relations, sociomaterial structures and anticipatory practices.
(+) Perrow's third and fourth level victims, stakeholder enagegment, and shared risk.

Figure 4. Summary of gaps and contributions to define CI as technical, social, and environmental systems

(or network-level vulnerability) stemming from heightened interconnectedness is maturing in DRR and CI climate resilience literature, the challenge remains on how to incorporate indirect exposure metrics, derived from network criticality assessments for example, to climate adaptation policies.

Finally, we underline those dialectic approaches to risk bridging the DRR vulnerability paradigm to the sociotechnical approach to CI is key to better align infrastructure network criticality to their societal utility. Theories of social construct of risk, are incipient in the current paradigm shift of CI as sociotechnical and socioecological systems, and necessary to better describe their complexity from qualitative and quantitative perspectives. The definition of functions and spatial boundary are less controversially addressed from the technical and ecological side, thus revisiting criticality perspective of CI network infrastructures begs a better incorporation from theories derived from social construct of risk. They have a latent potential to better inform complex system theories how to incorporate and interpret social dimensions of CI models (i.e., organizational networks and governance structures), that are equipped to leverage or at the very least, expose trade-offs depending on “whose system” is being considered; who are the stakeholders managing, planning, and designing CI resilience; and what is their agency in alleviating collective action problems. CI as sociotechnical and socioecological systems must fulfill socially valued functions. Therefore, theories of social construct of risk can help expose shortcomings of CI resilience approaches that lack articulation of shared risk (i.e., Perrow’s third and fourth level victims) or lack iterative examinations of CI services based on changing climate landscapes. Once we better address the question of “whose system” is being considered for CI resilience, new questions will need to be addressed on how to enhance collaborative governance among sociotechnical and socioecological systems to plan for and adapt to changing climate risk landscapes.

Chapter 3. Learning from the Contemporary Transportation Fuel System Wicked Mess for More Resilient Critical Infrastructure Climate Risk Governance



3.1. Introduction: The contemporary transportation fuel sector as source and effect of climate-induced disasters

Energy-dense fossil fuel powering internal combustion engines is the major technological innovation behind the Industrial Revolution. This technological innovation has set widespread modern living standards related to the movement of goods and people. Current plans to transition to a net-zero energy system by midcentury and deep decarbonization policies brings us to the brink of what could be called a second Industrial Revolution[213] that will reshape our transportation fuel systems.

Today, the energy sources used for transportation fuel in the U.S are electricity (0.1%), natural gas (1.6%), biomass (4.1%) and petroleum (94.2%)[214]. In California, where emission reduction policies have pioneered with air pollution concerns in the 1970's and gained strength in the early 2000's, petroleum represents 90.1% of transportation fuel source in 2020 [215]. The contemporary transportation fuel system (TFS) still relies predominantly on fossil-fuel sourced energy. However, we are compelled to think of the TFS resilience to climate change under an unprecedented policy mobilization for energy transition previewed to take place the next thirty years[10,13].

Our reliance on the contemporary TFS is not only the major cause of the climate change crisis, but it is also behind the potential for climate-induced hazards to cascade into major disasters. The TFS is at the crux of climate mitigation (emissions reduction to act on the cause of climate change) and climate adaptation (vulnerability reduction and capacity enhancement to better withstand the unavoidable effects of climate change hazards) to improve climate resilience. Research pointing to the co-benefits of better integrating climate mitigation and adaptation has been growing in the past two decades[216,217], however little is seen in sectoral level policy analysis of synergies and tradeoffs between them[218,219]. Even less research has been seen on the strategic decommission of the contemporary TFS given its function as a CI. While this chapter focuses on the latter issue (climate adaptation), failure to frame the TFS as both source and effect of climate-induced disasters will result in siloed climate resilience policy that focus on energy transition processes without considering the TFS vulnerabilities beyond carbon-emission and non-renewable technological fallacies. Focusing on CI resilience and adaptation goals, this study seeks to explore core vulnerabilities of the contemporary TFS without losing sight of the impending overhaul of what we know today as the fossil-fuel sector.

The energy transition requires rapid rates of change in research development and technology deployment accompanied by shifts in public policy and social systems that add extra layers of uncertainty to managing the projected impact of climate hazards to the TFS. Policy recommendations for the deep decarbonization of the U.S. target both technological and socioeconomic shifts in the next three decades[213]. Decarbonization policy technological goals include the electrification of energy services in transportation, buildings, and industry; investment in energy efficiency and productivity relative to fossil fuel boilers and internal combustion engines; production of carbon-free electricity; and building and upgrading electrical energy infrastructure. Decarbonization policy socioeconomic goals seek to compensate for historically marginalized populations which on one hand have suffered from lower access to energy efficient technologies and on the other hand are overly exposed to health and environmental hazards derived from fossil-fuel energy and climate change. We argue that better understanding the contemporary TFS as CI with sociotechnical and socioenvironmental dimensions is necessary to better plan for a transition into a TFS that achieve decarbonization socioeconomic policy goals.

From a CI resilience and supply chain sustainability perspective, this chapter rereads Lovins and Lovins' pioneering research on energy infrastructure and security[80] and Sovacool's overview of energy policy challenges, applying it to TFS-specific challenges. We then build on empirical research from the latest California Climate Change Assessments identifying resilience options for the state's transportation fuel sector given projected climate impacts. We expand Radke et al[62] first-time depiction of the transportation fuel sector physical network at the state level, to frame it as social, technical, and environmental system. This chapter explores the applicability of our theoretical framework, presented in chapter 2, for the investigation of climate resilience of CI systems, which in this case, is expected to undergo dramatic shifts in the next 30 to 80 years, and seek to answer the following question:

- **How can the TFS be framed as social, technical, and environmental CI system?**
- **Based on this framework, what can we learn from the contemporary TFS vulnerability to climate change that will help improve future TFS resilience?**

We start by defining what is currently known as the contemporary TFS, to bring forth five unique traits of this CI, contextualizing the "wicked mess" of the TFS resilience to climate change. TFS-related disaster cases in the U.S. then illustrate how these unique traits reveal underlying vulnerabilities of the TFS based on how they amplify disasters cascading impacts at different scales. We then gather contributions from research on California's fuel sector future exposure to climate threats such as wildfires and flooding, which together with lessons learned from past disasters, help point to the significant value of measuring network-level vulnerabilities and its implications for CI governance fragmentation and energy services. We then argue that framing the TFS as a complex system through better investigating its social, technological, and environmental interlinks is key to improve the TFS governance for CI climate resilience. Harnessing concepts from supply chain transparency and network science, we discuss the benefits of better understanding sociotechnical interlinks of the TFS. These interlinks are key to mapping sociotechnical network exposure; and can help address scale mismatches between the temporal and spatial scales of governance; and the scales of landscape processes related to natural hazards. This approach is expected to help move from simply managing supply chains of vital commodities for due diligence and risk reduction, to predicting and preventing lock-in of unsustainable practices which reinforce current TFS vulnerability patterns.

3.2. Understanding the contemporary transportation fuel system and its wicked mess

3.2.1. Defining California's contemporary transportation fuel system infrastructure and organizational network

From an industry perspective, the contemporary TFS is represented today mostly by the fossil fuels, or oil and gas sector, commonly subdivided by the crude oil upstream (unprocessed) and fuel products downstream (processed) sectors. Physically the contemporary TFS has been represented as the supply chain network of assets necessary to extract, process, stock, and transport crude oil derived fuel to consumers. From a geospatial modeling perspective, the TFS has been depicted through nodes, representing assets that store or transform crude oil into transportation fuel; and links representing assets that transport crude oil and its finished fuel products to final users through multimodal infrastructure (pipelines, roadways, railways, and waterways) (Table 2). The geospatial depiction of the TFS is essential to identify in space where there is co-occurrence of physical infrastructure assets and projected climate-hazards (Radke et al, 2018 and He et al 2021). In Radke et al (2018), to understand the exposure of fuel assets to climate-induced hazards, the infrastructure corresponding to the nodes and links of the fuel supply chain are conceptualized in the form of a schematic (Figure 5). This schematic helps identify the infrastructure assets that are necessary for the reliable supply and distribution of transportation fuels in the state as is illustrated in Figure 6. It is then used to build the geospatial model of the fuel supply chain, their multimodal connections, and their various dependencies (see chapter 2 and Appendix A, Radke et al, 2018)

Table 2. Contemporary transportation fuel infrastructure geospatial representation in California

Industry segment	*Commodity (Production % in CA[62])*	*Nodes*	*Links*	*Energy transition policy stage[10]*
Unprocessed (fuel feedstock)	In state crude oil (31%)	Oil wells Gathering station Marine Terminals Rail terminals Refineries	Crude oil gathering pipelines Crude oil pipelines Waterways Railways	Will reflect policies applied to end-use fuel products (see below) and other industries that rely on crude oil as feedstock
	Out-of-state crude oil (69%)	Marine terminals (crude oil docks) Rail terminals	Waterways Railways	
Processed	Vehicle	Vehicle fuel	Product pipelines	Commercial:

(ready to use fuel product)	fuel (80%)	stations Terminals Break out tanks Refineries	Waterways Roadways	deployment underway*
	Aviation fuel (16%)	Airport fuel terminals Terminals Break out tanks Refineries	Product pipelines Waterways Roadways	Pre-commercial: Expansion in innovation and investment in clean energy research development.
	Marine fuel and Gasoil (<5%)	Marine fuel stations Terminals Refineries	Product pipelines Gasoil pipelines Waterways Roadways	
	Alternative fuel for vehicles (<1%)	Alternative fuel stations (fast charging stations, biodiesel, ethanol, hydrogen, natural gas) Biofuel Plants Natural gas processing plants	Roadways Railways Waterways Transmission and distribution power lines	Commercial: deployment underway*

*Major policies setting rules and standards to accelerate the formation markets for clean energy directly affecting regular and alternative vehicle fuel commodities include: GHG emissions budget reaching net-zero by 2050; Set national standards for light-, medium-, and heavy-duty zero-emissions vehicles, and extend and strengthen stringency of Corporate Average Fuel Economy (CAFE) standards. Light-duty zero-emission vehicle (ZEV) standard ramps to 50% of sales in 2030; medium- and heavy-duty to 30% of sales in 2030; set clean energy standard for electricity generation, designed to reach 75% zero emissions electricity by 2030 and decline in emissions intensity to net-zero emissions by 2050; enact five federal actions to advance clean electricity markets, and to improve their regulation, design, and functioning; deploy advanced electricity meters for the retail market, and support the ability of state regulators to review proposals for time/location varying retail electricity prices; expand electric vehicle (EV) charging network for interstate highway system.

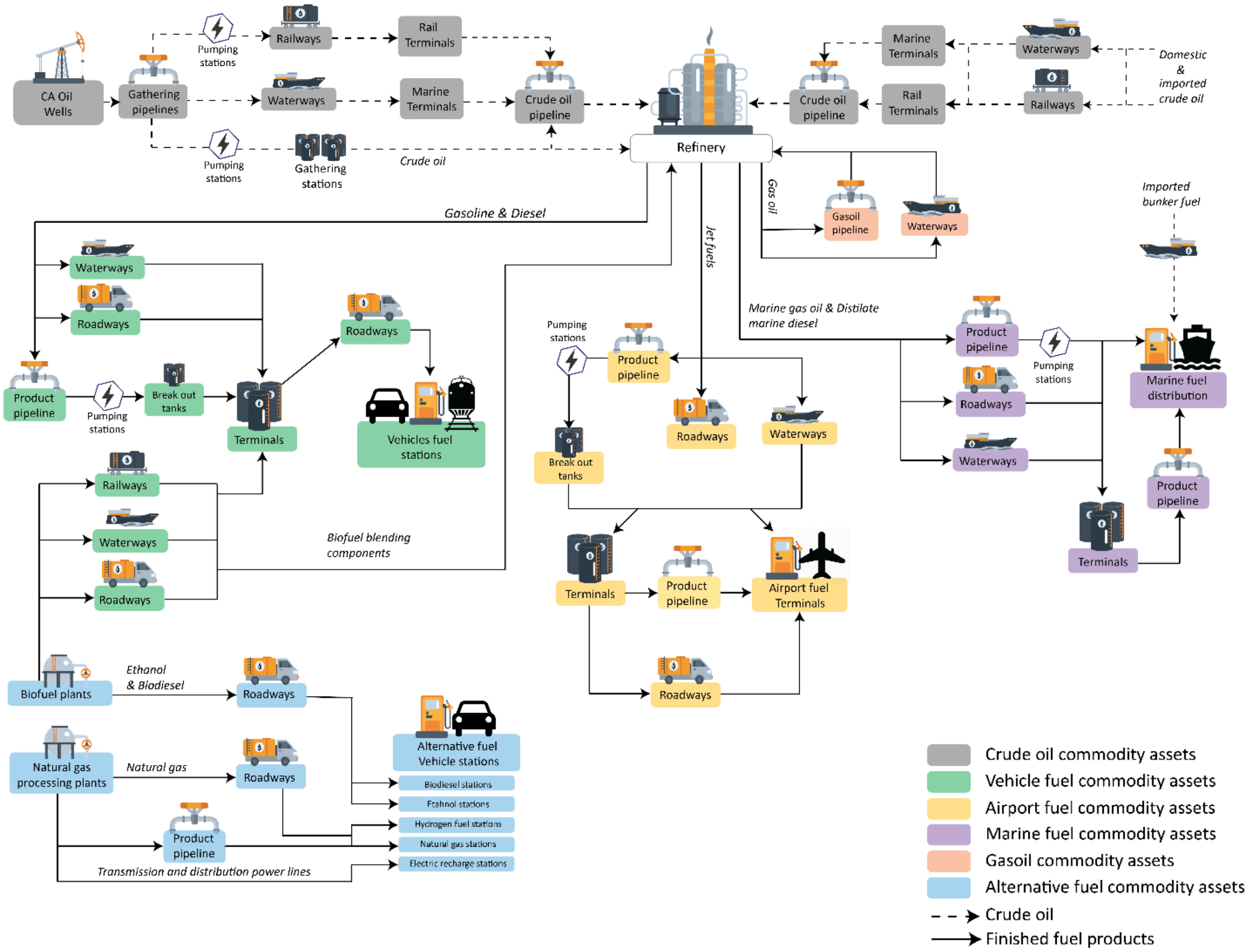


Figure 5. Conceptual model of the contemporary transportation fuel sector in California (adapted from Radke et al, 2018)

The conceptualization of the fuel sector in California and its geospatial representation heavily relied on a stakeholder engagement process. The stakeholder engagement process was iterative involving industry asset owners, operators, and regulators to help understand organizational relations, governance frameworks, and perceived vulnerabilities against the projected climate-hazards. A total of 47 organizations participated in the representation of the fuel sector including: those that own or operate key node and link assets; those that depend on the fuel commodities (power and water supply, emergency services); or those that are involved in research and development, or regulation of the transportation fuel sector (see chapter 4 and Appendix E of Radke et al for more information). This geospatial depiction was necessary to understand the connectedness and complexity of the state-level fuel sector at the physical level, but also at the organizational level, where governance is fragmented through a vast and unknown number of majorly privately owned organizations (Table 3). The fuel sector depiction in California will be used in this chapter to understand how the boundaries of the contemporary TFS are drawn and to model sociotechnical network exposure to future climate hazards (developed in Chapter 5).

Table 3. Estimated number of owners and operators of fuel assets in California based on geospatial data attribute (adapted from Radke et al 2018)

Key assets		*Number of organizations*	*Dominant industrial sector*
Nodes	Refineries	10	Energy
	Terminals	30-35	Energy and Transportation
	Ports	100-200	Transportation
	Airports	150-200	Transportation
	Gas stations	1000-2000	Energy
	Oil wells	750-800	Energy
Links	Pipelines	35-40	Energy and Transportation
	Trucks	200-250	Transportation
	Rail	15-20	Transportation
	Vessels and Barges	No available data	Transportation

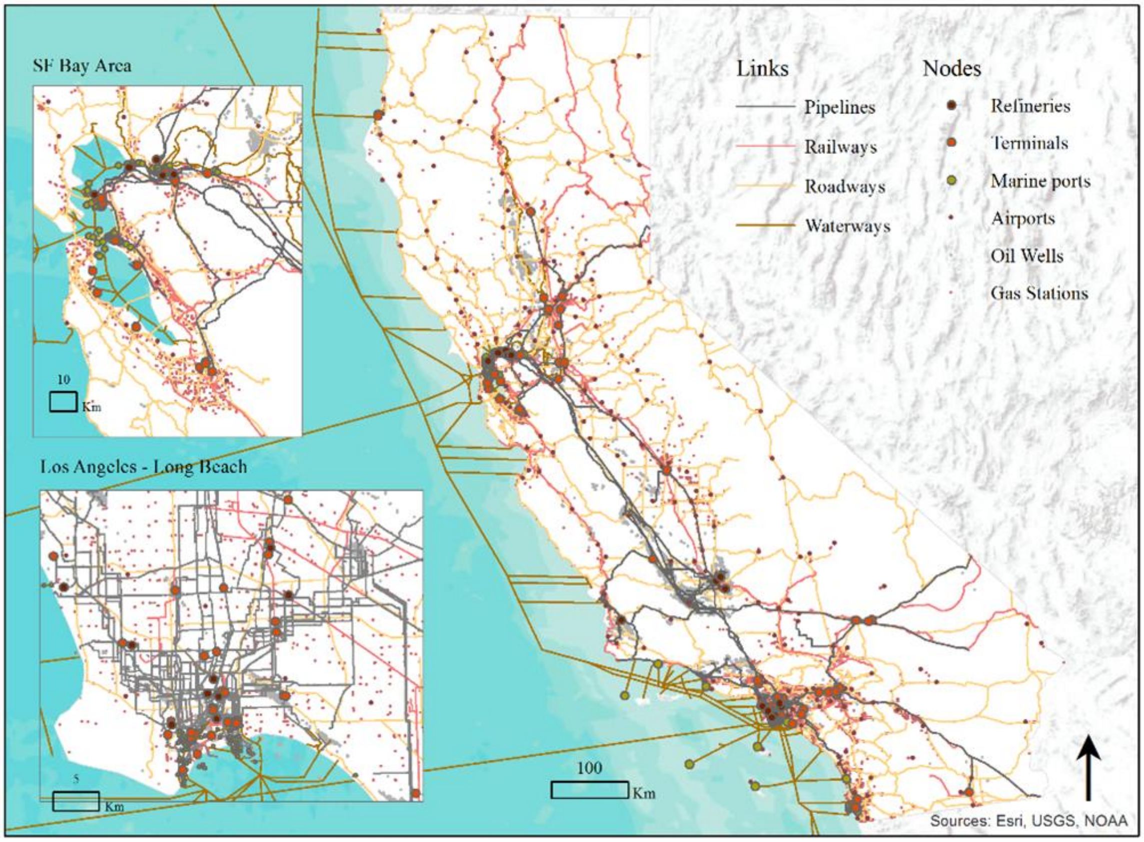


Figure 6. **Geospatial representation of the contemporary transportation fuel infrastructure in California (data source: Radke et al, 2018)**

3.2.3. The uniqueness of the contemporary TFS climate risk governance and its wicked mess

The contemporary TFS presents unique features that differentiate it from other CI. These distinct features help contextualize the wicked mess of the TFS climate risk governance problem. The term *wicked mess*[220], combines the term *wicked problems*[31,221] and *mess* that stems from systems theory terminologies developed in design, management, and planning fields. Between the late 1950's and 1970's, these terminologies rose to challenge the rationalistic approach to planning and underline the social complexities of policy problems, notably the subjectivities and perversities in problem identification and resolution; an overreliance on linear causal relationships for foresight; and the assumption of consensus on goals and means.

Wicked problem describes a "class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision-makers with conflicting values, and where the ramifications of the whole system are thoroughly confusing". Failure to acknowledge the wickedness of these problems often ends up with solutions that are "worse than the symptoms"[221]. A *mess* describes "problems that are interdependent of each other, but with dynamic situations that consists of complex systems of changing problems that interact with each other"[32]. The concept of mess brings forth the importance of holistic problem-solving where "a partial solution to a whole system of problems is better than the whole solutions of each of the parts taken apart"[32]. The incorporation of *wicked problems* and *mess* concepts in planning and design fields highlighted the need for a paradigm shift to broaden ways in which problems are defined and addressed given our growing understanding of a complex, interconnected, and pluralized yet inequitable society. The idea of wicked mess provides a "pedagogy of interconnectedness"[222], or inquiry system, which is evermore required to address socioenvironmental and collective action problems[41,223], notably those related to the "mega mess"[32,220] of the climate change crisis[224,225]. Human-induced climate change presents unique extra challenges described by Levin et al[226] as "super wicked problem" distinguished by the notion that:

- time is running out
- the risk of impact is amplified as we reach tipping points
- every concerned person trying to reduce climate change is contributing to it
- authority on global climate policy regime is fragmented and diffused
- there is a declining social discount rate of long term benefits that permeate decision-making.

Cost-benefit assessments struggle to value future benefits at the expense of short-term benefits at the individual cognitive level and at the policy level.

Similarly, the TFS resilience as a CI in the context of climate change is a wicked mess, which means that understanding its unique features and vulnerabilities, and how they are interconnected, is key to develop and sustain more "partial solutions to the whole system of problems" as opposed to whole solutions of each of its parts taken separately".

Furthermore, supply chain risk literature demonstrates that over 82% of publications do not explicitly define risk, where 9% of those that do explicit, define risk as the probability of an adverse outcome (Heckmann et al. 2015). Research on this subject is therefore hazard-centric, disregarding the vulnerability component of risk. In the context of a CI such as the TFS that functions as a supply chain system, focusing on hazard as a probability of failure means that the intrinsic traits of supply chains that corroborate for creating risk (consequences of failure) are overlooked. Based on CI resilience, supply chain sustainability, and energy infrastructure policy literature, we identify five unique features that differentiate the TFS from other CI which can help grasp the current system's vulnerabilities. These unique characteristics capture the wickedness of the TFS resilience problem, and helps frame the fuel sector as both source and effect of climate change threats:

(1) *unprecedented transition*: the global policy mobilization for a rapid shift into low anthropogenetic GHG emission energy sources is expected to metamorphize economic sectors. Energy transition is being pushed in the transportation, electricity production, and industry sectors which primarily rely on fossil fuels and

were responsible respectively for 29%, 25%, and 23% of U.S. GHG emission in 2019[227]. This unprecedented transition combined with projected impacts of climate change brings a double layer to the expected changes to energy landscapes: first due to shifts in natural resources used for transportation fuels; and second, due to changes in natural hazards threatening transportation fuel services.

(2) *complex and widespread interdependencies*: as part of the energy sector, the TFS is a vital commodity on which most vital services depend on. Sovacool (2012) describes this as "vertical complexity" where energy production is the precondition for all other commodities, cutting through multiple infrastructure systems and economic sectors at various scales. In the context of CI, these widespread interdependencies become a major issue of energy security on the supply side and energy justice on the demand side. To avoid reproducing fallacies of the current TFS in our transition to a future more resilient TFS, we need to equitably provide "affordable, reliable, efficient, environmentally benign, proactively governed, and socially acceptable energy services to end users" [228]. In the context of disaster risk, this is especially problematic given the dependency of emergency response on transportation fuel (i.e., mass evacuation transportation; first responders workforce and machinery mobilization; and distribution of medical and other emergency supplies)[62]. Furthermore, empirical studies show that cross-sectoral CI failure dominantly originates in the energy sector {94,163} reinforcing the necessity of expanding system boundaries when modeling the energy systems "choke points" {149,180}.

(3) *hazardous materials (hazmat)*: the TFS supplies large volumes of hazmat as a vital commodity (crude oil and derived fuels) and the industrial processing of crude oil involves handling a diverse set of hazardous chemical products and wastewater. The outcome is a compound risk effect, where there is an amplification of consequences to society in the case of infrastructure damage from climate-induced hazards: natural hazard triggering technological hazards from hazmat release which can be combined with shortage in transportation fuel supply.

(4) *complex organizational network and fragmented governance*: as supply chains are composed of a numerous and dynamic population of mainly private organizations. Each stakeholder optimizes their individual performance, and most organizations have limited awareness of neighboring supply and demand organizations beyond one degree upstream or downstream, resulting in highly fragmented governance. Sovacool described this as "pronounced horizontal complexity" where many governmental and private actors at multiple governing scales are involved. Fragmented governance constitutes a patchwork of stakeholders with overarching common goals that differ in character (organizations, institutions, regimes, and norms), their constituencies (public and private), their jurisdiction, and their predominant subject matter[229] in ways that can either enable or impede coordination and collaboration. Fragmented governance is an inevitable pattern for complex infrastructure (with cross-sectoral and cross-scale interdependencies) that goes together with globalization, growing prominence of non-state stakeholders (notably the private sector), and decentralization of decision making[40]. It is often,

but not exclusively, associated with disarticulation. Fragmented governance is also discussed as an inherent character of collaborative governance systems involving multiple, but coordinated, independent centers of decision-making across sectors and scales[47]. However, coordination and collaboration for improved resilience and crises involving networked infrastructure can be challenging in fragmented governance systems. At the operational and planning level, fast and systemic decisions on how to allocate scarce resources or services are considered key to advance planning for restoration activities after a disruption, or to increase long-term resilience. Minimum levels of stakeholder orchestration is needed to understand potential choke-points, where flow is limited, or lead time is increased[230]. This implies on the systematic knowledge of the supply chain network, mapping decision makers in the commodity flow, all the way to the users of the commodity services.

(5) *high path-dependency*: path-dependency, a common phenomenon in complex systems, arises when initial conditions and the sequence of states, actions, or decisions following those conditions have strong influence on future outcomes. Due to powerful network effects, switching costs is high, reinforcing sometimes obsolete systems despite their proven social, environmental, and economic disadvantages. Path dependence has also been used to describe the resistance to transition into alternative energy sources described as *carbon lock-in* in climate change economic research[231]. Path dependence is considered especially strong in energy systems that rely on increasingly capital-intensive investments for large-scale infrastructure and technology. We argue that path-dependence also describes locked-in mechanisms of technocentric and hazard-centric climate adaptation policies that are counterproductive to disaster risk management and undermine socioeconomic goals of energy transition.

3.3. Contemporary transportation fuel system cascading risk: past and future

The TFS unique characteristics will be further explored in this section to illustrate how they become outstanding vulnerability traits during emblematic disasters in the U.S., at local, regional, and national scales. The San Jacinto river flooding, Hurricanes Harvey, Sandy, and the hyperactive hurricane season of 2017 followed by the extreme wildfire season of 2018 are examples of climate-induced disasters amplified by impacts to the TFS. This section ends with an overview of future exposure and vulnerability of the fuel sector in California. Aligning with impact patterns of past TFS-related disasters, projected climate exposure helps highlight specific TFS challenges of the compound effects from hazardous material release; complex organizational networks and fragmented governance; and widespread interdependencies, including cross-sectoral cascades to emergency services fuel demand (Figure 7).

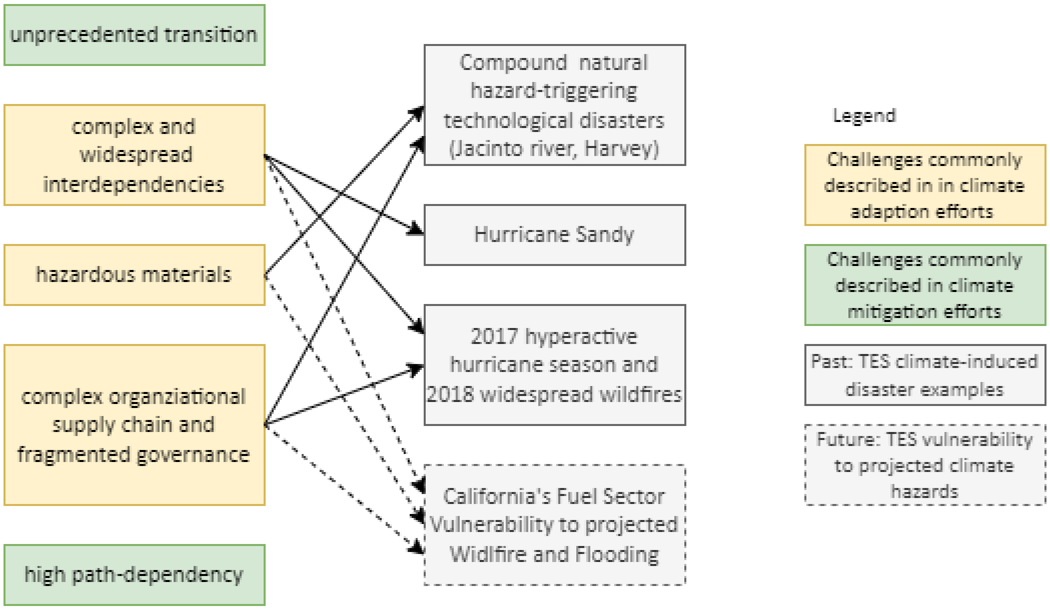


Figure 7. Unique features of the TFS at the source and effect of climate-induced disasters (disaster examples developed in section 3.3.)

3.3.1. Compound effects of natural and technological hazards: San Jacinto river flooding and hurricanes on the Gulf Coast

TFS cascading failures due to weather hazards have been studied through natural hazard triggering technological hazards literature, also known as "natech". TFS natechs cover natural hazards triggering hazmat release from handling, processing, storing, and transporting oil & gas feedstock and byproducts. TFS climate risk management intersects therefore with Natech mitigation, which brings a new layer of complexity including a new set of industry safety standards and high reliability organizational behavior. TFS natechs need to be managed from the perspective of disruption to energy services concomitantly considering technological hazards and risk of environmental catastrophes from hazmat breeches.

The 1994 San Jacinto river flooding in Texas, leading to the spillage of 36.000 barrels of petroleum and crude oil products into the flooded waters, is a classic example of compound effects of technological and natural hazards affecting the TFS. An intense and widespread rainfall event between October 15-19 caused severe river flooding events. The flooding exceeded the 100-year peak streamflow in the San Jacinto River basin (citation 150) inundating 69 hydrocarbon fuel pipelines. Several of these inundated pipelines, operated by 30 different organizations, became uncovered and undermined leading to the eruption of eight pipeline transects (Krausmann and Cruz 2017). Asides from the spillage and environmental contamination, consequent multiple explosions and hazardous fumes amplified human and environmental impact. The fires and hazardous fumes caused 545 injuries, escalating the emergency already implemented by the flood event. After-action reports highlighted lack of industry standards for pipeline design in flood-prone areas, absence of remote-control systems technology for valves and flow operations, as well as issues regarding multiple operator situational awareness and preparedness (151).

Hurricanes like Katrina (2005), Rita (2005), Sandy (2012), and Harvey (2017); and their associated wind, storm surge, and flooding hazards are emblematic cases of how extreme weather impacts the TFS (153). They illustrate the transboundary effects of TFS failures and provide insights on the amplification of disaster due energy security failure (fuel outages) combined with impacts from hazmat spills that cascade from energy CI to emergency services.

Katrina and Rita, on top of being the deadliest hurricane series in U.S. history, caused unprecedented onshore and notably offshore TFS facility damage producing substantial fuel outages and hazmat spills. Globally, the loss of commodity production and refinery shutdowns that coincided with disruptions to the Gulf Coast port complex, impacted the energy market with spikes in oil prices (154). The recurrence of oil release from the Strategic Petroleum Reserve (SPR) under emergency loans due to hurricanes, covering 50% of exchange agreements (DOE, 2020), is an important indicator of the climate threat to national energy security. Nationally, the inoperability of the Gulf Coast Petroleum District provoked the second – out of three - presidentially-directed emergency drawdown from the SPR at the time (155), indicating extraordinary threat to the supply of transportation fuels. Regionally, the hazmat release of 30.2 million liters further pressured emergency services across Louisiana, Mississippi, and Alabama. The crisis was amplified due to combined pressure on workforce and fuel supply for emergency response cleanup, evacuation, and search and rescue operations. Hazmat release from the hurricane damage was still being reported one year after the disaster (Cruz and Krausmann, 2008). During such events, hazmat-specific impacts are difficult to untangle from direct hurricane hazards such as wind, storm surge, and flooding. Hazmat impacts have been measured in terms of oil spill clean-up activities; oil spill-related property loss or damage; damage to commercial fishing areas; disruption to subsistence activities; disruption to recreational or dietary patterns; job loss or loss of work activity due oil spill; among others[232].

More recently, hurricane Harvey, ranking the second most costly hurricane in U.S. history[4] leading to $141.3 billion in damages[233], provides other insights on the complexities of Natech disasters involving the TFS. Harvey damage was particularly pronounced due to intense and highly cumulative rainfall causing severe flooding in the greater Houston Area. The flooding was the major cause of 68 direct fatalities, but the event overall caused power outage to more than 2.02 million customers between August 25th-30th [234], and more than 100 industrial spills including half a billion gallons of hazardous chemicals and wastewater into the greater Houston area[235]. Harvey, Rita, and Katrina hurricane damage to chemical and process facilities, including in large part assets from the petrochemical industry, indicate that flares where the source of massive hazardous chemical release into the atmosphere. These flares are mostly related to shut-down and start-up operations, indicating that preventive Natech disaster procedures can trigger socioenvironmental impacts due the release of massive toxic materials into the biophysical environment even

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[4] Behind Katrina with $ 182.5 billion in damages

without damage to facilities[234]. Natechs have also been increasingly connected to heightened social impacts compared to natural-hazards triggered disasters. Studies on survivor's perception of large Natech events point to increased corrosive impacts including deterioration of relationships, conflict, confusion, and stress linked to increased uncertainties based on the compound nature triggering the event and highly adversarial litigations that follow. Particularly after Houston, adverse effects on people's mental and physical health and perception of institutional failure heightened feelings of helplessness of those affected by hazmat release[235] in the 50-mile industrial corridor known as the Houston Ship Channel[5].

Overall, the impact of these hurricane provides examples of prolonged effects of compound and cascading TFS failure from energy to emergency services, which from the perspective of hazmat release will not only extend contingency cleaning operations but will also have local, long-lasting, and often intangible effects on socioenvironmental systems, particularly for residents that are already exposed to chronic industrial hazards and communities that rely on healthy coastal ecosystem (156). A TFS Natech represents a cascade of natural-to-technological hazards that can lead to the impedance of transportation fuel services (Cruz and Krausmann, 2013; Krausmann, Cruz et al., 2017),

3.3.2. Hurricane Sandy: the fragility of energy systems' widespread interdependencies and fragmented CI governance

On the East Coast, the 2012 Hurricane Sandy, is "textbook case study" of TFS fragility based on its interdependencies and complex governance structure. The disaster caused cascading impacts from the power shutdowns to transportation, telecommunication, and fuel supply system, with concentrated damages in the metropolitan area of New York and New Jersey (157–160). Sandy's storm surge and flooding effects were particularly damaging due to its unusual track, which made landfall perpendicular to the coast due to other weather systems occurring in the Atlantic Ocean. Moreover, Sandy made landfall an astronomical high tide, compounding with the effects of high speed winds which caused intense storm surge and wave runup impacting over 1000km of U.S. coastline[236]. From the 117 hurricane-related deaths, drowning was identified as the most common cause, occurring primarily in residences of evacuation areas[237]. Sandy damage analysis confirms a high degree of interdependency between CI and amplification of disaster impacts based on lack of vital services[238]. Extensive power outages, which at peak affected over 4,600,000 customers, caused the loss of 40% to the fuel supply chain operating capacity (161). Even with restoration of some fuel facilities operations such as refineries and terminals a few days after the outage peak, at the last node of the fuel distribution network, backup power for pumps was not available. Commercial gasoline facilities were unable to function, which in turn, led to immediate disruptions of aboveground transportation services, including emergency response equipment (DOE, 2013). Due to the inoperability of liquid fuel

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[5] The Houston Ship Channel is home to 10 major oil refineries, more than 500 chemical plants; 4,546 aboveground storage tanks, and 6,670 miles of intertwined oil, gas, and chemical pipelines[235]

facilities, deployment of utility restoration crews and emergency vehicles to impacted areas was delayed. Lack of fuel and power outages also caused evacuation of hospital and critical healthcare centers[239]. Hurricane Sandy disaster brought visibility to the issues of CI cascading failures based on complex and widespread interdependencies which start at energy systems (fuel and power) and reaches emergency services (Figure 8).

Lessons learned highlighted: (1) the need to expedite regulation for gasoline rationing or waivers that provide flexibility to the fuel supply chain companies in the production and distribution of commodities; (2) the need to improve situational awareness of fuel resources and interdependencies between electricity and the fuel sector; and (3) the need to ensure mutual assistance networks for the fuel sector, which differently from the electric utility, is challenged by the competitive nature of its business and does not have decades of experience with multi-organizational arrangements to respond to disasters (157,162). These lessons significantly influenced current U.S. CI and DRR planning policy, including the latest National Infrastructure Protection Plan (NIPP) (2), the Energy Sector-Specific Plan (163), as well as California's Emergency Fuels Set-A-Side Exercise (164). A major policy change motivated by Hurricane Sandy was Executive Order 13653 "Preparing the U.S. for the Impacts of Climate Change" which established the interagency Council on Climate preparedness and Resilience that is tasked to promote engagement and partnership between governmental agencies (163). The Climate Action Plan, issued in June 2013, that establishes the National Strategy for Information Sharing and Safeguarding (NSISS) was another policy reaction to the vulnerabilities uncovered by the event. The NSISS establishes "information-sharing process and sector specific protocols with private sector partners" to improve timeliness and information sharing practices for the security of CI. Overall, these policies reflect challenges of current governance frameworks that are not adequate for real-time information sharing, coordination, and collaboration considering the commercial arrangements of private and public organization networks involved in CI operations, nor for collective organizational collaboration for CI climate resilience in the long term.

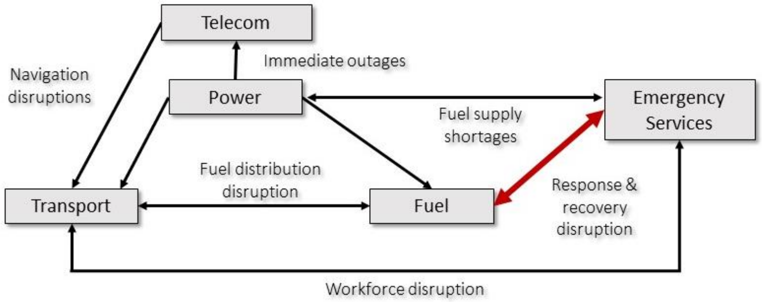

Figure 8. Cross-sectoral cascading failure of CI during Hurricane Sandy (adapted from [240])

3.3.3. Emergency services pressure from the extreme wet-and-dry disaster season of 2017-2018

With recent trends of rapid transition from record multi-year dryness to extreme wetness (Swain et al., 2018), climate projections indicate not merely an increase in frequency and intensity of these extremes but also in the velocity of the variability between extreme dry and extreme wet climates. The final TFS cascading disaster example is therefore on the 2017-2018 hurricane and wildfire disaster season impacting the U.S. The concomitance of extreme-dry with extreme-wet weather conditions highlight new challenges of CI interdependencies, crossing from energy to emergency services involving complex organizational and fragmented governance issues.

On the extreme dry spectrum, the 2017-2018 wildfire season provided the deadliest and most destructive wildfires in U.S. history with the Camp and Tubbs fire, among others (Table 4). On the extreme wet spectrum, 2017 was a hyperactive hurricane year with a high number of consecutive Atlantic hurricanes. In late August, Harvey, category 4 hurricane, produced the highest total rainfall for any recorded tropical cyclone in the U.S (168) (Figure 9). Ten days later, hurricane Irma, advanced towards Florida as the strongest storm in terms of absolute and sustained peak winds in the open Atlantic Ocean, marking the only time when two consecutive major hurricanes made landfall on continental U.S (169). Hurricane Jose peaking category 4 in early September, marked the first simultaneous occurrences of major hurricanes in the Atlantic basin. Finally, Maria, category 5 hurricane on September 19th, caused the worst power outage in U.S. history (170) and is the deadliest hurricanes of the country in recent history (171). Massive pressure on the fuel supply caused cascading impacts across lifelines and severe capacity reduction of emergency medical services. Fuel supply shortages consequent to demand spikes from the population and emergency responders were due to fuel facility damage; disruption in transportation networks; work force shortage for fuel truck drivers. An epidemiology study on hurricane Maria shows substantial underestimation of the official death toll (172) attributed to indirect effects of CI failure. The government reported at the time, 64 deaths. Three months after Hurricane Maria made landfall, that associated excess deaths were closer to 3,000. This gap between the official count and the sur-mortality rate, measured in the immediate aftermath of the disaster, reflects worsening chronic health conditions from delayed medical treatments because of failing transportation and energy CI. Five weeks after the hurricane, only 8% of Puerto Rico's roads were open, and three months later, only 45% of the population had regained access to the power grid. The delayed access to power increased the pressure on fuel supply because residents, commerce (notably food distribution), and other critical health care services (i.e., hospitals, pharmaceutical supply chain), were relying on diesel and gasoline backup generators for a prolonged time. Multiple studies underline that difficulty recovering lifeline functionality, power, fuel, and transportation infrastructure prolonged and intensified human impacts worsening health and living conditions and delaying the recovery process[241–243]. Cases like Hurricane Maria illustrate how the severity of disasters, and cascading effects from CI failure align with underlying vulnerability conditions, including the accessibility of the population to vital goods and services. It also illuminates reproduction of power asymmetry through colonial governance of centralized infrastructure services.

At the U.S. level, the 2017 and 2018 concurrence of large-scale impacts from extreme wet and extreme dry hazard-related disasters presented a complex and novel scope of challenges to the disaster response system related to widespread interdependencies and complex organizational networks. According to FEMA's 2017 After-Action Report, the nation faced unprecedented force shortages, both in staffing and commodities, including fuels: "By May 2018, nearly 4.8 million households affected by the 2017 hurricanes and California Wildfires registered for assistance – more than the previous 10 years combined"[244]. Overall, the report makes several recommendations to improve staffing for concurrent and complex incidents; understanding of local, regional, and national supply chains; relationships with critical private sector partners, and coordination across CI sectors.

Table 4. 2017-2018 impact from the top 20 deadliest[245], most destructive[246], and largest[247] California wildfires (Source: CalFire, Jan 13, 2022)

Fire name	Date	County	Acres	Structures	Deaths
Atlas	October 2017	Napa & Solano	51,624	781	6
Redwood Valley	October 2017	Mendocino	36,523	544	9
Nuns	October 2017	Sonoma	54,382	1,355	3
Tubbs	October 2017	Napa & Sonoma	36,807	5,643	22
Thomas	December 2017	Ventura & Santa Barbara	281,893	1,063	2
Carr	July 2018	Shasta County & Trinity	229,651	1,614	8
Mendocino Complex	July 2018	Colusa, Lake, Mendocino & Glenn	459,123	280	1
Camp Fire	November 2018	Butte	153,336	18,804	85
Woolsey	November 2018	Ventura	96,949	1,643	3

Ranks for area, structures, and deaths for 2017-2018: 1 2 3 4 5

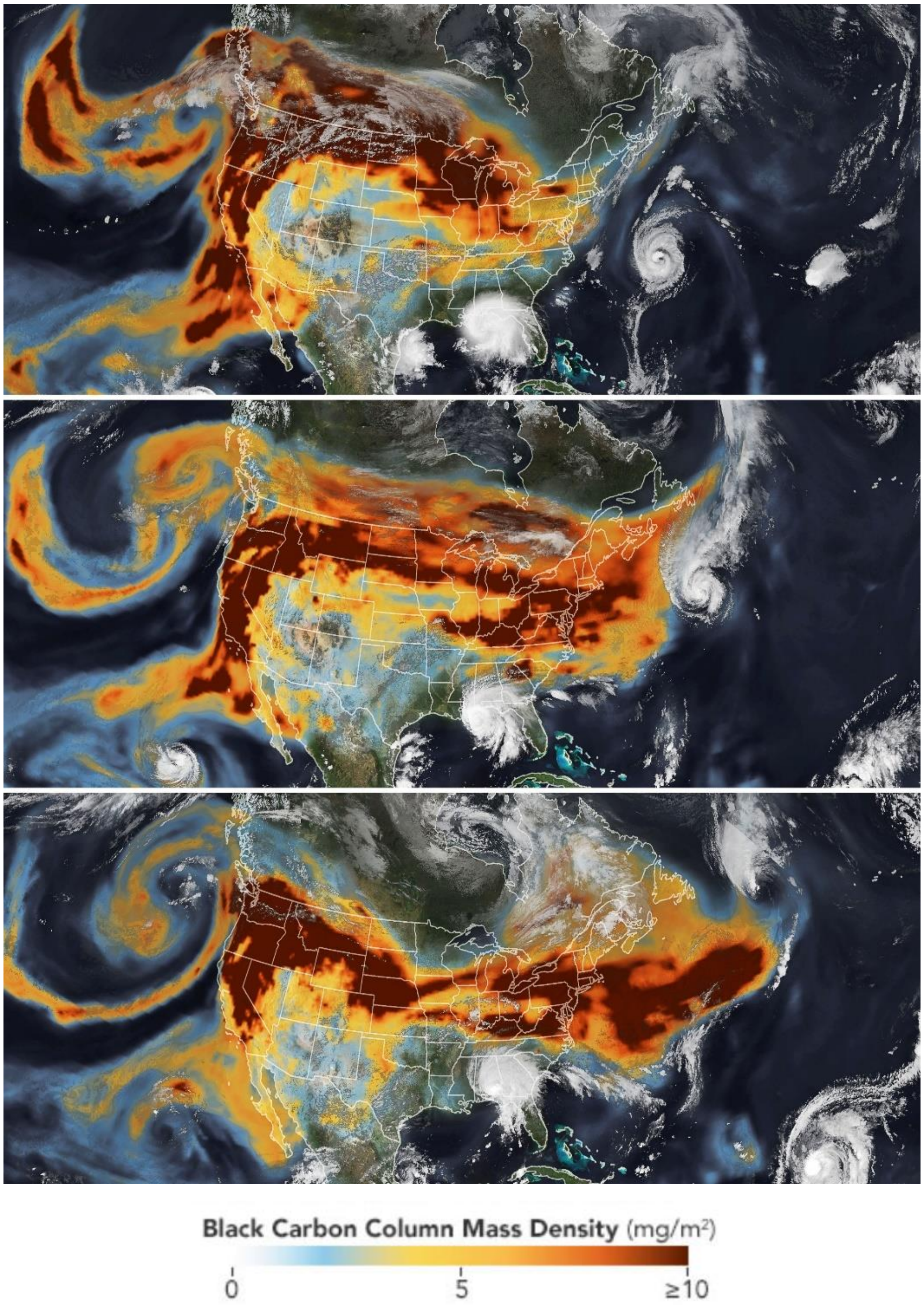

Figure 9. Concomitance of wildfires and hurricanes September 14-16, 2020– East migration of black carbon mass. Source: NASA Earth Observatory, 2020

3.3.4. Projected exposure of California's contemporary transportation fuel system to climate-induced hazards: understanding network-level vulnerabilities

We now shift focus on what is currently known about future vulnerabilities of the TFS as a CI to climate change. Radke et al technical report for California's Fourth Climate Change Assessment (C4CCA) reinforces TFS unique traits related to the widespread complexity of interdependencies, notably between energy systems (power and fuel) and emergency services; as well as the vulnerabilities pertaining to the complexity of organizational networks and fragmented governance.

(a) Exposure to future hazards and understanding network-level vulnerabilities of the TFS

In Radke et al (2018), the exposure of California's fuel assets to flooding and wildfire events under projected climate change scenarios. The exposure models contain both fine and coarse spatial resolutions. Coarse resolution (50m) covers the fuel transportation network at the state level for coastal flooding (sea level rise combined with extreme storm surge event) and threat of large wildfire occurrence. Finer resolution (5m) for coastal and inland flooding as well as wildfire behavior covers areas and assets of concern indicated by stakeholders. Exposure results of these models are further discussed with key industry stakeholders (owners and operators of fuel assets); regulator stakeholders (energy, and utility regulators) and interdependent sector stakeholders (water and emergency management) allowing to gain perspective on asset-level vulnerability and system-wide choke points of the cotemporary TFS in California. Figure 10 presents an overview of the exposure results, illustrating how near term exposure (2040) evolves to long-term exposure (2100) based on the fuel sector nodes and links. Essentially fuel nodes are more exposed to coastal flooding, especially refineries and terminals; and fuel links are more exposed to wildfires, especially roadways and railways. The change in exposure to the threat of large wildfires in the near and long-term is less pronounced than the change in exposure to coastal flooding. However, wildfire may be the biggest immediate threat due to the co-occurrence of critical fuel assets, such as fuel pipelines in regions at high risk of near-term large wildfires (between 2020-2040). Deeper understanding of exposure characteristics, especially for coastal flooding, requires an assessment based on geography (northern versus southern California), asset type, and ownership.

Major contributions of this C4CCA report aside from the exposure to climate change threats include advancing the understanding of the fuel sector interconnectedness and interdependencies, notably considering there is no formal definition of what this CI constitutes at the state-level. Radke et al underline for the first time network-level vulnerabilities of the system pointing to combined issues of (1) limited substitutability of nodes and links (lack of redundancy), (2) centralization of supply and long-haul distances, (3) complex interdependencies, and (4) the sector's organizational complexity.

(1) Limited substitutability of infrastructure assets and commodities is one of the network-level TFS vulnerabilities. Transportation fuel commodities are not interchangeable; there is great variety of fuel types that supply distinct transportation industries (i.e. multiple fuel types for aviation, marine and ground transportation vehicles) and a variety combustion engines with distinct technological requirements within the same industry (i.e. diesel, gasoline and ethanol for ground transportation vehicles engines and multiple strands of jet fuels that are unique to aircraft's safety design expectations). This variety and lack of interchangeability of fuel commodities also result in a supply chain that is specialized and not easily interchangeable. Assets that stock and transport crude oil

feedstock are not interchangeable with those that transport refined and readily usable fuel products. This commodity specialization reinforces the rigidity of the supply chain system as for instance; each refinery is designed to process specific grades of crude oil, each refinery requires specific input materials for petrochemical processing of crude oil (i.e. separation, distillation, conversion, enhancement, blending techniques), and each refinery will have to deal with different waste management systems for the material outputs of the refining process. This limited substitutability translates into the inflexibility and low redundancy of infrastructure supply and delivery network, notably for facilities such as refineries, terminals, and pipelines, which are continuously operating near maxim capacity, within inflexible routes, or rights of way (ROW) and flow directions.

(2) Issues based on the centralization of supply and long-haul distances reproduce scale-free properties of CI networks: i.e. few node assets that are highly interconnected, thus more critical to the fuel production and distribution and systemically more vulnerable to disruptions. Assets reproduce scale-free properties of CI net-works: i.e. few node assets that are highly interconnected, thus more critical to the fuel production and distribution, and systemically more vulnerable to disruptions. The criticality of certain assets can also be attributed to the lack of redundancy with its role serving as bridges, frequently interconnecting other assets on the fuel supply chain (i.e., betweenness centrality). Lovins and Lovins highlight long-haul distances render energy systems more vulnerable to environmental hazards simply through higher probability of infrastructure spatial exposure.

(3) Issues based on complex interdependencies renders the fuel sector vulnerable to failure not only because of dependencies on a diverse and large set of node and link assets within the sector, but also dependencies at cross-sectoral level (notably power, and emergency management). This is especially complicated given California’s reliance on high fuel demand emergency response related to wildfire suppression activities.

(4) Through the engagement of a diverse set of stakeholders, it drew light on the organizational complexity of the sector, where hundreds to thousands of organizations coordinate fuel flow based on contracts, agreements, and regulation. The corporate governance structures of the contemporary TFS are extremely complex, where a single organization or a consortium of multiple organizations can own a TFS asset designed to transport and deliver commodities owned by one organization, commodities owned by several organizations, or a single commodity belonging to multiple organizations. This complexity develops unique and fragmented governance systems. Governance fragmentation is a major barrier to improve supply chain resilience at the system-level given that no one organization alone can monitor, let alone manage, the movement of crude oil from supply segments, to refining, to end-users in this highly networked system. Most owners and operators of fuel assets in the state have operational control of the system one degree upstream and downstream of their assets.

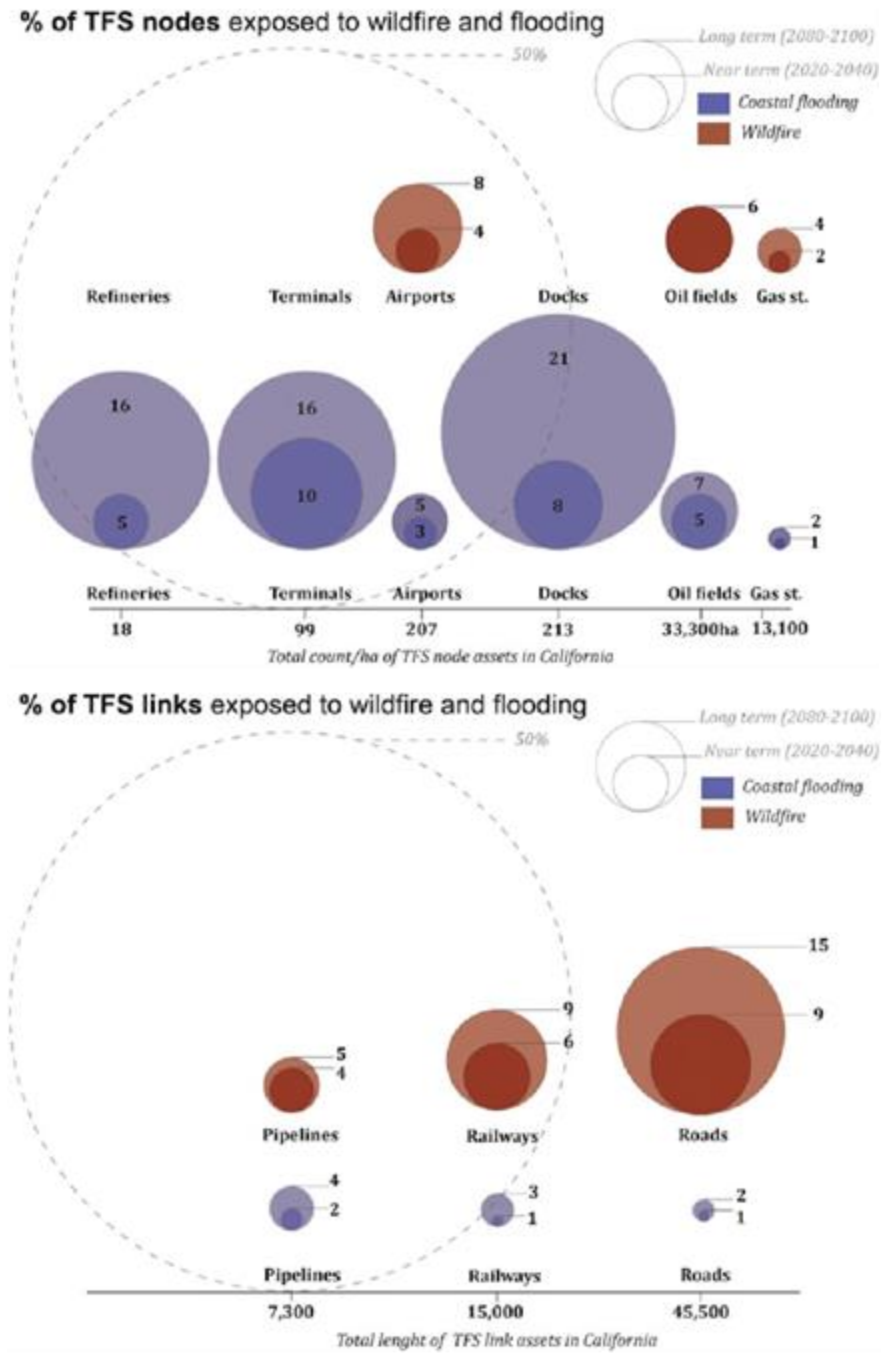

Figure 10. Overview of projected wildfire and coastal flooding exposure to California's fuel sector (data source: Radke et al 2018)

(b) Implications of the TFS governance fragmentation on energy service

The fragmentation of the TFS is intrinsic to the commercial and competitive nature of the supply chain business, which has been discussed as both a vulnerability and resilience factor. Competition ensures certain redundancy and flexibility in the demand and supply equilibrium. If any company suffers unscheduled inoperability, another competitor will often take its place. It’s also common to observe cooperation for purchase and sales of products to fulfill contractual obligations. However, there are cases where there is no redundancy in the system. Radke et al pointed to some of choke points such as fuel pipelines and their central distribution terminals (both for refined product), which not only lack redundancy in terms of physical infrastructure for network links[6] and nodes[7], but also lack redundancy in competitors. Since there is only one major organization that owns and operates fuel product pipelines in California, this could also be considered as an “organizational choke point”, meaning the funneling of responsibility for the operability of the supply chain network on one organization, for whom a relatively larger number of organizations in the system rely on more than on any other single organization.

Fuel supply has limited lead time, meaning that disruption to key nodes or links can quickly escalate to fuel shortages since onsite storage is limited, especially for processed fuel products as highlighted in the C4CCA report. In emergency situations, where the supply chain is required to shift from a commercial function to a contingency function, the competitive and fragmented nature of the TFS can also lead to lack of coordination and orchestration. In a disaster context the TFS mutates into a public health and “humanitarian” supply chain. Such supply chains are mobilized only after demand occurs (reactively) meeting demand late by default [230].

This is a major preoccupation underscored in this study which was brought up in Radke et al confirming the increased pressure on California’s emergency services due to projected climate change impacts. A disruption of the TFS as a supply chain can impact both supply and demand as well as the viability and capacity of the nodes and links to move fuel commodity to end nodes. Often, resilience options for TFS as a fuel supply chain focuses on understanding the vulnerability of node and links moving commodities. We argue that focusing on how it might impact the demand side can help better understand the relationship between CI failure and energy services functionality. This requires therefore rethinking our currently known TFS boundaries, restricted to the physical supply chain system (feedstock origin nodes to end-nodes of ready-to-use fuel products).

Understanding energy services, according to Sovacool, is regarded as “the benefits that energy carriers produce for human wellbeing”, thus sharpening our focus on the elements that will remain *critical* about the TFS regardless of its underlying supply chain infrastructure or energy source. Considering the high interdependency between the fuel sector and current emergency management infrastructure and projections of increased

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[6] Fuel pipelines are considered as critical links and a choke point in the supply and distribution of fuel products because many of these assets are singular links between refineries and intermediate transshipment nodes or end node terminals, with no redundancy in place. If failure occurs to some of these key links transporting end-use fuel products, the alternative links, such as trucking through roadways and marine transportation, do not hold the same capacity or cover the demand areas.

[7] There are two central distribution terminals in California, one converging refined product pipelines from the northern refinery hub in the San Francisco Bay Area and another converging refined products from the southern refinery hub between Los Angeles and Long Beach. If either of these nodes fail, there is serious risk of fuel disruption in the state. Furthermore, there is no connection between the fuel pipeline distribution system in the north and the one in the south, making these central distribution terminals more critical.

severity and frequency of climate-related disasters, better understanding transportation fuel services for emergency management users is key to advance our knowledge of the TFS as CI. Prioritizing emergency management as critical users of transportation fuel services should allow not only to improve the TFS resilience but also to better plan the energy transition process to low carbon transportation systems.

Major methods that seek to mitigate CI failure, traditionally focus on physical infrastructure interdependencies, bounding them to traditional supply chain networks without critically examining impacts to the CI services. Studies on fuel distribution show that network-level resilience, i.e., network capacity to overcome a diverse set of disruptions, has not been explicitly addressed for the industry[248,249]. Uncertainty and risk management from a strategic and tactical planning perspective are commonly bound to a speedy operations return after a disruption. Risk management strategies aim for the quick "rebound effect" (engineering resilience) and mostly apply optimization models where risk is quantified based on profit distribution at the organizational level. Cooperation among stakeholders, even within a subsector of supply chain, is underdeveloped; as strategic planning and socio environmental issues are not incorporated into planning and design, but addressed as quality constraints in optimization models, where the key goal is to keep the quality of products within legislation requirements.

As developed in chapter 2, mainstream CI resilience methods overlook potential cascades through sociotechnical and socioenvironmental interlinks. In past disasters where impact to the TFS amplified cascades and disaster severity, as well as in future assessment of the fuel sector vulnerability; a recurrent challenge was and will be related to the complexity of organizational networks and governance of CI both of which are intrinsic to the social dimensions of critical infrastructure systems. In section 3.4. we further develop a theoretical approach to the TFS as a social, technical, and environmental system and particularly focus on understanding its social dimensions through organizational networks and energy services

3.4. TFS as a social, technical, and environmental system: understanding energy services and organizational complexities

After having laid out some unique traits of the TFS in section 3.2., and how these unique traits can be seen as intrinsic vulnerability aspects during disasters or projected climate impact, the goal is to provide a framework that illustrates how technical, social, and environmental dimensions of CI need to be better addressed as interconnected systems to move towards a resilient TFS. We end by illustrating how to focus on the social dimensions of the TFS to improve governance of complex systems by better understanding sociotechnical interlinks and sociotechnical network exposure to climate threats.

3.4.1. Understanding the links between energy services, disaster risk reduction, and socioeconomic goals of decarbonization policy

Decarbonization is challenged by the need to expand ways in which energy technology and policy is designed, assessed, and optimized. Decarbonization policy typically focuses on technological performance and energy efficiency, overseeing critical elements of energy effectiveness and quality of energy service. Today effective energy services are becoming increasingly linked to social equity issues, notably those related to energy and environmental justice. These concepts have been operationalized in policy design as socioeconomic goals of decarbonization which seek to reduce socioenvironmental costs paid by those exposed to the externalities of current energy systems and disproportionate climate change impacts. Historically marginalized and low income population have concomitantly suffered from unequal access to energy services (difficulties to reap benefits from higher-efficiency fuel technology), have had higher exposure to health hazards related to TFS polluting industry, and have suffered from amplified climate-related Natech disasters involving hazardous material release. Communities that pay higher costs of the contemporary TFS and receive a small share of the energy services from a financial and other perspectives, have often suffered from misinformation and been disenfranchised in decision-making about energy infrastructure siting, oil infrastructure divestment strategies, or carbon-neutral transition policies.

Studies have underlined how the incorporation of energy and environmental justice into decarbonization policies is key to avoid exacerbating inequity and concentrating opportunities in the hands of few. Failure to address the vulnerabilities of the TFS as a CI can jeopardize specific socioeconomic policy goals of decarbonization:

- Access to growing, reliable, low-cost, clean energy supply
- Broad and equitable distribution of clean energy benefits as well as its burdens, risks, and costs.
- Explicit and effective inclusion of current and historically marginalized communities into clean energy planning and decision making
- Reduction of socioeconomic inequalities and insecurities exacerbated by current U.S. energy systems
- Identification of highly vulnerable localities where net-zero carbon transition will exacerbate existing socioeconomic disadvantages and health disparities
- Accountability of fossil fuel energy infrastructure for proper decommission, remediation of long-term environmental impacts prevention of persistent environmental pollution and derived health impacts

3.4.2. Towards framing the TFS as a social, technical, and environmental system for climate change resilience

Resilience of CI presumes the ability to preserve function under changing circumstances. For the overhauled contemporary TFS, this involves the simultaneous changes occurring in climate and energy landscapes. In this context a holistic understanding of the interlinks between technological, social, and ecological shared states of the TFS is needed. Figure 11 outlines a set of non-exhaustive sociotechnical, socioenvironmental, and environmental-technological shared states, or interlinks, of the TFS.

National or state level climate exposure assessments such as the C4CCA are important steps to begin to investigate *environmental-technological interlinks* of the TFS or other CI. This step is key to researching the dynamics between the TFS technical element (physical infrastructure and technology) and the landscape. At this step, these dynamics are commonly studied through natural hazards exposure (as was developed in Radke et al, 2018), natural resources dependencies for the energy technology in question (hydrocarbon extraction, harvest of solar and wind energy), or environmental exposure to technological hazards (hazmat release, environmental impact). *Socioenvironmental interlinks* would incorporate natural hazard or resource management and governance; ecosystem services protection; landscape stewardship; and environmental justice as key subjects to better understand and improve TFS resilience. Similarly *sociotechnical interlinks* would lean towards preoccupation with technological hazard management and infrastructure governance by looking at the complex and diverse network of stakeholders within the supply chain and users of energy services.

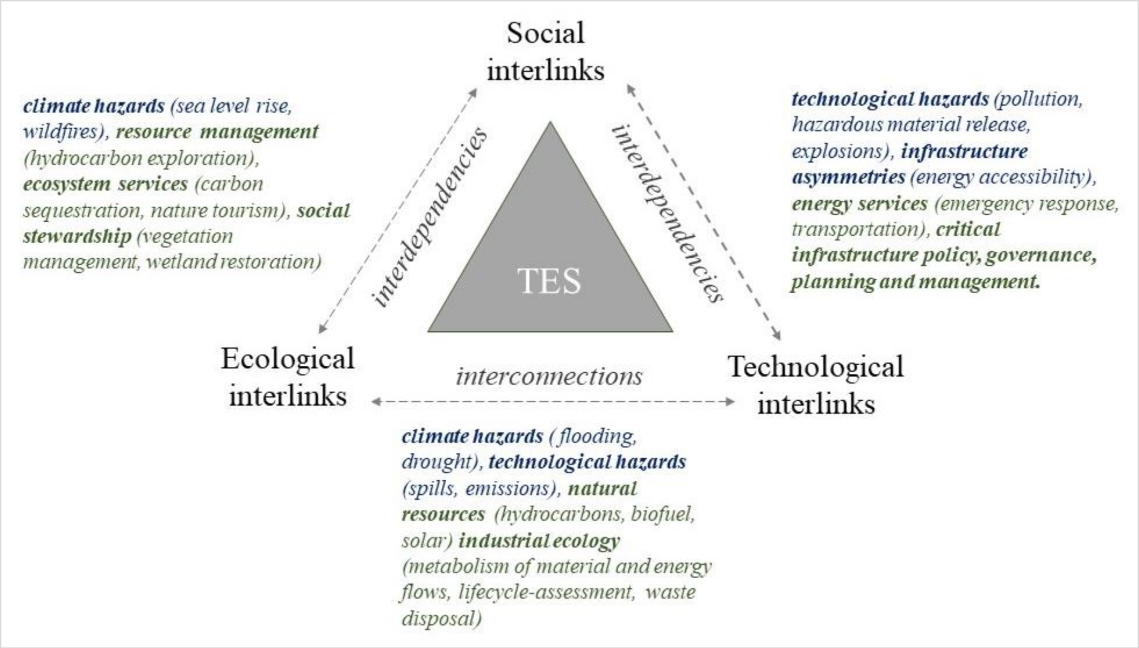


Figure 11. Conception of the TFS interlink with social, technological, and environmental dimensions considering changing climate and energy landscapes (adapted from Markolf et. al, 2018).

From a socioenvironmental and sociotechnical perspective, the incorporation of technological hazard management is necessary given the dangerous nature of hydrocarbon-based fuel commodities and natech risk. As has been developed by Lovins and Lovins, this hazardous technology creates the potential for misuse of energy distribution systems and increases limited public acceptance. The potential for misuse, of deliberate nature or not, is at the core of Perrow's normal accident risk theory, where tight coupling between technical and social systems allows a seamless escalation from "normal accident" to catastrophes. The technological hazard behind TFS-related disasters enhances risk. Limited public acceptance is related to TFS infrastructure externalities (i.e., emissions and pollution impact on public health and environment) which reinforces our concerns over the divorce of socioenvironmental costs and benefits of energy services. This divorce is addressed in Perrow's distinction of 3rd and 4th order victims who share risk but have little or no agency over their exposure.

Another important sociotechnical and socioenvironmental dimension of the contemporary TFS is the distinctly high value of petroleum as a natural resource, thus the industry's entanglement with global power struggles, violent political conflicts, and public disinformation regarding the externalities of this energy service. This is intensely political – not simply a technological or environmental matter. Petroleum resources have played a pivotal role in the misuse of transportation fuel source accessibility for leveraging wars (176), dodging environmental liability, and undermining climate change threats (177–179). Although outside the scope of this chapter, understanding the historical and future political contingencies of not only the contemporary TFS but also the energy transition process, is key to a more resilient CI that provides safe, accessible, and sustainable or all[250–252]. This awareness is especially important given the heightened sensibility of crude oil feedstock prices under geopolitical instability, directly affecting the accessibility of end fuel products to consumers which often cascades to other vital supply chains such as food and medical supplies. Aspects leading to the misuse of energy sources and its accessibility is an increasing concern in energy justice literature[250,253]. For instance, research has recently shown how technical limitations of California electric grid infrastructure may hinder the state's electric vehicle adoption policies[254]. Notably residential load electrification goals are jeopardized in increasingly disadvantage census block-groups, illustrating how current infrastructure systems and transition policies will exacerbate existing energy access inequalities if equity goals are not well incorporated into the design of grid upgrades. Overall, there remains a gap in understanding how uneven landscapes of energy natural resources, territorial variation of energy affordability, and uneven access to energy services (i.e., emergency response) can mutually reinforce current patterns of vulnerability to disasters. More investigation is needed to prevent the unequal distribution of externalities of current, transient, and future TFS.

One example is a better integration of TFS climate adaptation governance with energy transition processes. The near-term steps needed to improve resilience of the TFS are challenged by the strategic and "just" decommissioning of fossil-fuels assets and transition to a low-carbon economy. Strategic decommissioning is being positively framed as an opportunity to explore technological renewal, create green jobs, and invest in local communities[255] while divesting on oil and gas assets close the end of their life-cycles[213]. There are however conflicting tradeoffs impacting the industry's workforce[250,256] and expectations of less industrialized nations to "leapfrog" into green energy sources[257]. Given the increasing exposure to projected climate hazards, we argue strategic divestment in fossil-fuel infrastructure also needs to ensure transportation fuel security for areas where emergency management capacity is projected to be challenged. This is an understudied problem in environmental and energy justice. For those who currently suffer from extraordinary disaster risk vulnerability due to exposure to the contemporary TFS hazmat or climate-related hazards, a “just” energy transition also needs to ensure there is no lag in terms of emergency services capacity due to sociotechnical and socioenvironmental shifts promoting low-carbon economies.

Finally, from an energy transition perspective, the concept of heightened path-dependence applied to the TFS is important because it underlines the sociotechnical interlinks of carbon lock-in processes, notably through the co-evolution of technological systems and governing institutions. Dominant energy infrastructure systems benefit from scale economies and increasing returns to scale. Economically, this means that technology deployment is accelerated compared to alternative technologies because unit production costs decline while production volume increases, and fixed cost are spread (Aghion, 2019). Large investments made into the contemporary TFS have therefore created powerful positive feedback-loops with industrial economies, transportation systems, and users and creators of these systems. In other words, the resistance in adopting net-zero economy and transitioning to low carbon energy sources is high because the predominant system leverages much better from existing infrastructure. From a socioeconomic perspective these positive feedback loops have been framed as complementarities and inertia (Aghion 2019). Complementarities arise when the benefits of group collaboration are greater than the sum of the benefits of its parts. One stakeholder’s productivity will likely benefit all other stakeholder’s productivity. Therefore, individual costs that break this inertia tend to be higher, notably for energy infrastructure. Heightened path-dependency reinforces therefore the role of governmental and system level intervention for breaking these positive feedback-loops. This reinforces the importance of mapping the TFS sociotechnical network from a governance perspective to enable the traceability of decision making from organizations (through protocols and policies) to physical infrastructure assets and their relationships with the landscape. CI governance can thus leverage from sociotechnical networks to strategically intervene through technology push or capacity pull. Most governmental interventions are centered on “technology push” of low carbon energy sources (cap-and trade market and carbon emission thresholds) (Tid, 2006; Aghion, 2019). Intervention involving capacity pull can be further expanded by meeting energy users’ needs and engaging in multi-stakeholder collaborative processes for development, diffusion, and appropriation of energy transition and climate resilience benefits. A more balanced view of innovation process (technology push and capacity pull) is necessary to break path- dependence, and better incorporate energy services into a future, more resilient TFS.

In the next section we focus on a modeling approach to better understand the interlinks, or shared states, between the organizational and physical infrastructure networks (namely social and technical dimensions of the TFS). Ultimately, identifying and acknowledging these shared states of the organizational and physical networks considering landscape hazards allows for mapping sociotechnical network exposure. As will be developed in the next section sociotechnical network exposure assessment can promote complex system governance.

3.4.3. A focus on social dimensions and governance: mapping sociotechnical networks and their relationships with the landscape

A common difficulty in managing complex systems arises due to spatial and temporal scale-mismatch between decision-making (social dimension), scale of landscape processes (environmental dimensions), and scale of infrastructure systems (technical dimension) (developed in section 1.2.3.). We argue that better understanding shared states at the sociotechnical and socioenvironmental systems will help address this scale mismatch for CI resilience. One of the baselines of scale-mismatch for CI is therefore related to our lack of understanding widespread interdependencies and the complex organizational and stakeholder networks influencing and making decisions pertinent to fragmented interests. The complex organizational network of the CI creates governance challenges that impede cohesive emergency response mobilization at the operational and strategic planning levels which includes both long-term climate change impact and energy transition. Improving our ability to understand the TFS sociotechnical interlinks requires mapping the shared states between organizations and infrastructure at their individual and network scales. From one perspective, this allows to elucidate relationships between decision-making at the organizational level and impact on the physical infrastructure system. From another perspective, this allows to assess how any change to the infrastructure, derived from natural hazard natural or resource management, might have organizational-level repercussions at the individual or collective-level. CI organizational complexity, rooted in Perrow's depiction of modern risk as tight coupling between technical and social systems, has been subject to study in high reliability organizational behavior fields (64) including critical infrastructure risk management (189,190) and supply chain modeling (186). However, knowledge of organizational factors playing a key role in infrastructure failures highlights a new important question as to how the task of seeking resilience for a single organization must be considered within a system of interacting organizations (117,191,192).

Figure 12 provides a concept of how models of large-scale sociotechnical networks can incorporate landscape information, such as exposure to natural hazards, to measure the organizational exposure at the collective level and improve CI climate governance. From a governance perspective benchmarking the TFS, or other CI as sociotechnical networks, would provide a map of the relationships of organizations responsible for decision-making in the supply chain as well as of stakeholders who rely on their commodities and services indirectly. With the help of social network analysis, mapping these sociotechnical relations can help uncover key global network metrics to assess effectiveness and efficiency of connections for information flow, or collaboration processes based on the topological structure; as well as the role of each stakeholder within the entirety of the network based on local network metrics such as centrality (further developed in chapter 5).

Governments, for instance who own and manage a large part of infrastructure assets, present high fiscal exposure to climate hazards[258], which can be better understood at the organizational level by assessing sociotechnical network exposure. Benchmarking sociotechnical exposure can improve the identification of cross-sectoral and cross-jurisdictional stakeholders, extending for example the TFS supply chain to specific users of energy services. Recent policy has developed platforms to facilitate public-private partnerships at the national level, under the auspices of the National Plan for Critical Infrastructure Protection, i.e.: the oil and gas sector coordinating council (187) and the emergency services sector coordinating council (188). Nevertheless cross-sectoral collaboration remains challenging, especially within the TFS. The complex public-private partnerships that govern the TFS requires the integration of new and inclusive forms of business risk management, notably when it mutates from commercial to a “humanitarian” supply chain.

One of the major challenges in these partnerships is the difficulty of private companies to fully integrate into systems such as mutual-aid as this requires levels of transparency and information sharing that is incompatible with industry performance. Bringing forth the institutional legacy of CI developed in Chapter 2, in the U.S. regulations such as the Homeland Security Act of 2002 and the Intelligence Reform and Terrorism Prevention Act of 2004 ensure that CI owners and operators can voluntarily share information with the government while exempting CIs from the Freedom of Information Act (185). While for organizations that rely on the TFS for its energy services (i.e., emergency management), the value of this collaboration is essential for understanding risk and preserve public safety; for the industry, the interest of such propositions is conflicting with competitive business models. Identifying sociotechnical exposure can help create specific coalitions for information sharing given their shared exposure to hazards, or higher network-level risk transmission. Measuring sociotechnical exposure can be a baseline for transparency and risk accountability, or for how to attribute and manage consequences of exposure at the collective organizational scale.

The relevance of supply chain transparency is growing in sustainability governance[259–261], and there is much room for CI governance to develop with similar approaches. There is growing recognition for stakeholders, including producers and consumers, to become more involved in every step of global supply chains and to share responsibility for transforming current production systems. Transparency has a normative and legal connotation[262]. From a normative perspective transparency serves principles of democratic, participative decision making and accountability. It is expected to counteract deep asymmetries on how stakeholders access information. In a corporate and legal sense, it is related to improved accountability (disclosure and dissemination) of a business’s environmental, social, and governance due diligence, also known as ESGs. Climate risk is an emerging issue in corporate environmental due diligence, which include regulatory and physical risk related to climate change impacts. Long-term investment practices, within corporate and utilitarian decision-making frameworks, are increasingly focusing on ESGs performance as these becoming more linked to profitable operations that create long-term value of commodity[263,264]. On the other hand, advances in attribution science has improved the traceability of historical emissions to individual companies, causing increased climate accountability litigation cases, notably of fossil fuel companies[265]. Similar expectations of accountability could be developed to trace back public or private organizations responsible for the increase of infrastructure development and population exposure to current of projected climate-induced hazards.

We argue that, given ESGs performance or other government incentives, methods for assessing sociotechnical network exposure can benefit from supply chain transparency concepts to transform the resilience of commodity production of the transient and future TFS. Much progress has been made in supply chain sustainability by systematically linking individual supply chain actors (sociotechnical interlinks) with specific production regions, allowing to better understand exposure of specific commodity markets like cattle, soy, cotton, or cacao, to risks of deforestation and slavery (socioenvironmental interlinks)[266–268]. Understanding these sociotechnical networks and their relationships to natural resources in the landscape have (1) strengthened accountability through more accurate assessment of commodity market's positive or negative impacts in land use changes, biodiversity loss, carbon emissions, etc.; (2) uncovered the connections between supply chain stakeholders and locations where their sourcing operations have a high footprint; (3) targeted specific stakeholders in the supply chain and consumer markets that have higher leverage for improving sustainability goals; and (4) enabled sector-wide assessment of the progress of interventions to improve sustainability of a specific commodity trade. Although research in supply chain transparency is commonly applied to global agricultural and manufacturing commodities, its conceptual and practical application can be harnessed to improve transparency of climate change exposure and risk at new collective organizational scales. Given the difficulty for supply chain organizations to see clear causality between climate risk as global phenomena and operational risk [269], this step can further increase the awareness of shared risk between a large set of CI stakeholders. Mapping sociotechnical network exposure can help demystify complex organizational networks, help each stakeholder identify and minimize risks based on transactional and consumer behavior, and monitor whether and where progress is being made in supply chain transparency and how it aligns or not with resilience and climate adaptation goals.

Mapping sociotechnical networks and improving supply chain transparency of the TFS can help identify stakeholders currently or historically marginalized in decision-making processes of fossil-fuel and renewable energy supply chains; the siting of energy facilities; and decommission of legacy fossil-fuel infrastructure or dependent facilities. Effective inclusion and explicit integration of broader and more diverse stakeholder into energy planning is key to strengthening the social contract for deep decarbonization and to counter misinformation on climate risk.

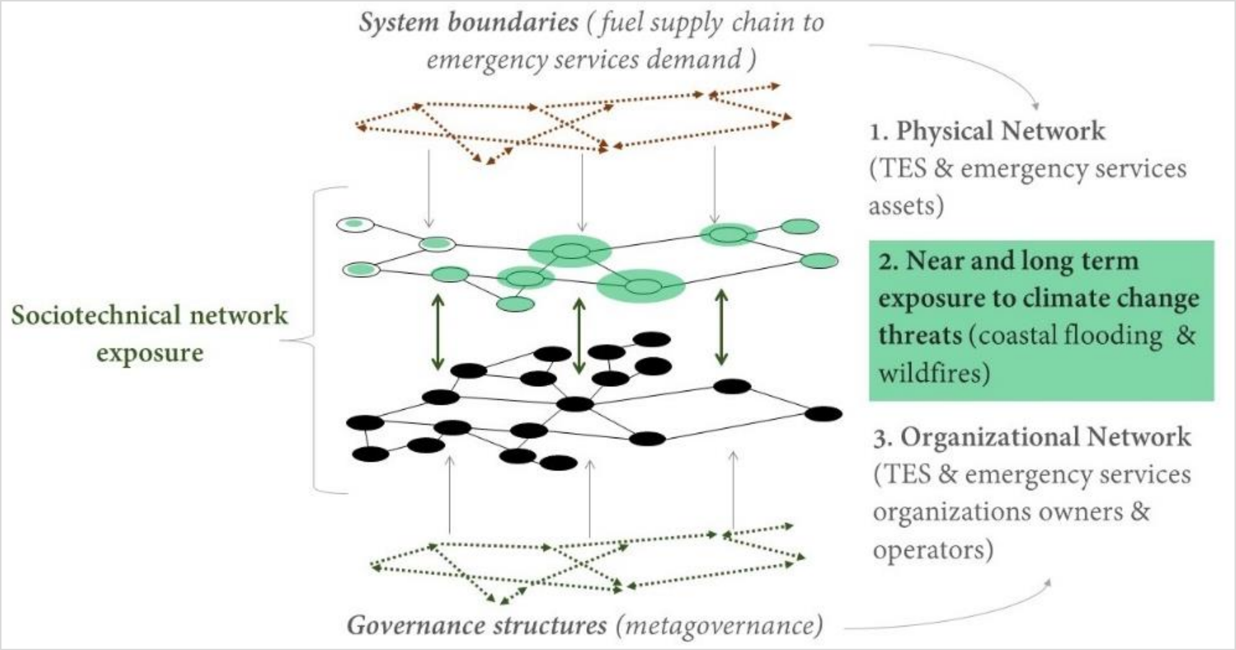


Figure 12. TFS as social, technical, and environmental system to identify sociotechnical network exposure to climate threats and improve complex systems governance (adapted from Peck, 2007)

The complexity of the TFS requires unique frameworks to rethink functions and boundaries of this CI, which in the advent of energy transition, needs to better incorporate the criticality of energy services. For large and complex supply chains such as the TFS, improving our awareness of sociotechnical networks can help address scale mismatches between the temporal and spatial scales of governance; and the scales of landscape processes (resources and hazards) (182–184). Ultimately the knowledge of these social, technical, and environmental interlinks should help move from simply managing supply chains for due diligence and risk reduction, to predicting and preventing lock-in of unsustainable practices which reinforce vulnerability patterns, notably those deriving from the organizational complexity and fragmented governance of the contemporary TFS.

3.5. Conclusion

Well-designed climate change policies advocate swift and “sticky” transition to low-emission pathways needed to proactively avoid locking into low resilience urban futures. In this chapter we bridge knowledge in CI resilience, supply chain sustainability, and energy systems policy to identify five unique traits of the TFS climate risk governance problem: unprecedented transition; widespread interdependencies; complex organizational networks and fragmented governance; hazardous materials; and path-dependency. The 1994 San Jacinto river flooding and Hurricanes Rita (2005), Katrina (2005), and Harvey (2017) in the Gulf Coast illustrate issues related to the compound effects of natural and technological hazards involving hazmat release. Hurricane Sandy (2012) is an emblematic example of the fragility of fuel and energy systems wide interdependencies. The extreme-wet-and-dry season of 2017-2018 in the U.S., which included major Atlantic hurricanes of category 4 and above (Harvey, Irma, Jose, and Maria), and a series of high-impact wildfires in the Pacific Coast, reveal how the concomitance of climate-induced disasters can be amplified by fuel disruptions and jeopardize emergency service capacity at the U.S. scale. Projected exposure of the fuel sector in California illuminates network-level vulnerabilities of the TFS and adumbrates the implications of TFS complexity and governance fragmentation for the resilience of energy services.

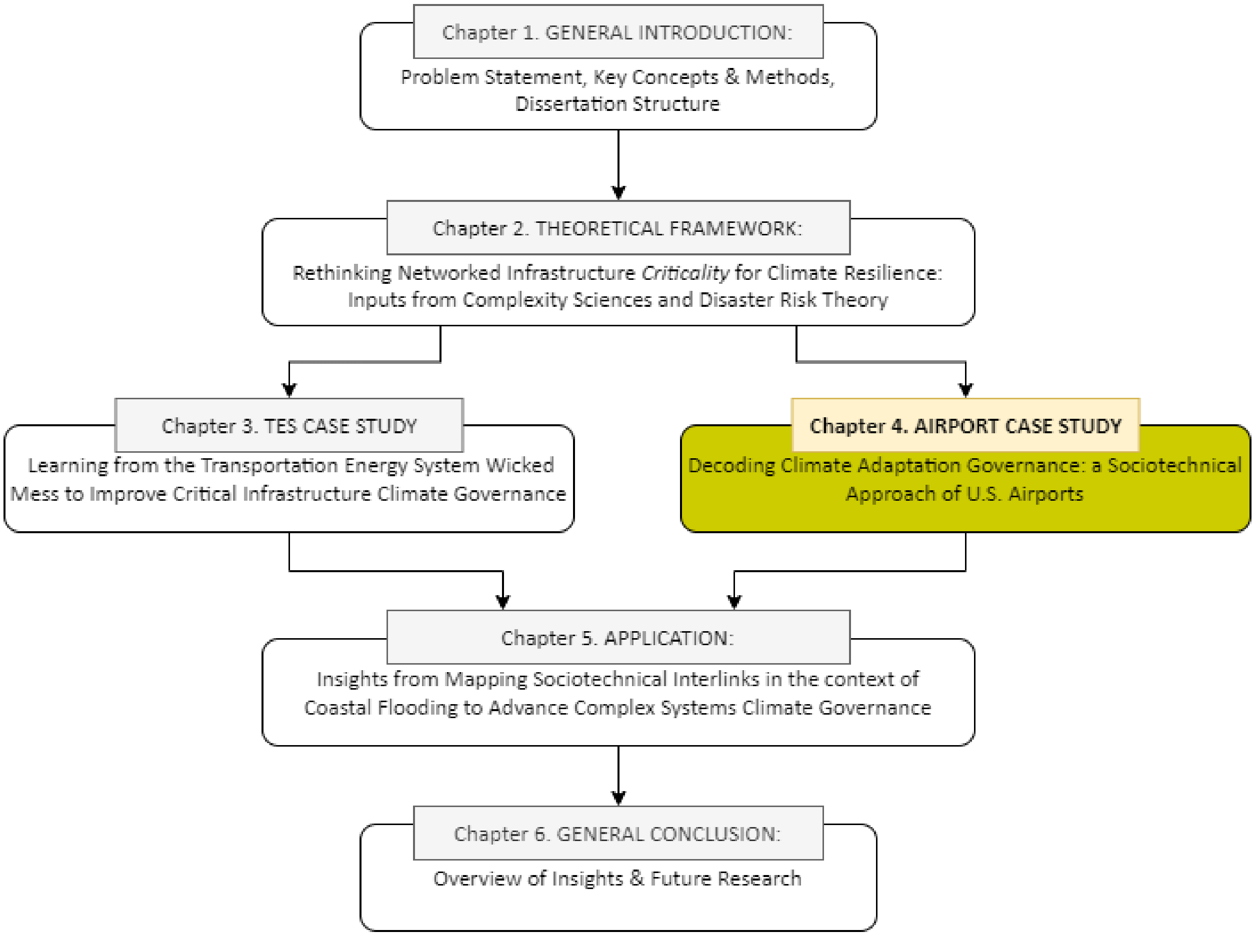
Better understanding these unique characteristics of the TFS, their underlying vulnerability explaining past disasters and future climate risk, helps explain the pressing challenges of CI climate resilience. For all these past disasters and future assessment of TFS vulnerabilities, the complexity of organizational networks and fragmented governance is a recurrent theme. Better understanding the TFS unique vulnerabilities and how they amplify disaster risk have implications for CI governance, but do not provide fixed solutions. Instead, they constitute a set of core characteristics that help frame the TFS as a social, technical, and environmental system to explore current gaps in planning and to provide guidelines, from a complex system perspective, for a more resilient future TFS.

Framing the TFS as a social, technical, and environmental system implies understanding environmental-technological, socioenvironmental, and sociotechnical interlinks. We argue that given the set of unique vulnerable conditions of the TFS as a CI, improving our knowledge of it socioenvironmental and sociotechnical interlinks implies (1) a better incorporation of technological hazard management to decrease the intentional or unintentional misuse of TFS commodities and derived externalities; (2) the promotion of energy justice by preventing unequal distribution of transportation fuel access as well as inequal burdening of externalities of current, transient, and future TFS; (3) understand the co-evolution of technological systems and governing institutions to break path-dependency of high-emission economy and improve collective governance of complex CI.

Finally, we propose a modeling approach to better understand the interlinks, or shared states, between the organizational and physical infrastructure networks namely the sociotechnical networks. We illustrate how mapping sociotechnical networks and their relationship with landscapes can help understand sociotechnical network exposure to climate-hazards. We argue this approach helps address governance scale-mismatch typical of complex systems, and that it can help advance research on collective organizational resilience. By applying metrics of social network analysis combined with advances in supply chain sustainability and transparency, sociotechnical network exposure can promote complex system governance by (1) improving shared risk awareness; (2) increasing accountability of stakeholders responsible for higher network-level vulnerabilities; (3) targeting specific stakeholders with higher or lower leverage to act on network-level resilience, and (4) monitoring sector-wide interventions and how they progress or not towards climate resilience goals.

If we fail to critically assess the fallacies of the contemporary TFS in its ability to provide energy services, then technology push for renewables and low-carbon economies will provide a partial and unacceptable solution to the TFS climate resilience wicked mess. This partial solution risks deepening environmental and energy injustice due to a general oversight of the TFS social, technological, and environmental interlinks. In this chapter, we shed light on known vulnerabilities of the current TFS, notably vulnerabilities that have surfaced under ever more frequent and severe climate-induced disasters. We hope that the opportunity of planning for transient and future fuel systems considers these known vulnerabilities which would go hand in hand with socioeconomic goals of the energy transition. From a research perspective, there is a pressing need to improve knowledge exchange between experts of the contemporary TFS with their consumer needs (especially for emergency services) and key stakeholders of energy transition policy design and technology deployment without forgetting to incorporate lessons learned from cascading TFS-related disasters such as Hurricane Maria and Sandy among others. Given the recurring theme of organizational complexity and fragmented governance barriers, we propose that next steps in designing a future more resilient TFS takes into consideration the importance of understanding sociotechnical and socioenvironmental interlinks of CI.

Chapter 4. Decoding Adaptation Governance: a Sociotechnical Approach to U.S. Airports



4.1. Introduction

4.1.1. Climate adaptation policy lag and the case for adaptation governance

Improving our understanding of governance mechanisms is a key step to measure policy operationalization and bridge the gap between planning and implementation. The latest overview of the Nationally Determined Contributions under the Paris Agreement indicates that capacity-building for climate adaptation2 policy design and its integration into sectoral planning processes is in high demand (UNFCC, 2021). In the context of global and complex socioenvironmental problems, decoding governance mechanisms is becoming ever more essential moving beyond traditional forms of policy monitoring based on target-setting (Shepherd et al., 2015; Sanchez Rodriguez et al., 2018), to a process-based approach that is iterative, collaborative, proactive, and transformative (Shi and Moser, 2021).

Governance is defined as the “totality of interactions in which government, other public bodies, private sectors and civil society participate to solve public challenges” (Meuleman, 2018). It describes a “collection of rights, rules principles and decision-making procedures that give rise to social practices, assign roles to participants of these practices, and guide interactions among participants” (Meuleman, 2018; Young, 2017). It describes how decision-making takes places and by whom (Gieseke, 2019), also respectively referred as “architecture” and "agency", or institutional “frameworks” and "actors". Governance agency describes the players within the policy domain and their roles, and their ability to create, diffuse, orchestrate, modify, and demise the current institutional framework (Burch et al., 2019). Governance architecture can be defined as a network of shared principles and practices guiding decision-making. The key to effective governance lies in assessing the interactions between agency and architecture and whether governance matches the issues it is designed to address.

Adequate adaptation management ultimately contributes to almost every aspect of sustainable development through adaptive capacity, vulnerability reduction, and resilience strengthening (UNEP, 2020). Adaptation was explicitly included as one of the United Nations (UN) Sustainable Development Goals (SDG) for the 2015–2030 agenda resolution under SDG 13 to take urgent action to combat climate change and its impacts (UN, 2015b). Specifically, airport climate adaptation directly contributes to making cities inclusive, safe, resilient, and sustainable; and by building resilient infrastructure, promoting sustainable industrialization, and fostering innovation (Di Vaio and Varriale, 2020) through mainstreamed airport sustainability practices (Prather et al., 2016; Martin-Nagle, 2015; Klauber, 2019; Lurie Eggeet al., 2019).

Adaptation management is considered as the operationalization of adaptation governance (Cradock-Henry et al., 2019). Adaptation governance is expected to coordinate policy solutions that are transparent, representative, and accountable through inclusive, participatory and multiscalar processes (Singh et al., 2021; Tanner et al., 2009).

Reviewed literature on adaptation policy underlines how actionable adaptation policy has suffered a substantial lag when compared to climate mitigation (Shi and Moser, 2021; Bulkeley, 2010; Grafakos et al., 2018; Urwin and Jordan, 2008), particularly due to the lack of operationalization processes (Sanchez Rodriguez et al., 2018). Airport climate adaptation focuses on strategies to reduce the inevitable impact of climate on airports, whereas climate mitigation focuses on strategies to prevent climate change through emissions reductions.

Investigations on the reasons for this lag have received scant attention but point to the utilitarian perspective of global climate action agenda (Chan and Amling, 2019; Pielke et al., 2007). One of the reasons for neglecting adaptation policy when prioritizing climate actions has also been attributed to difficulties in measuring the implementation and effectiveness of these policies. Others have pointed out that the diverse normative views of adaptation effectiveness result in inherent tradeoffs and implementation differences between them (Singh et al., 2021). These distinct normative perspectives ultimately strain consensus for monitoring and operationalizing adaptation policy.

We argue the adaptation lag, particularly for industrial sectors, is in part due to climate mitigation goals fitting more seamlessly to traditional airport environmental goals. Environmental policy frameworks have developed based on clear scientific attribution, where consensus on the monitoring and the effectiveness of policy is, for instance, more easily attained using monetization of costs and benefits, and marketable solutions through emissions thresholds and reduction targets. The aviation sector environmental policies, which emerged from noise pollution concerns at the end of the 1960's, has more easily integrated climate mitigation goals. Programs dedicated to removing barriers of large-scale commercial use of sustainable aviation fuels by airlines (Abrantes et al., 2021, IATA, 2020; Khoo and Teoh, 2014), electrification of airport operations (Barrett et al., 2019; Monsalud et al., 2015; Soltani et al., 2020) and aircraft (Greer et al., 2021; Afonso et al., 2021; Bills et al., 2020; Baumeister et al., 2020), and market strategies3 to limit airport emissions, have taken a large space in aviation research and policy in the last two decades (Greer et al., 2020).

Furthermore, adaptation costs and benefits are inadvertently diluted in almost every aspect of safety and environmental management goals, making it hard to differentiate adaptation effectiveness from regular business performance and sustainability standards. Due to the idiosyncratic nature of climate impacts, and fragmented responses across jurisdictions, little systemic work on climate adaptation governance at supra-local scales has been done (Koski and Keating, 2018). Climate adaptation governance remains underdeveloped (Andrijevic et al., 2020), especially when contrasted to other environmental policy agendas focused on climate mitigation and pollution reduction across industries and government sectors world-wide.

4.1.2. The compelling case of airports to assess governance systems: transboundary nature and centralized safety standards

Airports are critical infrastructure that we rely on heavily for long-haul transportation, global mobility, and accessibility of communities that lack surface transportation. The air transportation industry employed 87.7 million workers world-wide, dropping to 41.7 million following the Covid-19 pandemic impact (ATAG, 2020). Airports power global economic growth through trade links, tourism, and by generating tax revenue. Airports also provide essential services to local communities by routinely serving as staging areas for emergency response operations and for the distribution of emergency supplies and workers. During the first few months of the pandemic response, air transportation was key to repatriating 5.4 million citizens after borders where closed, delivering 1.5 million tons of cargo (mostly medical equipment), and providing 245,500 medical staff transfers (ATAG, 2020). Airports provide lifeline reliability during emergencies where surface transportation is disrupted due to disasters, famine, or war. As critical infrastructure systems, airport adaptation is vital to support cities' resilience and sustainability.

The aviation sector, due to its strong centralized regulatory structure, provides an interesting lens to assess supra-local governance systems. Since 2013, U.S. federal agencies have been commissioned to reduce their fiscal exposure to climate hazards (GAO, 2013, GAO, 2015, GAO, 2017, GAO, 2019, GAO, 2021). This action raises questions on the role of the federal government in the metagovernance of airport adaptation as major financiers of airport infrastructure, leaders of system and strategic planning, and as providers of knowledge and technical assistance to airport decision-makers. The "government of governance" (Bell and Park, 2006, Rayner, 2015), or metagovernance studies, seek to enhance the role of central actors (usually the state). Metagovernance has been transitioning from simplistic hierarchical command and control powers to orchestrating diverse governance processes including more and more transboundary collaborative mechanisms (Sørensen, and Torfing, 2009). Airports, like cities, face diverse challenges due to different roles within the global air transportation system and market dynamics. In addition, airports face numerous national and local regulatory constraints, unique ownership and management structures, operation models, and financing strategies. Airport governance systems mirror the complexity of the city that harbors them and are highly influenced by the cities they service. These transportation nodes represent a compelling case of transboundary governance, where the operationalization of policies through standards, protocols, and planning guidelines in one country can have rippling effects world-wide. Given the historical emergence of municipal response to climate change and the leadership roles of city coalitions around the world (Bulkeley, 2010; Chu, 2018; EEA, 2020), airports present a high potential for developing transnational centers for collaborative adaptation governance in urban areas (Papin, 2020).

Airports are considered high reliability organizations (HRO). Accordingly, airport reliability and safety goals override productivity goals (Roberts, 1990). Such organizations operate under risk of catastrophic consequences in case of an accident or failure, and therefore they must present nearly failure-free operations. To achieve and maintain such HRO norms, strict safety-oriented regulatory frameworks are standardized and reinforced at international and national levels.

In this chapter, the compelling case of airports, their transboundary nature, and their tight policy interdependencies due to safety standards, is utilized to assess adaptation governance mechanisms at supra-local scales. An innovative method to decode adaptation governance based on the United States (U.S.) airport policy system is proposed. This study, based on a critical review of over 200 policy documents, benchmarks governance processes which support the emergence of adaptation guidelines and practices so that adaptation regimes can be better characterized, monitored, and improved.

4.1.3. Research questions and chapter overview

Despite the rise of adaptation guidelines within airport sustainability and climate risk management policy in the last decade, actionable adaptation policy remains fragmented and embryonic. We seek therefore to benchmark U.S. airport adaptation governance and scrutinize the institutional capacity to adapt to the effects of our changing climate proactively and iteratively. We propose a review of key adaptation guidelines and standards, and airport specific policy at international and U.S. levels. This review informs how adaptation governance is emerging through centralized airport policies, and decodes implicit adaptation mechanisms currently embedded in technical and organizational airport standards for the U.S. While describing these policy mechanisms we seek to understand the potential for climate-cognizant policies to emerge within current airport regulatory documents. In other words, we disclose current barriers and prospects of operationalizing adaptation regimes through the following questions:

- **How can climate adaptation emerge within current airport regulatory frameworks?**
- **What are the barriers and pathways for airport adaptation governance?**

We start by contextualizing challenges that airport policy and decision-makers face when dealing with climate risk. Challenges related to climate impact idiosyncrasy and scale mismatch justify our sociotechnical approach to airports. We then describe materials and methods used in our policy review, which has two levels. The first level reviews international and national adaptation policy milestones to contextualize the emergence of adaptation in global climate governance, and then identifies prescribed adaptation pathways. The second level systematically reviews airport-specific regulations (U.S. Federal Aviation Administration Advisory Circulars) and applies a policy coding scheme based on their content. Based on the first level review, we develop a coding scheme that reflects key characteristics to assess actionable adaptation policies: policy target, timescale, and governance mode. This coding scheme seeks to uncover: (a) what aspects of airport operations and planning are being targeted, (b) what timescales for decision- making these policies are defining, and (c) what are the governance processes incentivizing compliance (hierarchical, market or collaborative). Ultimately, our policy coding system investigates how airport policies create conditions for the production and use of climate data as decision-relevant information. Our method identifies these policies' potential for incorporating forward-looking climate data and promoting adaptation pathways. Finally, we discuss how potential-climate cognizant policies reveal barriers to adaptation governance related to institutional path-dependence. We also highlight the potential of collaborative policy to enhance and transform airport adaptation governance. Our methods are general, and results should help advance systemic thinking in shaping policies for large, multiscalar complex infrastructure. Figure 13 provides an overview of how the chapter's theoretical framework, methods and results answer our research questions.

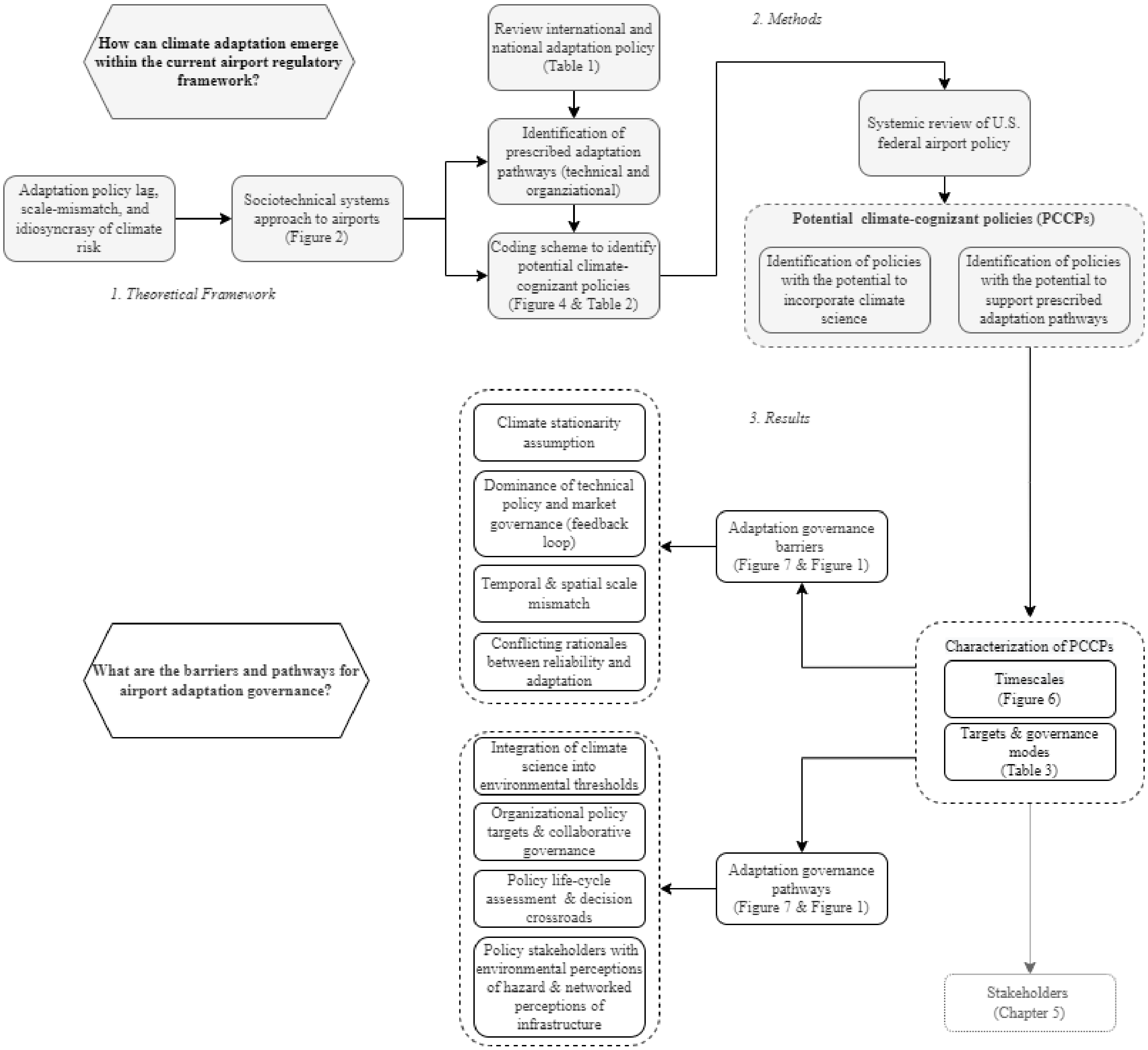


Figure 13. Chapter overview: decoding adaptation governance steps

4.2. Background and theoretical framework

4.2.1. Climate change impact concerns to airport stakeholders

One of the main issues in developing adaptation policies is the idiosyncratic nature of climate impacts. Sea level rise, increased intensity storms, temperature change, changing precipitation, changing icing conditions, changing wind direction, desertification, and changes to biodiversity are among the top ten world-wide airport operator concerns when thinking of future climate change impacts (Baglin et al., 2012). There is a wide range of expected climate impacts throughout a single country as well as within each airport. The sensitivity to different hazards varies when considering airside (and its airfield part – runways, taxiways, apron), landside (terminal curbside, parking, roads), local intermodal transportation interconnection, and overall regional exposure (GRA, Inc., 2019).

Rising temperatures, for example, impact both airside and airfield operations, and are problematic because air density directly affects aircraft ability to takeoff. This results in increasing aircraft takeoff weight restrictions, possible flight delays, and occasional major investments for increasing runway lengths (Ren et al., 2019; Hane, 2016; Coffel et al., 2017). More intense storm activity, including higher wind loads and wind variability, impact the airside by increasing aircraft turbulence, and increasing fuel burn when flying into the wind during cruise. At the airfield, storms can cause damage to structures, increase runway operations complexity leading to delays in takeoff and landing, and leading to the eventual redesign of runway orientations to match changes in prevalent wind patterns (Gultepe et al., 2019). Coastal flooding currently puts at risk 269 airports in the world, while projections indicate that this number doubles by 2100 (Yesudian and Dawson, 2021). Due to intermodal connections between airports and cities located in low elevation coastal zones, flooding has a high potential of impacting airport operations even when it occurs outside airport premises. Airport vulnerability is also context-specific and will differ based on regional socioeconomic characteristics; airport size and capacity; the services provided; airport tenant composition and assets; and airports' distinct governance model and organizational capacity to identify climate hazards, mitigate losses, respond to incidents, and proactively adapt.

As described above, climate hazards, vulnerability, and institutional capacity to manage climate risk are context-specific and create the need for iterative, collaborative, and transformative policy solutions that align with overarching airport sustainability goals. These process-based policies challenge our current standardization systems that are fundamentally based on rigid target-setting frameworks, repeatability, and hierarchical governance structures. The idiosyncratic nature of climate impact has also resulted in the assumption that adaptation policy is hyper-local. This implies that costs, externalities, and benefits from adaptation knowledge and technology are not integrated into the established transboundary and multi-scalar infrastructure network. In fact, like climate mitigation policy, adaptation policy costs, benefits, and procedures should be seen at regional and global scales including networked dimensions of infrastructure and collective dimensions of organizations.

4.2.2. Airports as technical, social, and environmental systems

Airport infrastructure is framed as a multiscalar complex system where policies guide sociotechnical relations between airport physical and organizational assets. This framework is applied to address issues of climate risk idiosyncrasy and scale mismatch. These issues can be linked to the difficulties of assessing the effectiveness of adaptation policy and inadequate governance systems reduced to target-setting mechanisms. The scope of this study is then described based on the airport federal regulatory structure and on the geographic distribution of technical assets governed by the reviewed airport policies.

Many problems encountered by societies managing natural resources or hazards arise because of a mismatch between the scale of governance and the scale of landscape processes (Bai et al., 2010; Calliari et al., 2019; Hamilton and Lubell, 2018; Forino et al., 2018). Scale is a central issue for effective governance that refers to a specific spatial or temporal boundary where a phenomenon is recognized. Such boundaries may be natural (watersheds, biomes, geomorphological landforms); administrative (county, state, national); socioecological (land tenure, land use types); or sociotechnical (metropolitan transportation regions; power distribution regions). Adaptation related to flood hazards for example, have greatly developed by promoting transboundary governance systems that consider geomorphologic and hydrographic scales (Calliari et al., 2019; Chaffin et al., 2016; Lewis and Ernstson, 2017; Ceddia et al., 2017; SFEI; SPUR, 2019). These scales best describe for example, how flood management decision-making results in effective outcomes at the catchment, delta, or coastal scale, and their geomorphologic time processes.

Given the global and networked nature of air transportation infrastructure, we develop a sociotechnical framework to similarly address issues of temporal and spatial scale adequacy of airport policy. This framework is inspired by the natural resources management field which often tackles planning and policy decision-making issues at a jurisdictional or political scale that does not correspond to the scale of the natural resource or hazard at hand (Cumming, 2011; Cumming et al., 2006). In this case, we hypothesize on a mismatch between airport policy scales and the scale of expected impacts from climate change to the airport sector. It also draws from critical infrastructure resilience research which frames infrastructure networks as interdependent complex systems with multilevel boundaries, notably the technical, the social, and the environmental (Lindbergh and Radke, 2021; Markolf, 2018; Peck, 2005)

An emerging consensus holds that infrastructure resilience to climate change and extreme events require an alignment between governance structures and sociotechnical processes that characterize infrastructure systems beyond their physical assets (Northeastern University, 2018, OECD, 2019). In this study we look at airport technical and organizational assets where policies governing these assets act as sociotechnical interlinks. This framework helps us understand airports not only as technology and hardware, but as organizational and institutional networks tied together through constitutive and operational policies, and multiple governance modes. Framing airports as sociotechnical systems also helps include multiscalar approaches to temporal, landscape, and spatial aspects of complex systems that are scant in actionable adaptation policies (Figure 4.2).

This approach to airport adaptation governance focuses on the ability of sociotechnical systems to transform from one configuration to another in response to disturbances or shocks (Amir and Kant, 2018) and promote climate-cognizant infrastructure policy. Looking at airports as sociotechnical systems can help us link organizations and infrastructure across time, landscape, and space to optimize the scale of adaptation actions (Guerrero et al., 2013). Climate-cognizant policies for sociotechnical systems promote infrastructure robustness, redundancy, and reliability; as well as institutional preparedness (flexibility and learning capacity) and transformability (innovation agency) (Amir and Kant, 2018).

This approach is expected to better address scale mismatch. Scale mismatch can be the product of governance design inadequacy, or "the ineffectiveness of governance goals, frameworks, or the management thereof, to achieve policy goals" (Meuleman, 2018). Institutional framework inconsistencies with environmental processes have resulted in adaptation governance barriers based on technocentric infrastructure policy and institutional path-dependence.

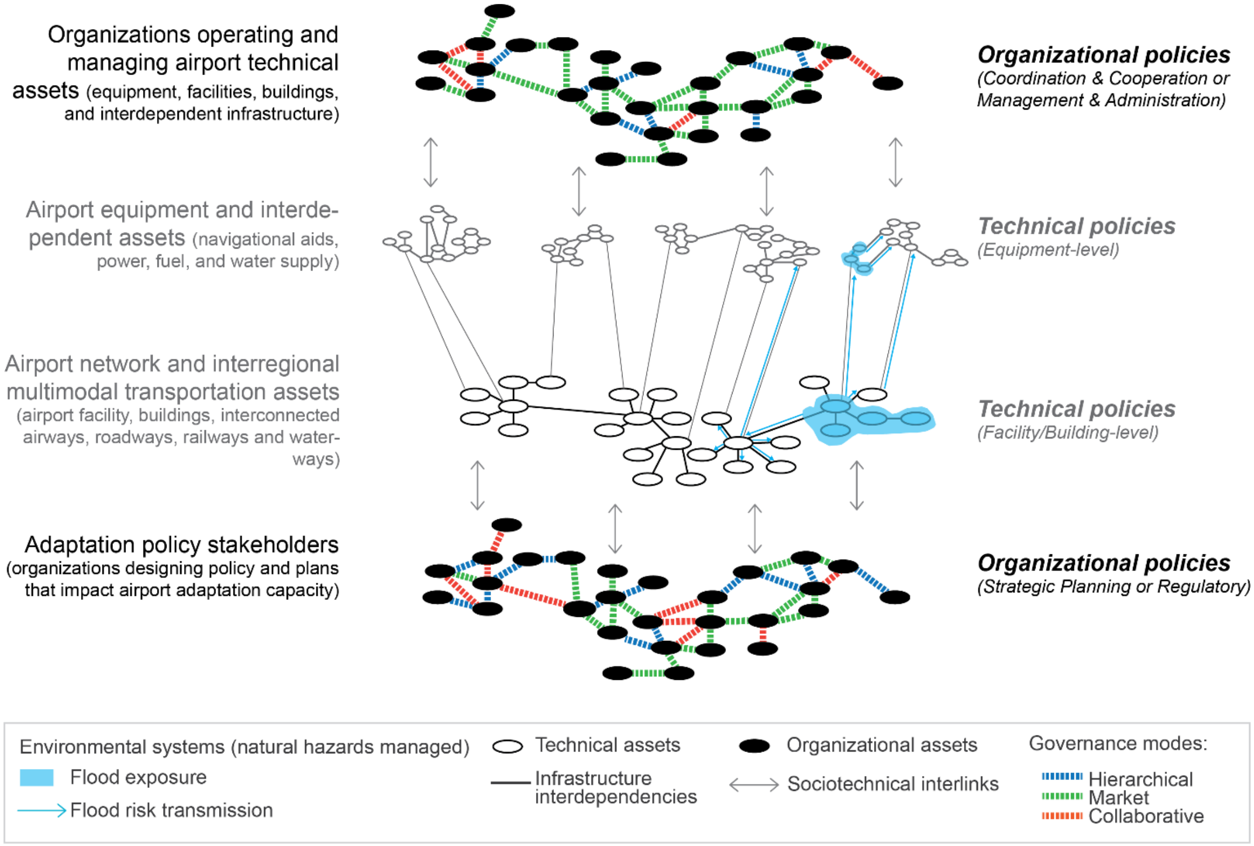


Figure 14. Airports as technical, social, and environmental systems

Technocentric policy limits adaptation to "climate-proofing" infrastructure, often in disregard of land-use policies, sustainability goals, and social dimensions of infrastructure (Shi and Moser, 2021; Lindbergh and Radke, 2021; Sovacool and Linner, 2016). The sociotechnical framework permits inclusion of organizational dimensions of infrastructure systems, that are often better equipped to manage the uncertainties of climate risk through decision-making heuristics and institutional value transformations (Savaget et al., 2019). In the case of large multiscalar infrastructure such as airports, these inconsistencies can cascade through technical and organizational policies and have effects at a global scale.

Complex systems are prone to non-linear behavior with the occurrence of tipping points, or regime shifts, that can set the system in a trajectory that is difficult to reverse. At the sociotechnical level, this translates to understanding how policy and decision-making in the present locks the airport infrastructure system into a path which will impose high transition costs in the future (Unruh, 2000). As a result, institutions display path-dependence (Cox et al., 2015; Adamson et al., 2018). A trajectory of decision-making will be set based on the usage of a particular technology or underlying normative value. At some point such technology or underlying normative value can become conflicting with uprising values or environmental change and result in counter-productive governance. The key to understanding path-dependence lies in investigating self-reinforcing dynamics (feedback loops) and identifying potential decision crossroads. Decision crossroads can be considered as critical junctures where decision and policy-making have the potential to cascade through organizational and technical networks to transform behavior. In our study, this transformation results in effective adaptation governance of large-scale infrastructure networks such as airports. We argue that better understanding governance processes is essential to support airport adaptation measures on the ground and promote the implementation of complex adaptation and sustainability goals beyond traditional target-setting mechanisms (Shepherd et al.,2015).

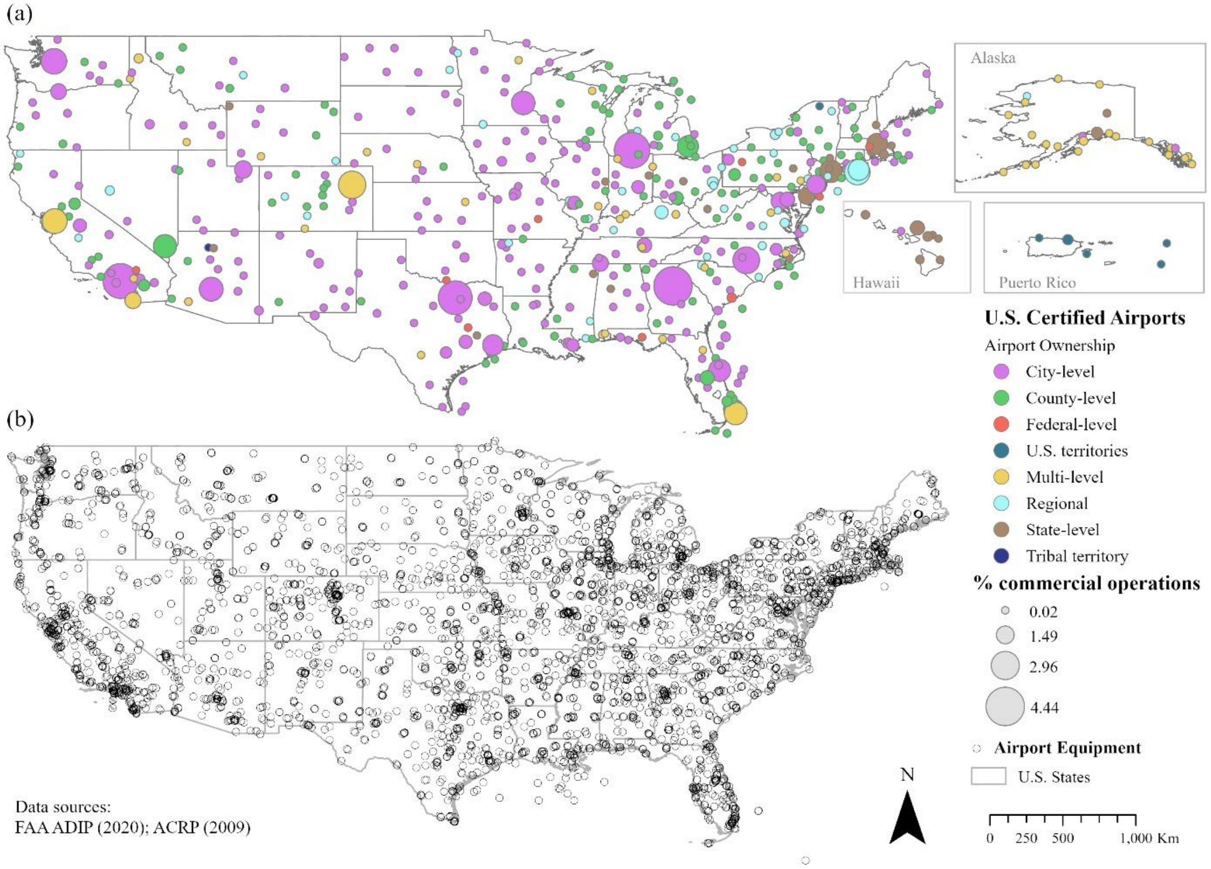
4.2.3. Study scope: airport regulatory structure and geographic distribution of assets

This research focuses on airport governance systems for the U.S., which have a significant impact on global air transportation. The U.S. carries the highest number of passengers (World Bank, 2016). and governs the largest number of airports world-wide with a dense network of navigation equipment under the National Airspace System (NAS). Due to the strong centralization of airport safety procedures world-wide, we believe the methods applied here solely to the U.S. are applicable to other aviation policy frameworks around the world, especially those that have a higher proportion of public-private partnerships for airport operations.

Numerous governance models are in use at U.S. publicly owned airports. Currently, most airports are owned by city or municipality governments, but multiple combinations of public entities can own, manage, and operate an airport; and changes to these structures are still occurring (Fig. 3). Furthermore, airport governance typologies vary based on the degrees of private and public control over decision-making and how essential powers are shared. In the U.S. airports are owned by a combination of national, regional, or local governments and they are operated by branches of these governments (ACRP, 2009). U.S.

airports are among the most privatized governance systems in the world since most functions of airport operators are executed through contracts (Neufville and Odoni, 2013).

Despite airport governance complexity, a minimum level of homogeneity within U.S. airport regimes is assumed in this study. The FAA is the overarching agency responsible for designing and reinforcing airport regulations at the federal level. More specifically it prescribes “rules governing the certification and operation of passenger carrying airports” in the U.S. As the main regulator of airport facilities, the FAA has the authority to issue, deny and revoke U.S. airports certificate to operate as well as the responsibility to ensure compliance. This authority represents the main policy mechanism that enforces minimum levels of safety for all airports governed by the U.S. The way in which the FAA communicates these rules to airport owners, operators, and other stakeholders is through Advisory Circulars (ACs). Our systematic airport-specific policy review covers all airport ACs. As of 2020, the U.S. registered approximately 3,310 (FAA, 2018) operational airport facilities that comply with standards, procedures, rules, and guidelines issued through FAA Airport ACs, and more than 40,000 pieces of NAS equipment. Figure 15 presents the study scope of technical assets under sovereignty of the policies reviewed in this chapter.



Data sources:
FAA ADIP (2020); ACRP (2009)

Figure 15. Scope of technical assets under sovereignty of airport policies reviewed. (a) Major airport facilities, their diverse governance typologies, and their contribution to commercial operations in the U.S. (b) Airport equipment under the NAS. Compiled from (ACRP, 2009; FAA Airport Data and Information Portal, 2020).

4.3. Materials and methods

This study is based on a literature review of 25 global and national policies on adaptation, 53 airport policy guidelines, and on a systematic review of 129 ACs. A content analysis (Bryman, 2012) and policy coding scheme (Saldana, 2020) was derived from this systemic airport policy review. Our policy coding scheme is designed to decode adaptation governance and identify pathways that enhance institutional capacity to design and operationalize adaptation policies. Processed data from the 129 airport ACs are available as Supplementary Data in Lindbergh et., al, 2022.

4.3.1. Literature and policy review on adaptation

Academic literature on airport adaptation is sparse (Ryley et al., 2020; Burbidge, 2016a, 2018; Pümpel, 2016), and academic literature specific to airport adaptation governance is rare or non-existent. This study integrates overarching literature in adaptation governance, airport adaptation, and airport policy, including substantive "grey" literature for the two later topics (government publications, report literature from aviation business organizations, policy guidelines, protocols, and standards). Our review of over 200 policy documents, helps contextualize airport adaptation policies within global and national adaptation regimes. Key guidelines and standards addressing infrastructure and adaptation more generally are assessed all the way to airport-specific regulatory documents at both global and U.S. scales (Table 4.1).

These global and national adaptation guidelines set adaptation solutions for infrastructure systems and are the baseline for our policy coding scheme. The airport policy review aims to uncover how sector specific adaptation governance is emerging and helps gauge the potential of airport policies to operationalize adaptation strategies. Our review also investigates the rationality of policy (Gale, 2001) and whether there are conflicting issues within institutional goals and means of operationalizing airport adaptation policy in view of global and national adaptation regimes.

Table 5. Key "grey" literature and policy sources at the intersection of infrastructure adaptation and airport governance

	GLOBAL	**NATIONAL**
CLIMATE ADAPTATION	IPCC: FAR (1990) SAR (1995) TAR (2001) AR4 (2007) AR5 (2014) UN: Paris Agreement (2015) SDG 13: Climate Action (2015) ISO: 14090 (2019) 14001 (2019)	NCA: NCA1 (2000) NCA2 (2009) NCA3 (2014) NCA4 (2018) GAO: 13-283 (2013) 13-242 (2013) 15-290 (2015) 17-317 (2017) 17-3 (2017) 19-157 (2019) 21-119 (2021)

	ASTM: E3032 (2016) WFEO: Model code of practice: principles of climate change adaptation for engineers (2015)	NIST: SP 1190 (2015) ASCE: Manual on climate resilient infrastructure (2018)
AIRPORT INDUSTRY	ICAO: 1st. Env. Report (2007) 2nd Env. Report (2010) 3rd Env. Report (2013) 4th Env Report (2015) Doc. 9184 (2018) 5th Env Report (2019) ACI: Climate Adaptation Report (2018) Policy brief on Adaptation (2018)	FAA: 129 airport policies from the Airport Advisory Circulars series ACRP: 5 explicit and 31 implicit reports on airport guidelines for climate adaptation and climate risk management

Acronyms: UN: United Nations (UN, 2015a), SDG: Sustainable Development Goals (UN, 2015b), IPCC: International Panel for Climate Change (IPCC, 1990, 1995, 2001, 2007, 2014), ISO: International Standard Organization (ISO, 2019), ASTM: American Society for Testing Materials International Standards (ASTM, 2016), WFEO: World Federation of Engineering Organizations (WFEO, 2015). GAO: Government Accountability Office (GAO, 2013, 2015, 2017, 2019, 2021), NIST: National Institute of Standards and Technology (NIST, 2015), ASCE: American Society of Civil Engineers (ASCE, 2018), NCA: National Climate Assessment (National Assessment Synthesis Team, 2001; Karl et al., 2009; Melillo et al., 2014; USGCRP, 2018). ICAO: International Civil Aviation Organization (ICAO, 2007, 2010, 2016, 2019), ACI-World: Airports Council International (ACI-World, 2018a, 2018b). ACRP: Airport Cooperative Research Program (ACRP reports repository), FAA's airport policies (FAA Advisory Circulars repository) which will be further described in section 4.3.2.

4.3.2. Airport policy review and coding scheme

Our airport policy review system is designed to decode how and where policies create conditions to insert and use climate data as decision-relevant information which produce adaptation actions. Step (1) is the identification of potential climate-cognizant policies. The consecutive steps are the classification of these policies into three domains: (2) timescales, (3) target, and (4) their governance modes. Figure 16 presents our coding scheme with three policy classification domains and their subclasses. Each subclass has discrete dimensions that are mutually exclusive. An inter-coder reliability was performed to measure the agreement between one coder's results and two other coders. For a total of 1,515 classification outputs covering steps (1) to (4) of 129 ACs the inter-coder reliability is 94.19%.

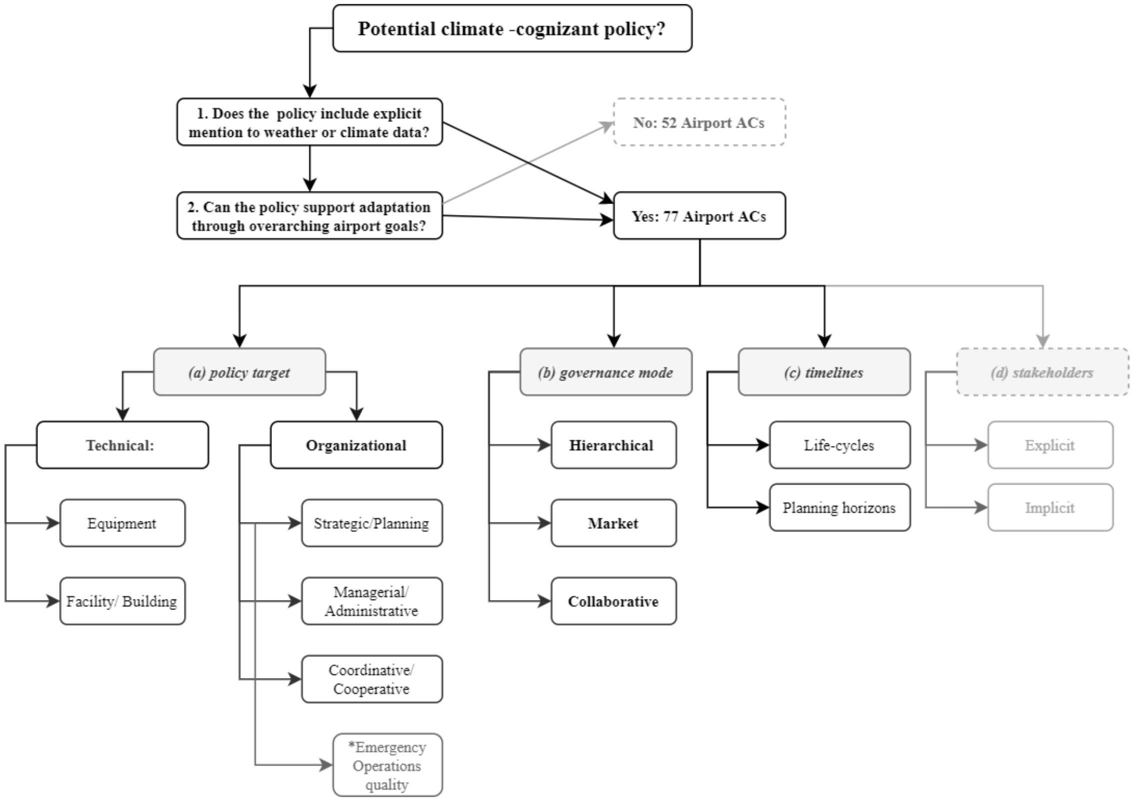


Figure 16. Coding scheme for potential climate cognizant policies. *Stakeholders analysis developed in Chapter 5

(a) Identifying potential climate-cognizant policies (PCCPs)

Our coding scheme seeks to first find policies with explicit mention to weather and climate data, and second, find policies which can indirectly support adaptation through overarching aviation goals such as capital planning, safety and risk management, sustainability, emergency preparedness, land use, and development codes. All ACs that conform to either the first or second criteria are classified as potential climate-cognizant policies (PCCPs). The underlying assumption is that these policies have the potential of incorporating forward-looking climate science into their standards, decision-making mechanisms, and organizational values. Therefore, PCCPs should be considered for review in institutional efforts to design and operationalize adaptation governance.

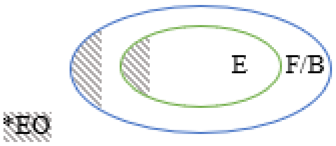
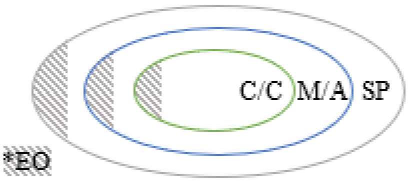
(b) PCCPs target: technical or organizational

Once PCCPs are identified, our coding scheme determines if climate risk management properties and weather thresholds can potentially be integrated into decision-making either at the technical or organizational level. This distinction between "technical" and "organizational" policy is adapted from internationally and nationally endorsed adaptation actions that are usually referred to as "hard" and "soft" measures respectively (IPCC, 2014; ISO, 2019; ASTM, 2016). "Hard" adaptation measures usually target engineering and architectural properties of physical assets using grey or green infrastructure. "Soft" adaptation measures are commonly linked to organizational change, from procedural behavior adjustments to institutional value transformations.

Technical PCCPs are further subdivided into two scales: equipment and facility or building (Table 6). They provide environmental design standards for equipment, buildings, or facilities that include weather and climate thresholds. Due to climate-nonstationary and continuous technological innovation of climate science, these thresholds require iterative reviews to incorporate climate projections, especially for long-lived assets.

Organizational PCCPs provide planning, managerial, cooperative, and collaborative protocols supporting adaptation actions (Table 4.2). The identification and classification of organizational PCCPs required careful evaluation of airport industry guidelines explicitly addressing adaptation from ACRP reports (Baglin et al., 2012; GRA, Inc., 2019; Dewberry, 2015; ICF et al., 2018; ICF International et al., 2016) and ICAO's environmental reports. Based on ACRP and ICAO's recommendations on how to mainstream adaptation into the existing airport management systems, another 31 ACRP reports are assessed to validate organizational PCCPs covering airport planning (Prather et al., 2016; Martin-Nagle, 2015; ACRP et al., 2012; ACRP, 2007; Kincaid et al., 2012; Meyer et al., 2020; James F. Smith, 2019; Varma, 2016), airport management (Prather et al., 2016; Klauber, 2019; Barich et al., 2013; Marsh Risk Consulting, 2012; Delaney, 2013; Landry et al., 2012; Malick, 2016; Quilty, 2015; Krop et al., 2019; Smith et al., 2016; Snyder et al., 2020) and collaborative or integrative efforts for airport safety and airport environmental goals (Lurie Eggeet al., 2019; Meyer et al., 2020; James F. Smith, 2019; Malick, 2016; ACRP, 2009; ACRP, 2011; Arora Engineers, Inc. et al. 2019; Cogliandro et al., 2016; Elliot et al.,2015; Haseman, 2013; IEM, Inc., 2012, Landrum and Brown, Inc., 2012; Smith, 2014; Woolwine Associates and Inc., 2013).

Table 6. Coding scheme for PCCPs targets

TECHNICAL:  Technical policies target physical and palpable airport assets. Their main goal is to set standards on hardware, which are subdivided in two scales: equipment vs. facility/building. They belong to the traditional "engineering domain" where materials & designs can be optimized through empirical evidence and controlled environments.	**Equipment (E):** E policies target airport technical assets of smaller scale: i.e., sensors, power & telecommunication, etc. Some examples include Glide Slopes, Runway Lights, Radars, and back-up generators. PCCPs standards here are often related to environmental conditions to which the equipment's were designed such as temperature, cumulated rainfall ranges, maximum wind speeds, etc.
	Facility/Building (F/B): F/B policies target airport technical assets of larger scale such as buildings and facilities. These technical assets usually contain airport equipment and people. Examples of airport buildings/facilities are tower buildings, terminals, runways, etc. Standards for facility/building assets are commonly referring to architectural design and land-use constraints/opportunities. PCCPs here determine design and construction restrictions for facilities which can be related to hydrometeorological hazard-prone areas (such as flooding areas), or explicitly determine that the facility needs to withstand certain weather-hazardous conditions (i.e., rainfall thresholds per hour). Sometimes they generically refer to local building codes.
ORGANIZATIONAL:  Organizational policies target human assets of airports. They include organizational behavioral standards for planning, management, and cooperation. They typically fit in the "social domain of expertise" and their goal is to set values, roles and procedures for airport owners and operators as well as stakeholders outside of the airport, such as organized civil communities, local government, other airports, and mutual aid systems. Airport organizational policies of interest are usually not explicitly describing climate-related hazards and issues, but emphasize coordination, cooperation, and collaboration mechanisms within environmental and safety-related policies which lead to higher ability to respond to emergencies, plan for and proactively train and organize the institution or stakeholders to incorporate climate risk in their business model. Organizational standards usually fall under 3 scales: Strategic Planning; Managerial/Administrative, and Coordinative /Cooperative. All strategic policies embed managerial and coordinative mechanisms. All managerial policies embed coordinative mechanisms.	**Coordinative/Cooperative (C/C):** C/C policies emphasize setting roles and interacting guidelines for specific airport stakeholders or for a specific asset trade i.e., contracting, certification, land acquisitions, etc. They will not pertain to long term and larger scale planning or managerial policies. When they are mandatory, they will often emphasize training mechanisms/procedures to homogenize behavior for safety purposes in case of construction or emergencies for example. They might also emphasize the need for cooperation in the form of annual meetings, organized events, and data-sharing between actors to improve airport stakeholder ability to fulfil their duties/goals. Some examples are communication standards between airport emergency responders and mutual aid systems, firefighting personnel training, coordination to share data, coordination of operations during construction activities, etc.
	Managerial/Administrative (M/A): M/A policies refer to smaller scale management documents that set procedures and clear protocols to maintain certain airport goals for specific facilities and functions: i.e., performance, waste management, safety management, buildings/facility management. They are more concerned with continuity and maintenance than with future projections or planning, very often they will have "management" in their title.
	Strategic Planning (SP): SP policies determine institutional path-dependence and memory. They refer to larger planning documents that set guidelines and methods to achieve overarching airport goals. These standards have a meta policy aspect, i.e., they set the guidelines for the rule-making. They are rarer and more complex than managerial or coordinative oriented policies, often larger documents (hundreds of pages) and determine guidelines that impact almost every aspect of airport policy. Very often they will have "plan" in their title and will have long term timescales or strong forecasting elements.
***Emergency Operations (EO):** We include a standalone Emergency Operations character which can automatically improve adaptation, and therefore deserves a distinct identification procedure. EO's can be applied to any PCCPs target and is therefore the only category which is not mutually exclusive.	

(c) *PCCPs governance modes: hierarchical, market, and collaborative*

Governance modes used in this research are based on environmental governance research, which identifies public managers as key stakeholders in the oversight and orchestration of governance arrangements (Meuleman, 2018; Bell and Park, 2006). In this context the FAA plays a key role in the metagovernance of airports in U.S. territories by overseeing legitimacy and accountability issues in air transportation. As the key “metagovernor” of airports at the U.S. level, FAA policies are responsible for producing an effective combination of governance modes to achieve safety and operational efficiency goals, but also sustainability and resilience goals. There are numerous ways in which governance modes are categorized in environmental and adaptation research. These are usually based on a combination of different spatial and organizational scales of jurisdiction; and multiple modes of incentives for stakeholder interaction under formal, or informal, and restrictive or voluntary, frameworks (Amundsen et al., 2010; Ariana, 2020; Bollinger et al., 2013; Hissen et al., 2012; Hurlbert and Gupta, 2016; Lidskog et al., 2010; Milman et al., 2020; Nieuwaal et al., 2009; Rose, 2018; Vignola et al., 2013). This study applies three governance modes: hierarchical, market, and collaborative, adapted from (Meuleman, 2018) which capture the incentive for compliance.

Hierarchical governance is enforced by means of legitimate authority and corresponds to traditional forms of top-down control and regulation, commonly referred to as “sticks” incentive. In the airport industry it refers to procedures and guidelines that meet the Code of Federal Regulation statutory and regulatory requirements.

Market governance, commonly referred to as “carrots’’ incentive, is driven by business models of economic efficiency and utilitarian decision-making typically based on cost-benefit assessment. Within the scope of this research, market governance modes correspond to economic-based incentives premised on the eligibility for resource allocation through public financial mechanisms. The FAA’s Airport Improvement Program (AIP), and Passenger Facility Charge represent the major funding resource of U.S. airports, and therefore the main market incentive for compliance. AIP funding is authorized and appropriated through Congressional action (TRB, 2021).

Collaborative governance concerns the interplay of complex networks of stakeholders that are incentivized to conform to given standards for collaborative purposes based on common challenges and goals. It is referred to the "engagement of stakeholders in a collective decision-making process that is formal, consensus-oriented, and deliberative where participants co-produce goal and strategies and share responsibilities and resources" (Ansell and Gash, 2018). PCCPs under this category are neither mandatory nor fit within eligibility criteria for federal funding.

For all PCCPs, the governance mode corresponds to the major compliance incentive for airport stakeholders. Governance modes are mutually exclusive and detectable under each AC “Application” section.

(d) PCCPs timescales

Two important timescales for PCCPs were noted: environmental and policy life-cycles. Environmental timescales refer to how PCCPs with environmental constraints define weather or climate ranges and thresholds. Policy life-cycles refer to any timescale reference that prescribes technical or organizational updates and planning horizons (i.e., guidelines on infrastructure life-cycles, maintenance frequency, training frequency, policy or program review frequency, coordinative agendas, and program or infrastructure planning horizons).

(e) PCCPs stakeholders

Data is collected based on who is the policy targeting, i.e.: who is being restricted under hierarchical policies, who is getting funding under market policies and who is getting collective or social benefits under collective policies? Usually described in introductory statements such as "Purpose", Overview", "Scope", "Application", " Intended Audience or Users", "Who is this policy for", etc. Most ACs will target the airport owner, operator, or airport sponsor, program sponsor and another party. If targeted stakeholder is not explicit, they are classified as “implicit stakeholders” and the category is assumed based on the purpose. For example, design policies will target airport sponsor and airport planners, engineers, and architects. Collaborative or emergency management policies often provide internal and external stakeholders with lists or tables of stakeholders involved. Key word search which helped coding this section includes cooperate, coordinate, collaborate, team, stakeholders, roles, engagement, outreach, responsibility, and authority.

4.4. Findings

4.4.1. Technical and organizational dimensions of PCCPs and their governance modes

Our analysis identifies 77 PCCPs out of 129 airport ACs issued between 1983 and 2018. This means that 60% of airport standards embed latent adaptation mechanisms and that there is a high potential for metagovernance agencies to seamlessly incorporate climate science and adaptation to their policy content.

Most PCCPs target technical assets. These represent 61% of potential adaptation mechanisms, against 39% for policies targeting organizational assets. Market incentives dominate PCCPs governance mode, representing approximately 67.5%, against 17% for hierarchical incentives, and 15.5% for collaborative incentives. Table 7 details PCCPs target and their relative governance mode with examples in Figure 17.

Table 7. Potential climate cognizant policy targets and governance modes

		GOVERNANCE MODE				
PCCP TARGET		**Hierarchical**	**Market**	**Collaborative**	Total	*Emergency Op.* [a]
Technical	**Equipment**	3[b]	22	0	25	*1*
	Facility/ Building	0	19[b]	3	22	*1*
Organizational	**Coord. & Coop.**	6[c]	5[b]	4	15	*4*
	Managerial/ Admin.	3	6[b]	3	12	*1*
	Strategic Planning	1[b]	1	3	5	*1*
Total		13	52	12	77	-
	Emergency Op. [a]	*5*	*3*	*0*	-	-

[a] Count of policies which target technical and organizational assets within emergency operations.
[b] Count includes 1 policy which belongs to emergency operations.
[c] Count includes 3 policies which belong to emergency operations.

(a) Dominance of technical policy targets and market governance modes

Technical PCCPs targeting *equipment* (E) have environmental design specifications with weather and climate-related thresholds. Such thresholds include temperature ranges, wind loads, snow and ice loads, solar radiation, and rainfall rates. Recurrence intervals for storm, precipitation, and flood events (i.e., 5-year storm, 100-year flood events) are also included. Other qualitative references to weather and climate-related hazards include resistance to heavy precipitation and equipment resistant to proximity fire intensities. Most equipment-targeted PCCPs have market governance modes (88%) and only a small portion have hierarchical modes (18%).

Technical PCCPs targeting *facilities and buildings* (F/B) require embedding climate thresholds in construction materials or design, commonly applied to stormwater runoff, drainage, and pavement designs. Facility and building PCCPs present recurrence interval thresholds for storm, wind, and flood activity often with higher complexity in procedures for hydrological design of surface for stormwater drainage. Some have qualitative references to weather and climate-related hazards (such as sufficient protection against weather or compliance with local building codes in natural hazard areas). Again, most facility- and building-targeted PCCPs present market governance modes (86%) and only a small portion have collaborative modes (14%).

Technical PCCPs presenting market governance modes are aligned with utilitarian decision-making. These PCCPs are not restrictive, but incentivized through financial mechanisms, notably FAA grants, for which such assets are eligible only when in compliance with these policies. Technical PCCPs hold the potential to incorporate forward-looking climate science in place of static environmental thresholds. Pragmatically, these policies need redesigning to embed standards that evolve due to technological innovation in scientific methods to collect data and assess climate patterns, but also due to climate's non-stationarity. Technical policies need to (a) strategize "climate-proofing" assets at the facility and infrastructure network levels, and (b) better connect with organizational policies that assert normative values of equity, justice, and inclusion within environmental and safety goals (Shi and Moser, 2021; Sovacool and Linn´er, 2016).

(b) Organizational targets and diverse governance modes

Organizational PCCPs targeting *coordinative and cooperative* (C/C) mechanisms set roles and interacting guidelines among internal airport stakeholders, and between internal and external airport stakeholders. A large portion of PCCPs which are oriented towards emergency operations belong to this category. Often, they provide coordination guidelines for training, data sharing, communication protocols during hazardous conditions, and underline mutual aid agreement requirements. In some cases, they also provide rules for contracting certifications, land acquisition, and relocation assistance.

Organizational PCCPs targeting *managerial and administrative* (M/A) mechanisms set procedures to manage specific airport facility functions. These facility functions commonly embed environmental goals, safety goals or long term design protocols. Environmental goals include environmental management systems, industrial waste management, and project quality management. Safety goals include safety management systems, winter field condition assessment, and hazardous wildlife management. Long-term design protocols that embed weather and climate thresholds include value engineering, and airport capacity forecast.

Organizational PCCPs targeting *strategic planning* (SP) mechanisms reflect long-term effects of institutional values, memory (stored knowledge), decisions, and their adaptability to changing circumstances. Planning documents guide initial considerations and decision-making processes that have systemic and long term impact on technical and organizational assets. Strategic planning policies have higher levels of complexity and naturally embed managerial and coordinative PCCPs mechanisms that promote adaptation pathways. PCCPs targeting strategic planning have a high potential to efficiently incorporate climate science and adaptation management to all airport policies through safety and environmental goals that cascade through the entirety of airport policies. "Airport Master Plan" and "Terminal Planning" ACs are the only two documents that explicitly include adaptation and resilience guidelines in their content (Box 5 Figure 17). Airport Design policy determines central aspects of development compatibility with landscape and governs many facility-level PCCPs. Master Plan policy determines planning horizons for managerial PCCPs, setting land-use, environmental management values, and leading guidelines for cooperative agendas among airport stakeholders. System Planning policy define overarching safety culture, norms, and service efficiency and effectiveness of an airport within the entirety of the U.S. airport network.

Overall, we argue that organizational PCCPs, especially managerial and strategic planning, are not only more effective in diffusing adaptation values, but they also have a better leverage to incorporate flexible and non-capital intensive adaptation standards. All these PCCPs embed potential organizational transformations that are needed for the development of adaptation values. Organizational PCCPs targeted to design and operationalize safety and environmental practices that have been proven to improve adaptation capacities include (a) mutual aid agreements, (b) familiarized training, (c) managerial meeting agendas where awareness of adaptation issues can grow based on inherent sustainability and resilience goals, and (d) community engagement standards for airport planning. Such organizational PCCPs enhance existing cooperative and inclusive efforts among stakeholders and should strive to align forward-looking climate science, asserting normative values of justice and equity within current environmental and safety airport goals. From all 77 PCCPs, those with organizational targets have diverse governance modes. The presence of traditional coercive and economic-based incentives is balanced with alternative collaborative governance modes. We notice that overall, safety-oriented PCCPs, notably those targeting emergency operations, are hierarchically governed. Environmental-oriented PCCPs tend to present market governance modes. PCCPs with collaborative governance are well spread through different PCCPs targets, but strongly weigh in strategic planning policies. The only two policies explicitly addressing adaptation have collaborative incentives (Figure 17, in italic).

These PCCPs patterns reveal governance priorities, assumptions, current tendencies and barriers of airports, and other infrastructure systems to adaptation governance (discussed in section 4.5).

1 EQUIPMENT TARGETS

Hierarchical PCCPs:

Aircraft Boarding Equipment (AC150/5220-21C): sets environmental loads to withsatnd 161 km/h for 3 second gusts up to 110km/h sustained winds. Environmental specifications require ambient temperature range of -32 to 52 celcius.

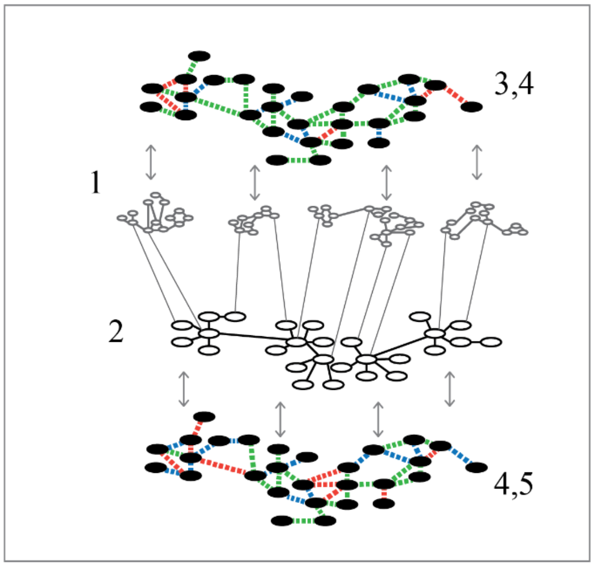
Aricraft Rescue and Firefighting (ARFF) Equipment (AC150/5210-14B): requires protective ensembles for proximity firefighting.

Market PCCPs :

Glideslope Indicators (AC150/5345): sets environmental requirements for solar radiation, snow and ice loading; wind loading of 161 km/h; temperature ranges from -55 to 55 celcius.

Airport Avian Radar System (AC150/5220-25): requires equipment performance under 2-year category storm in the local region; time required for equipment to recover after a rain or snow storm event needs to be specified.

Airside Applications for Artificial Turf (AC150/5370-15B): must be resitant to heavy precipitation as to avoid stormwater runoff washing or flushing any material from the turf surface.



2 FACILITY/BUILDING TARGETS

Market PCCPs:

Runway Length Requirements (AC150/5325-4B): defines how temperature, precipitation, and wind impact takeoff and landing safety protocols; recommends usage of 30-year climate data for defining mean maximum temperature for the hottest month.

ARFF station building (AC150/5210-15A): requires stations to use materials designed to withstand natural hazards to which the area is exposed.

Collaborative PCCPs :

Airport Driniage Design (AC/5320-5D): determination of peak flow rates using storm recurrence intervals of 2-50 years; for drainage with no encroachment on taxiway and runway , requires using 5-year storm interval.

Off-peak Construction of Airport Pavement (AC/5370-14B): sets issues of construction during inclement weather; i.e., temperature and wind influence base preparation for new pavements, cooling, viscosity and texture.

3 COORDINATIVE & COOPERATIVE TARGETS

Hierarchical PCCPs:

Programs for Training ARFF Personnel (AC150/5210-17C): guides familiarized training of emergency responders, air carriers and mutual aid organizations where agreements exist.

Architectural, Engineering, and Planning Consultant Services (AC150/5100-15E): defines roles for the engagement of consultants with key environmental guidelines.

Market PCCP:

Land Acquisition and Relocation Assistance (AC150/5100-17): guides coordination between airport owners, real property agencies and landwoners; sets weather thresholds for replacement dwellings.

Collaborative PCCPs:

Airport Lighting Equipment Certification Program (AC150/5345): rules eligibility of organizations to run quality tests for complaince with environmental specifications.

Community Involvement (AC150/5050-4A): sets standards for public outreach, information, and public involvement in airport planning and sustainability.

Field Data Collection (AC150/5300-18B): sets standards for data-collection & sharing; includes weather data thresholds for takeoff conditions and routes

4 MANAGERIAL/ADMINISTRATIVE TARGETS

Hierarchical PCCPs:

Airport Safety Inspection (AC150/5200-18C): sets protocols for special inspection necessary after unusual conditions such as a significant meteorological event.

Market PCCPs:

Foreign Object Debris (FOD) Management (AC150/5210-24): sets design barriers for weather-sourced FOD.

Field Condition Assessment & Winter Operations Safety (AC150/5200-30D): guides snow & ice monitoring, reporting, and mitigating protcols; ensures safety of wet runways.

Collaborative PCCPs:

Industrial Waste Management (AC150/5320-15A): procedures for the reduction of de-icing runoff & severe weather erosion.

Airport Capacity & Delay (AC150/5060-5): sets annual service volume forecast calculation assumes weather conditions favorable to instrument flight rules during 10% of the time.

5 STRATEGIC PLANNING TARGETS

Hierarchical PCCPs:

Airport Emergency Plan (AC150/5200-31C): sets protocols for emergencies occuring on or directly impacting airport.

Market PCCPs:

Airport Design (AC50/5300-13A): considers impact of asset development on proposed landuse & runway compatibility.

Collaborative PCCPs:

***Terminal Planning** (AC150/5360-13A): includes climate adaptation and resilience as a focus area for sustainability planning.*

***Airport Master Plan** (AC150/7070-6B): requires compilation of climate data for utility loads, storm water drianage, flood control, refers to climate adaptation ACRP study.*

Airport System Planning (AC150/5070-7): sets strategic safety values and rules at the air transportation system-level

● Organizational assets
○ Technical assets
↔ Sociotechnical interlinks
— Infrastructure intra-and interdependencies
🟦 Hierarchical governance
🟩 Market governance
🟥 Collaborative governance

Figure 17. Examples of PCCPs across technical and organizational targets

4.4.2. PCCPs timescales: addressing temporal mismatch

Policy timescale assessment is essential to characterize two aspects of PCCPs: (a) temporal dimensions embedded in environmental thresholds that relate to climate and weather data; and (b) the policy life-cycles that will inform how long technical and organizational assets are designed to last and how frequently they are scheduled for review or updates (rehabilitation, reconstruction, and replacement programs). These two timescale perspectives permit gauging temporal scale mismatches between planning horizons and expected impacts from projected climate scenarios. The way environmental timescales are framed in PCCPs reveal a climate stationarity assumption. Policy life-cycle assessment can help identify critical junctures in decision-making.

(a) Environmental timescales and climate stationarity assumption

There are inherent temporal mismatches between long-lived infrastructure plans and environmental timescales (Bai et al., 2010; Kondolf and Podolak, 2014). This temporal mismatch does not pertain to airport infrastructures specifically. Other infrastructure decision-making processes are often locked into short planning horizons when compared to *in loco* natural landscape processes timescales. A pressing issue when designing adaptation policy for long-lived infrastructure is how to course-correct the assumption of climate stationarity. Climate stationarity presupposes that climate is static or statistically predictable based on short sets of historical observations. As shown in recent reforms of international and national engineering association manuals (WFEO, 2015; ASCE, 2018), statistical values of extreme events or non-normal weather in the past no longer predicate what our current and future climate can exceed. Climate-stationarity assumption is deeply embedded in current design and engineering practice (Chester et al., 2020; CSIWG, 2018; Underwood et al., 2020; Walker et al., 2013).

Our airport policy review shows that climate and weather thresholds used to set technical and organizational design standards are also static (i.e., fixed temperature ranges, wind speed, or rainfall intensity) or statistically based on historical climate records (5-year storm, or 100- year flood event).

This temporal mismatch can be attributed to various complex issues such as: the rigidity of financial mechanisms needed for capital intensive infrastructure with long lead times for development; the difficulty of incorporating climate impact projections into infrastructure discount rates of cost-benefit analysis; administrative and service performance metrics that fail to incorporate long-term effectiveness metrics, or issues stemming from policy stakeholders that have “non-environmental perceptions of hazard” (discussed in section 5).

The current challenge to course-correct climate stationarity assumptions is designing policy that is iterative so it can align with (a) the dynamic societal demand of infrastructure services, and (b) the un- certainties of our changing climate (Haasnoot et al., 2013). The airport industry has recently developed risk assessment tools that incorporate climate science into decision-making processes for investment, rehabilitation, reconstruction, and replacement projects, notably through cost-benefit analysis (GRA, Inc., 2019; Krop et al., 2019). Further discussion in section 4.5, however, reveals that significant limitations remain when market-based governance modes and cost-benefit mechanisms override adaptation policy operationalization.

(b) Policy life cycle assessment: identifying decision crossroads

From a total of 77 PCCPs, 43 explicitly referred to asset life-cycle, or planning horizons in months or years. Airport operational and technical PCCPs present a diverse range of timescales varying from a couple of months to 50 years, with high frequency of life-cycles under 5 years, and two other peaks between 5-10 and 15–20 years (Figure 18). A significant number of long-lived policy cycles of 20 years or more reveal policies requiring special attention when incorporating climate science and adaptation pathways. Long-lived policy life-cycles are commonly a proxy to capital intensive technical assets or strategic organizational assets. These assets require decision-making processes that are adapt- able to higher ranges of uncertainty. Decisions made today must maintain validity and benefits in future scenarios and embed a certain level of flexibility allowing for course-corrections.

Policy cycles represent decision crossroads (critical junctions) which can be useful entry points for implementing adaptation action and opportunities for anticipated course-correction (ISO, 2019). Understanding policy life-cycles is essential to tackling temporal mismatch between infrastructure plans and environmental timescales. They are also critical to break from institutional path-dependence and represent a major opportunity to: (1) optimize the timing for the incorporation of most updated climate science; and (2) design methods for a timely evaluation of climate-cognizant standards effectiveness. Metagovernance agencies can strategize when policies should be considered for review to integrate environmental timelines, climate science, and adaptation pathways based on a holistic overview of these policy timelines.

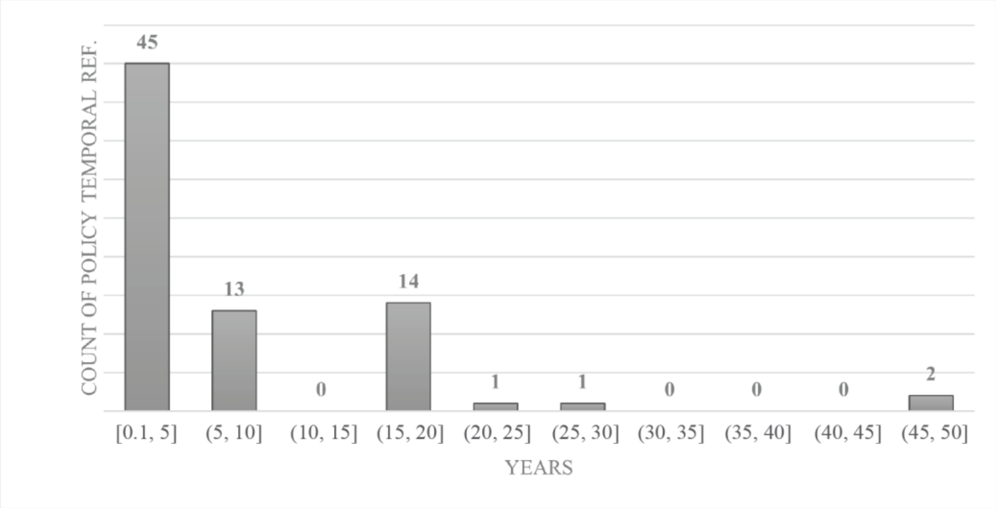


Figure 18. Frequency distribution of PCCPs life-cycles and count of temporal references in PCCPs concerning asset life-cycle or planning horizons

4.5. Discussions

4.5.1. Conflicting rationales between reliability and adaptation

Literature on adaptation governance and climate risk management policy indicates that adaptation values push towards “safe-to-fail “approaches instead of the “fail-safe” approaches that are intrinsic to HROs. Adaptation values also promote blending “predict to act” and “monitor to adapt”. This means policy must be proactive yet flexible for decision-making under uncertainty (Marchau et al., 2019). The combination of these values, however, is conflicting to organizations with the highest levels of safety standards and with dominance of technical policies oriented towards capital-intensive and long-lived infrastructure. From a governance perspective, however, the ability to transform and contest standards is inherent to the ecological premise of resilient systems (Folke, 2006; Markolf et al., 2018). Therefore, we question how the rigidity of organizations with high safety standards might be affecting the speed and effectiveness of adaptation policy implementation.

Despite identifying many policies with weather thresholds within our policy review, we found that they assume climate stationarity and are driven towards operational reliability. We further argue that this conflicting rationale can be traced to most HRO’s institutional memory, that has historically disconnected environmental temporal and spatial scales from safety management culture. This disconnection brings forth dangers of developing adaptation policy stakeholders with “non-environmental perceptions of hazard”, which is discussed in other studies of adaptation policy (Koski and Keating, 2018; Koski and Siulagi, 2016). These institutions focused on safety and protection of critical infrastructure often have operational reliability timelines which conflict with environmental timelines of adaptation. One is urged to dispense most resources in complex and demanding fail-safe, near-term procedures, whereas adaptation timelines require long-term planning outside of traditional investment cycles and planning horizons. Because adaptation planning requires decision-making facing high levels of uncertainty, it challenges HROs conventional utilitarian cost benefit and risk calculations (Young, 2017; Rose, 2018).

Institutions tend to incorporate past understanding of their organizational goals and memory of issues they have addressed over time. Thus, a contextualization of how traditional organizational values surrounding safety and environmental goals have been framed, implemented, and evaluated will help uncover institutional path-dependence and their deeper historical-social barriers to adaptation. Effective adaptation policies require minimal levels of agreement over how safety and environmental policies frame climate risk problems and the means to address it. Addressing conflicting rationales between reliability and adaptation is a key step to tackle institutional path-dependence and address temporal and spatial scale mismatches between airport policy and expected impacts from projected climate. Framing infrastructure as networked technical and social assets and understanding how these complex interrelations behave in space is a key step to incorporate forward-looking environmental processes into decision-making.

4.5.2. Temporal mismatch: feedback loop between technical policy and market governance modes

Government agencies promoting adaptation governance have declared difficulties in justifying the current costs of adaptation with limited information about future benefits. This brings up issues of (a) institutional memory, which is overpowered by market governance, and (b) inertia of obsolete cost-benefit technocentric policies for decision-making, especially considering climate-non-stationarity. Figure 19 illustrates how overpowering market governance and technocentric policies reinforce each other creating a feedback loop. As a result, there is a temporal and spatial scale mismatch between airport policy and expected impacts from climate change.

From a technical perspective, cost-benefit analysis is challenged at three different levels when informing adaptation projects: their evaluation periods, their discount rate, and their ability to quantify costs and benefits.

Market governance assumes behavioral-change based on economic incentives for operationalizing policies and is a leading mechanism for global environmental governance. In the U.S., eligibility for AIP funding requires airport sponsors to prove that the investment is needed within 5 years. Federally funded airport adaptation-oriented projects are likely to fall under rehabilitation, reconstruction, and replacement projects, which require an assumption of 10–20 years of useful life. Common industry cost-benefit guidelines suggest relevant evaluation periods to be less than 30 years. Longer life-spans can be justified to accommodate mechanisms that re-evaluate optimal timing of investment alternatives. Cost-benefit analysis discount rate guidelines also weigh in the ability to leverage the return of current investment for long-term returns. Federal guidelines suggest using both a 7% rate to better leverage long-term benefits, and a 3% rate to leverage more urgent near-term needs. Higher rates represent society's willingness to trade current investment for future investment, but rates used in governmentally funded airport projects have presented an average of 3% in the last five decades (GRA, Inc., 2019). The temporal scales of asset evaluation period and discount rate, embedded within market governance mechanisms, contribute to temporal mismatches of adaptation governance.

Furthermore, even sophisticated cost-benefit models have limitations to quantify certain impact typologies and to quantify non-technocentric solutions to climate impacts i.e., adaptation options which do not involve infrastructure retrofits. Hard to quantify costs are myriad and can include delay propagation throughout the air transportation network (Dunn and Wilkinson, 2016), effects on airport users (trust, comfort, and convenience), or the rate at which the depreciation of existing airport assets is accelerated due to climate risk (Making, 2019). Hard to quantify benefits can stem from organizational transformations such as effects from improving early warning systems, promoting leadership positions in resilience and sustainability, creating teams with exclusive roles in risk management and organizational psychology, and encouraging participative and collaborative processes with a broad range of stakeholders. Cost-benefit-centered decision-making has been critiqued due to methodological limitations of distributional risk assessment. A common issue is related to cost-benefit methods typically providing aggregate information, which ends up masking how gains and losses from climate impacts and adaptation investments are distributed among actors (Rose, 2018; Cutter, 1996). There is a lack of research on how distributional risk is aggravated when access to particular adaptation resources might be biased or unevenly distributed (Sovacool and Linn´er, 2016). Distributional risk assessment is also impaired due to the lack of interest in measuring externalities of adaptation projects and how these can impose unequal costs or benefits to stakeholders. Adaptation policy externalities, or maladaptation (Barnett and O'Neill, 2010), such as environmental encroachment, have been connected to technocentric policy, such as the overfocus of hardening using "grey" infrastructure (Jolley et al., 2017; Tubridy, 2020; EEA, 2021). Furthermore, environmental encroachment can be more easily justified to comply with critical infrastructure resilience and security standards (Walker and Cooper, 2011).

Finally, the efficiency and effectiveness of adaptation policies are in the domain of "near misses" (i.e., measuring the absence of disasters), which is very different from climate mitigation policies. In the past decade, the rise of green growth in the global environmental discourse, and the rise of clean and renewable energy subsidies, reinforces the complementarity of climate mitigation policies with infrastructure business cycles (Meckling and Allan, 2020). Climate change mitigation policy outcomes can be benchmarked and monitored more easily through carbon markets such as "cap-and-trade". Current environmental governance structures, when dominated by utilitarian decision-making processes, can therefore enforce the exclusion of adaptation efforts from climate action plans to focus on mitigation efforts. The dominance of market governance can reinforce technocentric solutions to climate risk which can also result in maladaptation by transferring risk to the most vulnerable stakeholders (Lewis and Ernstson, 2017; Burton et al., 1968; Wisner et al., 2003; Turner et al., 2003; Gaillard, 2010).

4.5.3. Latent collaborative policies to enhance adaptation

Collaborative governance mechanisms are gaining more capacity to address complex socioenvironmental issues. An important milestone is the inclusion of SDG 17 for the revitalization of global partnerships through the UN resolution for the 2030 Agenda (Vazquez-Brust et al., 2020). Knowledge of collaborative processes and incentives grows ever more relevant as environmental governance is increasingly extending policy issues beyond the boundaries of a single nation or organization. Collaborative processes have been identified as a knowledge gap to promote climate resilience for the European and the global aviation sectors (Burbidge, 2016b). The number, diversity, and agency of policy stakeholders in environmental regimes is growing. Novel roles for metagovernance and novel formats of partnerships for policy formulation and implementation are emerging (Vazquez-Brust et al., 2020; Biermann and Pattberg, 2012).

In environmental regimes, collaborative governance arose from the critique of the traditional "carrots and sticks" dichotomy of market and hierarchical governance respectively (Bell and Park, 2006; Bulkeley, 2010; Amundsen et al., 2010). This study highlights that hierarchical and market governance modes alone are becoming obsolete given the global scale of adaptation combined with the resilience challenges of increasingly complex infrastructure systems and vast policy stakeholder networks.

Dominance of market governance and derived utilitarian decision-making approaches enforces an institutional inertia that aggravates temporal scale mismatches between adaptation goals and traditional industry business life-cycles. Market governance can also undermine organizational policy targets at the expense of technical policy targets which present less flexible and often capital intensive adaptation pathways. In a world where current infrastructure upgrades have already strained existing financial capacity, added funding specific for adaptation is not always justifiable (ACI-NA, 2019; Schwarze et al., 2018), demonstrating the limits of solely relying on market governance processes for operationalizing adaptation regimes. Limits also exist for hierarchical governance modes that are stigmatized due to costly and sometimes oppressive bureaucracies that are less compatible with complex and busy airport performance. Although there is a call for promoting stronger compliance with restrictive policies to radically empower climate risk management authorities (The UN Environment Programme needs new powers, 2021), there is limited space for actionable hierarchical adaptation policies, especially for highly privatized airport operation models as in the U.S.

Collaborative governance has a promising role to fill the gaps of traditional market and hierarchical governance for better articulating adaptation regimes. In a technical and social capacity, collaborative governance can increase the quantity and quality of information exchange among stakeholders. By facilitating information exchange and acknowledging differences in capacity to face climate risk, the awareness of shared risk increases and can fundamentally alter decision-making process for collective action (Comfort, 1999, 2019).

Disaster response efficiency, for example, is intricately related to collaborative processes such as contingency planning, mutual aid systems, and other spontaneous collective efforts (Comfort, 2019; Hamilton et al., 2019; Bodin and Nohrstedt, 2016; Harris and Doerfel, 2017), and therefore enhances institutional adaptation capacity by default. Airport coalition networks are spontaneously formed to better manage irregular operations (ACRP et al., 2012; Cogliandro et al., 2016) or larger scale disasters, as was the case when Hurricane Katrina hit the Southern U.S. in 2005 and promoted the creation of regional mutual aid systems for airports (SEADOG and WESTDOG, Southern Airport and West Airports Disaster Operations Group respectively).

Growing amounts of empirical evidence point to the effectiveness of collaborative incentives when confronted with complex socioecological problems that range through multiple spatial scales and jurisdictional boundaries (Ceddia et al., 2017; Vignola et al., 2013; Bodin, 2017; Aminpour et al., 2020). Collaborative approaches to policy making inherently support non-technical adaptation management (ISO, 2019; NIST, 2015), and thus are essential for transformative organizational adaptation pathways (Herrmann and Guenther, 2017). Collaborative PCCPs can be enhanced by linking reputation to compliant behavior, by encouraging deeper and broader involvement in shaping policy content and principles, by encouraging stakeholders to collectively conceptualize problems, or by reinforcing coalition networks to share information, knowledge, and other resources to face common problems. Higher adaptation policy outputs and outcomes are associated with enhanced collaborative governance (Kalesnikaite, 2019).

Collaborative governance has been critiqued due to its voluntary and anarchic character, but we argue that it presents decentralized and emergent properties that open important new roles for "metagovernors" to invest in stakeholder network agency which is implicitly or explicitly involved in adaptation. Beyond disaster response and inter-airport coalitions, PCCPs have the potential to leverage existing relationships between a higher diversity of stakeholders involved in long-term environmental and safety goals. Latent adaptation stakeholder networks can be empowered to raise awareness and mainstream climate science and adaptation pathways into technical procedures, organizational culture, and institutional values.

Figure 19 presents a synthesis of governance barriers and pathways discussed here to enhance adaptation governance. We underline how organizational PCCPs, and collaborative governance are essential to break the feedback loop between technocentric policy and market governance dominance. We illustrate how framing infrastructure as networked technical and social assets helps understand how policy influence this complex interlinks, including how they behave in space where climate hazards occur. Monitoring sociotechnical interlinks is key to address spatial mismatch and better incorporate forward-looking environmental processes into decision-making. As a result, policy stakeholders gain environmental perception of hazard and networked perception of infrastructure at technical and organizational scales.

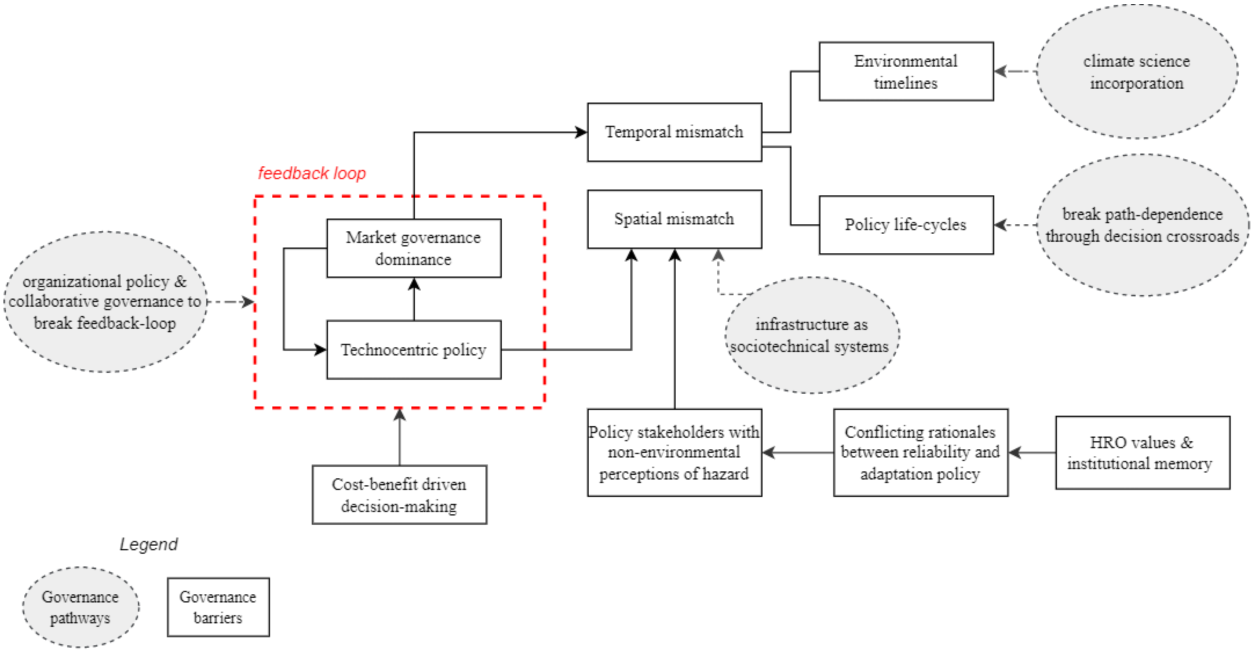


Figure 19. Institutional path-dependence and governance pathways to adaptation

4.6. Conclusions

4.6.1. What can be learned by better understanding adaptation governance?

This study provides, for the first time, a review of current airport governance mechanisms with the potential to create adaptation pathways. We develop an innovative and multi-scalar approach to decode governance processes that can operationalize adaptation policy. This benchmark is essential for monitoring and improving adaptation governance mechanisms beyond target-setting policy approaches.

Our approach highlights how airport adaptation capacity is not only determined by current infrastructure design standards for projected climate hazards, but how it also heavily relies on organizational interactions, institutional memory and decision-making processes that create, reinforce, and transform policy. Airports are framed as sociotechnical systems where policies guide the interaction between technical and organizational assets through distinct governance modes.

On a practical level, this study demonstrates how airport metagovernance can produce necessary and significant shifts to incorporate climate-science and adaptation pathways into policy and decision-making. Substantial shifts to improve airport adaptation governance do not necessarily require extensive new institutional arrangements focused on infrastructure retrofits alone but can be mainstreamed by rethinking existing airport management, design, and planning tools to incorporate forward-looking environmental perceptions of hazard and networked perceptions of infrastructure technical and social assets.

Due to the intrinsic global scale of air transportation and centralized structure of airport regulation, it is important to highlight the potential leadership role of airports in adaptation governance. Any shift in institutional value, organizational culture, and technical standards of airports can have significant network effects, not only on interdependent airport facilities, but on other organizations that are highly impacted by airport decision-making such as metropolitan planning and transportation organizations. A preemptive overview of these adaptation pathways is important to avoid locking air transportation and other closely connected organizations into governance systems that are counterproductive to resilience and sustainability.

4.6.2. Descriptive and prescriptive contributions from airport-specific policy review

We identify that although only a couple of airport policies explicitly include adaptation goals, the current governance system has a high potential to incorporate climate science and adaptation pathways into their environmental and safety goals. These potential pathways involve incorporating forward-looking climate science into technical policies developed at airport facility-and equipment-level, as well as organizational transformation and institutional value reconfiguration through strategic planning, managerial, and cooperative organizational policies. Our results also show that there is a dominance of technical policy targets and market governance in these potential adaptation pathways.

Technical adaptation pathways reinforce utilitarian and cost-benefit decision-making mechanisms that result in temporal mismatch. Technical PCCPs are challenged to leverage available knowledge on climate projections and expected societal services of long-lived infrastructure to make effective policy choices under uncertainty. We also reveal there is growing space for organizational policy targets with higher diversity in hierarchical, market and collaborative governance modes to enhance airport adaptation pathways cost-efficiently and effectively. Organizational PCCPs have more sway to incorporate flexible, non-capital intensive adaptation standards, and enhance existing cooperative efforts between stakeholders targeted to design and operationalize safety and environmental practices proven to improve adaptation capacity.

PCCPs timescales reveal climate stationarity assumptions. Current standards are based on historical data that are no longer suited for predicting future climate scenarios. We further argue that policy life-cycles represent important decision crossroads with a potential to break from path-dependence. Metagovernance agencies need to take into consideration a holistic overview of policy timelines to strategize optimal entry points for updating technical thresholds and organizational values or protocols. New knowledge on climate science and adaptation actions based on empirical applications and participative processes have the potential to define and refine some aspects of airport policy. With these updates, we pinpoint to a series of airport technical and organizational standards that have gradually become obsolete, and should opportunistically, within asset life-cycles and airport planning horizons, be revised to integrate forward-looking climate science and adaptation institutional values.

Our results identify significant barriers to adaptation governance deriving from institutional path-dependence that can lead to maladaptation. We question the impact of HRO values on policy mechanisms that diverge from adaptation management and are hard to break. Some divergent mechanisms include (i) conflicting rationales and (ii) over-powering market governance:

i. Conflicting rationales between reliability and adaptation values were identified. Institutional HRO memory has a historical disconnect of environmental scales from safety management culture. This disconnect develops policy stakeholders with “non-environmental perception of hazard”. Addressing conflicting rationales between reliability and adaptation is a key step to break institutional path-dependence and address temporal scale mismatch between planning horizons and projected climate impacts.

ii. Overpowering market governance and utilitarian decision-making is becoming obsolete considering climate non-stationarity. From a technical perspective, we argue that cost-benefit analysis can enforce temporal scale mismatch due to inappropriate evaluation periods and discount rates. Current governance structures that present technocentric solutions to climate-risk and dominance of market-based incentives can perpetuate competing interests between climate mitigation and adaptation favoring the former.

These barriers are not unique to airport governance and can be generalized to other sectors which are characterized by complex long-lived infrastructure systems.

We finish by underscoring the promising role of collaborative governance to fill the gaps of traditional hierarchical and market governance in operationalizing adaptation regimes. Beyond the traditional role of collaborative policies in improving disaster response and inter-airport coalitions, collaborative PCCPs have the potential to leverage existing relationships between a higher diversity of stakeholders involved in long-term airport environmental and safety goals.

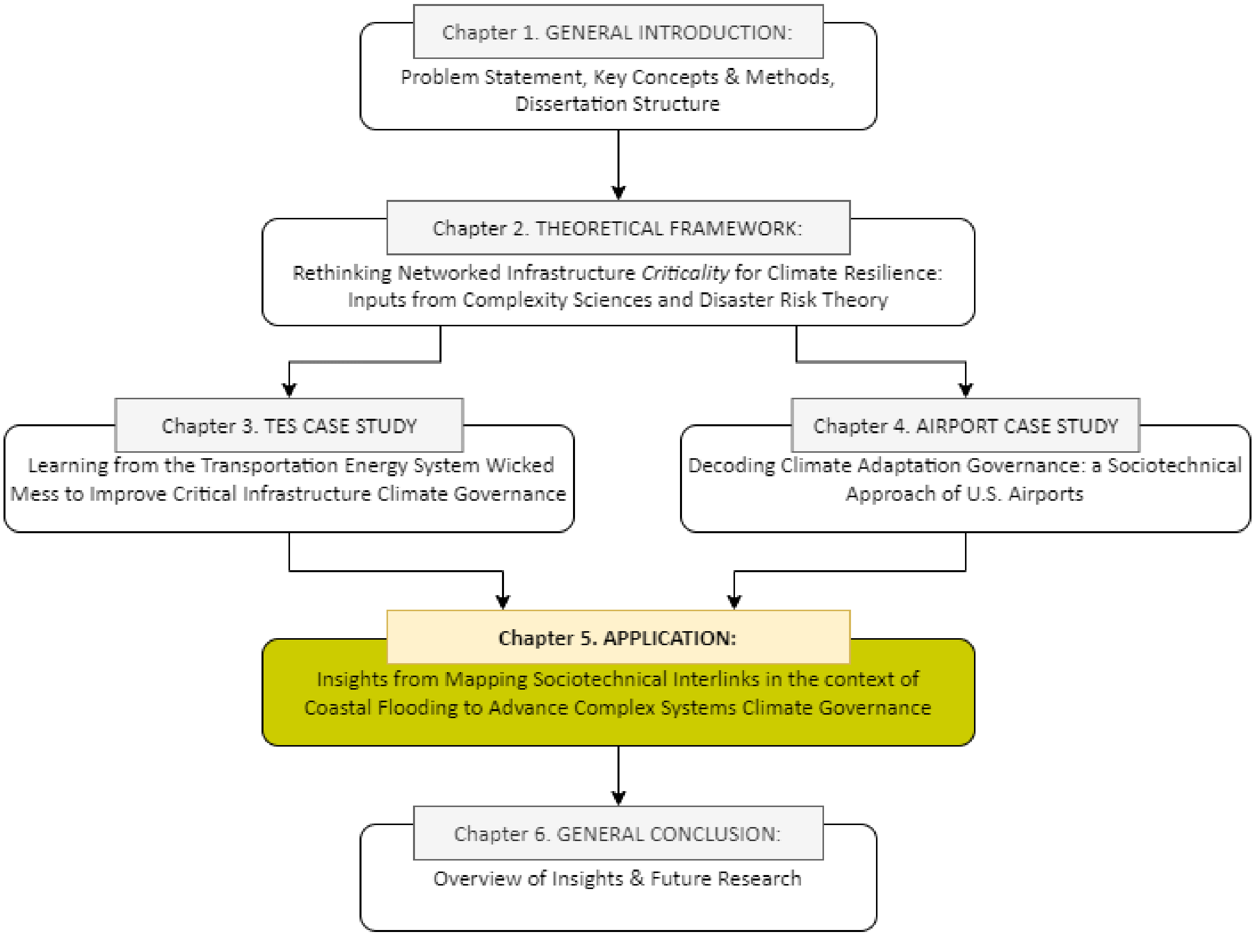
4.6.3. Limitations and next steps to improve adaptation governance research of complex infrastructure systems

Our study focuses on the FAA as "metagovernor" of airports, but other institutions also design and operationalize policies that influence airport adaptation regimes. These institutions can include other national agencies responsible for environmental or safety regimes (i.e., Bureau of Land Management, Environmental Protection Agency, Department of Homeland Security, Air Force); state infrastructure, public utility, and land-use regulators; and local development and planning organizations. Governance mechanisms do not pertain solely to formal policy and institutions, but range over a very large network of informal stakeholders who influence how climate data can be used as decision-relevant information. Opinion influencers, lobbyists, civil society advocacy organizations, and very importantly, insurance companies can highly influence policy systems informally.

It is important to convey the limitations of our results that apply only to what is described in formal policy. Further research with in-depth interviews could help uncover informal organizational culture, institutional stakeholder networks, reward systems, and leadership structures that enhance adaptation pathways outside of formal policy mechanisms. We developed an intricate process to benchmark adaptation governance necessary to improve policy output assessments. Improving policy output assessment is key to better understanding long-term policy outcomes and tracking their effectiveness in behavioral changes. Developing better assessment of climate policy effectiveness is particularly important because there are conflicting views of adaptation success. Outcomes of effective adaptation policy would include mitigating exclusionary forms of adaptation pathways decision-making; attenuating the externalities of adaptation costs that are imposed unequally on stakeholders; or equitably distributing adaptation resources and benefits.

This study brings forth the importance of investigating institutional path-dependence for planners and managers of long-lived and complex infrastructure. Future research on institutional path-dependence can benefit from integrating longitudinal studies over long periods of time to historicize organizational values and culture. Similarly, it is important to understand what types of institutional frameworks encourage path-dependence. Deeper spatial investigation could benefit from integrating exposure of technical assets to different climate hazards and optimize collaboration governance for organizations sharing similar risk scenarios. Finally, more research is needed to assess the behavior of coalition networks in collaborative governance systems; the cost of forming, monitoring, and facilitating collaboration; and how collaborative outcomes impact adaptation goals.

Chapter 5. Insights from Mapping Sociotechnical Interlinks in the context of Coastal Flooding to Advance Complex Systems Climate Governance



5.1. Introduction: the need of increased interaction of diverse decision-making stakeholders

Although climate change planetary crisis is marked by deep uncertainty, global warming projections since 1970 have been quite accurate in predicting climate-drivers associated to increased CO2 emissions and global mean surface temperature[270]. Regional climate change, which is subject to higher levels of climate unpredictability, has also developed by downscaling climate drivers projections from 100km to 6km[271,272]. Science-policy interface is also seeing an improvement in the translation of climate impact drivers at the human scale[273,274] and advancing governance structures for decision-making under uncertainty[275,276]. Increasing efforts to better understand vulnerability and risk using participatory research and stakeholder engagement has been key in enhancing our abilities to understand how climate-impact drivers threaten the integrity of infrastructure sectors, ecosystems, and communities. Continuous improvement in science-policy remains however challenged by decision-making capacity of absorbing this sheer volume of climate science information while also co-creating knowledge through the increased interaction of diverse decision-making stakeholders. The need for increased interaction among diverse decision-making stakeholders is often discussed in studies of socioecological and sociotechnical systems, however we lack applied methods illustrating how to map the interlinks between social and technical systems and their relationship with hazardous landscape processes associated with climate change.

In this chapter we are interested in better understanding the relational pattern allowing information exchange and knowledge building between CI stakeholders regarding projected exposure to coastal flooding hazards. This relational pattern is identified as sociotechnical interlinks, where physical infrastructure assets are associated with ownership or operational jurisdiction for the TFS and as policy design and implementation responsibility for airports. The research questions we seek to answer are:

- **How can we map the interlinks between climate-induced landscape hazards, infrastructure systems, and decision-making power?**
- **What new roles for TFS and airport adaptation policy stakeholders these interlinks reveal?**
- **What new forms of collaboration can be enhanced?**

Our hypothesis is that collaborative governance can be enhanced by better understanding the underlying network of decision-making stakeholders of CI taking into consideration the specific context of climate hazard projections. Governance structures geared towards climate adaptation and resilience need to generate and reorganize resources iteratively as new opportunities or challenges arise, providing adaptive and sustained multilateral relationships through coalition networks. Effective governance structures also need to embed mechanisms that allows for expanding and diversifying their decision-making stakeholders, while iteratively mapping their roles in the network while ensuring inclusive decision making processes.

Coalition networks specialize in enabling many-to-many collaborative relationships through different types of platforms. Collaboration is a nested concept, built on an increment of information sharing quality (Figure 20). Here we define collaboration as a dynamic process with real-time interaction between social entities that is iterative and evolutionary[49]. Collaborative platforms can present multiple formats such as mutual-aid systems, consortiums, associations, and forums brought together to pool resources based on similar goals and challenges[277]. We rely on network representations of these stakeholders to identify meaningful collaborative groups needed to govern these infrastructure as complex systems. These networks represent relationships between social entities with legitimate decision-making power over technical assets that are exposed to current and future coastal flooding. In this chapter we hope to shed light on different approaches to address temporal and spatial scale mismatch of current infrastructure climate governance which perpetuate technocentric policies and omit the social dimensions of infrastructure systems. Our analysis is based on applied examples of the TFS and airport's exposure to current and projected coastal flooding in California.

Information exchange: usually a one-way transfer of information but not necessarily a two-way exchange of ideas.

Coordination: there is an exchange of ideas between different social entities that are brought together to improve their strategies to achieve common goals. Coordination requires information exchange.

Collaboration: there is a dynamic process with real-time interaction between social entities that is iterative and evolutionary. Not only about agreement but rather about innovation. Can involve stakeholders with different goals. Collaboration requires coordination.

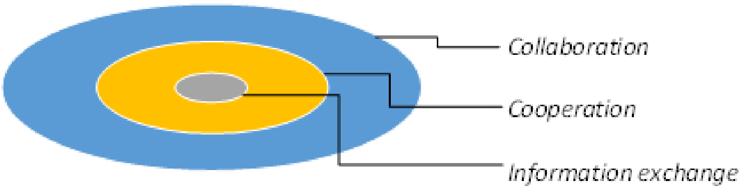


Figure 20. Nested concept of collaboration

We start by presenting the methods used to build social networks for the TFS and airport case studies using geospatial and policy data. We provide details on how centrality and community detection metrics are applied, how projected coastal flood models are used to measure infrastructure exposure, and how the geospatial models for the TFS and airport infrastructure were constructed. Details on the data processing based on the use of GIS, policy data, and their combination is described together with uncertainties and limitations of our methods. Our results are subdivided in two parts: one provides insights from the sociotechnical network exposure application to the TFS case study, and the second to the insights from policy stakeholder network and coalitions of the airport case study. We finish by highlighting the different insights related to the identification of new roles and communities for TFS and airport stakeholders which can be generalized to other complex infrastructure systems and other climate hazards. By revealing key stakeholders with decision-making power over complex infrastructure systems as well as their relational patterns our methods present innovative avenues to operationalize environmental justice normative dimensions.

5.2. Methods: network science, GIS, and policy review.

5.2.1. Network science data and metrics

(a) Building social networks for the TFS and the airport case studies using geospatial and policy data

The TFS and Airports are multi-dimensional networked infrastructures and can thus be represented as graphs, with nodes and links [101]. Our network analysis is based on two different types of social dimensions that are universal to infrastructure systems: organizational and policy stakeholders. The organizational dimension is illustrated through the TFS case study (section 5.3) and policy stakeholders' dimension is illustrated through the airports case study (section 5.4). The organizational and policy stakeholder networks are both social networks with two distinct characteristics: they portray sociotechnical interlinks allowing to connect decision-making power of social entities to specific parts of the technical infrastructure; and they retain a geospatial attribute allowing to connect physical infrastructure to landscape processes such as coastal flooding hazards. Identifying these sociotechnical interlinks and geospatial attributes furthers our capability of mapping the shared states between technical, social, and environmental interlinks. Due to the differences in the TFS and airport governance structures in the U.S. as well as data availability, their sociotechnical interlinks and geospatial attributes are inferred either through geospatial or policy data. Figure 21 illustrates how these interlinks are inferred for the TFS and the airport case studies, as well as how specific datasets are used to build our social networks for the TFS and the airports. Table 8 synthesizes the network, sociotechnical, and geospatial attributes of our two models applied to the TFS and airports.

The TFS and airport social networks topology draw the relational patterns between social entities (organizations and policy stakeholders). The underlying assumption is that linked social entities need minimum levels of information exchange for the functionality of the CI they belong to. This information exchange can range from coordination to collaboration (less to more intense exchanges). Most, importantly, the existence of links between nodes informs the potential for multi-actor coordination and collaboration at the operational or strategic decision-making-levels in both social networks.

The TFS sociotechnical links and geospatial attributes are inferred on the fuel transportation model developed in Radke et al 2018, however our network is bounded to the specific subset of crude oil pipelines in California. Each node represents an organization that owns or operates a crude oil pipeline transect. These nodes are linked based on the assets' geospatial interconnectivity following the crude oil supply chain in California, thus connected organizations represent the adjacency of pipeline transects. The

TFS organizational network is therefore a social network embedded in geographic space, where each node represents a collection of physical assets under the jurisdiction of a single organization, and the links represent the geospatial interconnection of these assets necessary for the flow of crude oil commodity. The exposure of each asset is then measured based on the spatial co-occurrence of pipeline assets with coastal flooding projections (developed in section 5.2.2). By identifying organizations who own or operate specific TFS assets, we provide a map of the social entities that have a range of managerial decision-making power over distinct parts of the TFS physical infrastructure. When this information is combined to the exposure metrics, we build a sociotechnical network exposure to projected coastal flooding (further detailed in section 5.2.4.a). The sociotechnical network exposure is bidirectional based on the hazard transmission or hazard receptivity potential. The links are weighted based on the organization's assets' aggregate exposure to projected coastal flooding.

The airport sociotechnical links and geospatial attributes are inferred on policy data. It is built based on the co-occurrence of targeted policy stakeholders in the 77 PCCPs identified in Chapter 4. The network is therefore bounded by FAA's airport-specific policies (Advisory Circulars). Each node represents a stakeholder being targeted for designing and implementing the policy in question, and these nodes are connected when stakeholders are co-targeted in the same policy. The airport policy stakeholder network is therefore a social network without direct geospatial attribute. However, the airport policy coding system (section 4.3.2.) identifies technical policies which target specific airport equipment, buildings, or facilities. These technical policies provide generic geospatial attributes to airport policy stakeholders that are commissioned for example to design and operate equipment (i.e. airport visual aid, lightning circuit equipment, automated weather observing systems); buildings and facilities (i.e. aircraft rescue and firefighting stations, runways, airport drainage system); which are all geocoded through the FAA NAS. By identifying stakeholders targeted to design and implement PCCPs, we provide a map of social entities that have a range of operational and strategic decision-making power over distinct airport infrastructure. The stakeholder policy network is not weighted and is undirected (there is no order in the flow direction), which means we assume reciprocity in the information sharing capacity between linked policy stakeholders.

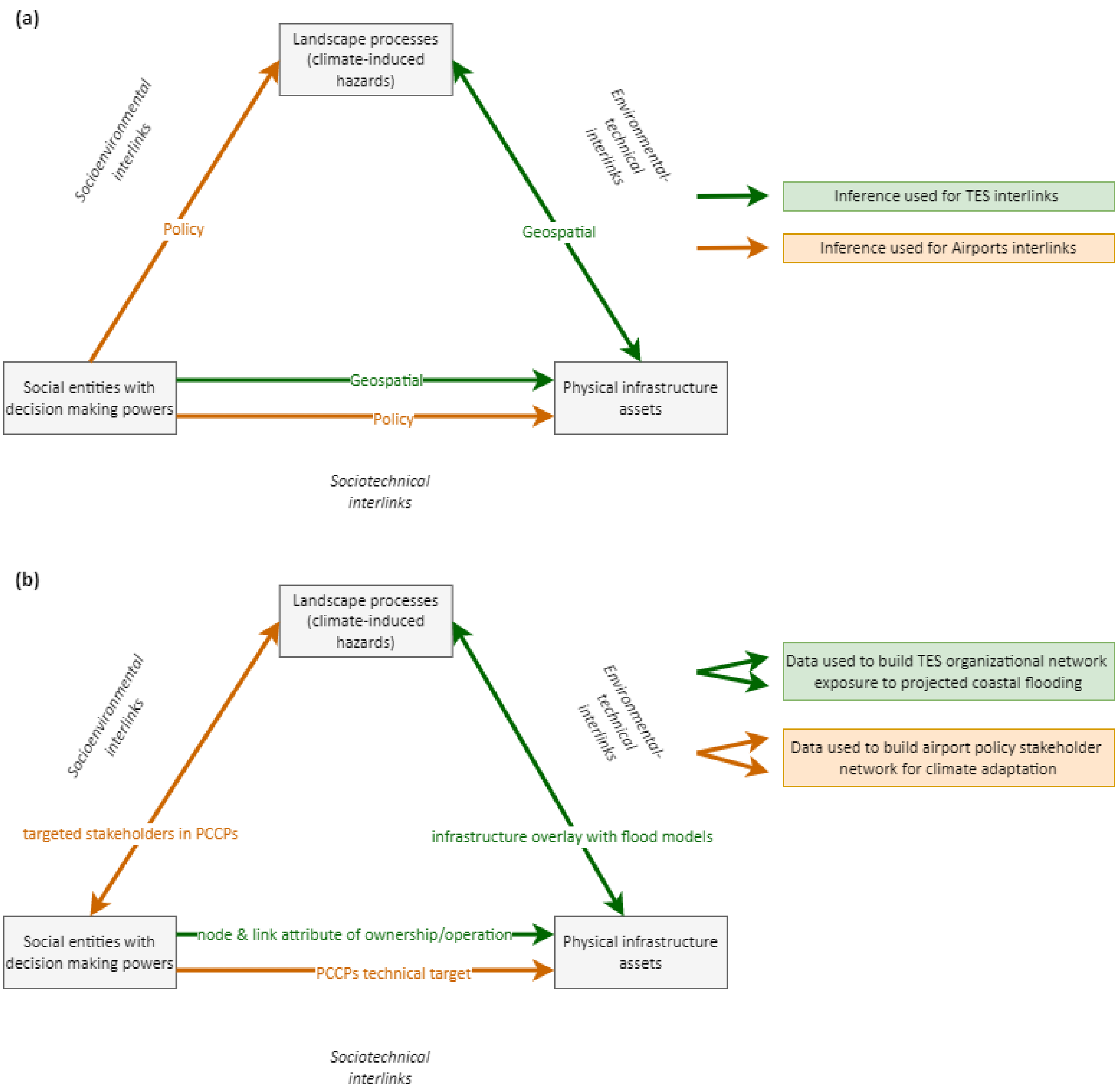


Figure 21. **Identifying shared states between technical, social, and environmental dimensions of the TFS and airport case studies. (a) shows the data type used to infer the interlinks; (b) shows the specific geospatial or policy data used to measure the interlinks.**

Table 8. Data description of the TFS and airport social networks

Infrastructure	Node (social entity)	Link (relational tie)	Weight	Geospatial context	Sociotechnical interface
TFS case study	Organizations that own or operate crude oil pipelines,	Nodes are linked when the TFS assets are geospatially interconnected according to California's crude oil supply chain. Links are bidirectional expressing the potential of coastal flood hazard transmission (out-degree) or receptivity (in-degree)	Weighted based on the organization's assets aggregate exposure to projected coastal flooding	Geospatial network where nodes represent a collection of real-world assets, and links represent geospatial connectivity between these assets.	Social dimension is represented by the organizations that own or manage specific infrastructure assets, linking decision making from organizational to technical dimensions of infrastructure
Airport case study	Stakeholders targeted to design or implement airport policy (PCCPs)	Nodes are linked when targeted stakeholders of PCCPs are co-cited in a policy document (FAA ACs). Links re Undirected	Not weighted	Aspatial network, nodes and links have no direct geospatial context	Social dimension is represented by targeted stakeholders in policy documents linking decision-making to specific airport infrastructure (equipment-or building/facility-level)

(b) *Network metrics*

For the organizational and stakeholder policy networks we assess their topological structures and the roles of the nodes within the network. Three types of network metrics are applied: centrality metrics, community detection, and global network models. It is important to specify which kind of relations are being implied and how they respond to the research question and governance issue studied. Due to the different nature, data sources, and boundaries of these networks, these metrics are interpreted differently for the TFS and airport social networks (Table 9)

- Centrality network metrics:

  Centrality metrics help inform the position of the node within the structure, how influential it is based on the number of connections (degree centrality), and its importance based on its role of connecting otherwise disconnected nodes (betweenness centrality) [106].

  - Degree centrality ranks a node's importance based on the number of links it carries. We name k_i as the degree of the i^{th} node in the network. Degree centrality often indicates the role of the node as a hub. The higher the degree, the higher its connectivity to other nodes and the higher the probability information or risk from any given node in the network will reach this node. Nodes with a higher number of connections tend to have more decision-making power and are more visible. Equation 1 provides degree centrality for undirected graphs.

$$C_i^D = k_i = \sum_{j=1}^{N} aij,$$

Equation 1. Degree centrality C^D of a node i in an undirected graph, where $k(i)$ is the number of links and aij is the adjacency matrix.

For social networks degree centrality reveals the importance and influence of a single node within the system, often indicating the network's hubs. Nodes or actors with higher number of connections tend to have more power and are more visible [85]. The general assumption is that the higher the number of relational ties, the higher the potential for information sharing and joint action of those central nodes [49,51,208,210,278–280]. The links of a network can be directed or undirected. In directed graphs, a high in-degree centrality (Equation 2) represents a measure of attraction, and a high outdegree centrality (Equation 3) represents a measure of influence [281]. For the TFS network, it identifies organizations that have a higher interconnectivity in the supply chain and thus a higher propensity to receive (in-degree) or transfer risk (out-degree). This information can help identify organizations who hold higher responsibility or burden in sharing risk information and coordinating for emergency response as well as strategic planning for adaptation

$$C_i^{Din} = k_i^{in} = \sum_{j=1}^{N} aij,$$

Equation 2. In-Degree Centrality C^{Din} of a node i in a directed graph, where k^{in} are in-degree.

$$C_i^{Dout} = k_i^{out} = \sum_{j=1}^{N} aij,$$

Equation 3. Out-Degree Centrality $Cout^n$ of a node i in a directed graph, where k^{out} are in-degree.

- Betweenness centrality (Equation 4) quantifies the number of times a node lies on any shortest paths in the graph, including every possible pair of nodes. A path represents an alternating sequence of nodes where no node is visited more than once. Different from degree centrality, betweenness centrality integrates how each node is associated with all other nonadjacent nodes in the graph (Grubesic et al., 2008). High betweenness centrality in a social network indicates the node has a brokerage role and can potentially be a bridge between otherwise isolated clusters, or policy implementation communities.

$$C_i^B = \sum_{\substack{j=1 \\ j \neq i}}^{N} \sum_{\substack{k=1 \\ k \neq i,j}}^{N} \frac{n_{jk}(i)}{n_{jk}}$$

Equation 4: betweenness centrality C^B of a node i where n_{jk} is the number of geodesics from node j to node k, whereas $n_{jk}(i)$ is the number of geodesics from node j to node k, containing node i.

- Topological community detection:

Networks have intermediate scales between local and global structures, called mesoscopic structures [281]. In this scale nodes are organized into subgraphs or communities that can be identified by “clusters” of nodes such that nodes within the same cluster are more tightly connected than nodes belonging to two different clusters. This process is considered as a classification method based on topology. One main goal of classification is the generalization of data by agglomeration or by division, where one can group nodes that have common properties. This analysis is only done for the airport policy stakeholder network.

Identifying topological communities can be done in different ways. Here we use algorithms that define intra-cluster density in Equation 5 (ratio between the number of internal links of the community and the number of all possible links) and inter-cluster density in Equation 6 (the ratio between the number of links running from the nodes of the community to the rest of the graph and the maximum number of inter-cluster links possible) and maximize the sum difference between the intra-and inter-cluster density over all clusters of the graph [282]. The Girvan and Newman[283] method is applied to progressively remove the links from the original graph to form subgraphs or modules. The indicator of where to separate the modules is given by the link betweenness centrality meaning that the model will remove the edges in decreasing order of their edge betweenness. The next step is to maximize modularity based on Blondel et al., [284]. The modularity of different subgraphs is maximum when nodes that are densely connected among them are grouped together and separated from other nodes in the network. One can proceed to measure the modularity of the graph to attempt an optimization by measuring the strength of the division of a graph into subgraphs. These subgraphs can also be called modules, clusters, or communities. The value of the modularity lies in the range [-1, 1]. The value is positive when the number of links within a module exceeds the number of expected links compared to a random distribution of links between the total nodes in the graph.

$$\delta_{int}\,(Cm) = \frac{\#\,internal\ links\ of\ Cm}{n_c\,(n_c\ - 1)/2}$$

Equation 5: Intra-cluster density defines the ratio between the number of internal links of the community Cm and the number of all possible links n_c

$$\delta_{ext}\,(Cm) = \frac{\#\,inter - cluster\ links\ of\ Cm}{n_c\,(n_c\ - 1)/2}$$

Equation 5: Inter-cluster density defines the ratio between the number of links running from the nodes of the community Cm to the rest of the graph and the maximum number of inter-cluster links n_c

- Global metrics: network diameter, clustering coefficient, and small world network

Global metrics are essential to understand how nodes and links are interrelated and arranged in a network and how the sequencing of nodes and edges can facilitate or impede the transmission of information, goods, services, and risk. Key global metrics used in this study are, network diameter and average clustering coefficient, which are combined to assess small world network behavior.

The network diameter indicates the size of the network since it measures the longest shortest path, or the distance between the two farthest away nodes within the network. A clustering coefficient expresses how likely it is for two neighboring nodes to be connected. The clustering coefficient quantifies the presence of triangles in a graph, also called graph clustering coefficient which takes values between [0-1] and it is calculated by averaging the number of triangles for each node and the maximum possible number of triangles for each node in the graph [281]. Certain topological structures help understand real world network behavior. In this study we use network parameters of small world network models to illustrate our airport stakeholder policy network. Small world networks, or the Watts and Strogatz model[114], have two important unique characteristics: a short diameter and a high average clustering coefficient, or a high ratio between the number of existing links and maximum number of possible links in a graph. Small world models illustrate the key role of shortcuts in network, especially in relation to risk sharing or information propagation.

Clustering coefficient is also used to express network link density, which can portray the potential for collective action in a social network and is applied to the TFS and airport social network [199]. Social networks with high link density can also point to enhanced potential of information exchange and development of knowledge due to higher exposure to potentially new information coming from different stakeholders or the potential for larger volumes of information flow. The potential for innovation is notable when there are several distinguishable communities and where there are broker nodes between different communities [285].

Table 9. Key network metrics and their application for the TFS and airport social networks

Social network	Centrality	Community detection	Clustering coefficient	Small world
TFS sociotechnical network exposure	In and out-degree centrality weighted based on aggregate exposure of organization's assets identifies organizations' hazard receptivity and transmission potential.	N/A	Average clustering coefficient indicates the potential for information sharing and joint action to improve at the operational level to improve emergency response or at the strategic level to improve TFS adaptation.	N/A
Airport policy stakeholder network	Degree centrality indicates influence and betweenness centrality indicates brokerage role	Topological communities represent sub-groups of airport policy stakeholders with higher relative relational density compared to the remainder of the network. They represent airport policy implementation niches.	Average clustering coefficient indicates the potential for information sharing and joint action at the strategic level to improve airport adaptation.	Networks with topological structures close to small world indicate the potential for effective shortcuts in information sharing and knowledge building for airport climate adaptation

5.2.2. Landscape modeling: projected coastal flooding

Given the range of coastal flooding scenarios and their applicability to diverse infrastructure stakeholders, different models are used and advocated by the U.S. government. The coastal flooding models used here are outputs of California's Fourth Climate Change Assessment (C4CCA) from Radke et al.,[62] based on climate variables made available for the state assessment by Pierce et al.,[272]. The model use climate change scenarios derived from the combination of (1) representative concentration pathways (RCPs) scenarios; (2) General Circulation Models (GCMs); and (3) probabilistic SLR and hydrodynamic flood models to incorporate storm surges to the Coastal flooding projection. For clarity purposes, coastal flooding hereafter refers to the combination of SLR, tides, and storm surge. The coastal flood model used is at 50 meter resolution statewide for which we use two time-horizons, 2020-2040 for the near-term and 2080-2100 for the long-term.

RCPs represent future GHG concentration in the atmosphere, and this study uses high (RCP 8.5) and medium (RCP 4.5) emission scenarios. RCP 8.5. portrays a similar continuation of the current path of global emission increase (business as usual), and RCP 4.5 assumes intermediate reduction in emissions given climate science and policy assessed in IPCC's AR5 and the fifth generation of climate models (CMIP5).

The GCMs are used together with the RCPs to model eight different climate scenarios precipitation and temperature variables. The GCMs are derived from a downscaling and bias correction effort to obtain climate variables at approximately 6 km (Pierce et al., 2018) for the California Assessment as opposed to the 100 km resolution from the CMIP5. The GCM's recommended by C4CCA include HadGEM2-ES (warm/dry); CNRM-CM5 (cool/wet); CanESM2 (average); and MIROC5 (complementary) as they together best cover a broad range of future climate scenarios for California.

The SLR values are based on a probabilistic projection that samples time-dependent probability distributions of global SLR components at the 50th, 95th, and 99.9th percentiles. These global SLR components include the thermal expansion of the ocean, meltwater from glaciers, pumping of continental ground water, interception of water that would otherwise flow into the oceans, and contributions from the large ice sheets on Antarctica and Greenland. Short-term sea level fluctuations based on observational data of tidal gages along the Californian coast were incorporated to consider astronomical tides; weather and wind patterns; and El Nino Southern Oscillation to develop hourly sea level projections up to 2100 [286].

Two RCPs, four GCMs, and three probabilistic SLR values are combined to produce a total of 24 SLR scenarios. To incorporate storm surge processes, Radke et al. [62] identify extreme high sea level events as the peak sea level of a given climate scenario and time horizon during a 72-hour storm event. These extreme sea level values are then inputs to a 2-

dimensional hydrodynamic model[8] for the entire coast of California that is combined to the 24 SLR scenarios to provide the final 24 regional coastal flooding scenarios.

The outputs from Radke, et al., [62] used in this study include 24 coastal flooding scenarios for the near-and long-term time horizons. These 24 coastal flooding scenarios are modeled as raster data for each of the 16 regional tiles associated with the hourly tidal gages of California's coast [286]. In this study we use the median coastal flooding scenario that corresponds to the median rank (rank 13 out of 24) of peak water levels for each time horizon and each regional tile (Figure 22 and Table 10). Examples of near and long term flood exposure for the TFS assets and airport assets in California are presented in Figures 23 and 24. Exposure is then measured based on the co-occurrence of TFS and airport assets and coastal flooding projections for the near-and long-term horizons.

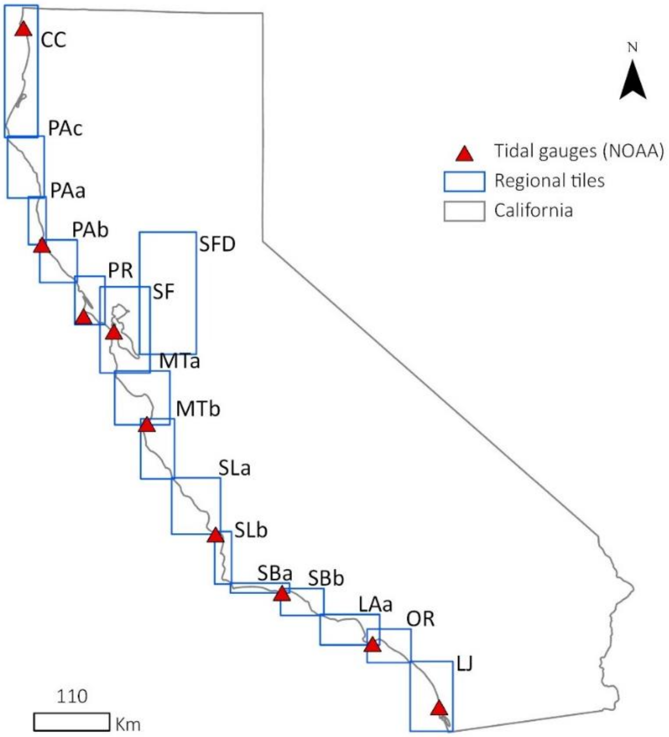


Figure 22. Regional tiles and tidal gauges from the National Oceanic Atmospheric Administration (NOAA) used for sea level hourly projections. Regional tiles use hourly sea level projections from the closest gauge.

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[8] The hydrodynamic model used is the CalFloD-3D [287] that uses a hydrodynamic model "3Di" [288] developed by Delft University. It dynamically simulates the movement of tides and flood events over digital surface models. The model can simulate a storm event at an hourly time-step, flow direction, velocity, and water depth. The inputs for the model include a 50-m surface with bathymetry and land surface elevation models; time-series of relative sea level, storm, and tide from nine NOAA gauges. For more details refer to Appendix C in Radke et al., [62].

Table 10. Selected Median Coastal Flooding Scenarios

Regional Tile*	Time horizon	RCP	GCM	SLR percentile	Peak SLR (m)
CC	2020- 2040	4.5	CanESM2	95.0	3.18
	2080- 2100	4.5	CanESM2	99.9	4.38
LA **OR**	2020- 2040	4.5	CanESM2	95.0	2.42
	2080- 2100	4.5	CNRM-CM5	99.9	3.85
LJ	2020- 2040	4.5	MIROC5	95.0	2.45
	2080- 2100	4.5	CNRM-CM5	99.9	3.93
MTa **MTb**	2020- 2040	4.5	MIROC5	99.9	2.61
	2080- 2100	4.5	CNRM-CM5	99.9	4.00
PAa **PAb** **PAc**	2020- 2040	4.5	MIROC5	99.9	2.89
	2080- 2100	4.5	MIROC5	99.9	4.16
PR	2020- 2040	8.5	HadGEM2-ES	99.9	2.80
	2080- 2100	4.5	CNRM-CM5	99.9	4.18
SBa **SBb**	2020- 2040	8.5	MIROC5	99.9	2.46
	2080- 2100	4.5	HadGEM2-ES	99.9	3.81
SFD	2020- 2040	8.5	CNRM-CM5	95.0	2.43
	2080- 2100	4.5	CanESM2	99.9	4.08
SF	2020- 2040	8.5	HadGEM2-ES	99.9	2.79
	2080- 2100	4.5	CNRM-CM5	99.9	4.22
SLa **SLb**	2020- 2040	8.5	CNRM-CM5	95.0	2.54
	2080- 2100	4.5	CNRM-CM5	99.9	3.94

*The regional tile geographical reference can be found in Figure 3. Peak SLR level is in meters above the stations mean sea levels under the most recent National Tidal Datum Epoch (1983-2001). The sea levels are here converted to National Elevation Dataset 88 (NVD88).

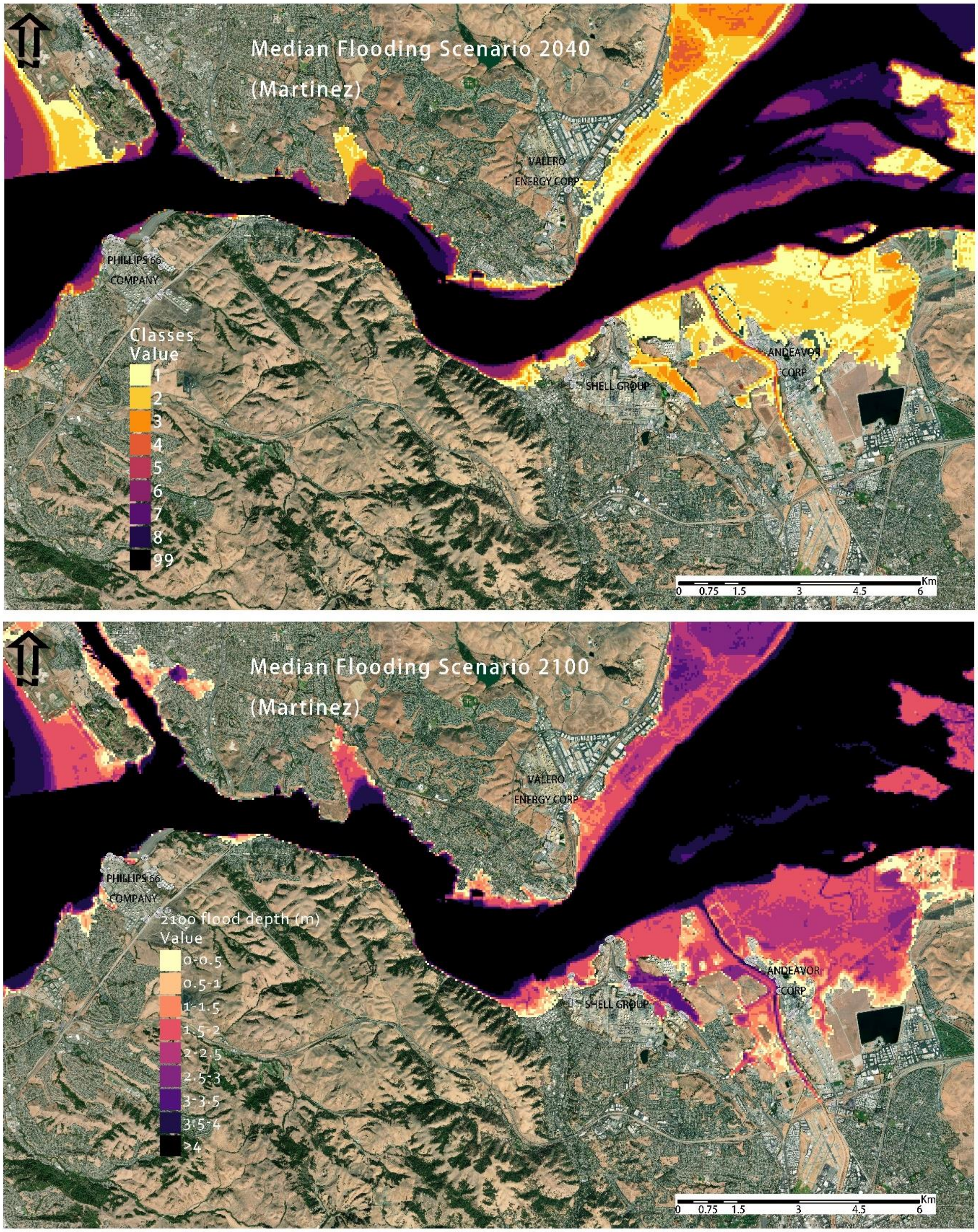
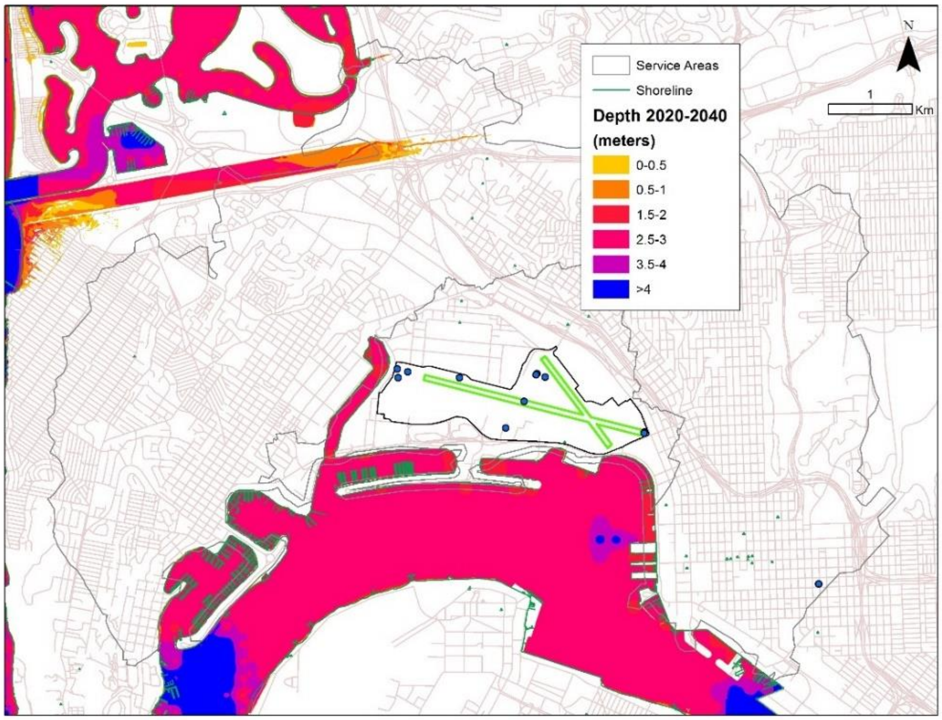


Figure 23. **Near-and long term coastal flooding hazard exposure of TFS assets (Martinez, San Francisco Bay Area)**



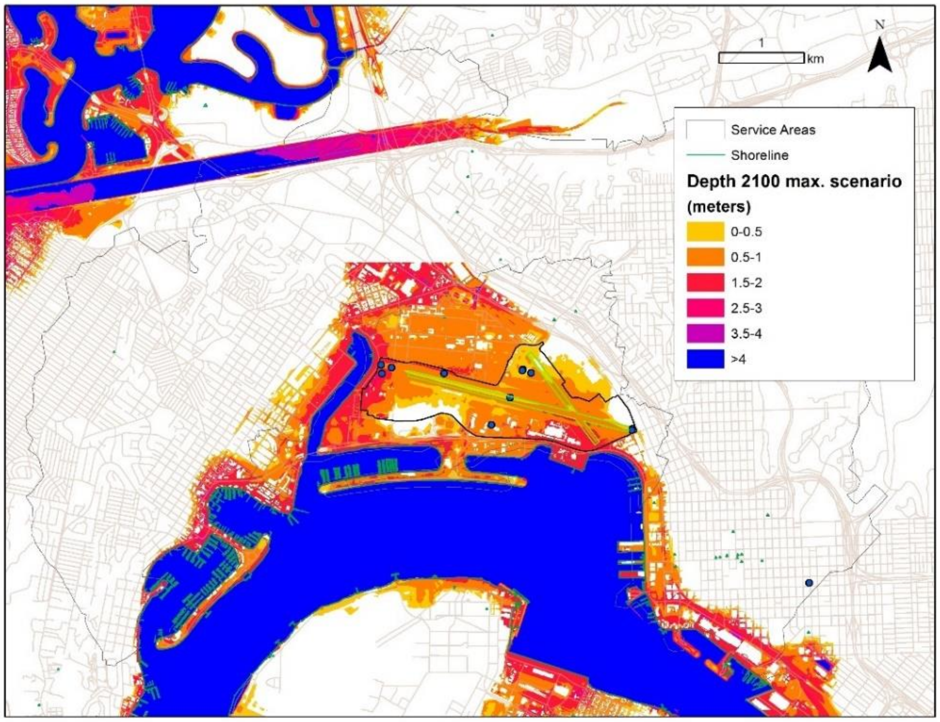


Figure 24. Near-and long term coastal flooding hazard exposure airport assets (International Oakland Airport example, San Francisco Bay Area)

5.2.3. Infrastructure geospatial models

Data processing requires the use of ArcGIS software to clean and build the TFS geospatial model and process it with coastal flooding models. Geospatial overlay is applied flooding tiles (raster) and TFS assets (vectors), the projected coordinate system used is California Teale Albers (NAD 1983 Datum) as this is a regional projection designed for representation of phenomena at the California scale.

(a) Transportation fuel Sector: Crude oil pipeline subset in California

The TFS GIS data is retrieved from the Radke et a., [62] conceptualization of California's fuel sector upstream subsystem (Figure 25). The upstream is also known as the pre-refinery segment of the fuel supply chain, where crude oil is the main commodity being extracted, transported, and stored before it reaches its final destination in one of California's refineries. Approximately 30% of California fuel come from San Joaquin Valley, most prolific oil-producing area in the state, and secondarily from the Los Angeles basin[289] . More than 50% of the crude oil processes in California come primarily from foreign supplies[289] in the Middle East and South America; and around 10% from Alaska; all through marine imports.

The subset of crude oil pipelines only was retrieved from the original transportation fuel sector GIS as polyline data from the Pipeline & Hazardous Materials Safety Administration (PHMSA) National Pipeline Mapping System [290]. An approximation of crude oil pipelines exposure area is determined based on estimated rights of way (ROWs) area. ROWs are the closest data to describe the jurisdiction area (property or lease) that pipeline owners and operators secure to install and maintain infrastructure. Generally, operators obtain ROWs by purchasing property, by mutual agreements with a landowner, or through court-ordered procedures involving single or multiple pipeline rights and other infrastructure systems (power, rail). A ROW width will vary from 7-53 meters (25-175 ft), PHMSA considers 15m (50 ft) width a small scale ROW[291]. According to PHMSA, the ROW width is determined to provide necessary space for daily operational activities and public safety but can be insufficient under contingencies that require pipeline repairs or extensions. We applied a 22m buffer (75ft) to all pipeline polylines to create pipeline polygons as an approximation of ROWs. These pipeline polygons are footprints indicating organizational jurisdiction which allows us to measure coastal flooding exposure.

Figure 25 illustrates where these assets belong in the state fuel supply chain and Figure 26 illustrates the footprint of these assets represented by parcels and ROWs.

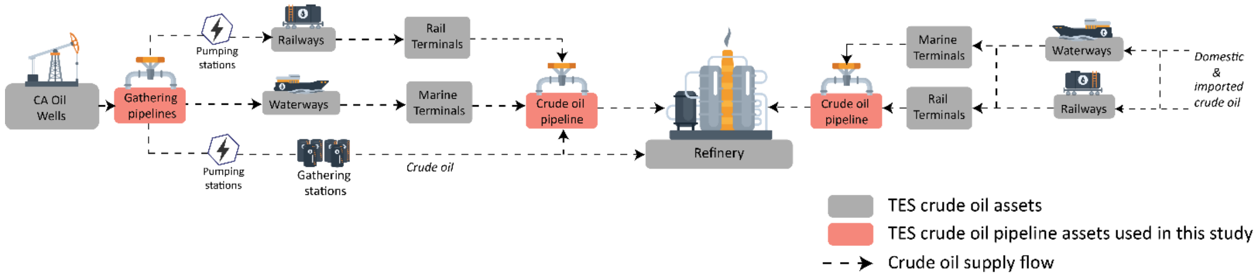


Figure 25. Overview of TFS upstream assets connected to crude oil pipelines

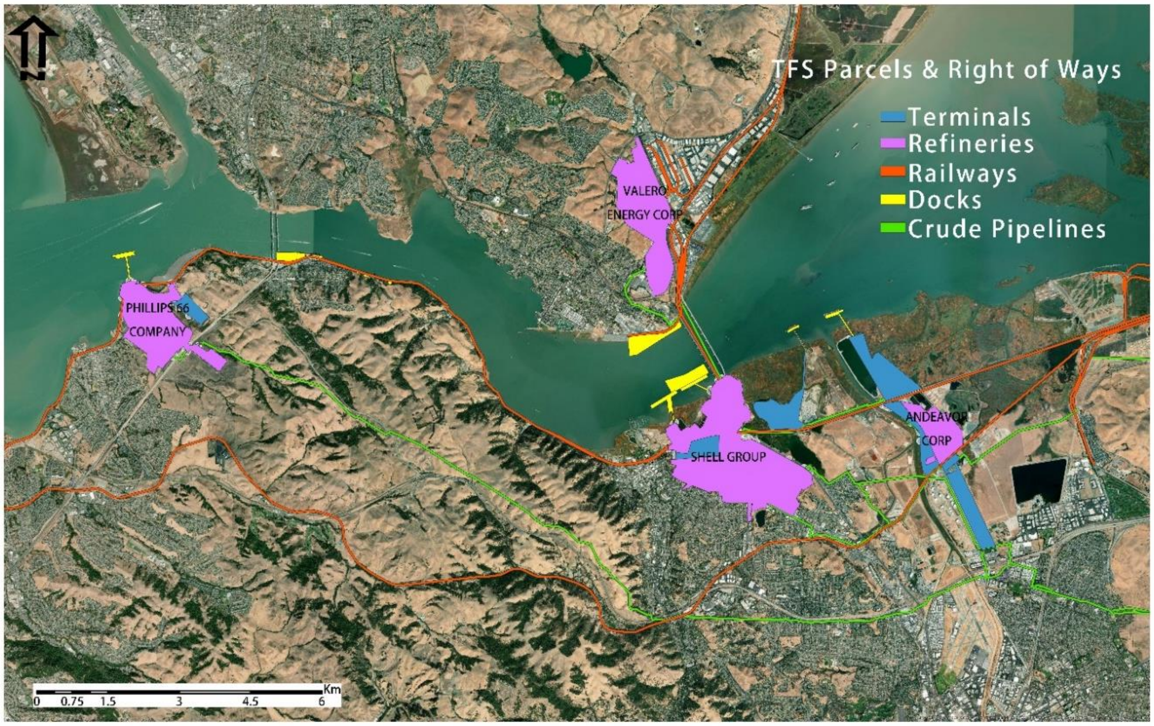


Figure 26. Crude oil pipeline and interconnected assets footprint (ROWs and parcels)

(b) Airport assets in California

A series of geospatial data was retrieved and processed to identify and build the airport assets against which the coastal flood models would be assessed. First low-lying coastal airports are identified (Figure 27), then these airport boundaries, runway and taxiways perimeters, and national airspace system equipment are identified as airport assets (Figure 28).

Low-Lying Coastal Airports (LLCA): The first step was to identify LLCA in California, which represents the potentially exposed airports to coastal flooding. This was done using the Caltrans Public Airports and Runway geodatabase. All airports or runways within a 10km buffer of the shoreline were classified as LLCA and gathered for assessing coastal flooding exposure. A total of 43 LLCA were identified from 242 public airports in California (Figure 5.10). From these 43 LLCA, three airport assets where assessed: airport boundaries, runways and taxiways, and national airspace system (NAS) equipment.

*Airport Boundarie*s: The polygon feature representing the airport parcel retrieved from Caltrans Aeronautics named “Airport Boundaries.” From the 43 LLCA a total of three airport boundary data were missing from the original Caltrans dataset. Oxnard Airport (OXR); Sacramento Executive Airport (SAC), and Zamperini Field Airport (TOA) boundaries were manually digitized based on Open Street Maps. Their runways were identified within the 10 km buffer threshold for identifying LLCA. The airport boundary data set was published on January 27, 2020, current as of September 3, 2015.

Runways and Taxiways: Is retrieved from the Caltrans Aeronautics geospatial dataset as a polyline feature named “Airport Runways”. The original polyline feature represents contours of airport runways that sometimes include taxiways. This information was recomposed into a polygon feature. For certain airports the new geometry results were inaccurate and were digitized manually based on Open Street Maps. Original data were published on January 27, 2020, current as of September 3, 2015.

National Airspace System (NAS) facilities: The NAS facilities are owned and maintained by the FAA, which is responsible for managing more than 45,000 facilities across the U.S. and maintaining data on NAS operations through the National Airspace Performance Reporting System – NAPERS. The NAS data used in this report are from NAPERS, shared by the FAA through UC Berkeley National Center of Excellence in Aviation Operations Research are transformed into point features based on their geocoordinates. Although most NAS facilities are located near airports, to ensure that NAS facilities potentially exposed to coastal flooding are assessed, this report includes a total of 681 NAS facilities located within 10 km of the California coastline. From these 681 potentially exposed NAS, only glide slopes (GS), and precision approach path indicator (PAPI) are selected to illustrate the sociotechnical interlink with PCCPs targeted stakeholders, resulting in a total of 74 pieces of equipment for LLCA in California.

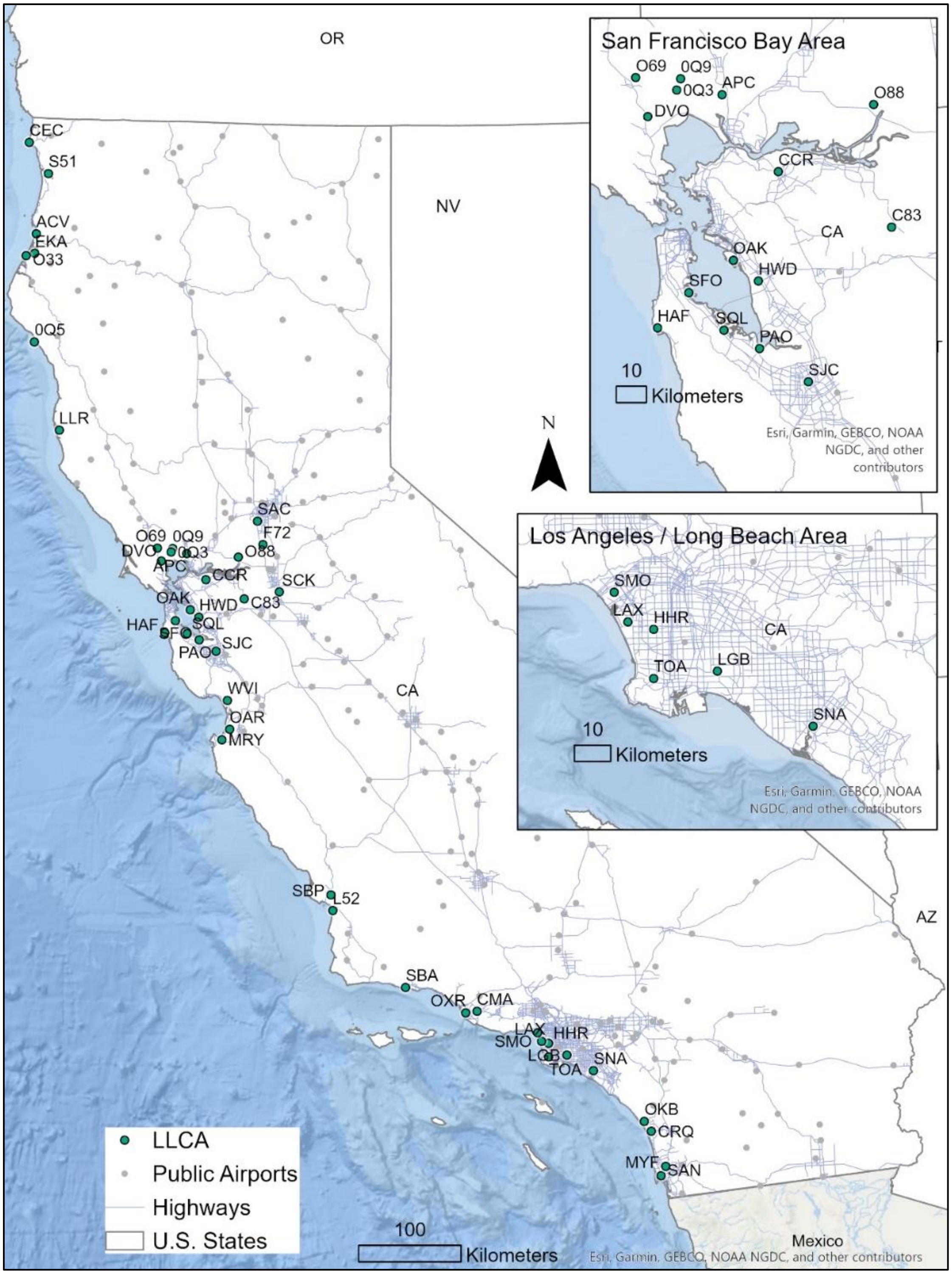


Figure 27. 43 Low-lying Coastal Airports in California (LLCA). For Airport Identification codes refer to Appendix C.

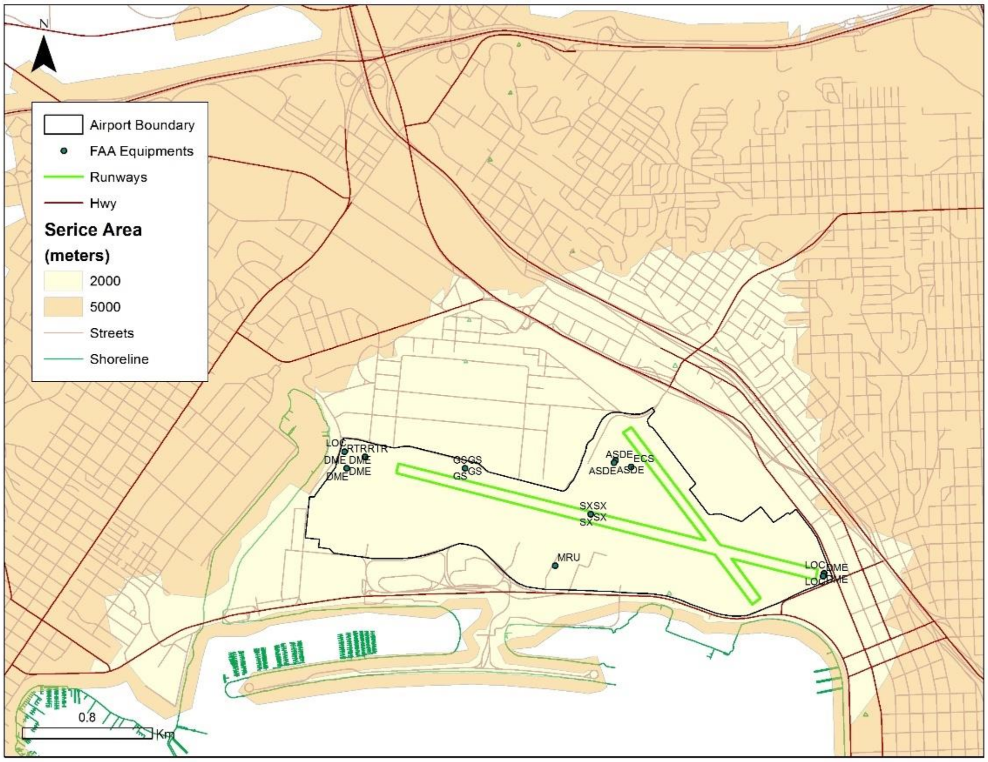
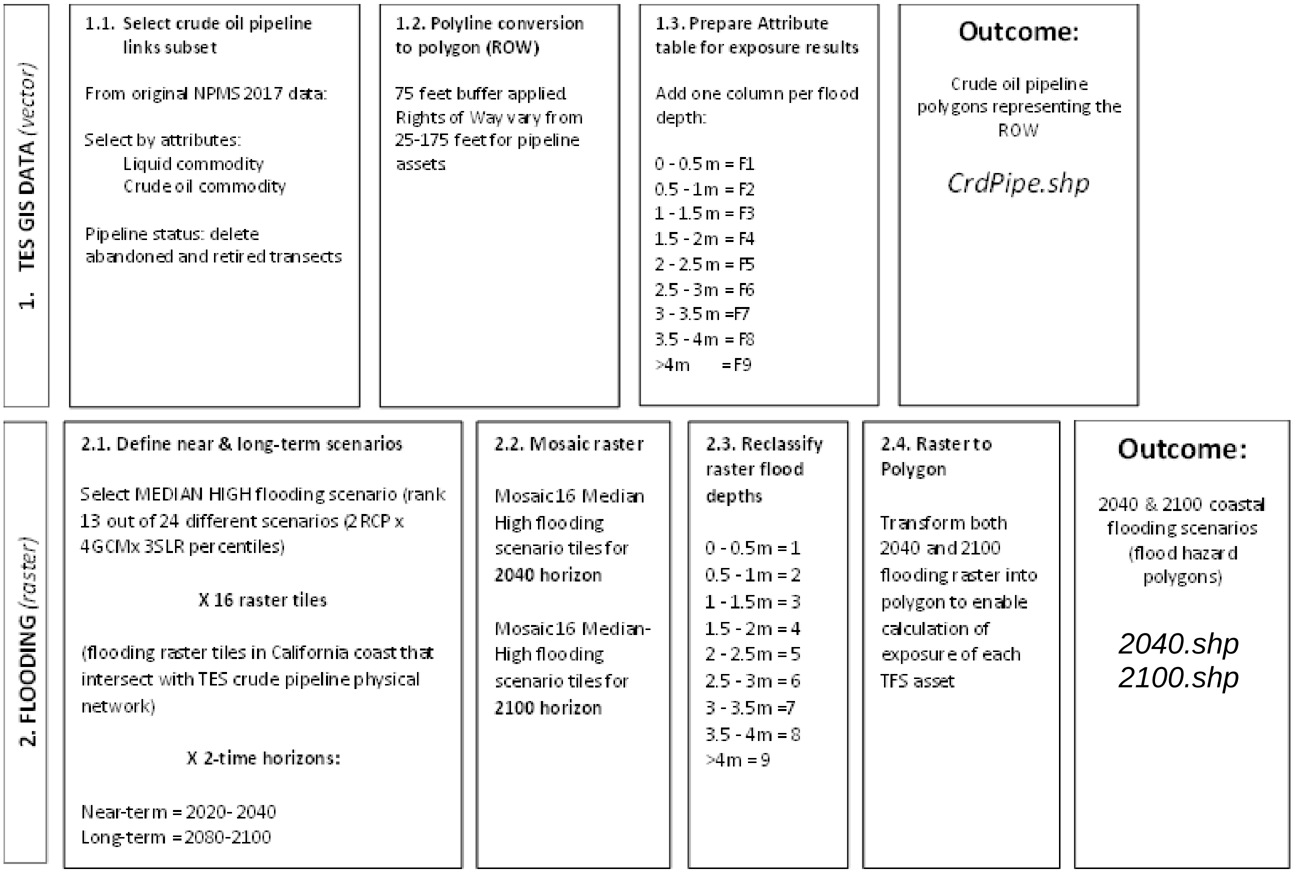


Figure 28. Illustration of airport assets: NAS equipment, runway, and taxiways at San Diego International Airport

5.2.4. Data processing

(a) Organizational network exposure data processing

There are five major steps to build the TFS social network: (1) preparing the TFS physical infrastructure layer; (2) preparing the coastal flooding layer; (3) the exposure assessment; (4) building the sociotechnical exposure organizational network, and (5) the social network analysis. Steps 1 and 2 are pre-processing steps to clean and prepare the coastal flood hazard and infrastructure GIS models. Steps 3-5 present the formal analysis. Steps 1-4 use ArcGIS software and step 5 uses Microsoft Excel and Gephi. Figures 29 and 30 present more details on each of these steps. Figure 31 illustrates how interorganizational junctions were identified in the pipeline GIS dataset for building the sociotechnical network (step 4).



1. TES GIS DATA *(vector)*

1.1. Select crude oil pipeline links subset

From original NPMS 2017 data:

Select by attributes:
Liquid commodity
Crude oil commodity

Pipeline status: delete abandoned and retired transects

1.2. Polyline conversion to polygon (ROW)

75 feet buffer applied Rights of Way vary from 25-175 feet for pipeline assets

1.3. Prepare Attribute table for exposure results

Add one column per flood depth:

0 - 0.5 m = F1
0.5 - 1m = F2
1 - 1.5 m = F3
1.5 - 2m = F4
2 - 2.5 m = F5
2.5 - 3m = F6
3 - 3.5 m =F7
3.5 - 4m = F8
>4m =F9

Outcome:

Crude oil pipeline polygons representing the ROW

CrdPipe.shp

2. FLOODING *(raster)*

2.1. Define near & long-term scenarios

Select MEDIAN HIGH flooding scenario (rank 13 out of 24 different scenarios (2 RCP x 4 GCMx 3SLR percentiles)

X 16 raster tiles

(flooding raster tiles in California coast that intersect with TES crude pipeline physical network)

X 2-time horizons:

Near-term = 2020- 2040
Long-term =2080-2100

2.2. Mosaic raster

Mosaic16 Median High flooding scenario tiles for **2040 horizon**

Mosaic16 Median-High flooding scenario tiles for **2100 horizon**

2.3. Reclassify raster flood depths

0 - 0.5m = 1
0.5 - 1m = 2
1 - 1.5m = 3
1.5 - 2m = 4
2 - 2.5m = 5
2.5 - 3m = 6
3 - 3.5m =7
3.5 - 4m = 8
>4m = 9

2.4. Raster to Polygon

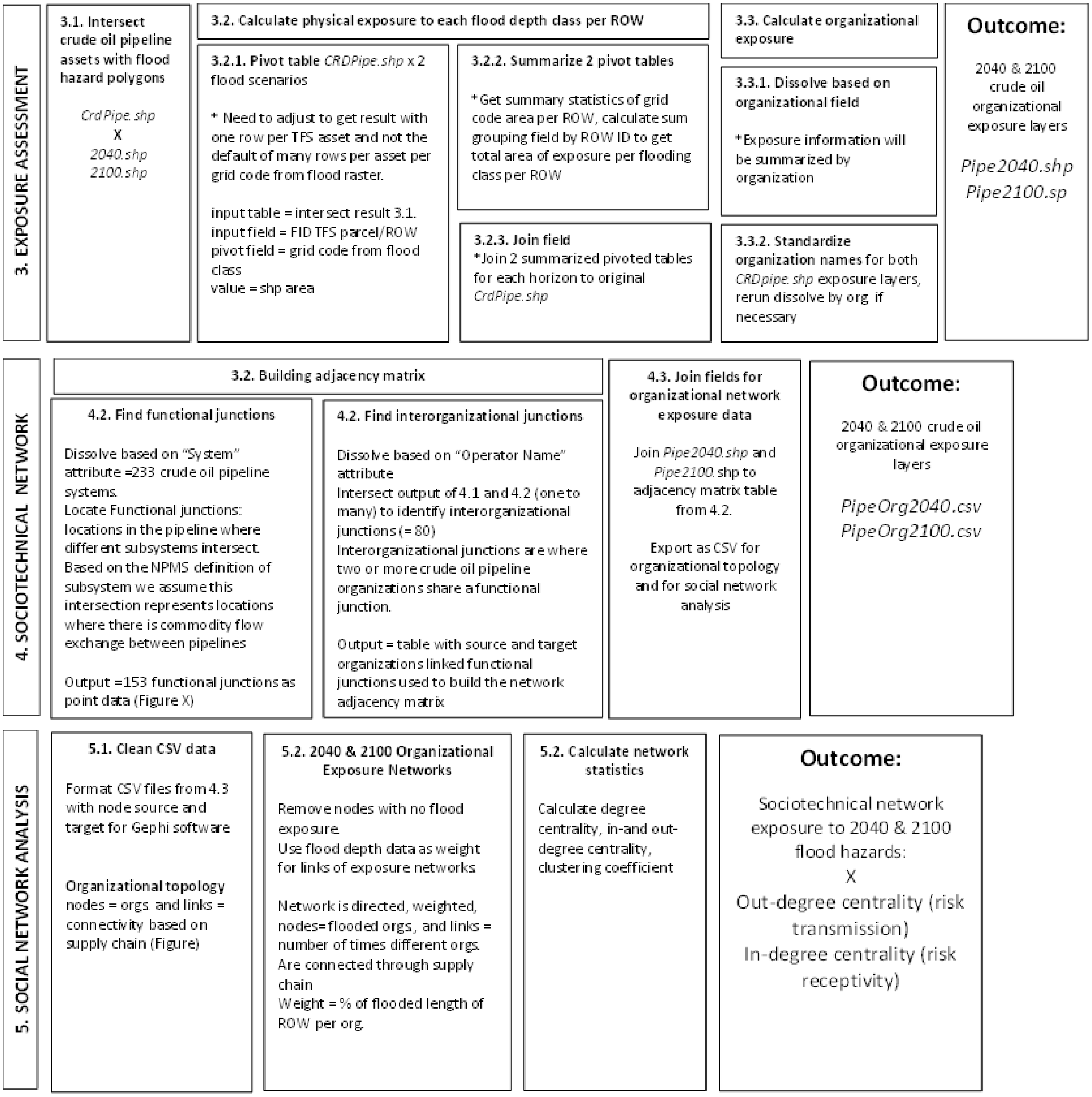
Transform both 2040 and 2100 flooding raster into polygon to enable calculation of exposure of each TFS asset

Outcome:

2040 & 2100 coastal flooding scenarios (flood hazard polygons)

2040.shp
2100.shp

Figure 29. **TFS organizational network exposure assessment pre-processing steps**



3.1. Intersect crude oil pipeline assets with flood hazard polygons

Crd Pipe.shp
X
2040.shp
2100.shp

3.2. Calculate physical exposure to each flood depth class per ROW

3.2.1. Pivot table *CRDPipe.shp* x 2 flood scenarios

* Need to adjust to get result with one row per TFS asset and not the default of many rows per asset per grid code from flood raster.

input table = intersect result 3.1.
input field = FID TFS parcel/ROW
pivot field = grid code from flood class
value = shp area

3.2.2. Summarize 2 pivot tables

*Get summary statistics of grid code area per ROW, calculate sum grouping field by ROW ID to get total area of exposure per flooding class per ROW

3.2.3. Join field

*Join 2 summarized pivoted tables for each horizon to original *CrdPipe.shp*

3.3. Calculate organizational exposure

3.3.1. Dissolve based on organizational field

*Exposure information will be summarized by organization

3.3.2. Standardize organization names for both *CRDpipe.shp* exposure layers, rerun dissolve by org if necessary

Outcome:

2040 & 2100 crude oil organizational exposure layers

Pipe2040.shp
Pipe2100.sp

3.2. Building adjacency matrix

4.2. Find functional junctions

Dissolve based on "System" attribute =233 crude oil pipeline systems.
Locate Functional junctions: locations in the pipeline where different subsystems intersect.
Based on the NPMS definition of subsystem we assume this intersection represents locations where there is commodity flow exchange between pipelines

Output =153 functional junctions as point data (Figure X)

4.2. Find interorganizational junctions

Dissolve based on "Operator Name" attribute
Intersect output of 4.1 and 4.2 (one to many) to identify interorganizational junctions (= 80)
Interorganizational junctions are where two or more crude oil pipeline organizations share a functional junction.

Output = table with source and target organizations linked functional junctions used to build the network adjacency matrix

4.3. Join fields for organizational network exposure data

Join *Pipe2040.shp* and *Pipe2100.*shp to adjacency matrix table from 4.2.

Export as CSV for organizational topology and for social network analysis

Outcome:

2040 & 2100 crude oil organizational exposure layers

PipeOrg2040.csv
PipeOrg2100.csv

5.1. Clean CSV data

Format CSV files from 4.3 with node source and target for Gephi software

Organizational topology nodes = orgs and links = connectivity based on supply chain (Figure)

5.2. 2040 & 2100 Organizational Exposure Networks

Remove nodes with no flood exposure.
Use flood depth data as weight for links of exposure networks

Network is directed, weighted, nodes= flooded orgs, and links = number of times different orgs. Are connected through supply chain
Weight = % of flooded length of ROW per org.

5.2. Calculate network statistics

Calculate degree centrality, in-and out-degree centrality, clustering coefficient

Outcome:

Sociotechnical network exposure to 2040 & 2100 flood hazards:
X
Out-degree centrality (risk transmission)
In-degree centrality (risk receptivity)

Figure 30. TFS organizational network exposure assessment formal analysis

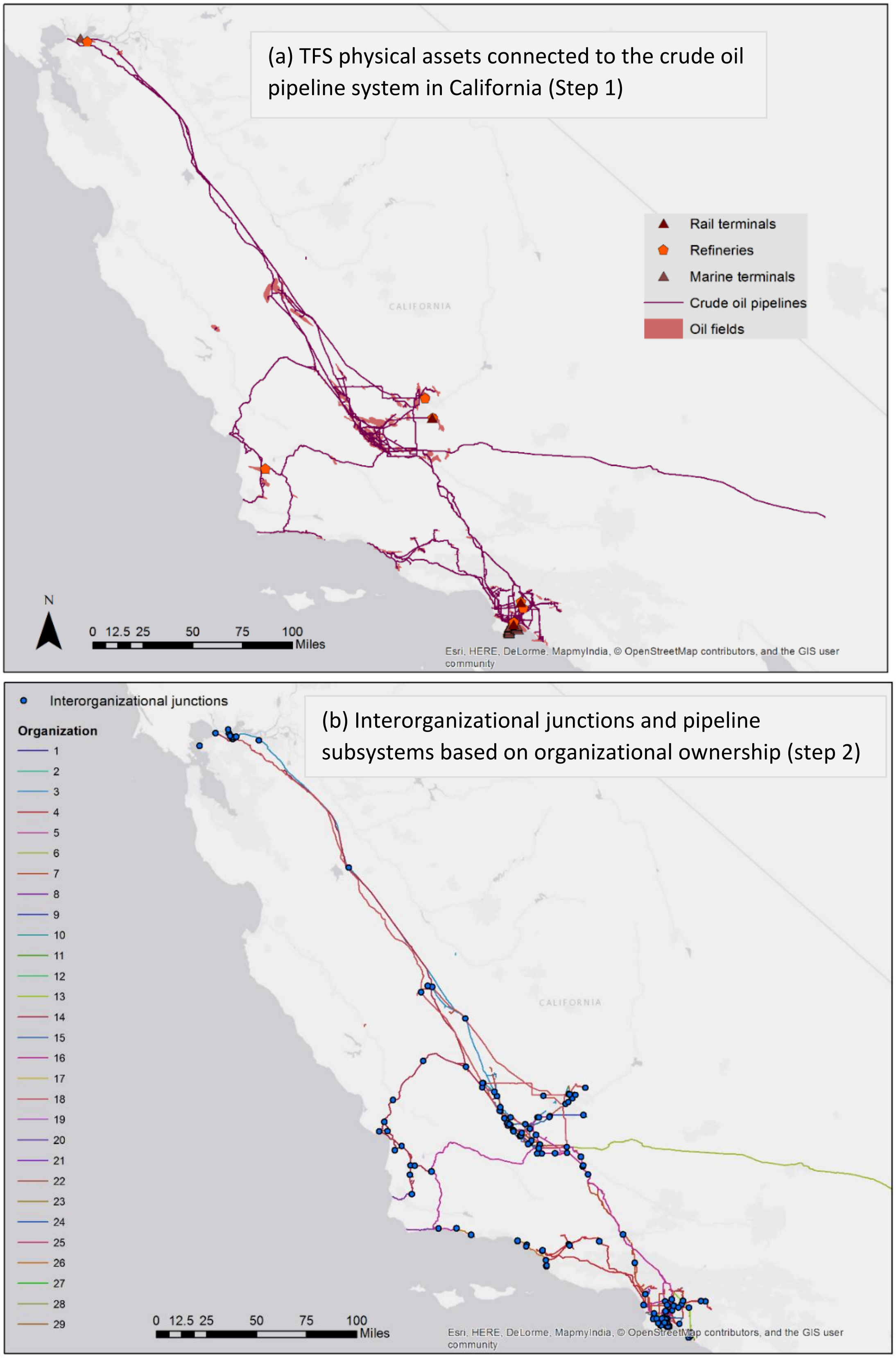


Figure 31. California crude oil pipeline physical and organizational GIS network

(b) Airport exposure to coastal flooding data processing

The airport exposure to coastal flooding used airport asset GIS and projected coastal flood models to find the relative exposure of airport runways and taxiways as well as NAS equipment (GS, and PAPI). The exposure results are then used with inputs from the policy review content analysis linking targeted PCCP stakeholders to their technical PCCPs to show how we can trace exposure to targeted policy stakeholders for improved collective-decision making, collaboration, and airport adaptation governance. Figure 32 presents more details on each of these steps.

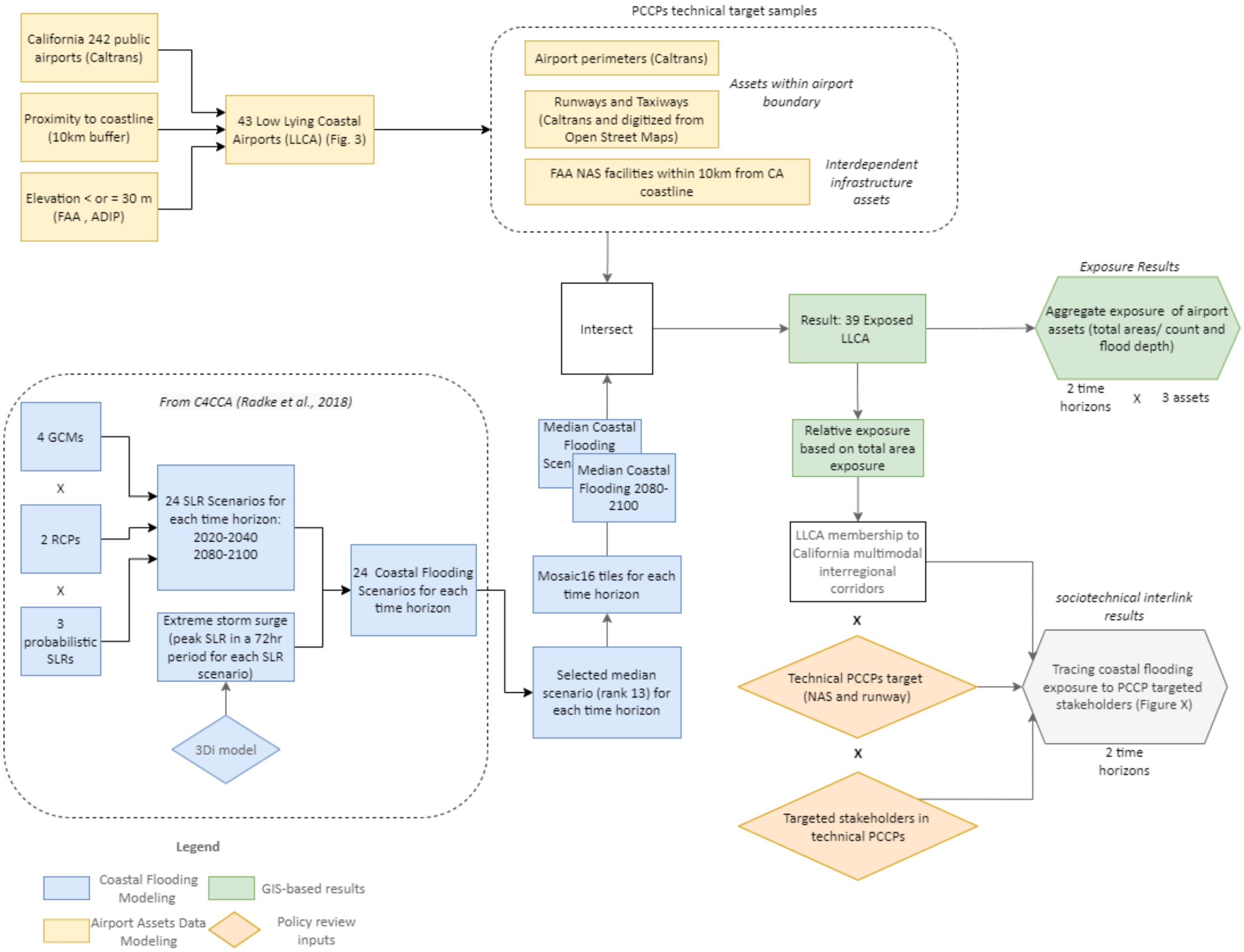


Figure 32. Data processing for airport coastal flooding exposure assessment in California and policy review data inputs to define sociotechnical interlinks

(c) Policy data processing for building airport sociotechnical interlinks

Four major steps in the policy data processing disclose the airport sociotechnical interlinks: (1) the content analysis of airport policy documents for data collection of stakeholder mentions; (2) the standardization of the stakeholder coding scheme; (3) building the code co-occurrence matrix; and (4) identifying the sociotechnical interlinks for integration with

GIS exposure data (Figure 33, step 4.1.) and building and assessing the stakeholder policy network (Figure 33, step 4.2).

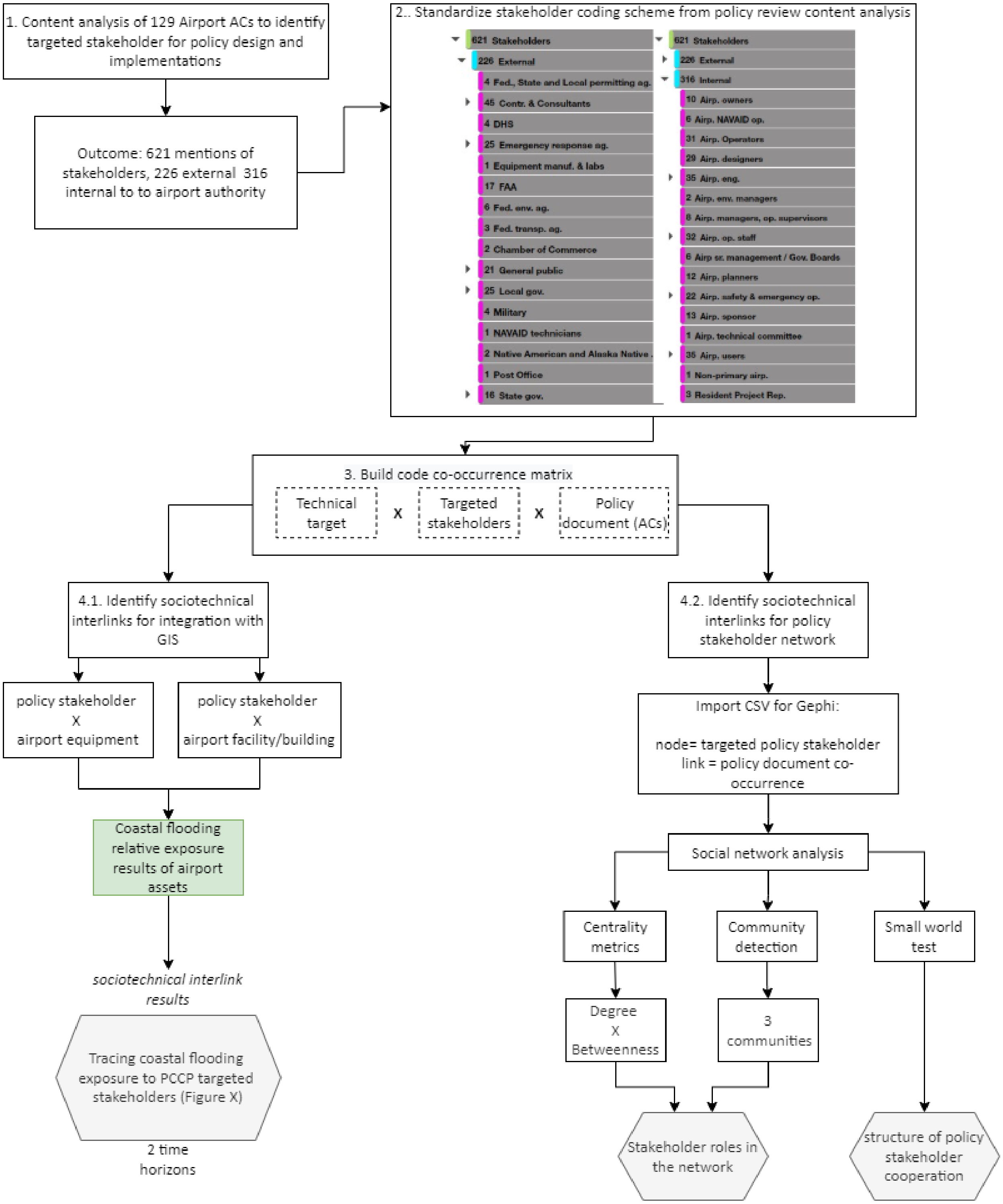


Figure 33. **Airport data processing steps to identify sociotechnical interlinks for the stakeholder policy network and GIS exposure results integration.**

In Figure 33, Data collection and processing steps of 1-3 uses Dedoose software for content analysis, step 4.1 integrates the GIS airport exposure to coastal flooding results from section 5.2.4(b), and step 4.2. uses Microsoft Excel, Gephi, and NetworkX for social network analysis.

5.2.5. Uncertainty and limitations of data analyses

(a) Uncertainty related to the social network models and stakeholder detection

Real-world networks are enhanced when there is richer information regarding the flows (i.e., hierarchy, frequency, intensity), such as the frequency of interaction between social entities based on participation of managerial and executive meetings, policy forums, money lending relationships for commodity trading systems, intensity of contractual agreement exchange, etc. However, such information can be hard to access because there is no systemic method of collecting it or simply because it is non-disclosed to the public. The underlying assumption is that connected social entities can potentially share information, cooperate, or collaborate. The connectivity is based on supply chain stream or co-occurrence in policy documents. This interconnectivity does not account for hierarchy, frequency, or intensity of information exchange. Stakeholder identification processes are limited to formal data sources regarding jurisdictional decision-making power (ownership and operation responsibilities), and also those targeted for designing or implementing airport policies. There is a range of informal stakeholders that can highly influence decision-making based on differences of organizational structure and degrees of involvement with civil society organizations.

For the TFS organizational network, our analysis conceptually takes into consideration the supply chain topology, but there are likely to be various crude pipeline organizational junctions that were over-or under-counted due to operational specificities of pipeline vaults, valves, and other assets that are not available in the NPMS data. We only consider the integrity of NPMS systems and subsystems combined with operator/owner information available in the GIS data attribute table.

For the stakeholder policy network data, coding targeted stakeholder in the content analysis embeds uncertainties at different moments of the data collection and processing. The first is related to the implicit or explicit level that ACs target stakeholder’s responsibility in designing and implementing each specific policy. In some instances, no explicit stakeholder is mentioned, therefore we implicate responsibility. When necessary, the implicit definition of targeted stakeholders was based on in-depth discussions with airport stakeholder interviews but was not systematically verified. Another level of uncertainty stems from the standardization process. From a total of 612 stakeholder mentions in the 77 airport ACs classified as PCCPs (see Chapter 4.3) we ended up with 91 distinct stakeholders. Some of the stakeholders mentioned presented no mutual-exclusivity in their categories due to the range of specificity of each policy. For example, some policies mention “state government”, others specify “state environmental agencies”, and one specifically mentioned the State Department of Natural Resources. Although they all represent the “state government”, we respected the specificity-levels of the stakeholder mentioned in each policy document, resulting in three distinct PCCPs targeted stakeholders or nodes.

(b) Limitations of the coastal flooding model

Projected coastal flooding models carry inherent uncertainties due to different political, socioeconomic, and technological assumptions such as (a) GHG emission and concentrations (i.e., RCPs), (b) selected climate models (GCMs), and (c) probabilistic SLRs. Given the coarse spatial resolution of the analysis (50m) the results are primarily appropriate to interpret at the statewide level (aggregate airport asset exposure). Furthermore, given that flooding dynamics are sensitive to surface conditions, models applied to flat coastal areas are more likely to present uncertainties when compared to those applied to areas with higher topographic variation[292].

From a temporal perspective, the uncertainty in projected coastal flooding from different GCMs and RCPs is relatively small in the near-term but start growing after 2040 to become much more pronounced by 2100. Thus, the range between the inundated area for the minimum and maximum coastal flooding scenario is smaller earlier in the century (2020-2040 time horizon) than in the end of the century (2080-2100 time horizon). Figure 34 shows how the exposed areas change through different time horizons given the minimum, median, and maximum coastal flooding scenarios using the example of OAK. Given that we produced results for only the median scenario, it is important that stakeholders keep in mind this range of possible outcomes for planning and decide what levels of exposure are acceptable so that adaptation measures can be prioritized.

Another coastal flooding model available for the California coast is the Coastal Storm Modeling System (CoSMoS) developed by the United States Geologic Service (USGS) . This model also incorporates SLR and dynamic aspects such as storm surge to better understand total water levels and has been developed at 2 m spatial resolution for all of California's coast [293]. The CoSMoS model present advantages for coastal flooding studies seeking higher resolution results, notably for large geographical scale studies (such the perimeter of an airport) but will have a very high computational cost for studies at a small geographical scale (such as the state of California). The CoSMoS model is also advantageous for stakeholders seeking to disentangle the SLR water levels from storm surge water levels. This effort can be very important to better prioritize adaptation measures that will differ if the airport asset in question is not exposed to gradual SLR throughout the century but becomes exposed to abrupt events such as storm surge when combined to projected gradual SLR. In this study, Radke et al., [62] coastal flood model was applied to conform with the latest California Climate Change Assessment. Radke et al. [62] provides the advantage of investigating the range of scenarios through multiple GCMs and RCPs to find the minimum, median, and maximum coastal flooding scenarios which is currently not possible with the publicly available data from CoSMoS.

Furthermore, impacts from SLR are often driven by regional changes in relative sea level that can be better attributed to land uplift or subsidence than global mean sea level [294]. Vertical land motion (VLM) influences California's coast and further studies combining the effects of coastal flooding to VLM should be developed to inform how future coastal flooding can impact airport infrastructure.

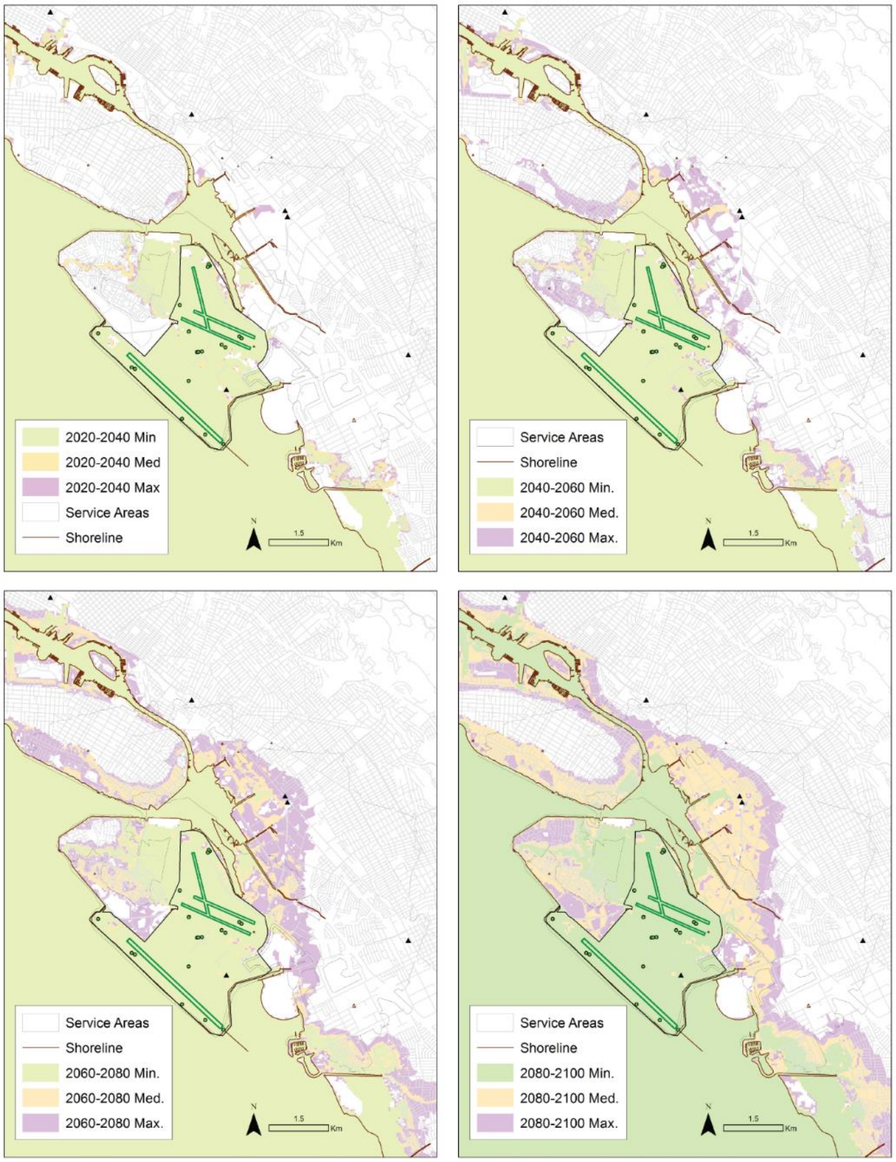


Figure 34. Contrast of minimum, median, and maximum flooding scenarios from 2020-2100 showing the increased uncertainty of flooded areas by the end of the century. Oakland International Airport example.

(c) Uncertainty related to the exposure assessment

Flood model overlay with infrastructure assets, parcels, or ROW does not automatically translate into damage or disruption, but we assume there is risk of impact to physical infrastructure or to operations. Risk can only be assessed with deep knowledge of the vulnerability of the infrastructure assets and system such as its sensitivity to different flood hazards, existing adaptive measures, and criticality of the exposed asset to the function of the system at the local and regional scales.

The risk of impact will be greater depending on other factors than flood depth hazard, such as duration, flow direction, velocity, wave kinetics and a combination of these hazard characteristics. Other factors that are intrinsic to the infrastructure asset type, material, design, function, and position underground or above ground are also main determinants of impact that we do not account for in this analysis. Importantly, an assessment at the infrastructure asset level requires higher spatial resolution models (at least 5 m or less) to better match the scale of the TFS and airport assets and see how modeled flood hazard characteristics can be directly translated to impacts on different assets (for example, tolerance thresholds for asset damage and system failures). Our coastal flooding models do not consider the effect of adaptive measures such as stormwater drainage systems or floodwall infrastructure that are not captured by the underlying topographic and bathymetric datasets used in the original coastal flood model (see Appendix C.2.2. of Radke et al.,[62]).

For the TFS, underground pipelines, for example, cannot be considered as vulnerable as above ground pipeline facilities such as vaults, tanks, and pumping stations. Full anchored crude tanks are not as vulnerable as empty non-anchored crude tanks, retrofitted pipeline transects will also be less vulnerable than older structures. Overall, it is also important to keep in mind that the crude oil subsystem is less critical to the functioning of the TFS since it specializes on feedstock for transportation fuel production and not a ready-to-use commodity.

For the airports, two very important analyses must be developed to interpret coastal flooding exposure information more clearly. The first analysis is to apply a finer spatial scale coastal flooding analysis at 5 m or preferably less. Doing so is essential to considering the finer variations of the surface and how that influences flood levels and hydrological connectivity, but also how smaller assets such as dikes, levees, and other buildings can influence flood water behavior. Secondly, one must understand the criticality of different infrastructures to airport operations (i.e., how severe is the impact to airport's performance, capacity, services, user experience from the damage or disruption of the infrastructure?), as well as its sensitivity or vulnerability to different flood hazard behaviors (i.e., what is the damage propensity of different assets to flood duration, flood depth, or flood frequency). For instance, certain equipment relying on power or containing water-sensitive materials can be highly damaged if flooded at any time. Some infrastructure assets are built to resist certain levels of episodic flooding (drainage systems, pavements, roads, and certain buildings), but with the increase in frequency and severity of flood events, these assets can suffer other types of long-term degradation and cumulative damage that will require higher frequency in maintenance, retrofits, or relocation. Other assets such as runways and taxiways are critical for airport operations and become inoperable under any type of flooding incident representing highly critical assets to protect from coastal flooding.

More accurate and richer data on infrastructure assets would be needed to better link hazardous aspects of flooding to specific infrastructure assets in space and their role in keeping the TFS or airports functional at local, regional, and global scales.

5.3. Insights from Sociotechnical Network Exposure: Application to the California Transportation fuel System Crude Oil Pipelines

In this section, insights on the development of TFS sociotechnical interlinks are presented. The interlinks are inferred based on geospatial data of crude oil pipelines that we combine with coastal flooding models to map the sociotechnical network exposure to near-and long-term coastal flooding in California. We start by showing how multiple organizations that own and operate pipelines rely on each other for the supply of crude oil to state refineries. The exposure assessment is presented in two phases: (1) shows the aggregate exposure per organization based on the projected flooding of pipeline measured in total length and by the proportion of asset's exposure per organization; and (2) the sociotechnical network exposure map is presented identifying the need for new modes of decision-making stakeholder interactions based on the identification of organizations with high hazard transmission and receptivity potential.

5.3.3. Uncovering the organizational network of the TFS: how are decision making entities of infrastructure assets interconnected through crude oil supply chain?

The TFS as a sociotechnical system is composed by a large network of interconnected organizations from the public, but mostly from the private sector, that own and operate different assets and have fragmented governance systems. Table 11 presents an approximate count of these organizations when looking only at the crude-oil supply chain system; thus, those organizations that are likely interconnected with crude oil pipeline organizations. Although the core structure of major organizations that own and operate key companies varies little, ownership of specific assets fluctuates continually through mergers and acquisitions, common in for CIs that behave as supply chains. This fluctuation renders tracking organizations even harder and increases uncertainties related to risk mitigation strategies that transgress the industry's business model time horizon.

Table 11. Organizational population of California's crude oil pipeline system and connected TFS assets (estimated based on GIS data from Radke et al, 2018).

TFS physical infrastructure		Count of owner/operators
Links	Crude oil pipelines	36
	Railways	9
	Waterways	5
Nodes	Refineries	10
	Crude oil terminals	31
	Docks	30-50
	Oil wells	>500

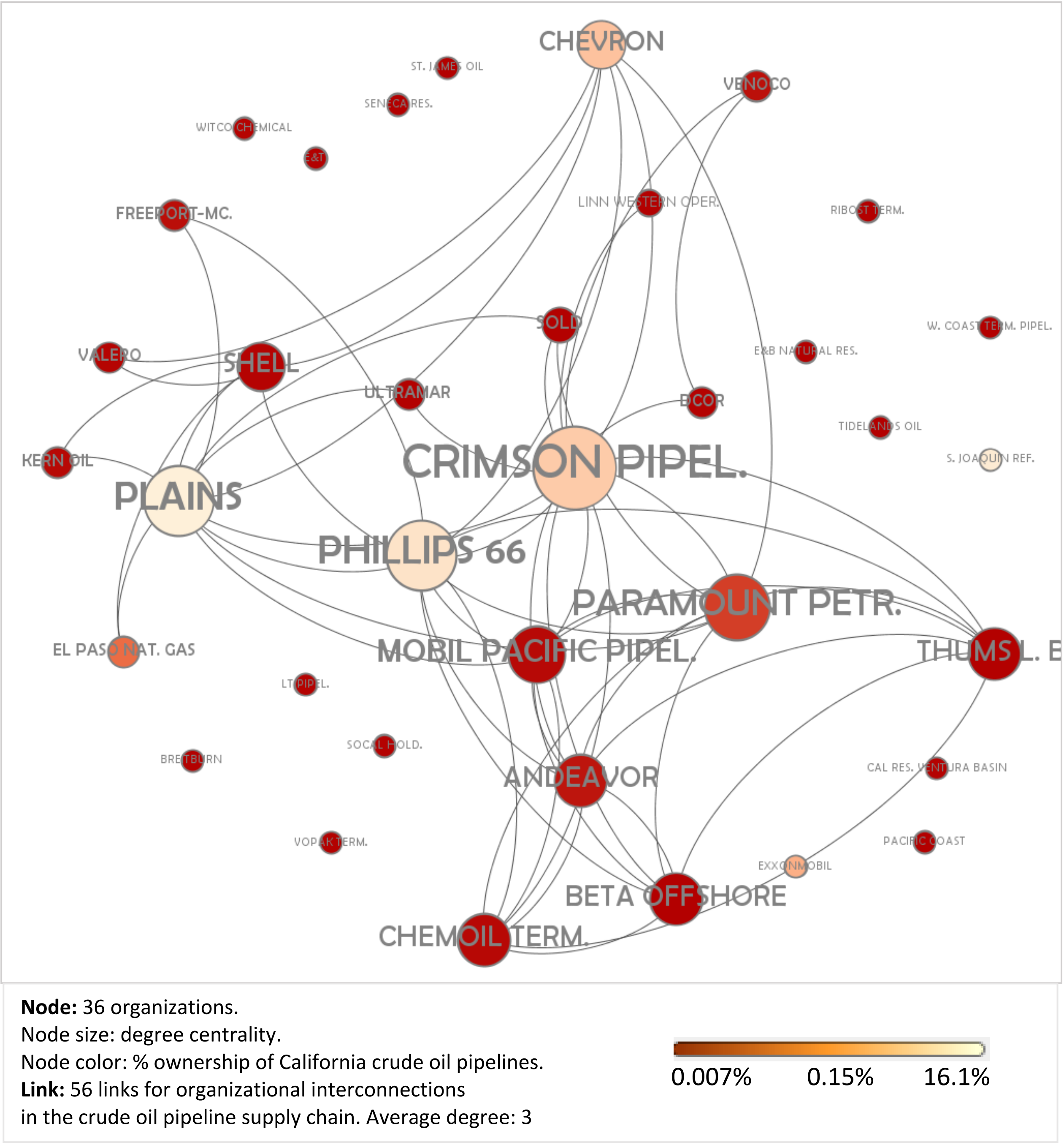
The fragmented set of organizations that own and operate these CI systems do not share centralized and hierarchical control of goods and services. These are provided by a large population of competing markets. Any CI that relies on a supply chain fits this category. Institutional fragmentation threatens high levels of reliability, but, on the other hand, it can help generate new strategies of supply and demand that enables these organizations to maintain reliability under unusually demanding conditions; given their competing market structures and equilibrium of supply and demand [295]. This flexibility can be better harnessed for contingency situations, where CI systems such as the TFS, are required to transform to respond to humanitarian crisis. Furthermore, it can improve our understanding of organizational resilience beyond a single organization to the reality of a system of interacting organizations that rely on each other for the functionality of the TFS as CI.

Figure 35 illustrates the sociotechnical network of TFS based on the crude oil pipeline subset. It identifies 36 organizations in California that own or operate pipeline segments. The node size represents degree centrality, or the total connections each organization has with other crude oil pipeline organizations. The node color helps us identify the relative percentage of linear pipeline asset ownership of each organization in California. This network helps identify central players in the California crude sector such as, Crimson, with the highest number of interorganizational connections, and Plains, with the highest % of linear asset ownership. A total of 56 links represents the number of interorganizational junctions in the NPMS pipeline data. Organizations that have no connections are likely interconnected through assets in the crude oil supply such as terminals and refineries that were omitted from the network analysis.

Table 12 presents the top 10 organizations owning close to 94% of California's linear crude oil pipeline infrastructure. The remainder 26 organizations each own less than 0.9%, summing up to approximately 5% of total crude oil pipeline infrastructure ownership in the state.

Table 12. Top ten owners and operators of crude oil pipeline assets in California (NPMS, 2017)

Organization name	% of linear crude oil pipeline ownership in CA
PLAINS LP	16.22432637
ROYAL DUTCH SHELL PLC	15.94129907
PHILLIPS 66 CO	15.10052966
CRIMSON PIPELINE LP	12.98722121
CHEVRON CORP	12.65540314
EXXONMOBIL CORP	10.38536149
EL PASO NATURAL GAS CO	6.372215931
PARAMOUNT PETROLEUM CORP	3.540374309
ANDEAVOR CORP	1.174754912
VENOCO INC	0.963345731



Node: 36 organizations.
Node size: degree centrality.
Node color: % ownership of California crude oil pipelines.
Link: 56 links for organizational interconnections
in the crude oil pipeline supply chain. Average degree: 3

Figure 35. Crude oil pipeline sociotechnical network

5.3.4. Measuring Organizational Network Exposure to Projected Coastal Flooding

(a) Direct organizational exposure

The direct exposure of organizations is measured based on the value of pipeline ROWs exposed to near-and long-term coastal flooding medium scenario, aggregated by organization. Figure 36 lists all 36 crude oil pipeline organizations and the total length of pipelines exposed by 2040 and 2100, where a total of 23 organizations have pipeline transects exposed to both time horizons. The organizations currently exposed will remain exposed by 2100 assuming the ownership structure remains similar. By 2040 the exposure ranges from approximately 195 m for Ultramar Inc. and 20,115 m for Crimson Pipeline L.P. By 2100 the exposure ranges from 425 m for Freeport-McMoran Oil & Gas and 66,900 m for Crimson Pipeline L.P.

Figure 37 further details depth exposure by length and by percentage of pipeline transects by organization. By 2040 a larger proportion of pipeline transects are exposed to extreme flood depths (2m and above). There is a large increase in the total length of pipeline transect exposure by 2100; however, a larger proportion is exposed to less than 0-5m to 1m flood depth.

The percentage of pipeline transects exposed relative to the total transects owned by the organization help contextualize the exposure results. From 2020 to 2040 Exxon Mobil Corp. will have the least relative exposure at 0.1%; and Valero Energy Corp will have the maximum at 27%[9]. By 2100 Royal Dutch Shell LCP will have the least relative exposure at 0.3% and Vopak Terminal LA reaches 99%. It is common to find that companies with highest percentage of pipeline exposed, such as Vopak Terminal LA, Ribost terminal LLC, E&T LLC, Valero Energy Corp. have a smaller percentage of ownership relative to the total assets in the state. However, based on stakeholder interviews and GIS analysis we can verify that some of these transects are critical connectors between marine terminals and refineries. Considering that 2/3 of the state crude oil demand finds its way to one of the California 18 refineries through marine imports, the exposure of these transects is potentially threatening to the TFS. However further investigation with industry experts is necessary to understand the potential risk of such exposure. More information Is needed notably to verify the existence of above ground pipeline assets associated to these transects; the changes of accessibility for maintenance, upgrade, or any contingency, the robustness; and the sensibility of pipeline and other interconnected TFS infrastructure equipment materials and design to coastal flood hazards, notably wave kinetics.

Better understanding how these organizations are interconnected based on the supply chain topology will improve understanding of network-level vulnerabilities of the crude oil TFS subsector.

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[9] A non-identified organization has the maximum relative exposure in 2040, however it represents a very small proportion of the total crude oil pipeline infrastructure in California

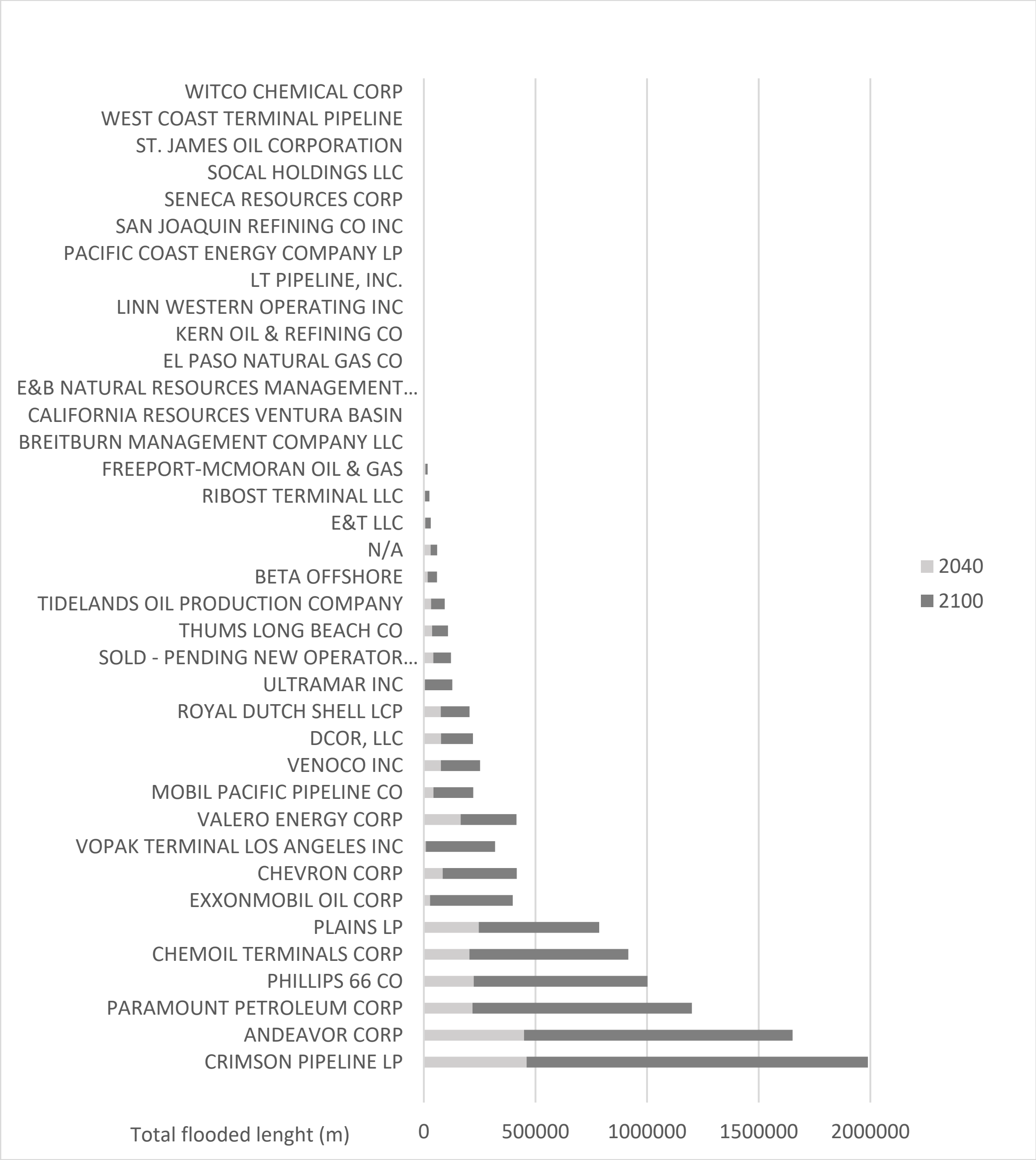


Figure 36. Direct organizational exposure of crude pipeline to near and long-term median flooding scenarios.

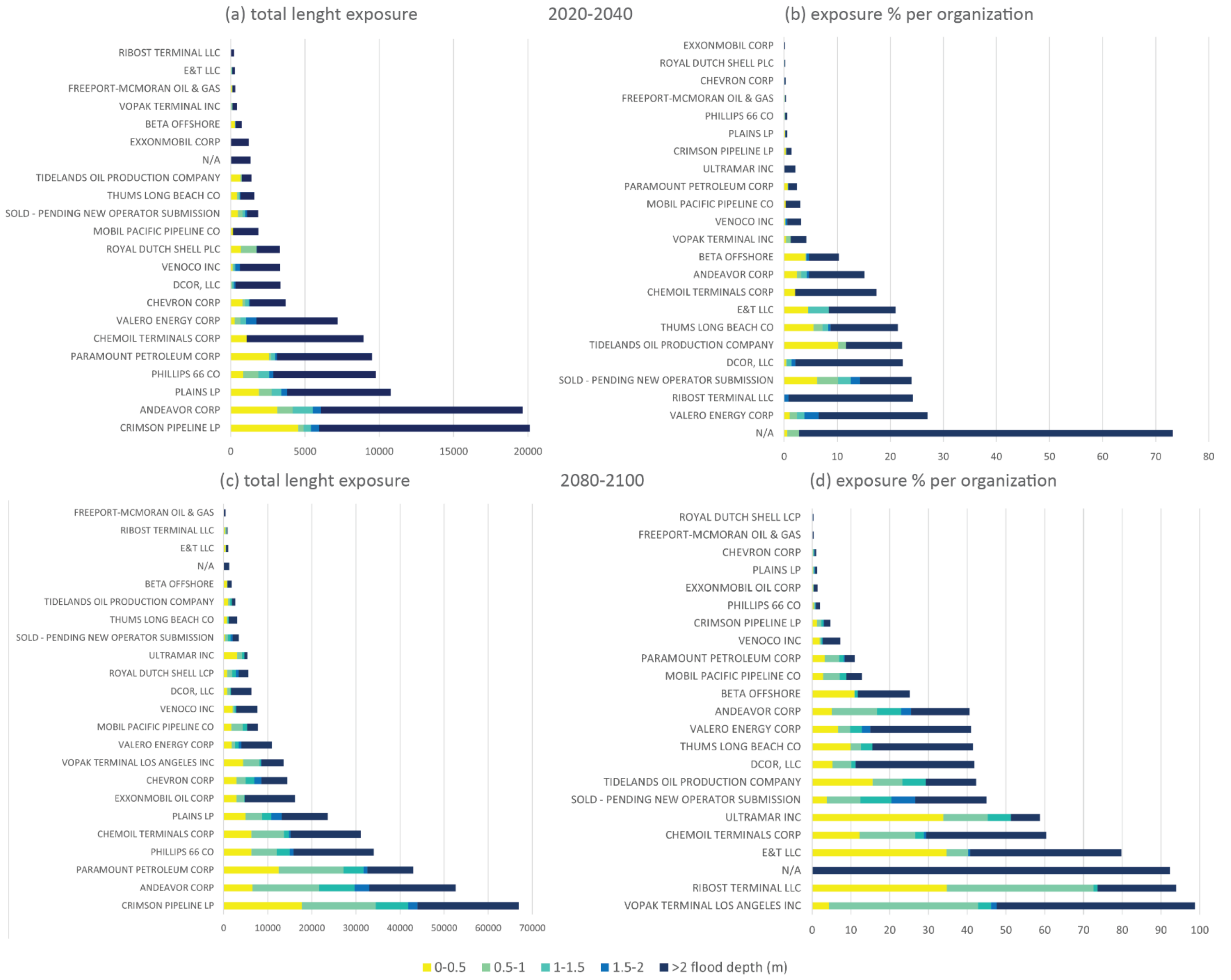


Figure 37. **Organizational exposure based on flood depth in the near-and -long-term: (a) and (c) total length of pipeline exposed in meters; (b) and (d) the percentage of flooded pipeline per organization.**

(b) Sociotechnical network exposure

By incorporating exposure metrics to the crude oil organizational network, we can improve our understanding of the TFS vulnerability as a sociotechnical system. Although here we only present the crude oil pipeline subset, we argue that this approach is especially relevant for CI systems like the TFS, which has fragmented governance and a complex web of owners and operators that lack system-level coordination. Identifying sociotechnical network exposure can present advantages for emergency response coordination, as well as for strategic decommission and adaptation measures in the context of energy transition and climate resilience.

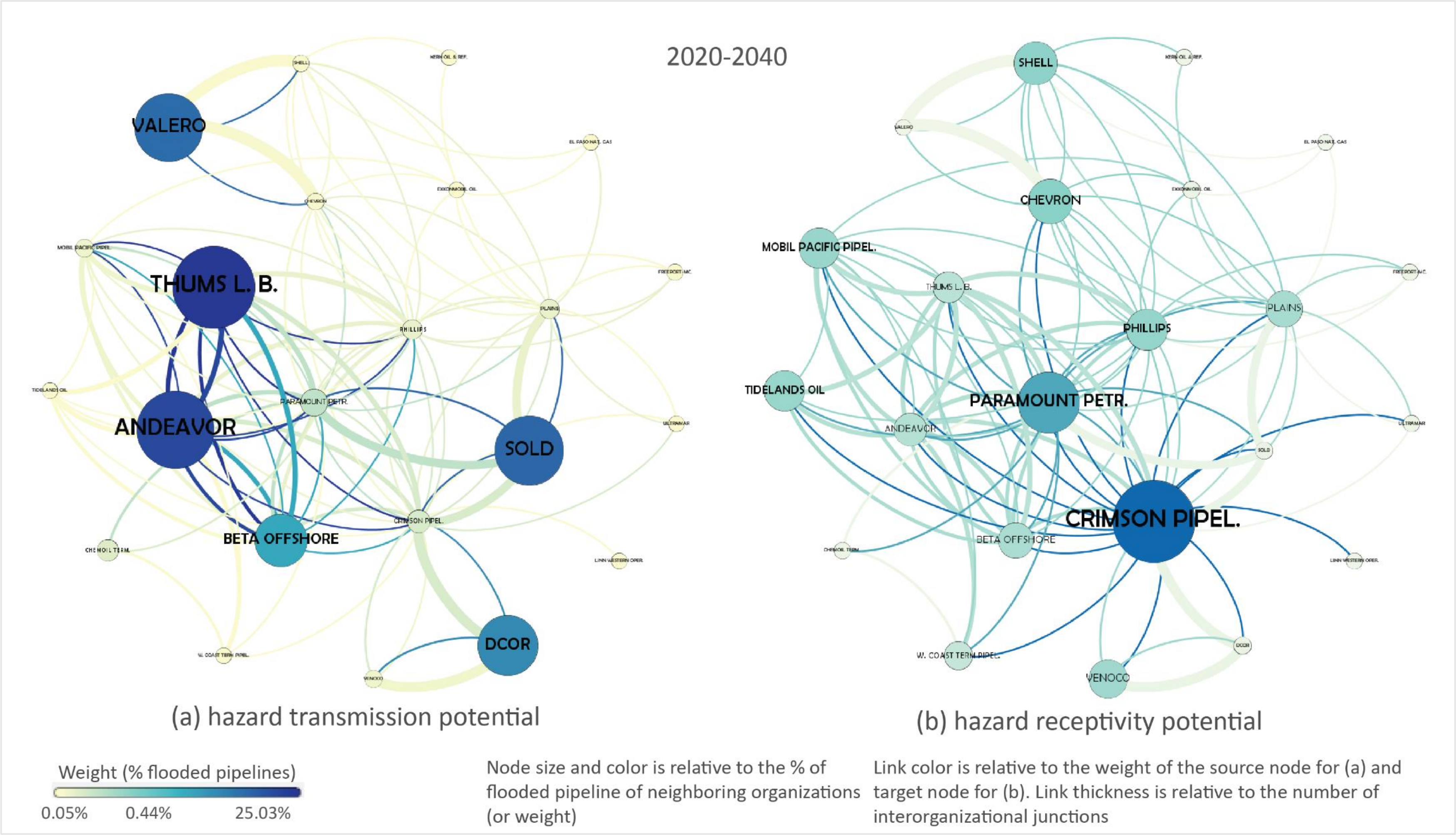
The sociotechnical network exposure of crude oil pipelines is presented in Figures 38 and 39. The nodes represent the 23 organizations that own or operate crude oil pipeline transects that are exposed to the near-and -long term coastal flooding. The nodes are weighted based on the percentage of flooded pipeline per organization which is visible based on node size and color. The links represent the number of times interorganizational junctions are flooded.

Out-degree centrality is applied to illustrate the potential of hazard transmission based on each organization's exposure and their first-degree relations; and in-degree centrality to illustrate the potential of hazard receptivity of each organization to the exposure of their first degree neighbors. The links are colored based on the % of flooded pipelines per organizations and their thickness reflects the number of connections to other organizations. By 2040 we identify 111, and by 2100 124 flooded interorganizational links with an average degree of 4.8 and 5.39 respectively.

The combination of these metrics is useful to identify the role each organization play at the network-level exposure to coastal flooding. The near-term exposure is especially useful for contingency planning and the long-term exposure for strategic decommission and adaptation measures. Nodes with high degree centrality (high transmission or receptivity potential) can be singled out as priority communities for increased transparency on coastal flooding risk management and improved coordination and collaboration. This increased transparency is key to start operationalizing distributive environmental justice, which is focused on improving the fair distribution of costs and benefits of climate adaptation. Examples include targeted participation in emergency fuel preparedness coalitions such as state collaborative platforms maintained and developed by the CEC and CalOES (Fuels Set Aside Program), the CSIWG, the State Lands Commission (CSLC) and the Office of Planning and Research (OPR). Another example would be targeted participation in platforms to facilitate public-private partnerships at the national level under the auspices of the National Plan for Critical Infrastructure Protection, i.e.: the oil and gas sector coordinating council (ONG SCC[296]) and the emergency services sector coordinating council (ES SCC[297]).

Differences between in-and out-degree centrality can help identifying which types of coordination should be envisioned when dealing with near-and long-term flood hazard scenarios. High receptivity organizations, such as Crimson, should have different operational and planning protocols to manage their heightened indirect exposure based on their reliance on a high number of organizations that have assets exposed to coastal flooding. Similarly, new responsibilities can be assigned to organizations with high transmission potential, such as Andeavor and Thumbs L.B., especially in relation to supply chain transparency and corporate environmental, social, and governance due diligence (ESG).

Current climate risk policies and guidelines remain restricted to direct exposure and siloed decision making at the single organization-level. The sociotechnical network exposure model helps identify new risk typologies beyond simple direct exposure of assets using topological and geographic space metrics. It becomes possible to refine policy to target decision-making stakeholders to further engage in climate risk governance. It also sheds light on the need of new modalities of interaction between decision-making stakeholders of CI which are difficult to identify in current infrastructure policy and jurisdiction regimes



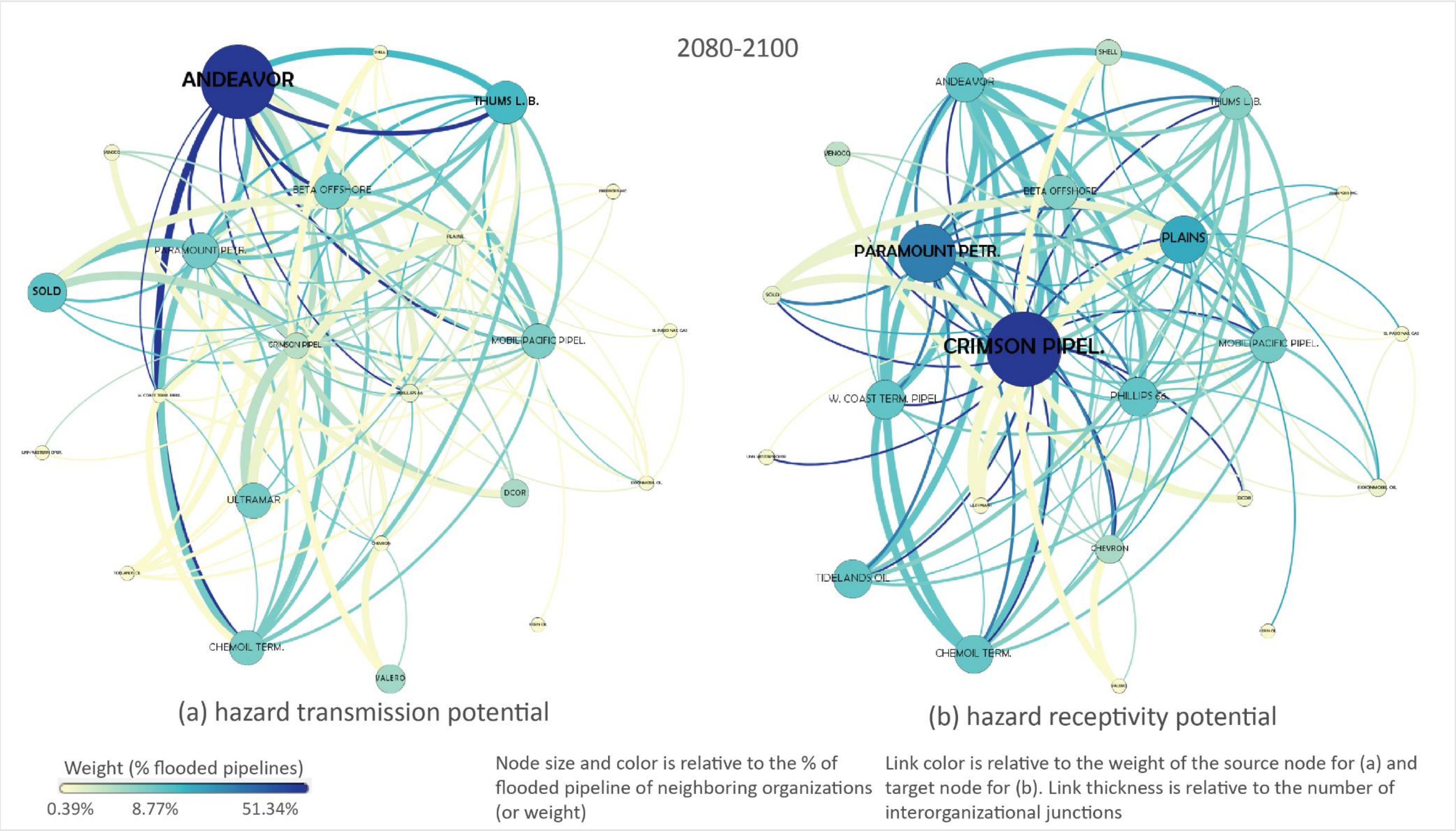
(a) hazard transmission potential

(b) hazard receptivity potential

Node size and color is relative to the % of flooded pipeline of neighboring organizations (or weight)

Link color is relative to the weight of the source node for (a) and target node for (b). Link thickness is relative to the number of interorganizational junctions

Figure 38. **Sociotechnical network exposure of the TFS crude oil pipeline subset based on median coastal flooding scenario of 2020-2040: (a) out-degree centrality; (b) in-degree centrality**



Node size and color is relative to the % of flooded pipeline of neighboring organizations (or weight)

Link color is relative to the weight of the source node for (a) and target node for (b). Link thickness is relative to the number of interorganizational junctions

Figure 39. **Sociotechnical network exposure of the TFS crude oil pipeline subset based on median coastal flooding scenario of 2080-2100: (a) out-degree centrality; (b) in-degree centrality**

5.4. Insights from Policy Stakeholder Networks and Multi-level Coalitions: Application to Airports

Insights from airport sociotechnical interlinks inferred from policy data point to different strategies to operationalize adaptation policy based on two analyses: (1) the network of airport stakeholders targeted in potential climate cognizant policy, and (2) multi-level coalitions in the context of coastal flooding exposure of airport facilities.

5.4.1. How airport governance affects adaptation policy operationalization?

Climate adaptation policy was pushed by formal or informal regional scientific networks and assessments in California [298]. There is a growing understanding of the importance of collaborative governance and coalition networks to design and implement transformative policies for public challenges, such as climate adaptation and infrastructure system resilience. Collaborative governance is understood as the “engagement of stakeholders in a collective decision-making process that is formal, consensus oriented and deliberative where participants co-produce goals and strategies and share responsibilities and resources” [277].

This section aims to enhance collaborative governance systems in designing and implementing airport climate adaptation policy. California airports can leverage from well-established coalition networks at local and state levels that share adaptation resources to increase local institutional capacity and community building for climate resilience. From these coalitions, airports can leverage successful strategies to develop regional partnerships between business and community leaders, non-profit organizations, and research institutions to reduce duplicate efforts in climate adaptation and gain from collective and diverse technical expertise while still preserving their regional identity. This resource is even more relevant for airports that have difficulties leveraging traditional technocentric funding sources for implementing alternative adaptation structural measures (i.e., nature-based and hybrid infrastructure) or non-structural adaptation measures (i.e., increase awareness, transform organizational culture and institutional values).

5.4.2. Airport policy stakeholder networks: towards collaborative adaptation governance at the U.S. level

Recent research in collaborative governance modes and social networks has developed insights on the positive effects of network coalitions on governance processes, outcomes of natural resource management, and sustainable development[157,199,205,299]. There is a growing interest in exploring how to improve governance of complex systems by improving the engagement between actors of policy design and of implementation who rely on each other’s contribution to operationalize science-policy[46,300]. Social network analysis has been applied to climate adaptation to understand the strength of relationships between formal organizations working on climate adaptation and on disaster risk to prescribe policy implementation and to improve collaborative outcomes in adaptation governance systems[43,49].

In this section we provide an exploratory policy stakeholder network assessment based on our review of FAA airport policies. This exploratory analysis uses principles of network science and basic statistical analysis and requires subsequent investigation. The analysis, however, allows us for the first time, to map the topological structure of airport policy stakeholders. Thus, we can understand who is formally being targeted to implement policies that have the potential of being updated to incorporate forward-looking climate science or can mainstream adaptation measures through organizational culture and institutional values (as developed in chapter 4).

Within the 77 potential climate-cognizant policies from FAA AC's, stakeholders were identified as those who were being targeted for implementing the policy in question. In this stakeholder policy network, the nodes represent the stakeholders being targeted in these 77 airport policies, and these stakeholders are linked when cited in the same policy. This network illustrates how potential climate-cognizant policy stakeholders relate to each other in formal regulation. The way this network is built implies that stakeholders share responsibilities for operationalizing similar policies and, therefore, have more potential to share resources, information, and knowledge to implement the policy in question.

The stakeholder policy network is composed of 91 nodes and 1,499 degrees (number of links), with an average degree of 32, which means that, on average, every stakeholder is cited with another stakeholder in a policy 32 times. The policy network presents a high average clustering coefficient of 0.81. This means that the probability that two random stakeholders are cited in the same policy is of 81%. The network diameter, or that the distance between the two furthest away nodes is three, meaning that policy stakeholders are separated by a maximum of three degrees of policies. Networks characterized by high clustering coefficient combined with a short diameter are known as efficient structures for network-level flow, or the transmission of information [85,114]. Although further statistical analysis is required to confirm these results, these initial metrics indicate that the formal structure in which airport stakeholders are set to implement policy can be efficient in sharing information, knowledge, and values.

This topological map of airport policy stakeholders can be used to better understand not only who can be targeted for implementing climate-cognizant policies but also how to optimize adaptation policy design by understanding policy stakeholder's interconnectivity patterns given the current national regulatory framework. Based on node centrality analysis, we can distinguish hubs (high centrality) from non-hubs (low centrality). The hubs, or top ten nodes with the highest number of links (degree centrality) include:

1. the FAA

2. airport operators
3. airlines and air carriers
4. airport senior management and government boards
5. metropolitan planning agencies
6. federal environmental agencies
7. tenants
8. the Department of Homeland Security
9. fire and rescue department units
10. state aviation agencies.

These policy stakeholders have a central role in articulating and leading the implementation of current policies that have the potential to be updated for a better integration of forward-looking climate science and adaptation pathways.

Another type of hub is one of nodes with high betweenness centrality, with a brokerage role of linking communities and sub-communities. Top ten nodes with high betweenness centrality include:

1. the FAA
2. airport operators
3. airport senior management and government boards
4. airlines and air carriers
5. airport engineers
6. airport sponsors
7. federal environmental agencies
8. metropolitan planning agencies
9. ground operations and airfield maintenance
10. airport owners.

Nodes with overlapping centrality metrics, or “super-hubs,” have an even more important role in mainstreaming airport adaptation policy updates because they potentially influence a higher number of stakeholders. Super-hubs act as a bridge with stakeholder clusters that are not so well connected with the entirety of the network. Airport policy stakeholder “super-hubs” are:

1. the FAA
2. airport operators
3. airport senior management and government boards
4. airlines and air carriers
5. metropolitan planning agencies
6. federal environmental agencies.

This topological map also helps identify stakeholders who are frequently co-targeted (solicited together) in potential climate-cognizant policies, which are highlighted with thicker links, such as airport engineers, designers, and contracting engineers and designers.

The non-hub nodes could represent policy stakeholders with peripheral roles in implementing climate adaptation policies given the current regulatory framework. This information is relevant since it might point to stakeholders that need a more central role in implementation adaptation measures and should therefore be more explicitly targeted in policies. The non-hub stakeholders with lowest degree centrality and lowest betweenness-centrality are:

- equipment manufacturing labs
- navigational aid technicians
- non-primary airports
- apron crews
- airport risk management office
- airport electrical and electronic engineers
- local development regulating agencies
- tenant supervisors
- pollution prevention team
- the National Response Center
- officers originating NOTAMs
- state transportation agencies
- state department of natural resources.

Figure 40 shows the partition of our policy stakeholder network into topological communities [283]. These communities represent policy stakeholder clusters that are more highly connected to each other than to the rest of the network. The modularity result is 0.215, optimized at a total of three communities [284]. The topological partition reflects stakeholder communities with the potential to implement climate-cognizant policies divided in: (1) traditional airport operators and regulators; (2) emergency management services; and (3) local governments. Traditional airport community (Figure 41) represents 46,15% of targeted stakeholders in FAA policies, emergency management services community (Figure 42) represent 28,57%, and local government community (Figure 43) represent 25.27%. This classification is based on the dominating role of most stakeholders.

Certain stakeholders, such as airport tenants, airport owners, airport senior management and government boards, and airport state agencies are categorized under the “emergency services” community but could also belong to the “traditional airport operators and regulators” community. Within current policy structure, these stakeholders are co-targeted more often in policies that are implemented by emergency services stakeholders.

Furthermore, most stakeholders with high centrality tend to hold multiple roles and can fit multiple topological communities.

Climate adaptation policy design can also be enhanced by further investigating the role of these actors within their communities and within the entirety of the policy stakeholder network. For instance, airport managers and operations supervisors have high degree centrality as well as high betweenness centrality specifically between traditional airport operators and regulators and emergency management services communities. Tenants also have a high degree centrality and a brokerage role between emergency management services and local government.

There are many assumptions and limitations to these network metrics when assessed from a purely quantitative perspective. This stakeholder map, however, is relevant if combined with empirical policy reconfiguration prospects to incorporate climate adaptation pathways and enhance the roles of certain stakeholders. For example, when updating policies addressing environmental management systems for airport sponsors (AC 150/5050-8) or land acquisition and relocation assistance (AC 150/5100-17) it might be useful to target stakeholders with high connectivity between local government, environmental planning agencies, and airport planners and sponsors. Further analysis can be developed to confirm the topological structure metrics, and better assess how the centrality metrics combined with community detection metrics can help optimize the roles of different airport policy stakeholders to implement technical or organizational climate adaptation measures. By mapping the topological structure of policy stakeholders, we can better understand who is being targeted for implementing potential climate adaptation policy, their interrelationship, their roles, and their communities so that collaborative governance can be explicitly supported and facilitated. Better understanding policy stakeholder networks can provide new roles of facilitating or managing networks with strategic direction to widen and deepen relationships producing effective outcomes for airport climate adaptation. Mapping climate adaptation policy stakeholders can also provide promising avenues to operationalize recognition and procedural environmental justice, which is concerned with the fair consideration of diverse perspectives and the legitimacy and fairness of who decides and participates in the decision-making process.

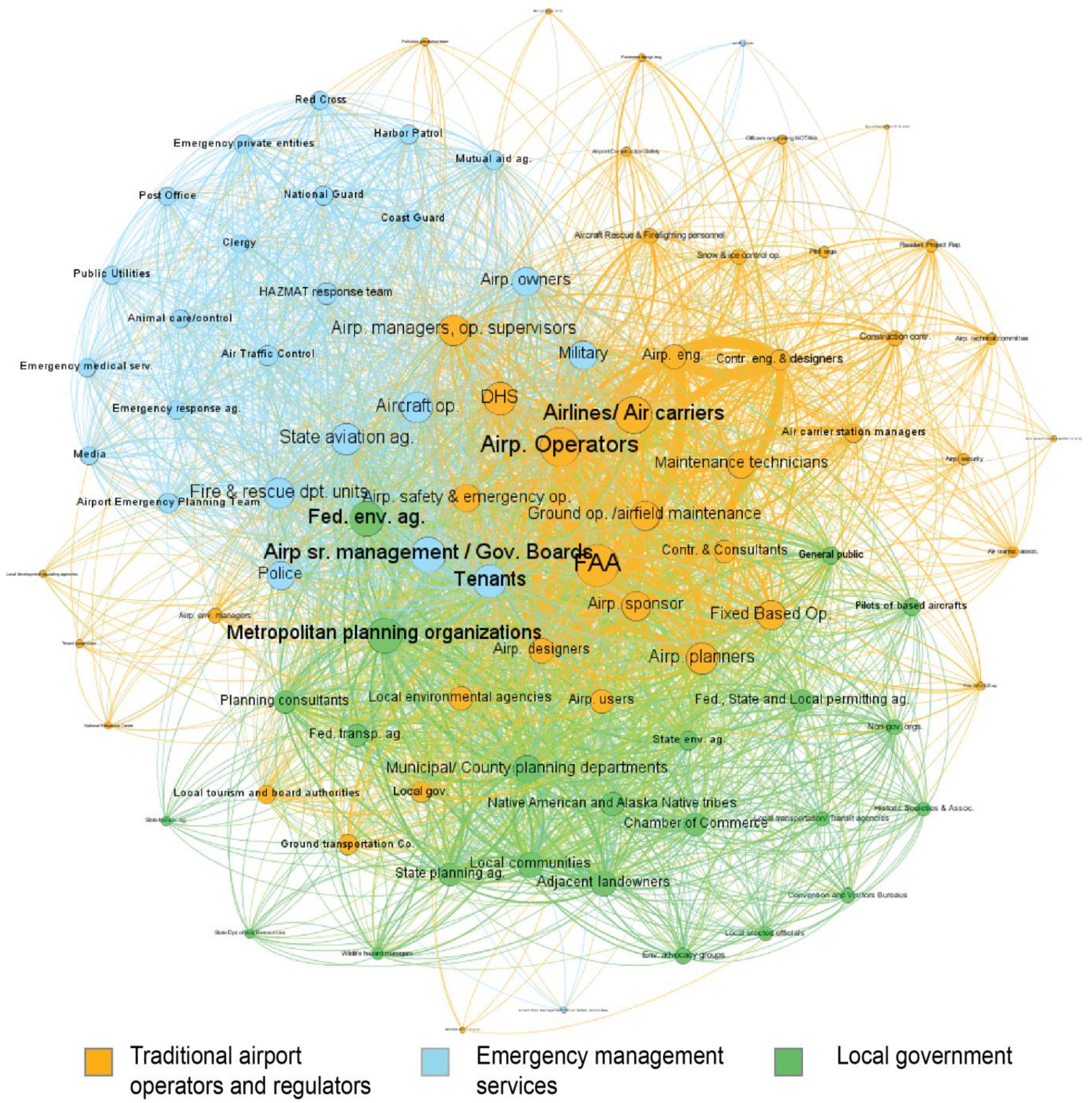


Figure 40. Airport stakeholder network with potential to implement climate-cognizant policy: full network

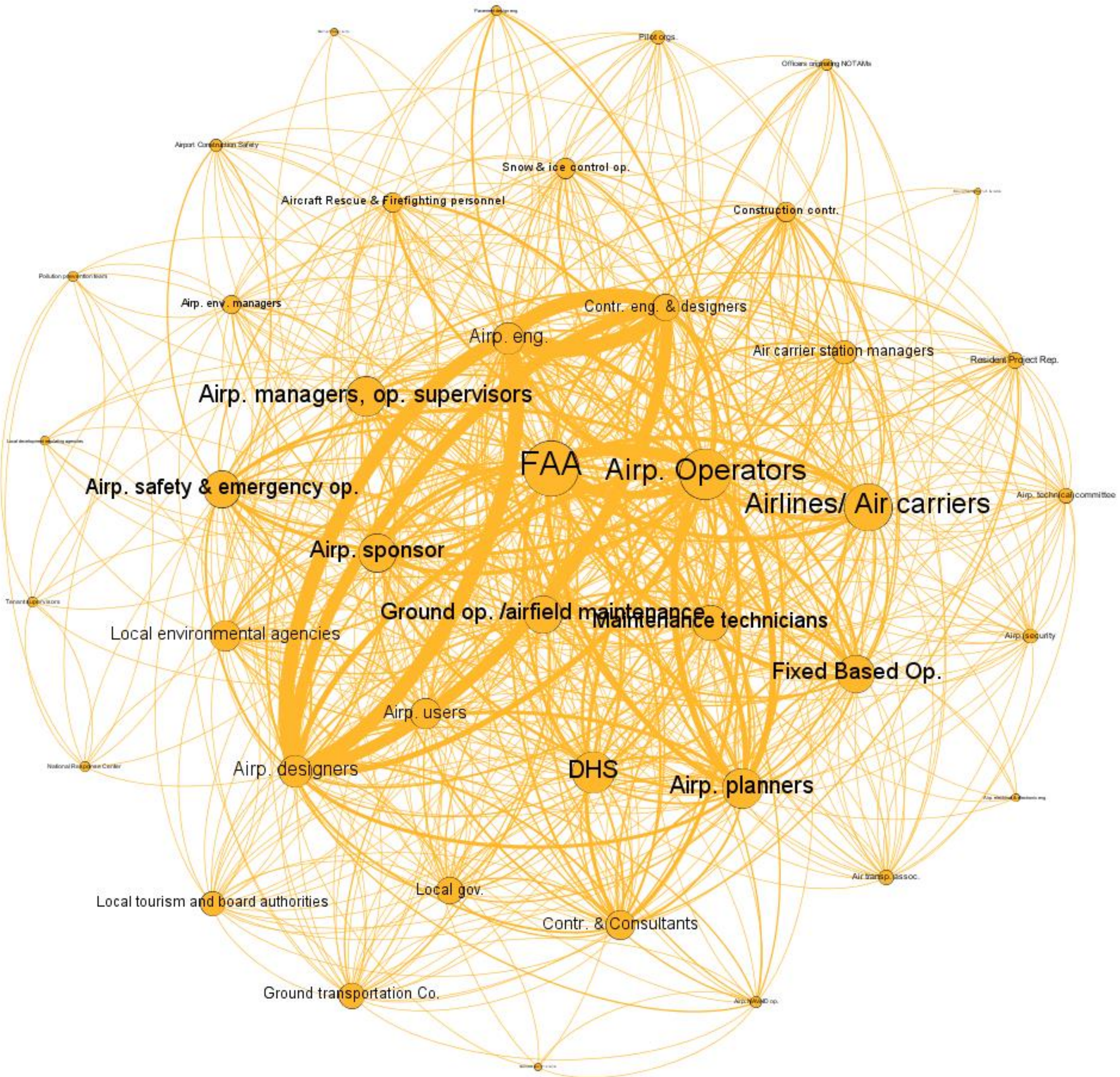


Figure 41. Policy stakeholder network: traditional airport operators and regulators topological community

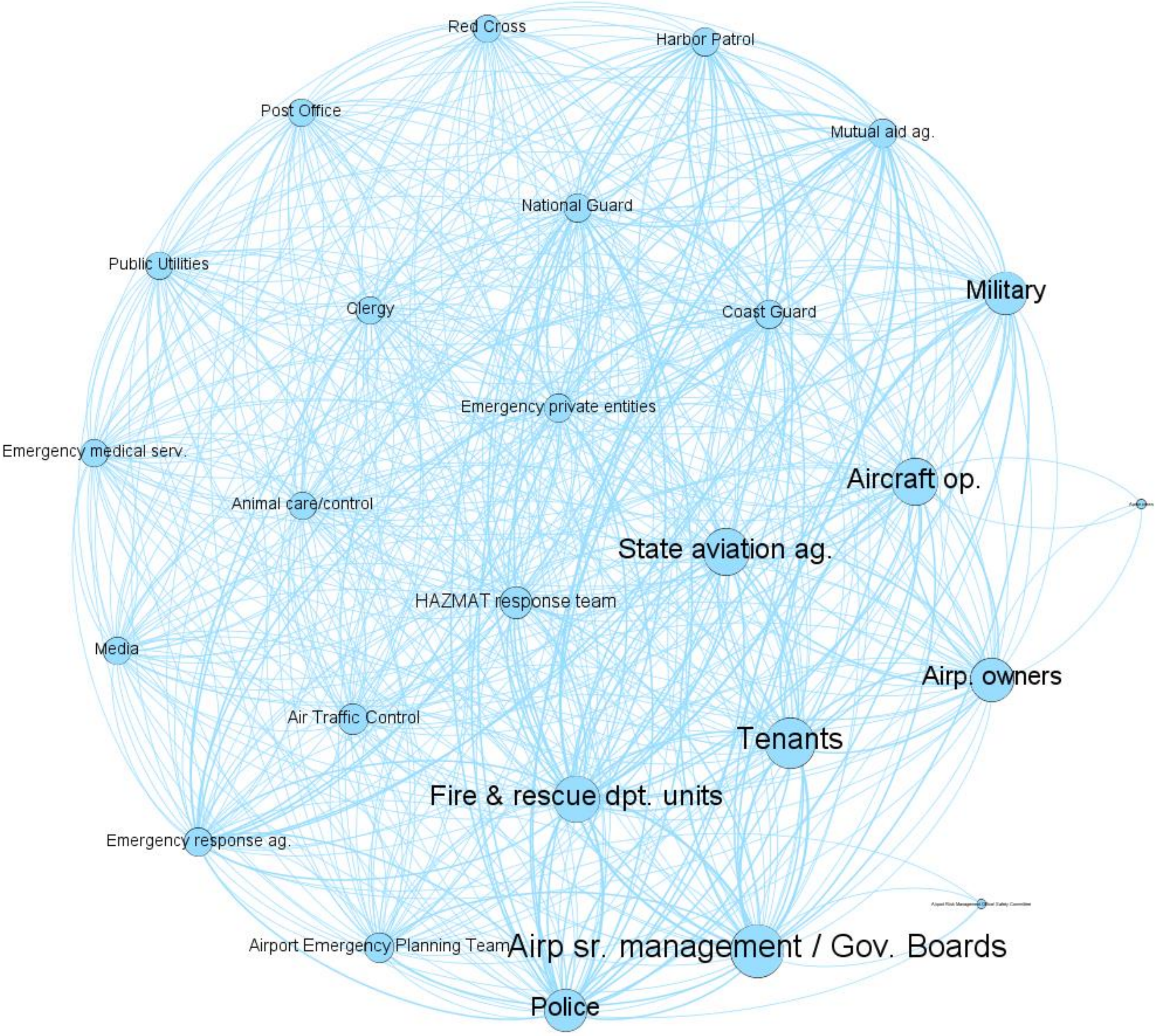


Figure 42. Policy stakeholder network: emergency management services topological community

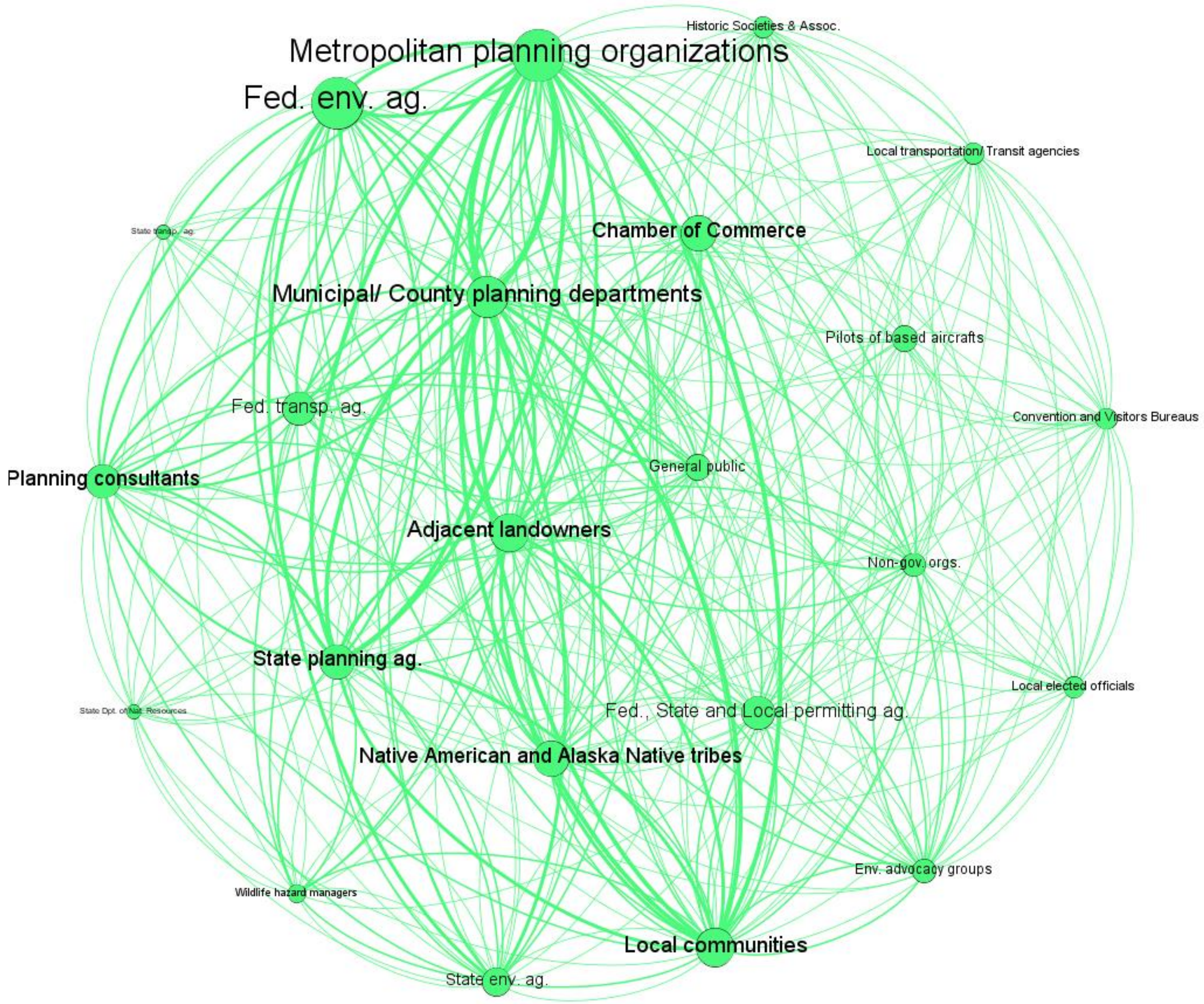


Figure 43. Policy stakeholder network: local government topological community

5.4.3. Multilevel coalition networks and airport adaptation policy stakeholders in the context of coastal flooding exposure in California

Because of the state's pioneering history in climate change research, progressive climate action, and growing legislature in climate adaptation, a significant relationship has been established between climate research and public policy implementation that can be leveraged to improve airport climate adaptation. Based on our policy review and interviews with California airport stakeholders, two main governance mechanisms promote airport climate adaptation policies at the California-level: (1) hierarchical incentives from environmental quality control and land use regulations and (2) collaborative incentives from outstanding climate adaptation coalition networks. These governance mechanisms are usually operationalized at the county or city level, for airports, and at the state transportation department levels. However, airport sector state adaptation policy presents a lag in relation to surface transportation policies. Airport planning documents have developed in isolation from multimodal transportation plans until recently. The latest California Aviation System Plan (CASP[301]) and the Interregional Transportation Strategic Plan (ITSP[302]) point to the necessity of better integrating the role of airports at the regional level. We illustrate how to leverage from existing coalitions by connecting airport and transportation communities emerging from state efforts reinforcing interregional corridors with strong climate adaptation coalitions at the state level. We then trace the interlinks between airport facility exposure to coastal flooding, and California-level coalition networks. Together with the policy stakeholders targeted to design and implement policy of exposed airport assets we point to potential new forms of collaboration for climate risk governance. The goal is to link airport-specific exposure data to potential stakeholder coalitions in the state and formal policy stakeholders.

(a) Exposure of airport facilities: focus on runways and associated equipment

Runways and taxiways are two of the most critical and costly facilities within airport's premises; a coastal flooding incident has the potential to stop airport operations. The 43 LLCA runway and taxiway area cover approximately 7.04 km^2, of which 1.33 km^2 are exposed by 2020-2040; 1.55 km2 are exposed by 2040-2060; 1.67 km2 are exposed by 2060-2080; and 1.86 km2 are exposed by 2080-2100. The average yearly rate at which newly exposed runway and taxiway areas increase is of 0.009 km2 in the near term; 0.007 km2 in the mid-term; and 0.0109 km2 in the long-term. Flood depth exposure is also increasing over time. In the near- term a total of 0.12 km2 of new runway and taxiways area are exposed areas to extreme flood depths (above 2 m), in the mid-term this area increases by 0.22 km2, and in the long term it increases by 0.45 km2 (Appendix D, Figure D.1.).

NAS facilities are critical enablers of airspace surveillance, weather monitoring, aircraft navigation, and airport ground operations. The NAS includes a large variety of navigational aid facilities such as approach light systems, radars, air traffic control tower, small portable generators, and glide slopes. Air transportation safety and reliability depend on the high performance of these facilities, which is why they are included as a major airport asset in this study.

Within the area 10 km inland of California's coastline there are a total of 681 NAS of which 105 are exposed by 2020-2040; 113 are exposed by 2040-2060; 137 are exposed by 2060-2080; and 166 are exposed by 2080-2100 (Appendix D, Figure D.1.). In the near-term an additional 8 NAS become newly exposed; in the mid-term this addition jumps to 24; and in the long-term there are 29 newly exposed NAS. The exposure of NAS to extreme flood depth increases over time, reaching 88 facilities exposed to extreme flood depth by the end of this century (Appendix D, Figure D.2.). Some of these NAS facilities exposed to extreme flood depths are commonly located near runways and taxiways[10].

(b) Linking exposure to potential coalition networks

Two multilevel coalition networks are considered: (1) at the transportation sector level, strategic interregional multimodal corridors, and (2) at the climate governance level, the Alliance of Regional Collaboratives for Climate Adaptation (ARCCA).

Eleven strategic interregional corridors are defined to connect the regions with the largest populations and those experiencing fastest growth, and to improve interregional investment strategies that better match interregional funding needs [303]. Implementing airport climate adaptation matching multimodal and interregional scales is of significant importance since the bulk of airport funding often prioritizes capital investments within airport boundaries [301]. CASP 2021 identifies a total of 29 commercial service and 91 priority general aviation airports belonging to the strategic corridors (all airports within 3.2 km of the corridors). Based on the ITSP definition these airports are "key to long distance trips that facilitate the movement of people and goods between two or more regions" and are "critical first and last mile connectors." [302].

More than half of California's LLCAs belong to these strategic corridors. Results show that 24 airports exposed to coastal flooding by 2100 belong to nine different interregional corridors. Figure 44 represents the strategic corridors, how public airports and LLCA overlay them, and LLCA airports that have runways & taxiways facilities exposed to coastal

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[10] Airport Lightning System (ALS), Automated Surface Observing System (ASOS), Airport Surveillance Radar (ASR), Automatic Terminal Information Service (ATIS), Automated Weather Observing System (AWOS), Distance Measuring Equipment (DME), Flight Data Input/Out[put Remote (FDIOR), Fiber Optics Transmission System (FOTS), Glide Slope (GS), Localizer (LOC), Medium Intensity Approach Lights (MALS), Medium intensity Approach System with Rail (MALSR), Inner Marker (IN), Outer Marker (OM), Precision Approach Path Indicator (PAPI), Power Conditioning System (PCS), Precision Runway Monitor (PRM), Remote Center Air/Ground Communication facility (RCAG), Radio Communication Link terminal (RCLT), Remote Communication Outlet (RCO), Remote Transmitter/Receiver (RTR), Standard Terminal Automation Replacement System (STARS), Engine Generators (SX), Terminal Voice Switch (TVS), Tower Building (TDWR), Voice Recorder System (VRS), and others. Among these facilities there are Air Traffic Control Towers (ATCT) of OAK and SQL Airports exposed starting at 2020-2040 and SBA Airport ATCT starting at 2080-2100.

flooding by 2100. Most of these airports have 50 to 100% of their runways and taxiways areas exposed to coastal flood hazards by the end of the century.

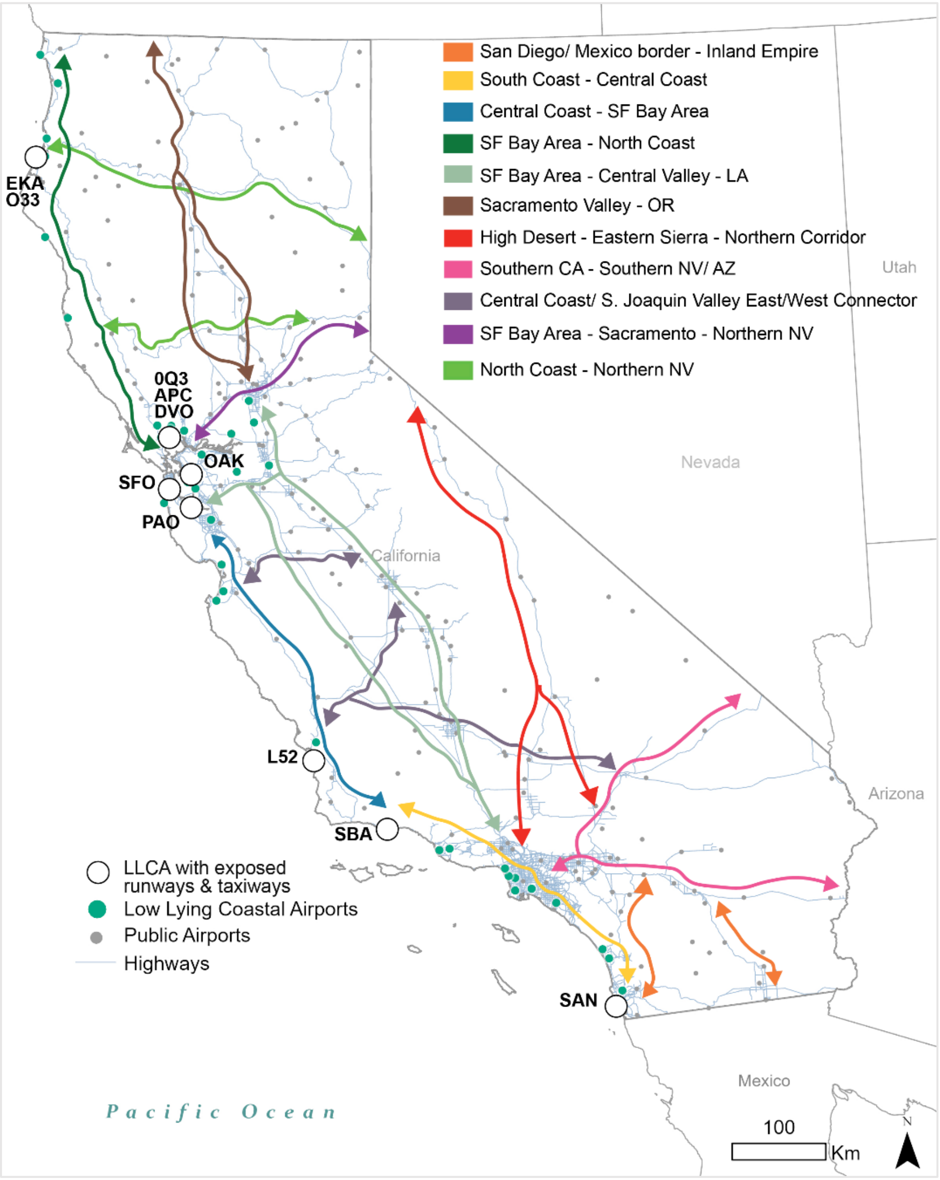

Figure 44. Interregional transportation Corridors and LLCA with exposed runways and taxiways by 2100.

The Alliance of Regional Collaboratives for Climate Adaptation (ARCCA) is a relevant state-level coalition of regional networks supported by the Local Government Commission, integrating the Office of Planning and Research, and participating in the state's climate assessment and influencing legislature. Its main function is to connect leaders advancing policies and implementing solutions related to climate resilience through the creation of programs to share best practices and resources for individual actors and collective efforts.

Some of these tools are geared towards organizational behavior, stakeholder network strategies, and institutional capability to pursue climate adaptation initiatives more effectively through governance. ARCCA encompasses seven regional coalitions more focused on local resources and partnerships for environmental resource management, sustainability, and climate adaptation described in Figure 45.

In Figure 45 we use relative runway and coastal flooding exposure data to link specific airports to associated interregional corridors and potential climate adaptation coalitions from ARCCA. The relative runway exposure is calculated based on the percentage of flooded area in relation to the total flooded runways of the state by 2100 and weighted based on airport passenger enplanement in 2018. This analysis helps tailor coalition membership based on measured exposure of critical airport assets, thus providing methods to improve the efficacy of governance networks in the specific context of coastal flooding hazards. BayCAN coalition presents the highest potential to address a higher relative exposure of airport facilities, as evidenced by the higher number of airports exposed in the San Francisco Bay Area. Less evident but relevant result is the central role of LARC coalition in improving adaptation, since it harbors no airport with runway exposure, however it belongs to multiple interregional networks who do harbor airports with extreme exposure such as SF Bay – Central Valley – LA; Southern Coast – Central Coast, and San Diego/Mexico-Inland Empire corridors.

Although this is an exploratory result considering the uncertainties on the hazard metric for airport risk assessment (see section 5.2.5.c.), it provides an applied example of how mapping the interlinks between decision-making stakeholders and hazardous processes "footprint" can improve climate risk governance and operationalize distributive environmental justice. In this case collaborative governance enhancement is focused on linking traditional transportation planning stakeholders and local and regional organizations responsible for the operationalization of airport or climate adaptation policies in California. The operationalization of distributive environmental justice can be further developed by identifying specific stakeholders that have more responsibility in coastal flooding risk management and transparency to avoid or dimmish potential impact at the regional scale.

The participation in such collations often improves access to climate adaptation and resilience grants being managed by state agencies such as the California Natural Resource Agency (CNRA), California Office of Emergency Services (CalOES), California Air Resource Board(CARB) , OPR, Strategic Growth Council, Ocean Protection Council (OPC), State Coastal Conservancy (SCC), California Infrastructure Development Bank, Department of Water Resources (DWR) , California Coastal Conservancy (CCC) and others. Airports located in any of these jurisdictions can benefit from integrating these collaborative efforts as has SAN airport, which has been highly active in the San Diego Regional Collaborative.

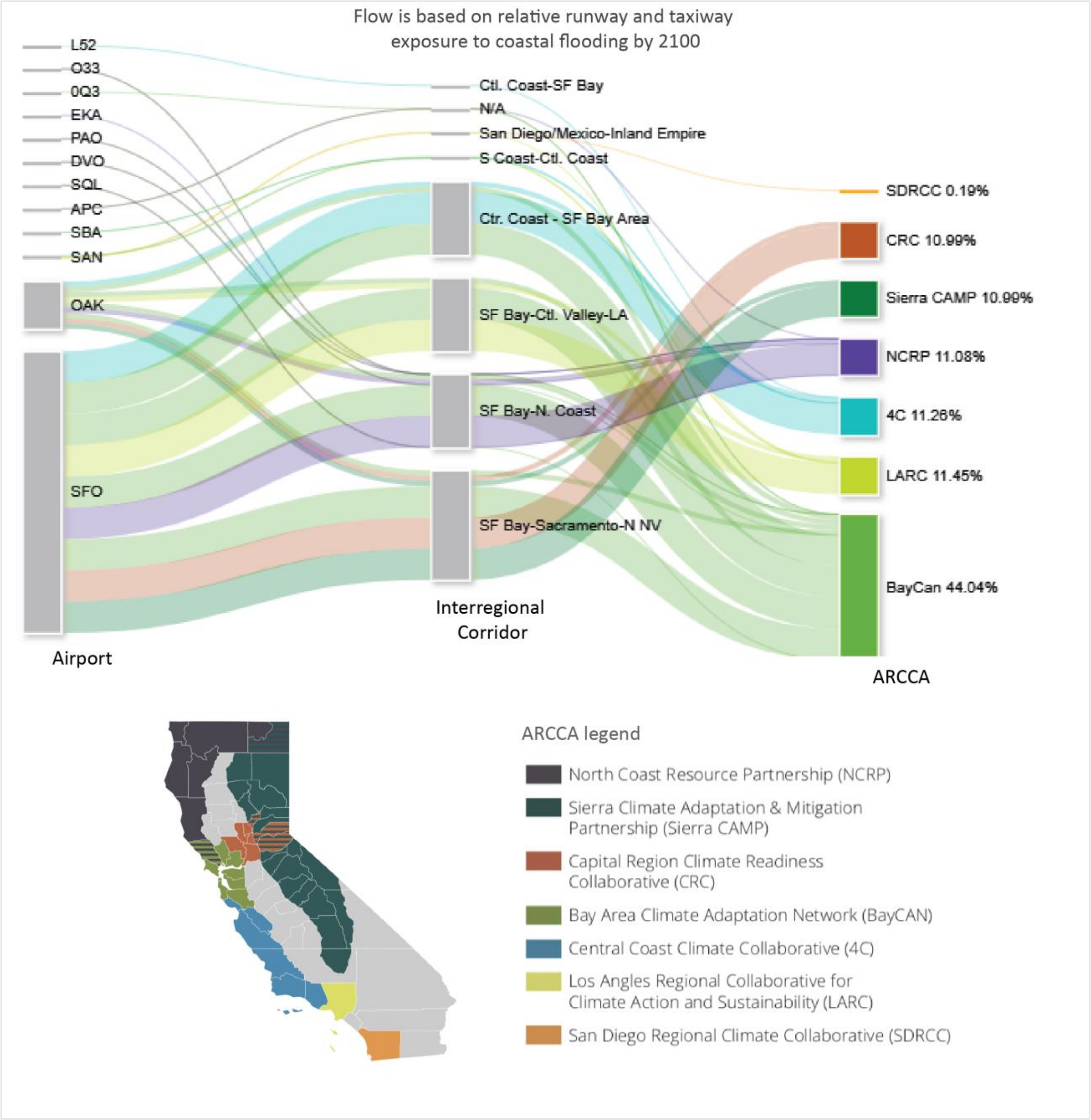

Figure 45. Airport runway coastal flooding exposure "flow" to transportation planning and adaptation coalitions in California

(c) Targeting potential climate-cognizant stakeholder communities

Finally, we retrieve from our airport policy review all stakeholder targeted for designing and implementing technical PCCPs associated with runways and taxiways facilities and equipment. Figure 46 identifies 24 of these stakeholders, where "Airport designers" present the highest number of mentions across the 129 ACs. Figure 47 focuses on Airport designer's co-occurrence in national airport policy to further identify which policy communities and specific stakeholders can be targeted for deeper involvement in adaptation implementation that is specific to runways and taxiways facilities.

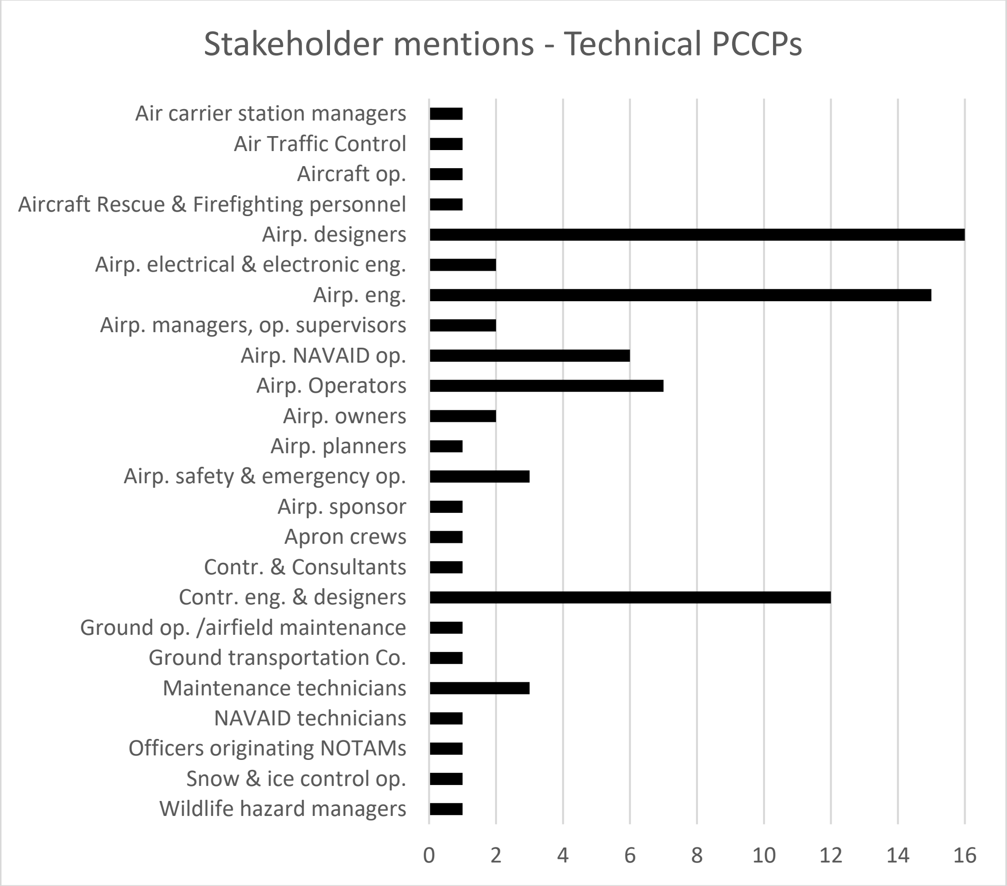

Figure 46. Count of stakeholder mentioned in technical PCCPs associated with runway & taxiways facilities and equipment's

Results in Figure 47 helps identify other stakeholders that have a latent potential to operationalize adaptation policy emerging from local coalition networks identified in our California example. Attention to policy community can help ensure diversification of inputs in policy decision-making and implementation. Attention to node degree can help target specific stakeholder hubs with higher potential for coordinating policy implementation with a higher number of stakeholders and at different communities. At this level we seek to further understand sociotechnical interlinks at the policy design level, identifying PCCPs airport policy stakeholders responsible for operating, maintaining, and managing specific assets for which exposure can be measured. Mapping these policy stakeholder networks is essential to build on existing social structures to advance climate adaptation policy implementation in complex infrastructure systems such as airports. This analysis points to active cross-community interactions that can be fostered to expand and intensify existing relations in areas where climate adaptation is needed across sectors and regions.

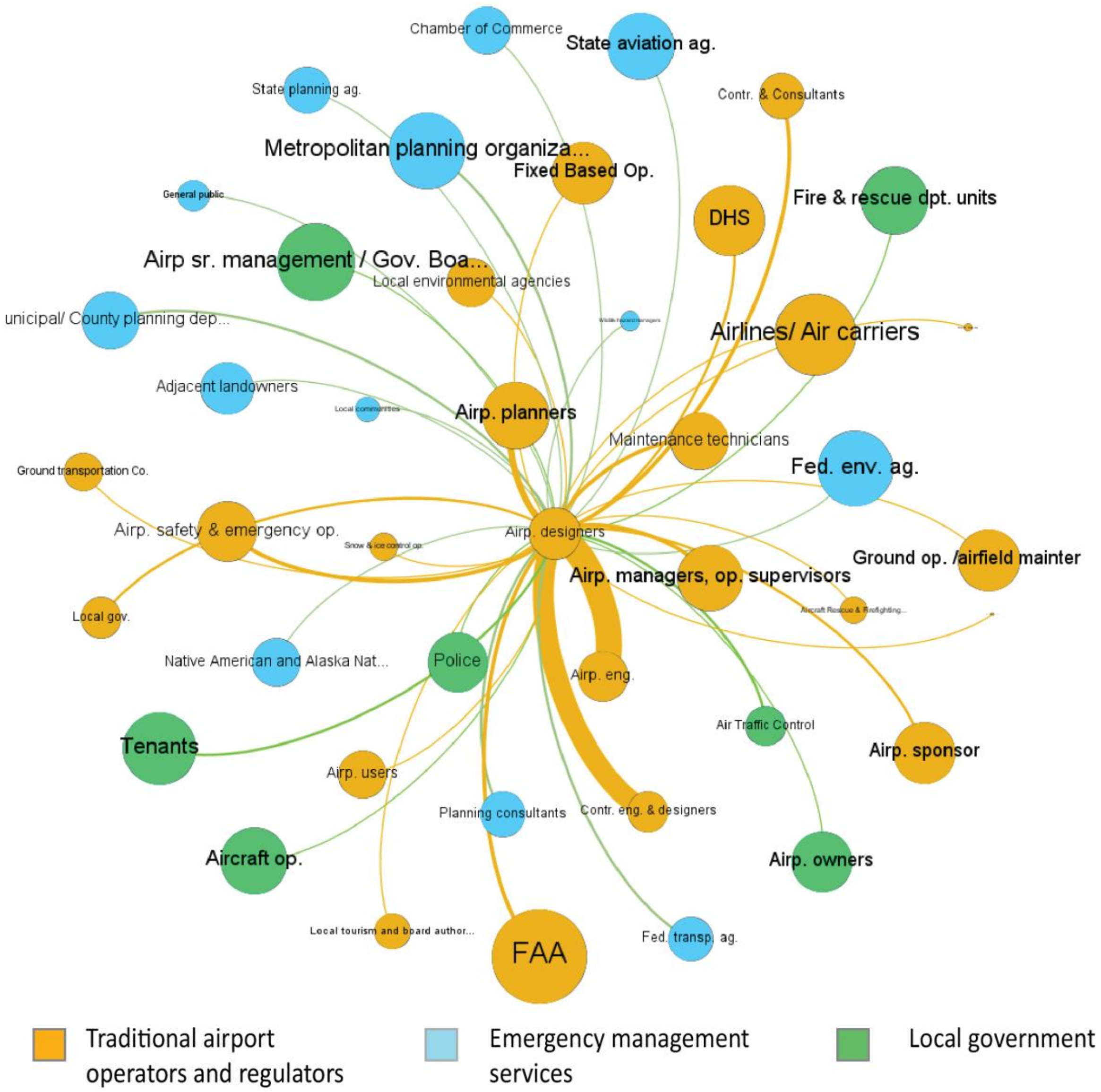

Figure 47. Airport designers' direct connection with other PCCPs targeted stakeholders. Node size reflect the number of co-occurrences within the full policy stakeholder network. Node color reflect the stakeholder community.

5.5. Conclusions

Governance of CI for DRR and climate adaptation is inherently challenged by the interconnected nature of social entities that have decision-making power over complex physical networks and their dynamic interactions with landscape hazards. However, responses to CI climate risk often omit the interconnectedness of social entities with decision making power and the physical infrastructure network under their jurisdiction (sociotechnical interlinks). The result is a scale mismatch between CI climate risk governance. This mismatch can have an unintentional effect of solving a problem for one stakeholder or sector, or at one particular scale that may reinforce or create new problems for another stakeholder or sector at another scale.

In this chapter we develop exploratory approaches to map sociotechnical complexity using geospatial and policy data. Harnessing from our in-depth analysis of the TFS and airports as complex social, technical, and environmental systems (chapters 3 and 4), we combine geographic and topological proximity metrics to measure exposure to climate hazards. Our innovation lies in the data sources used to build networks of infrastructure decision-making entities that retain their geospatial information, which in turn allows for the incorporation of climate exposure metrics. We argue our methods are valuable for revealing underlying and often forgotten social dimensions of infrastructure systems. Better understanding these social dimensions are key to improve network-level vulnerability awareness, identify the roles of different stakeholders, and to accordingly develop system-level coordination and collective-action for emergency response and adaptation plans.

Pragmatically, the results of the TFS sociotechnical network exposure point to key stakeholders which should be targeted for collective-action in the context of coastal flooding given their central role in the network. It also points to new risk typologies based on the organization's propensity to transmit or receive risk given their reliance on other organization who are exposed. Understanding these roles at the organizational network level can increase supply chain risk transparency and promote more effective risk management and adaptation practices for complex systems. Mapping these new roles for organizations at the network level based on exposure metrics also provides avenues for operationalizing distributive environmental justice by targeting organizations with higher hazard transmission potential for increased transparency in coastal flood management practices for example.

The topological map of airport policy stakeholders' information can be used to better understand not only who can be targeted for implementing climate-cognizant policies but also how to optimize adaptation policy design by understanding policy stakeholder's interconnectivity patterns given the current national regulatory framework. By mapping the topological structure of policy stakeholders, we identify different roles based on their centrality and community. Airport policy stakeholder hubs have a key role in articulating and leading the design and implementation of climate adaptation policies. Three topological communities with the potential to implement climate cognizant policies are found: (1) traditional airport operators and regulators; (2) emergency management services; and (3) local governments. We find that the formal structure in which airport stakeholders are set to implement policy can be efficient in sharing information, knowledge, and values, and can therefore be leveraged to deliberatively facilitate collaborative governance for airport climate adaptation. Mapping climate adaptation policy stakeholders can also be used to operationalize recognition and procedural environmental justice, where it becomes possible to identify the extent and diversity of players behind decision-making processes, as well as their central or peripheral role in the network.

Finally, by linking the coastal flooding exposure of airport runway facilities and associated equipment to potential coalition networks, we can improve the efficacy of collaborative adaptation governance across sectors and regions in California. In this case, collaborative governance enhancement is focused on linking traditional transportation planning stakeholders participating in interregional multimodal transportation corridors and local and regional organizations responsible for the operationalization adaptation policies in California such as ARCCA. This information is interpreted together with a subset of the airport PCCP stakeholder networks to point to potential new forms of collaboration across local and national level policy stakeholders for airport climate adaptation governance.

These results are exploratory, but the methods provide a promising approach to address scale mismatch, reduce maladaptation, and operationalize different normative dimensions of environmental justice. We argue an underlying contribution of this approach is providing empirical and conceptual methods to expand ways in which we define different types of climate risk governance stakeholders. This approach can be expanded to improve our understanding of who is regarded as vulnerable and at risk; to increase transparency on who is included in decision-making processes; and eventually who pays and benefits from adaptation measures. While our methods systemically link decision-making power to technical assets and landscape processes based on GIS and policy data, there is much room to qualitatively improve our understanding of these links based on different typologies and degrees of power in decision-making.

Chapter 6. General Conclusion

The highly-coupled human-natural systems and unprecedented rates of change, characteristic of our anthropogenically-driven climate change crisis, urges us to move from short-term, single sector, compartmentalized, and reactive practices to iteratively address the conditions and systems at the root cause of vulnerabilities. The effective governance of climate risk is ever more dependent on systemic, integrated, and deliberatively inclusive approaches. However, governance of infrastructure systems for disaster risk reduction and climate adaptation is inherently challenged by the interconnected nature of social entities that have decision-making power over complex physical networks and their dynamic interactions with landscape hazards. Climate risk policy often omits the networked scale of human exposure related to our dependence on critical infrastructure systems and infrastructure policy often omits the interconnectedness of social entities with decision making power over their physical assets. The result is a temporal and spatial scale mismatch between governance and landscape processes, which can have an unintentional effect of solving a problem for one stakeholder or sector, or at one scale, and may reinforce or create new problems for another stakeholder or sector at another scale.

A paradigm shift is therefore needed in environmental planning practices to move from threshold-based to transformational and inclusive process-based policies that proactively respond to these challenges of scale mismatch and maladaptation. This dissertation hypothesizes that a better understanding of the links between decision-making power and landscape processes related to climate hazards is an important next step to move towards transformational and inclusive process-based policies. Understanding these links is also key to advancing complex systems governance given our limited capacity of implementing climate policies that incorporate networked dimensions of infrastructure systems and difficulties of co-creating knowledge through the increased interaction of diverse decision-making stakeholders.

Two case studies are proposed to help us better understand the links between decision-making and landscape processes: the transportation fuel (TFS) and airport infrastructure systems. Our approach frames these two sets of critical infrastructure as technical, social, and environmental systems. The framework developed here is pertinent to address these scale mismatch issues inherent to landscape systems and infrastructure networks and can be generalized to other complex sociotechnical systems. Our approach draws from political ecology, disaster risk reduction, and complexity science theory to better address socioenvironmental and collective-action problems that are often characterized as wicked messes. From a science-policy standpoint, we provide in-depth information about the vulnerabilities of these two sectors, while also developing insights on how to benchmark, monitor, and improve climate-cognizant policy, taking into consideration collaborative governance.

This dissertation traces theoretical baselines to frame critical infrastructure as sociotechnical and socioenvironmental systems in chapter 2, which based on a literature review, points to different ways disaster risk theory and complexity sciences can complementarily address major gaps of critical infrastructure climate risk governance. Chapter 3 presents the TFS case study drawing from the sociotechnical and socioenvironmental framework. This framework helps reveal critical gaps in climate risk policies that point to important lessons we need to carry from the contemporary TFS to transition into a more resilient future TFS. Chapter 4 draws from the sociotechnical system framework to identify barriers in the national-level airport policies that are counterproductive with infrastructure climate adaptation guidelines. In this chapter we contribute by developing a method to review policy for the incorporation of climate-cognizant practices. It also provides pathways to address these barriers which would enhance airport climate adaptation governance. Chapter 5 converges the in-depth analysis of our two case studies to develop innovative methods using GIS, coastal flooding models, network science, policy data, and interview data; to model the TFS and airports as sociotechnical and socioenvironmental systems. The results reveal applied insights to enhance climate adaptation governance of these complex infrastructure systems in California. More detailed contributions of each of these chapters as well as future research directions are synthesized below.

In chapter 2 we lay our theoretical foundations arguing that critical infrastructure (CI) functions and spatial boundaries are implicit premises which can often result in misalignments between CI resilience goals and their societal utility. We illustrate how the historical legacy and institutionalization of CI, powered by national security issues, has resulted in technocentric approaches of infrastructure systems that can be counterproductive to disaster risk reduction. Rethinking concepts of infrastructure network criticality quantitatively and qualitatively is a necessary step to address this misalignment and to apply the current paradigm shift which defines CI, beyond hardware, as sociotechnical and socioecological systems. Rethinking these concepts of criticality requires a reexamination of infrastructure networks functions and spatial boundaries. We then harness complementary approaches to CI resilience within two large and sometimes disconnected bodies of literature: complexity science and disaster risk theory. Complexity science has significantly advanced quantitative definitions of infrastructure criticality by modeling interconnectivity and extracting network level metrics of vulnerability and resilience. At a conceptual level, complexity sciences further revolutionized our understanding of CI as complex adaptive systems through the idea of ecological resilience and panarchical cycles of stasis and change. We note that nevertheless, the application of ecological resilience to CI risk management still struggles to recognize and assess sociotechnical functions of complex systems, for which disaster risk theory has a latent potential to address, notably within concepts of social construct of risk and the vulnerability paradigm. This chapter provides a theoretical bridge that helps realign infrastructure network criticality with CI services and ecological resilience goals. On a practical level, we converge contributions from multiple fields and provide direction for assessing sociotechnical network exposure to climate change threats and identifying network-level organizational stakeholders to support CI collaborative risk governance. More specifically, we underline that dialectic approaches to risk, bridging the DRR vulnerability paradigm to include the sociotechnical approach to CI which is key to better align infrastructure network criticality to their societal utility. Theories of social construct of risk, are incipient in the current paradigm shift of CI as sociotechnical and socioecological systems, and necessary to better describe their complexity from qualitative and quantitative perspectives. The definition of functions and spatial boundary are less controversially addressed from the technical and ecological side, thus revisiting criticality perspectives of CI network infrastructures begs a better incorporation from theories derived from a social construct of risk. They have a latent potential to better inform complex system theories how to incorporate and interpret social dimensions of CI models (i.e., organizational networks and governance structures), that are equipped to leverage or at the very least, expose trade-offs depending on “whose system” is being considered; who are the stakeholders managing, planning, and designing CI resilience; and what is their agency in alleviating collective action problems. CI as sociotechnical and socioecological systems must fulfill socially valued functions. Therefore, theories of social construct of risk can help expose shortcomings of CI resilience approaches that lack articulation of shared risk (i.e., Perrow’s third and fourth level victims) or lack iterative examinations of CI services based on changing climate landscapes. Once we better address the question of “whose system” is being considered for CI resilience, new questions will need to be addressed on how to enhance collaborative governance among sociotechnical and socioecological systems to plan for and adapt to changing climate risk landscapes.

In chapter 3 we present the contemporary TFS case study. The TFS, which predominantly relies on the fossil-fuel sector, is not only the major cause of the climate change crisis, but as a CI, it is also behind the potential for climate-induced hazards to cascade into major disasters. While the TFS is at the crux of climate mitigation and adaptation problems, few efforts are seen in integrating energy transition policy goals, strategic decommissioning of the vital energy services provided by the current TFS, and adaptation needed for the transient and future TFS. In this chapter we argue that failure to frame the TFS as both source and effect of climate-induced disasters will result in siloed climate resilience policies that focus on the energy transition process without considering the TFS vulnerabilities beyond carbon-emission and non-renewable technological fallacies. Based on CI resilience, disaster risk reduction, supply chain sustainability, and energy policy literature, this chapter sheds light on what can be learned from the contemporary TFS fallacies so that we can avoid perpetuating known vulnerabilities in the future TFS. We define five unique traits that help contextualize the wicked mess of the TFS climate risk governance: unprecedented transition; complex and widespread interdependencies; hazardous materials; complex organizational networks; and path-dependency. Emblematic TFS-related disasters in the U.S., and the projected impact of climate hazards to the fuel sector in California help illustrate these unique characteristics, underscoring the recurrent challenge to organizational network complexity and derived fragmented governance. The TFS is then framed as a social, technical, and environmental system to better understand the shared states between organizational networks, physical infrastructure networks, and landscape hazards. Policy directions for improved resilience of transient and future TFS need to better address these core vulnerabilities of the contemporary TFS and explore collective organizational scales of CI. We end by providing guidelines on mapping sociotechnical network exposure to climate-related hazards, which can promote complex system governance necessary to advance socioeconomic goals of decarbonization policies. Overall, if we fail to critically assess the fallacies of the contemporary TFS in its ability to provide energy services, then the technology push for renewables and low-carbon economies will provide a partial and unacceptable solution to the TFS climate resilience wicked mess. This partial solution risks deepening environmental and energy injustice due to a general oversight of the TFS social, technological, and environmental interlinks. In this chapter, we shed light on known vulnerabilities of the current TFS, notably vulnerabilities that have surfaced under ever more frequent and severe climate-induced disasters. We hope that the opportunity of planning for transient and future fuel systems considers these known vulnerabilities which would go hand in hand with socioeconomic goals of the energy transition. From a research perspective, there is a pressing need to improve knowledge exchange between experts of the contemporary TFS with its consumer needs (especially for emergency services) and key stakeholders of energy transition policy design and technology deployment without forgetting to incorporate lessons learned from cascading TFS-related disasters such as Hurricanes Maria and Sandy among others. Given the recurring theme of organizational complexity and fragmented governance barriers, we propose that next steps in designing a future more resilient TFS take into consideration the importance of understanding sociotechnical and socioenvironmental interlinks of CI.

Chapter 4 presents the airport case study. Based on a review of over 200 policy documents, this chapter benchmarks for the first time, the current airport climate adaptation regime in the United States and applies a sociotechnical system framework to scrutinize institutional capacity to address climate change impacts. We design an innovative policy review system to decode how airport policies create conditions to use climate data as decision-relevant information and produce adaptation actions. Potential climate-cognizant policies are identified and characterized based on their target, timescale, governance mode, and stakeholders. Review results show that the assumption of climate stationarity is widespread. However, there is high potential for technical and, especially, organizational airport policies to incorporate climate science and adaptation pathways. Results also uncover governance barriers related to institutional path-dependence that include: (1) conflicting rationales between adaptation and reliability values, and (2) overpowering technical policies and market governance. We argue these barriers perpetuate scale-mismatch between airport policies and expected impacts from climate change. Finally, we highlight the latent capacity for collaborative governance to advance adaptation regimes in airports and other multiscalar complex infrastructure systems. Our proposed methods and review results identify pathways to enhance institutional capacity for designing and operationalizing transformative adaptation policies. Overall, this chapter brings forth the importance of investigating institutional path-dependence for planners and managers of long-lived and complex infrastructure. Future research on institutional path-dependence can benefit from integrating longitudinal studies over long periods of time to historicize organizational values and culture. Similarly, it is important to understand what types of institutional frameworks encourage path- dependence. Deeper spatial investigation could benefit from integrating exposure of technical assets to different climate hazards and optimize collaboration governance for organizations sharing similar risk scenarios. Finally, more research is needed to assess the behavior of coalition networks in collaborative governance systems; the cost of forming, monitoring, and facilitating collaboration; and how collaborative outcomes impact adaptation goals.

In chapter 5 we use empirical data to study the TFS and airport exposure to current and projected coastal flooding in California. Exploratory methods are developed to map sociotechnical complexity using geospatial and policy data. Based on our in-depth analysis of the TFS and airports as complex social, technical, and environmental systems, we combine geographic and topological proximity metrics to measure exposure to coastal flooding. The TFS and airport social networks topology is used to draw the relational patterns between social entities (organizations and policy stakeholders). The underlying assumption is that linked social entities need minimum levels of information exchange for the functionality of the infrastructure system to which they belong. The existence of links between nodes informs the potential for multi-actor coordination and collaboration at the operational or strategic decision-making-levels in both social networks. Our innovation lies in the data sources used to build networks of infrastructure decision-making entities that retain their geospatial information, which in turn allows for the incorporation of climate exposure metrics. Our methods are valuable for revealing underlying and often forgotten social dimensions of infrastructure systems. Better understanding these social dimensions are key to improving network-level vulnerability awareness, identifying the roles of different stakeholders, and to accordingly develop system-level coordination and collective-action for emergency response and adaptation plans. These methods also provide a promising approach to address scale mismatch, reduce maladaptation, and operationalize different normative dimensions of environmental justice. An underlying contribution of this approach is providing empirical and conceptual methods to expand ways in which we define different types of climate risk governance stakeholders. This approach improves our understanding of who is regarded as vulnerable and at risk beyond simple direct exposure and it identifies who is included in decision-making processes as well as the relational patterns between decision-makers. The results can be used to increase the visibility and transparency of the complex network of decision-makers behind infrastructure systems and operationalize different dimensions of environmental justice. While our methods systemically link decision-making power to technical assets and landscape processes based on GIS and policy data, there is much room to qualitatively improve our understanding of these links based on different typologies and degrees of power in decision-making.

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Appendix A. Stakeholder Semi-Structured Interview Questions

TFS stakeholder interview questions

I. Introductory questions:

1.Where does your organization fit in our conceptual TFS model?

2.What products does the organization work with and in what way? (i.e., crude oil, gasoline,

diesel, jet fuel, etc.)

3.Has the organization had any wildfire or flooding incidents?

II. Questions associated with damage to individual assets (i.e. depth damage curves).

4.What specific infrastructure is the organization worried about in relation to wildfire and flooding

exposure?

This might relate to:

o “microscale” assets such as specific joints

o “mesoscale” assets such as valves or pumps

o “macroscale” assets such as specific building/tank or office, i.e. Control Rooms

o “system” assets such as entire pipeline systems

5.When considering wildfire and flooding, what information is more valuable to the organization to

prevent and mitigate adverse events due to exposure? Why?

o Wildfire hazard metrics: Rate of Spread/ Fireline Intensity (BTU) /Flame length

o Flood hazard metrics: Depth / Duration/ Scouring

6.If the asset is permanently damaged how difficult, financially and/or time-wise, would it be to replace it?

III. Questions associated with damage to network functionality/ flow of fuel (criticality metrics)

7. What are the origins and destinations of the products the organization works with in this mapped area?

8. How are normal operations defined?

9.How would a disruption and failure of operations of the organization be defined? Due to wildfire or flooding?

10. Assuming assets that could suffer damage from flooding and wildfire, how would this damage cause disruption of operations? How likely would the damage cause failure of operations?

11.In what way(s) would this disruption or failure affect other assets of the organization? Would this affect other organization's assets?

12.If another organization's asset is permanently damaged, how long would it take to affect the operations of this organization? (If dealing with transport infrastructure type use nearby fixed infrastructure damage scenario or vice versa).

IV. Questions related to the organizational structure while facing wildfire/flooding

13.Considering the damage scenario, what position(s) in the organization are responsible for responding to the incident and returning assets to normal operations? What actions would be taken?

14.Which external organizations would this organization need to contact or work with to recover normal operations? What position at that organization would be responsible and what actions would be taken by that organization?

15.Does the organization undertake near or long-term planning with any other interconnected (TFS or not) organizations with regards to wildfire and flooding scenarios? How so, and what organizations/industries does this include?

V. Questions related to the institutional framework

16. What are the organization's planning horizons?

17. What is the organization's level of interest in undertaking near or long-term planning for wildfire and flooding risk with relation its assets?

18. How is interaction with TFS industries/organizations enabled or restricted by procedures, licensing & regulation when dealing with wildfire and flooding risk?

VI. Concluding Topics

19. What would be a worst-case scenario/ nightmare for the operations of the organization? (not necessarily wildfire or flooding)

20. How does the organization plan around this?

21. Does planning involve interaction with people within the organization but from other sectors/premises?

22. Does this involve interaction with people outside the organization? Which organizations and function? What actions are taken?

23. What other organizations in the TFS have dealt with wildfire or flooding events or that engage with strategic planning around these risks?

*For more information on TFS stakeholder engagement, population sampling, data collection, and processing please see Appendix E of Radke et al, 2018.

Airport stakeholders interview questions

I. National level interview: FAA Questions

1. How did climate adaptation emerge in in FAA /Airport policy agenda? (trace back to ICAO 2010? To ACRP Baglin, 2012?)
2. Are there any key organizations that influence climate adaptation policies in the FAA?
3. What are key policy documents important to review airport national regulatory framework (i.e., ACs, Orders, standards, guidelines, ACRP publications)?
4. What would trigger an Airport AC/ Order review process?
5. How could we find historical airport documents database with information of participants internal and external stakeholders in airport master plan/ airport system planning?
6. How do Environmental departments incorporate climate adaptation? Fit within sustainability (NEPA, env. review process?) or safety? How does this affect the agency's capacity to manage the issue?
7. What would be good indicators of environmental work-force in airports?
8. How can this policy review become informative for airport governance agencies?

II. National-level interviews: Questions to consulting company researching airport adaptation through ACRP reports

1. What were the economic incentives and institutional concerns driving your organization's research on cost-benefit analysis for climate adaptation? main mechanism to implement resilience in airports?
2. What are the connections of your organization's publications to other ACRP publications on climate adaptation and disaster risk reduction?
3. Are sustainability departments involved in climate adaptation research or climate mitigation? Which departments are usually dealing with climate adaptation?

4. What are time horizons for airport plans – what are conflicting time horizons based on different organizational roles (investment and planning vs. operational)?
5. Have your organization's research encountered any barriers in the AIP financing system to promote airport adaptation?

III. California-level interviews: Questions for Caltrans Aeronautics Department

1. When did climate resilience/ adaptation become a strategic element in the state aviation plans?
2. What are the major policies that pushed for this change?
3. Were there specific coalitions from governmental or non-governmental organizations that helped push climate adaptation into the CASP agenda?
4. Are there any thoughts on accountability or monitoring mechanisms the agency could propose to ensure adaptation efforts described in the CASP are implemented?
5. What are some of the major barriers to coordinate and implement airport climate adaptation policies at the State level?

IV. California-level interviews: Questions for California airports

1. What type of flooding information your airport currently uses to develop and implement costal flood risk mitigation and SLR adaptation (i.e., FEMA Flood Insurance Maps, California's 4th Climate Change flood models, CoSMoS USGS models?)
2. What the current efforts/strategies your airport is making to manage coastal flood and SLR risk?
3. Which airport departments are usually involved in managing coastal flooding mitigation and SLR adaptation at your airport?
4. Are there other key federal, state, municipal, multilateral agencies, or private partners that engage in coastal flooding and SLR adaptation efforts with the airport? Which ones? What do you think about the level of collaboration between these agencies? {Please refer to Figures below for some examples}
5. What are the main policies that support coastal flooding mitigation efforts or sea level rise adaptation efforts? (i.e., FAA Advisory Circulars? State Policies? ICAO guidelines? Industry Business Association guidelines? Airport Master Plans, Layout Plans, Terminal Plans?)
6. What are the main barriers to invest, develop, and implement coastal flooding mitigation and sea level rise adaptation?
7. How can coastal flooding and sea level rise modeling results be more informative?

Appendix B. Policy Review Data for the Airport Case Study

International policy data

Key international guidelines on infrastructure and adaptation include the vulnerability and impact assessment series from the International Panel for Climate Change (IPCC) [174,304–307] and its latest update to global climate science knowledge [308], and recent adaptation infrastructure standards from the International Standard Organization (ISO) [309], the American Society for Testing Materials International Standards (ASTM) [310], the World Federation of Engineering Organizations (WFEO) [311]; and the International Federation of Landscape Architects [312].

Key airport-specific policies covered at the international level include the environmental report series from the International Civil Aviation Organizations (ICAO) [313–317] and Airports Council International (ACI) recent policy brief on adaptation [318].

Please use this interactive mind-map to access key international climate science and aviation industry documents reviewed for this study:
https://www.mindmeister.com/2034184105/international-aviation-and-climate-adaption-policy

Table B.1. International policies reviewed in the nexus of climate adaptation and aviation

	KEY INTERNATIONAL POLICIES		**Notes**
CLIMATE ADAPTATION	IPCC	AR5 (2014)	WGII: Impacts Adaptation, and Vulnerability
		AR6 (2021)	WGI: The Physical Science Basis
	ISO	ISO 1490 (2019)	Adaptation to Climate Change – Principles, Requirements and Guidelines
		ISO/TS 14902 (2020)	Adaptation to Climate Change- Requirements and Guidance on Adaptation Planning for Local Governments and Communities
		ISO 14091 (2021)	Adaptation to Climate Change- Guidelines on Vulnerability, Impacts and Risk Assessment
	ASTM	ASTM E3032 (2016)	Standard Guide for Climate Resiliency Planning and Strategy
	WFEO	Model Code of Practice (2015)	Principles of Climate Change Adaptation for Engineers
	IFLA	Global Climate Action (2019)	Principles of resilient, transformative, and sustainable societies to manage climate risk for Landscape Architects
AVIATION INDUSTRY	ICAO	Doc 3184 (2018)	Airport Planning Manual Part II -Land Use and Environmental Management
		Environmental Report (2019)	5th Environmental report on Aviation and Environment
	ACI – World	ACI Resolution 3/2018	Policy Brief – Airport's Resilience and Adaptation to a Changing Climate

National policy data

At the national level, our policy review includes the National Climate Assessment (NCA) series [319,180,320,321], the reports and recommendations to Congress from the Government Accountability Office (GAO) on climate risk management [258,322–327] the National Institute of Standards and Technology (NIST) guideline on community and infrastructure system resilience [328], the American Society of Civil Engineers (ASCE) manual on climate resilient infrastructure [329], the National Academies of Sciences, Engineering and Medicine guidebook on the incorporation of cost-benefit analysis to prepare for climate change and extreme events [330], the National Infrastructure Protection Plans specific to the transportation sector and to the integration of resilience in infrastructure decision-making process [69,331], and the most recent national infrastructure investment plan (the White House, 2021).

At the national level, airport-specific policy documents covered include a systematic overview of 36 Airport Cooperative Research Program (ACRP) reports explicitly or implicitly addressing adaptation (details available in Appendix A), ASCE's most recent aviation infrastructure report card [334], and a systematic review of 129 FAA's airport policies [335], which is synthesized in section 3.3 and further described in a forthcoming peer-reviewed publication [336]

Table B.2. National policies reviewed in the nexus of climate adaptation and aviation

	KEY NATIONAL POLICIES		Notes
CLIMATE ADAPTATION	NCA	NCA4 (2018)	Latest Climate Assessment: Volume II: Impacts, Risk, and Adaptation in the U. S
	GAO High Risk Series	GAO-13-283 (2013)	"Limiting the Fed. Gov. Fiscal Exposure by Better Managing Climate Change Risks" is included in High Risk Area
		GAO-(2021)	Fed. Gov Needs Cohesive Strategic Approach with Strong Leadership and the Authority to Manage Climate Change Risks
	GAO Reports & Recommendations to Congress	GAO-13-242 (2013)	Climate Change: Future Federal Adaptation Efforts Could Better Support Local Infrastructure Decision Makers
		GAO- 16-37 (2015)	A National System Could Help Federal, State, Local, and Private Sector Decision Makers Use Climate Information
		GAO-17-13-3 (2016)	Improved Federal Coordination Could Facilitate Use of Forward-Looking Climate Information in Design Standards, Building Codes, and Certifications
		GAO-17-720 (2017)	Climate Change: information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure
		GAO-20-127 (2019)	Climate Resilience: A Strategic Investment Approach for High-Priority Projects Could Help Target Federal Resources
		GAO-20-100 (2020)	Disaster Resilience Framework: Principles for Analyzing Federal Efforts to Facilitate and Promote Resilience to Natural Disasters
	NIST	NIST (2016)	Community Resilience Planning Guide for Buildings and Infrastructure Systems
	ASCE	ASCE (2018)	Committee on Adaptation to a Changing Climate: Climate Resilient Infrastructure and Risk Management Manual
	NASEM	NASEM (2020)	Incorporating Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change Guidebook
	NIPP	Transportation Sector-Specific Plan (2015)	Includes global climate change, such as SLR resulting in increased frequency and severity of extreme weather events, such as coastal flooding, as a major risk to the sector.
		Supplemental tool (2013)	Incorporating Resilience into Critical Infrastructure Projects first

			recommendation is the incorporation of climate change impacts into decision-making process
	The American Job Plan	The White House (March 31, 2021)	Investment plan with large focus on transportation infrastructure and climate resilience, including airport modernization
AVIATION INDUSTRY	FAA Advisory Circulars	Airport Series	129 Advisory Circulars for Airports
	ACRP reports explicitly addressing climate change adaptation	ACRP (2012)	Airport Climate Adaptation Resilience
		ACRP (2015)	Climate Change Adaptation Planning: Risk Assessment for Airports
		ACRP (2016)	Addressing Significant Weather Impacts on Airports: Quick Start Guide and Toolkit
		ACRP (2018)	Using Existing Airport Management Systems to Manage Climate Risk
		ACRP (2019)	Climate Resilience and Benefit-Cost Analysis: A Handbook for Airports
	ACRP reports implicitly addressing climate change adaptation	31 reports published between 2007-2020 (list in annex)	Reports that address safety, emergency, sustainability, risk, water infrastructure, land-use compatibility, and environmental management; planning; operations forecast; collaborative planning; stakeholder communication; mutual aid systems
	ASCE	Infrastructure Report Card: Aviation (2021)	"Resilience" criteria are used to grade and point to solution on improving score.

California policy data

At the California level key documents on climate adaptation include the reports intersecting the airport sector, climate scientific basis, and climate adaptation governance from the latest state climate assessment (California's Fourth Climate Change Assessment) [337,62,338,339,274,340,272]; updated plans from the Integrated Climate Adaptation Program (ICARP) such as Safeguarding California Plan [171], the Adaptation Planning Guide [341] and governance alignment plans such as the General Plan Guidelines [342], the State Hazard Mitigation Plan [343] the state's Sea Level Rise Guidance Document [344], the Sea Level Rise Policy Guidance [345]; the Strategic Growth Council (SGC) special working group integrating climate science into infrastructure engineering and design standards [181]; SLR planning guidance for critical infrastructure in California's coastal zone [346]; and a systematic review of 87 legislative document such as Assembly Bills (AB), Senate Bills (SB), and Executive Orders (EO) compiled from the Alliance of Regional Collaboratives for Climate Adaptation (ARCCA) legislative updates [347,348], from the Georgetown Climate Center clearinghouse review on California's adaptation policy [349]; and from the state's Adaptation Clearinghouse case studies including transportation infrastructure relevant to the aviation sector [350]. These 87 legislative documents include only adaptation policies that impact airport owners, operators, business organizations, and regulatory agencies (further information available in Appendix B).

Key airport-specific policies and plans at the California level include Caltrans strategic documents for multimodal transportation which have been updated recently and for the very first time have incorporated climate adaptation goals and recommendations. These statewide plans include Climate Action Plan for Transportation Infrastructure (CAPTI) (CalSTA, 2021), the California Transportation Plan 2050 (CTP) [351], and the Interregional

Transportation Strategic Plan (ITSP) [302]. Inside the aviation sector, the state aeronautics department developed two major plans informing adaptation governance which include the latest update of the California Airport System Plan (CASP) (Caltrans Aeronautics, 2021) and the California Airport Land Use Planning Handbook (ALUCP) currently started an update process to align with the CASP, CAPTI and CTP. Finally, a couple of local pioneering planning documents informing climate adaptation are the San Diego Airport Climate Resilience Plan, the first climate resilience-specific plan developed at the airport scale in the U.S. [352], and the San Francisco Bay Shoreline Adaptation Atlas, which describes various nature-based, conventional physical infrastructure, and non-structural adaptation measures that could be employed for nine LLCA.

Please use this interactive mind-map to access California's legislative documents reviewed for this study: https://www.mindmeister.com/1979804551/california-key-climate-adaptation-legislation

Table B.3. California policies reviewed on the nexus of climate adaptation, multimodal transportation systems, and aviation

	KEY CALIFORNIA PROGRAMS AND POLICIES		DOCUMENT DETAILS
CLIMATE ADAPTATION	Climate Change Assessment Program- 4th CCCA (2018) Under CNRA & CEC	Statewide Report	Synthesis of the Fourth CCCA, high-level findings for the state (Bedsworth et al.)
		Technical Reports including aviation infrastructure	Transportation fuel sector (Radke et al.) Emergency management infrastructure (LaTourrette et al.) Lifelines in Los Angeles (Moser and Hart)
		Technical Reports on Adaptation Governance	Implementing local government adaptation strategies (Kay et al.) Current state of coastal adaptation in California (Moser et al.)
		Technical Reports on Climate Science Basis (SLR)	Climate, Drought and SLR Scenarios (Pierce et al.)
	ICARP's State Adaptation Clearinghouse Program under OPR	Plan alignments (adaptation governance)	General Plan Guidelines (OPR, 2017)
			Third update to the State of Cal. Sea Level Rise Guidance Document (Griggs, et al., 2017)
			Sea Level Rise Policy Guidance (CCC, 2018)
			State Hazard Mitigation Plan (CalOES, 2018) integrates for the first time climate change projections
		Safeguarding California Plan	Second update to Safeguarding California Plan (CNRA, 2018). Framework for Agency implementation and guidance to track progress on climate adaptation and "climate-smart" infrastructure
		Adaptation Planning Guide	Second update to the State's APG (CalOES, 2020). Focus on multilevel agency coordination for adaptation guidance and financing
		Case Studies	Summaries of 36 Case Studies under Transportation Topic and Planning & Policy Guidance Resource types (2015-2021)
	Strategic Growth Council	Climate-Safe Infrastructure Working Group	Paying it Forward: A path to climate-safe infrastructure in California (SGC, 2018)
	California Coastal Commission	Critical Infrastructure Risk: Sea Level Rise Planning Guidance for California's Coastal Zone	Combines the latest climate change science with the requirements of the Coastal Act and other relevant laws and presents potential adaptation strategies for critical infrastructure (Final Draft, November 2021)
		Local Coastal Program Planning (LCP)	Local

	Compilation of Legislative Documents on Climate Adaptation (2004-2020)	87 legislative documents (Executive Orders, Senate and Assembly Bills) enacted or amended between 2004-2020 informing directly or indirectly airport climate adaptation	ARCCA Legislative updates (2015-2021)
			Georgetown Climate Center Resource for State and Federal Policy (2005-2019)
			California State Adaptation Clearinghouse reports on transportation (2004-2021)
TRANSPORTATION SYSTEMS AND AVIATION	Caltrans Aeronautics	California Aviation System Plan 2050 (CASP, 2021)	First CASP since 1989 to develop an integrated a multimodal approach with climate adaptation goals
		California Airport Land Use Planning Handbook (ALUCP, 2011)	Land use compatibility plans from Airport Land Use Commissions – no information on natural hazard or climate change. ALUCP currently being updated
	Caltrans Strategic Plans with climate adaptation goals	ITSP (2021)	Interregional Transportation Strategic Plan
		CTP 2050 (2021)	California Transportation Plan 2050
		CAPTI (2021)	Climate Action Plan for Transportation Infrastructure
	Local pioneering documents	San Diego Airport Climate Resilience Plan (2021)	Strategic plan integrates climate resilience into airport operations and development decisions
		San Francisco Bay Shoreline Adaptation Atlas (SFEI, 2019)	Applies Operational Landscape Units to propose integrated and science-based strategies for coastal flooding adaptation of the SF. Bay Area – includes strategies for 9 LLCA

Appendix C. Low Lying Coastal Airports (LLCA) Codes

ID	Airport Name	CITY	County	State Function Class
0Q3	SONOMA VALLEY AIRPORT	Schellville/Sonoma	Sonoma	Community
0Q5	SHELTER COVE AIRPORT	Shelter Cove	Humboldt	Community
0Q9	SONOMA SKYPARK AIRPORT	Sonoma	Sonoma	Community
ACV	ARCATA AIRPORT	Arcata	Humboldt	Primary-Non Hub-Reg.-Business/Corp.
APC	NAPA COUNTY AIRPORT	Napa	Napa	Reg.-Business/Corp.
C83	BYRON AIRPORT	Byron	Contra Costa	Community-Recreation
CCR	BUCHANAN FIELD AIRPORT	Concord	Contra Costa	Metrop.-Business/Corp.
CEC	JACK MCNAMARA FIELD AIRPORT	Crescent City	Del Norte	Commercial Service Non-Primary
CMA	CAMARILLO AIRPORT	Camarillo	Ventura	Metrop.-Business/Corp.
CRQ	McCLELLAN - PALOMAR AIRPORT	Carlsbad	San Diego	Commercial Serv.Non-Primary
DVO	GNOSS FIELD AIRPORT	Novato	Marin	Reg.-Business/Corp.
EKA	MURRAY FIELD AIRPORT	Eureka	Humboldt	Reg.
F72	FRANKLIN FIELD AIRPORT	Franklin	Sacramento	Community-Agriculture
HAF	HALF MOON BAY AIRPORT	Half Moon Bay	San Mateo	Reg.
HHR	JACK NORTHROP FIELD/HAWTHORNE MUNICIPAL AIRPORT	Hawthorne	Los Angeles	Metrop.-Business/Corp.
HWD	HAYWARD EXECUTIVE AIRPORT	Hayward	Alameda	Metrop.-Business/Corp.
L52	OCEANO COUNTY AIRPORT	Oceano	San Luis Obispo	Limited use-Recreation
LAX	LOS ANGELES INTERNATIONAL AIRPORT	Los Angeles	Los Angeles	Primary-Large Hub-Metrop.-Business/Corp.
LGB	LONG BEACH AIRPORT DAUGHERTY FIELD	Long Beach	Los Angeles	Primary-Small Hub-Metrop.-Business/Corp.
LLR	LITTLE RIVER AIRPORT	Little River	Mendocino	Community
MRY	MONTEREY PENINSULA AIRPORT	Monterey	Monterey	Primary-Non Hub-Reg.-Business/Corp.
MYF	MONTGOMERY FIELD	San Diego	San Diego	Metrop.-Business/Corp.
O33	EUREKA MUNICIPAL AIRPORT	Eureka	Humboldt	Community
O69	PETALUMA MUNICIPAL AIRPORT	Petaluma	Sonoma	Reg.-Business/Corp.
O88	RIO VISTA MUNICIPAL AIRPORT	Rio Vista	Solano	Reg.
OAK	Metrop. OAKLAND INTERNATIONAL AIRPORT	Oakland	Alameda	Primary-Medium Hub-Metrop.-Business/Corp.
OAR	MARINA MUNICIPAL AIRPORT	Marina	Monterey	Community
OKB	OCEANSIDE MUNICIPAL AIRPORT	Oceanside	San Diego	Reg.
OXR	OXNARD AIRPORT	Oxnard	Ventura	Metrop.-Business/Corp.
PAO	PALO ALTO AIRPORT	Palo Alto	Santa Clara	Metrop.-Business/Corp.
S51	ANDY MCBETH AIRPORT	Klamath Glen	Del Norte	Community
SAC	SACRAMENTO EXECUTIVE	Sacramento	Sacramento	Metrop.-Business/Corp.

	AIRPORT			
SAN	SAN DIEGO INTERNATIONAL AIRPORT	San Diego	San Diego	Primary-Large Hub-Metrop.-Business/Corp.
SBA	SANTA BARBARA MUNICIPAL AIRPORT	Santa Barbara	Santa Barbara	Primary-Small Hub-Metrop.-Business/Corp.
SBP	SAN LUIS OBISPO COUNTY REG. AIRPORT	San Luis Obispo	San Luis Obispo	Primary-Non Hub-Reg.-Business/Corp.
SCK	STOCKTON Metrop. AIRPORT	Stockton	San Joaquin	Primary-Non Hub-Metrop.-Business/Corp.
SFO	SAN FRANCISCO INTERNATIONAL AIRPORT	San Francisco	San Mateo	Primary-Large Hub-Metrop.-Business/Corp.
SJC	SAN JOSE INTERNATIONAL AIRPORT, NORMAN Y. MINETA	San Jose	Santa Clara	Primary-MEDUIM Hub-Metrop.-Business/Corp.
SMO	SANTA MONICA MUNICIPAL AIRPORT	Santa Monica	Los Angeles	Metrop.-Business/Corp.
SNA	JOHN WAYNE AIRPORT, ORANGE CO.	Santa Ana	Orange	Primary-MEDIUIM Hub-Metrop.-Business/Corp.
SQL	SAN CARLOS AIRPORT	San Carlos	San Mateo	Metrop.-Business/Corp.
TOA	ZAMPERINI FIELD AIRPORT	Torrance	Los Angeles	Metrop.-Business/Corp.
WVI	WATSONVILLE MUNICIPAL AIRPORT	Watsonville	Santa Cruz	Reg.-Business/Corp.

Appendix D. Coastal Flooding Exposure of Airport Assets

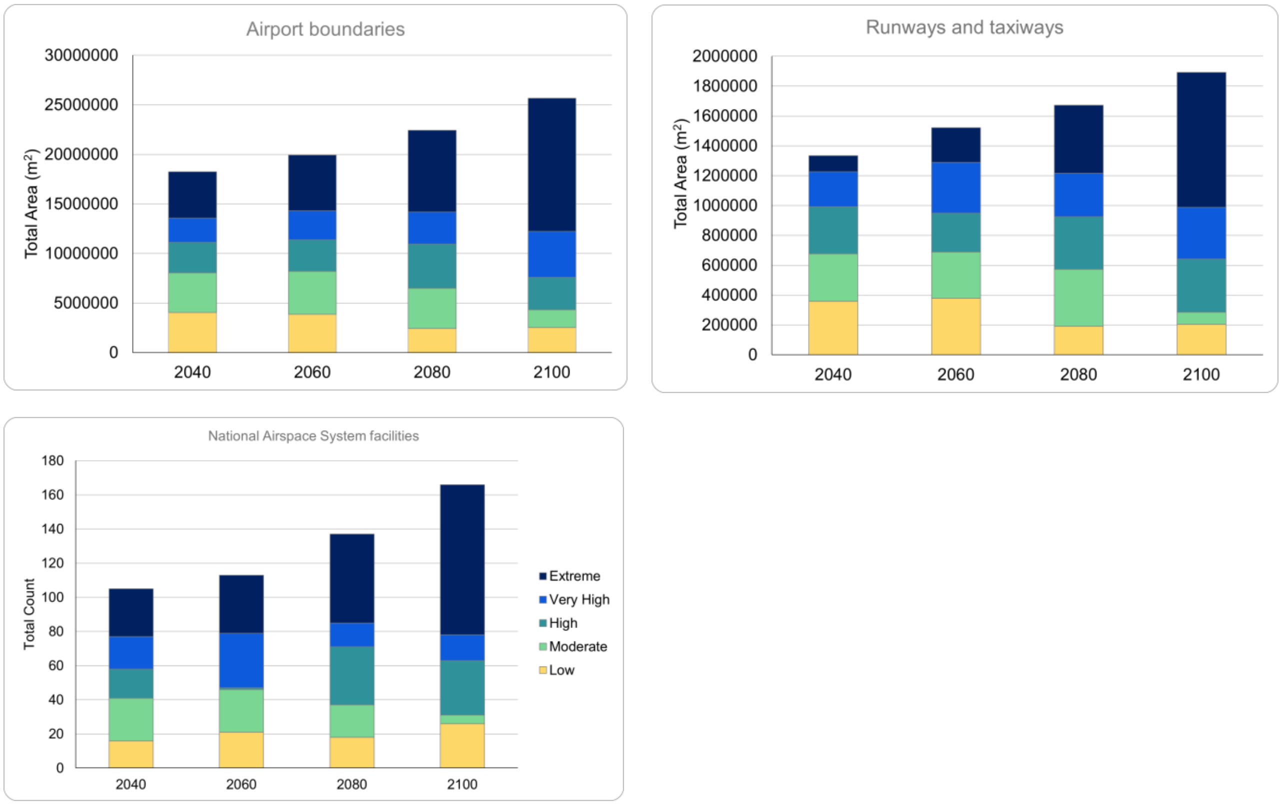

Figure D. 1. Aggregate Exposure of Airport Boundaries, Runways and Taxiways, and NAS

Airport boundary

	2040	2060	2080	2100
0Q3	37%	56%	84%	97%
APC	3%	4%	9%	22%
DVO	100%	100%	100%	100%
EKA	63%	86%	99%	100%
HAF	0%	0%	0%	0%
HWD	2%	2%	4%	6%
L52	17%	14%	79%	79%
O33	38%	43%	50%	65%
O88	0%	0%	0%	0%
OAK	95%	96%	99%	100%
PAO	100%	100%	100%	100%
S51	0%	0%	0%	0%
SAN	0%	0%	5%	26%
SBA	4%	11%	26%	62%
SFO	64%	75%	85%	91%
SQL	100%	100%	100%	100%

Runways and taxiways

	2040	2060	2080	2100
0Q3	26.68%	60.26%	100.00%	100.00%
APC	0.00%	0.00%	0.00%	34.04%
DVO	100.00%	100.00%	100.00%	100.00%
EKA	16.86%	64.81%	94.47%	100.00%
L52	0.62%	3.54%	90.30%	90.30%
O33	0.00%	0.00%	0.00%	50.09%
OAK	100.00%	100.00%	100.00%	100.00%
PAO	100.00%	100.00%	100.00%	100.00%
SAN	0.00%	0.00%	0.90%	16.90%
SBA	0.00%	0.00%	3.05%	64.01%
SFO	68.65%	86.78%	99.38%	100.00%
SQL	100.00%	100.00%	100.00%	100.00%

National Airspace System facilities

	2040	2060	2080	2100
APC	0%	0%	0%	8%
CCR	33%	33%	33%	33%
EKA	50%	50%	100%	100%
MZB	100%	100%	100%	100%
NUQ	50%	50%	50%	100%
OAK	79%	81%	81%	81%
PAO	90%	90%	90%	90%
SAN	0%	0%	17%	20%
SBA	0%	0%	0%	81%
SFO	53%	67%	100%	100%
SGD	100%	100%	100%	100%
SQL	100%	100%	100%	100%

Figure D. 2. Airport-by-airport Exposure of Airport Boundaries, Runways and Taxiways, and NAS