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Collective action problems and governance barriers to sea-level rise adaptation in San Francisco Bay

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Abstract
This paper translates Ostrom's "diagnostic approach" for social-ecological systems to identify the collective action problems and core governance barriers for sea-level rise adaptation in the San Francisco Bay Area. The diagnostic approach considers variables related to the resource system, the resource units, the users, and the governance system. Coupled ecological-infrastructure models identify two core collective action problems: vulnerability interdependency and adaptation interdependency. Qualitative social science case study methods identify the key structural governance and behavioral barriers to cooperation and ongoing activities to address them. The diagnostic approach is potentially applicable to any coastal regions that are vulnerable to sea-level rise and also other climate adaptation issues where vulnerability and adaptation interdependencies require overcoming governance challenges to collective action.

Keywords Climate adaptation · Sea level rise · Polycentric governance · Cooperation · Social-ecological systems

1 Introduction

Through the example of sea-level rise, this paper analyzes how climate impacts cascade through environmental and infrastructure systems to define collective action problems that

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must be addressed by governance institutions and actors. Responding to these collective action problems involves the major governance challenge of "coordination within and between governance levels and domains" (Oppenheimer et al. 2019, p. 325), which is variously described as a "governance gap" (Lubell 2017), "black box of adaptation decision-making" (Biesbroek et al. 2015), or "implementation deficit" (Dupuis and Knoepfel 2013). Even when the vulnerabilities and adaptation solutions are known, implementation requires overcoming governance barriers in the context of complex, polycentric institutional arrangements (Adger et al. 2009; Eisenack et al. 2014; Jordan et al. 2015; Morrison et al. 2017). Our analysis centers on a case study of sea-level rise adaptation in San Francisco Bay (SF Bay), California, a large, urbanized embayment with a variety of infrastructure vulnerabilities.

To organize our analysis, we translate Ostrom's "diagnostic approach" for social-ecological systems (SES; Ostrom 2007; Ostrom and Cox 2010) into the context of sea-level rise adaptation. Partelow (2018, p.36) characterizes the core intellectual foundation of the SES diagnostic framework as "the need to understand how and why cooperation (via collective action and institutions) influences governance arrangements and their ability to achieve sustainable outcomes." The SES diagnostic approach identifies aspects of the resource system, resource units, users/actors, and governance system that may accelerate or impede the interactions that affect system and individual-level outcomes related to resilience and adaptive capacity (Ostrom et al. 2007).

Methodologically, we operationalize the framework by triangulating approaches from environmental sciences, infrastructure engineering, and the social sciences. Coupled environmental infrastructure models are used to characterize the resource system and units related to sea-level rise, flooding, and infrastructure disruption. Regional linkages among these components give rise to the core collective action problems involved with sea-level rise adaptation: vulnerability and adaptation interdependencies. Vulnerability interdependence occurs when a climate impact experienced at the local level has cascading regional effects. Adaptation interdependence occurs when adaptation actions taken by one actor entail costs and benefits for other actors through linked biophysical or infrastructure processes.

These collective action problems must be addressed by the governance system and users, which we analyze with a qualitative case study approach combining archival analysis, focus groups, in-person interviews of 43 policy leaders conducted from Fall 2016 to Winter 2017, and ongoing participant observation and policy engagement. The qualitative case study diagnoses the structural and behavioral barriers to adaptation and potential solution strategies. The structural barriers include the need for network governance in polycentric governance systems, development of a regional plan, integrated permitting, funding, and a science enterprise to link science and policy. The behavioral barriers include political leadership and community engagement.

Sea-level rise and coastal flooding provide an important research setting for the application of the SES diagnostic framework. Sea-level rise is recognized as one of the most immediate and serious consequences of global climate change. Even if global climate emissions were immediately reduced to zero, significant levels of sea-level rise are already locked-in to the system (Nauels et al. 2019). Because coastal regions have high levels of human development, critical infrastructure, and valuable ecosystems (Kummu et al. 2016), increases in coastal flooding catalyzed by sea-level rise are likely to cause serious economic, social, and environmental damage (Hauer et al. 2016; Kulp and Strauss 2019). Barnard et al. (2019) estimate that by 2100, sea-level rise may impact \$150 billion or 6% of GDP in California. In addition, the costs of adaptation actions for sea-level rise are expected to be extremely high. Leroy et al.

(2019) estimate that coastal adaptation costs in the USA will be at least $400 billion over the next 20 years and likely much higher. Hinkel et al. (2014) estimate *annual* adaptation costs of between US$ 12 and 71 billion by 2100, but also estimate that adaptation costs are expected to be lower than the social costs of additional flooding.

While the challenge of sea-level rise in coastal communities is global, the interdependencies that necessitate collective action occur within regions. The case study we present here is centered on SF Bay, a globally important economic region with a high level of coastal urban development. SF Bay is vulnerable to sea-level rise and enjoys a political culture where most citizens and government officials agree that sea-level rise is a critical issue and that adaptive actions should be pursued. Hence, stakeholders in SF Bay are in the throes of trying to overcome the barriers of creating new governance institutions, which provides an opportunity to analyze institutional change in motion. While the diagnostic approach avoids panaceas and recognizes case-specific factors, the framework and case study developed here can serve as a guideline for analysis in other coastal regions around the world and for other climate adaptation issues featuring interdependencies in environmental processes and the built environment.

2 Methods

Our conceptually integrated analysis triangulates environmental-infrastructure models with qualitative social science methods. The coupled environmental infrastructure model quantifies the cascading impacts of flooding and feedbacks that emerge in the coupled environmental-built system, thus establishing the existence of the collective action problems associated with sea-level rise. The social science methods analyze the barriers to adaptation associated with the governance system and behavior of actors and users. This section summarizes the methods at a level needed to understand the basic results but refers the reader to other sources for a more detailed description from a disciplinary perspective. The figure captions also include method details to make the analytical source of the figures quickly accessible.

2.1 Coupled environmental infrastructure models

Understanding regional collective action problems requires resolving the interactions and interdependencies that emerge through environmental and infrastructure dynamics. These interdependencies include feedbacks between the built and natural environments, as well as the cascading of impacts between infrastructure systems or throughout the region. To quantify these dynamics for the SF Bay case study, we use a combination of models to analyze disruptions from sea-level rise, including a hydrodynamic model for the direct projection of water levels and coastal inundation, a geospatial model to predict flooding of wastewater infrastructure, and an agent-based traffic model to simulate transportation infrastructure capacity. The choice of these infrastructure systems to analyze was based on their critical roles in the region, the network dynamics that govern them, and their vulnerability to coastal inundation. Inundation here will be defined as the extent of water coverage at the highest tides under various scenarios for mean water level. We will interpret these mean water-level scenarios as different future times along the sea-level trajectory, but they could equally be considered the result of intermittent extreme events (e.g., a 100-year precipitation event might create a mean water level in SF Bay that is equivalent to mean sea level in 2050).

To capture feedbacks between components of the environmental infrastructure system, it is critical that the hydrodynamic model resolves tidal motions at a fine enough scale to define the inundation of components of the infrastructure systems, where the infrastructure component is considered inundated if it is covered by water at high tide for the particular mean water-level scenario. At the same time, the model domain must extend throughout the embayment to resolve basin-wide responses. The multiscale nature of this problem motivates the use of an unstructured model of variable resolution, with high-resolution where needed to resolve infrastructure interactions and lower resolution elsewhere. In our application to SF Bay, we make use of the Coastal Storm Modeling System (CoSMoS), a high-resolution, unstructured-grid hydrodynamic model developed by the US Geological Survey using the Delft3D software (Barnard et al. 2014). The model simulates tidal hydrodynamics and interactions with shoreline infrastructure under current and future sea level scenarios to map the extent and depth of flooding along the SF Bay shoreline. For future scenarios, we assume that the bathymetry of the Bay and the surrounding topography remains unchanged; this creates an artificially static landscape but allows for the scenarios to focus on the interplay between sea levels and shoreline management actions. Shoreline infrastructure scenarios are defined along shoreline segments and consist of "no intervention," in which waters are allowed to freely flow over existing topography, or "containment," in which a hard boundary (simulating a seawall or levee) is placed along the shoreline segment to prevent new inundation at that location.

Coastal inundation elevations from the hydrodynamic model are overlaid with a digital elevation model of the regional wastewater and transportation network to determine which wastewater treatment plants and roadways experience flooding and associated capacity disruptions. For wastewater infrastructure, we quantify direct flood impacts by calculating the percent of each facility's physical footprint that experiences inundation along future trajectories of mean sea level (in increments of 25 cm). We also estimate indirect impacts by extracting the total population in each facility's service area from the US Environmental Protection Agency's Facility Registry Service (Hummel et al. 2018a). For transportation infrastructure, we incorporate the flooded roadway (reduced) capacities into a dynamic, discrete-choice traffic model, MATSim Bay Area (Pozdnoukhov et al. 2016), to simulate how travelers are redistributed through the system following inundation events and to map the resulting traffic congestion across the network. The time it takes for all travelers from a census tract to reach their destination is calculated with and without the sea-level rise-induced disruption of the network and then averaged to report the sea-level rise-induced delay for that census tract. The resulting delays, reported in minutes, represent the average traffic delay experienced by commuters from a particular neighborhood created by future inundation scenarios. It should be noted that not all commuters from a neighborhood will experience that same delay, since the delay experienced by an individual will depend also on their commute destinations. For example, commuters who live in a particular census tract may work in locations spread throughout the region, resulting a wide range of delays they experience due to inundated areas, but the average of their delays will be calculated in our analysis.

To estimate regional interdependencies due to shoreline management decisions, we focus on how adaptation actions at the local level have regional effects due to environmental interactions among different sites. We first apply the hydrodynamic model to the existing shoreline configuration, assuming no shoreline adaptation actions are taken to mitigate coastal flooding. We then run additional scenarios that account for adaptation actions implemented by individual actors to protect their shorelines at the county level or smaller. As shoreline management decisions are made by local actors (i.e., intervening with seawalls or levees),

the basin-wide tidal dynamics are altered, leading to increases or decreases of tidal high-water levels depending on the nature and location of the action. For example, the construction of seawalls at the southern end of SF Bay would prevent future tidal dissipation that would otherwise occur in newly inundated areas, leading to larger tides for the case with seawalls than the case without. This leads to higher water levels and increased inundation in other parts of SF Bay.

For a given protective action (construction of shoreline infrastructure in a particular jurisdiction, not considering accommodation or retreat strategies), the change in inundated area in other parts of the region is calculated based on the maximum extent of flooding at high tide (compared to the case without protective action). To control for different sizes of the regions being analyzed, we divide this change in inundated area by the length of shoreline; the result is a metric describing how much the shoreline will shift for a given protective action. For example, if a seawall constructed by one city causes inundation to increase by 10,000 m^2 in another jurisdiction with a shoreline that is 1000 m long, this action would produce a 10-m landward shift of the shoreline (on average) in the other jurisdiction. The hydrodynamic interactions resulting from these management actions are described in more detail in Wang et al. (2017, 2018) and Hummel and Stacey (2021), and the economic impacts of changes in bayfront flooding are quantified in Hummel et al. (2021).The transportation interactions are discussed in Papakonstantinou et al. (2019), Lee et al. (2019), Madanat et al. (2019), and Hummel et al. (2020).

2.2 Qualitative case study

We use a qualitative case study to elicit directly from SF Bay stakeholders the governance adaptation barriers they are facing, the political and social processes driving those barriers, and how they are thinking about solutions to regional collective action problems. The qualitative case study approach in Fall 2016-Winter 2017 involved a combination of document review, personal interviews with stakeholders, stakeholder focus groups, and participant observation ongoing through 2021. The document review focused on a list of sea-level rise adaptation projects curated by the UC Berkeley Climate Readiness Institute. We developed a basic understanding of these projects by analyzing their online documentation and coded them for year of inception, level of geographic scale, and types of issues addressed. Because the archival analysis required considerable effort, we did not continue collecting data on new projects that started after 2017, when the interviews were initiated. Furthermore, the time of data collection coincides with the major acceleration in the number of policy forums addressing sea-level rise.

We conducted 43 in-person interviews with policy leaders at multiple levels of the SF Bay governance system, including all 9 counties, a representative range of local governments, special districts, and non-governmental organizations. The interviews covered professional background, perceptions of risk from sea-level rise, sources of climate change information, current adaptation actions being implemented, funding needs, overall governance challenges, participation in climate adaptation policy venues, collaboration partners, and barriers to collaboration. We use quotes from the interviews to illustrate some of our core findings.

The personal interviews were followed-up by three regional focus groups in the North Bay (15 participants), Central/South Bay (18 participants), and South Bay (12 participants). The focus group participants were first asked to choose the highest priority governance challenge and then discuss the possible solutions from the perspective of resiliency, cooperation, social

capital, equity, economic feasibility, and political feasibility. The results section describes the most important current activities underway to address these governance barriers. However, the regional focus groups deliberated about a wide range of potential solutions that were identified in the personal interviews (see Table 1 in Appendix for full range of solution concepts explored and Lubell 2017 for detailed discussion).

Ongoing participant observation has occurred through 2021, mainly through author Mark Lubell's participation in the Bay Adapt: Regional Strategy for a Rising Bay planning process. Sponsored by the San Francisco Bay Conservation and Development Commission (BCDC 2020), Bay Adapt is seeking to develop a joint platform to guide regional sea-level rise planning in SF Bay and has included extensive stakeholder and community engagement. As a member of the Bay Adapt Leadership Advisory Group, author Mark Lubell directly engaged in deliberation and writing of different components of the joint platform. In addition, both authors frequently make presentations to actors and policy forums throughout SF Bay, which provides additional opportunities for policy-engaged research and participant observation.

3 Results: translating the SES diagnostic framework to sea-level rise adaption

Ostrom's (2007) diagnostic approach organizes the social-ecological system into four main subsystems: the resource units, resource system, governance system, and users/actors. Figure 1 summarizes our translation of the framework into the context of sea-level rise adaptation, including the main system components we analyze along with the scientific methods and outputs described above. The *resource units* are disrupted by flooding associated with sea-level rise, and those disruptions cause collective action problems by cascading through the hydrodynamic and infrastructure processes of the *resource system*. Solving the collective action problems requires interactions among the *users* (i.e., residents who rely on these infrastructure systems and decision-makers who manage the systems; often described as "stakeholders" in policy parlance), which are shaped by the multilevel *governance system* tasked with sea-level rise planning and adaptation project implementation.

We focus on the critical resource units of wastewater treatment and traffic conveyance capacity, which will be disrupted by different levels of land inundation from flooding associated with sea-level rise. Hydrodynamic models are used to predict levels of inundation, which are overlaid with the physical geography of the infrastructure systems and then coupled to models of tidal dynamics and infrastructure processes that reflect the structure of the resource system. Thus, the coupled environmental infrastructure models explicitly represent a link between the resource units and the resource system.

The structure of the hydrological and infrastructure components of the resource system, in combination with the projected flooding, gives rise to two key collective action problems involved with regional adaptation: *vulnerability interdependence* and *adaptation interdependence. Vulnerability interdependence* occurs when an environmentally forced disruption that occurs in one locality creates regional impacts, usually through interactions across networked infrastructure systems. *Adaptation interdependence* occurs when the adaptation actions taken by one actor may increase or decrease the adaptive capacity or vulnerability of other actors. These linkages emerge when physical or ecological processes cascade spatially and create interactions between actions and responses at geographically dispersed locations (Zimmerman 2001; Little 2002;

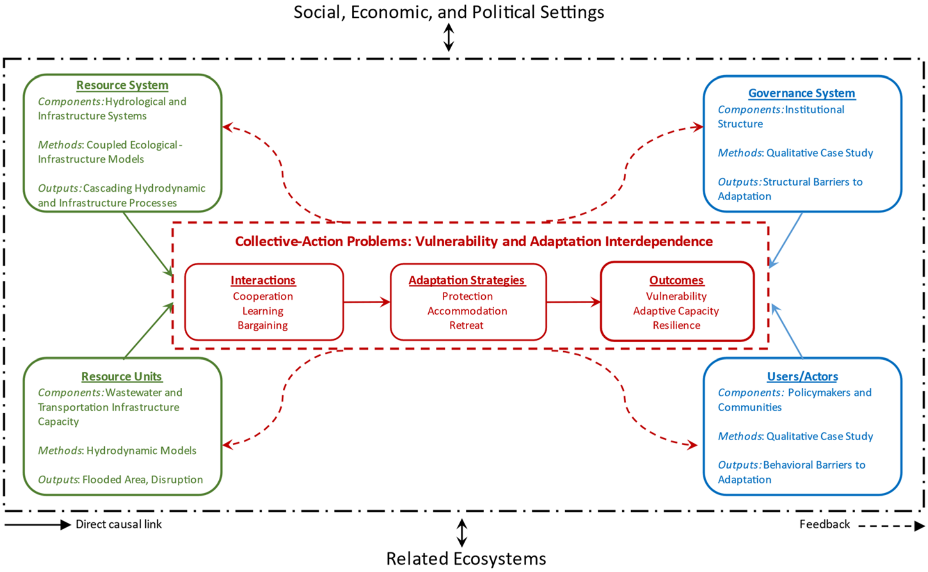

Figure 1 A SES diagnostic approach to sea-level rise adaptation

Wilbanks et al. 2015). These interdependencies create collective action problems because climate impacts or adaptive actions occurring in any individual jurisdiction will affect the benefits and costs of sea-level rise experienced by other jurisdictions. Because individual jurisdictions have incentives to ignore the social costs and benefits experienced by others, their adaptation decisions may not be optimal from a collective, regional perspective.

The social system responds to these collective action problems through user interactions that are structured by the governance system. The polycentric governance system is composed of many policy forums where participating stakeholders deliberate and make decisions about sea-level rise adaptation (Jordan et al. 2018; Lubell and Robbins 2021). Formal institutional rules and informal norms structure decision-making within and across forums (Libecap 1989; North 1990). The governance system determines the structural barriers that actors must overcome: the types of institutions needed to govern networks of actors, the development of adaptation plans, the permitting of infrastructure and environmental projects, the distribution of funding, and how science is linked to policy.

The user/actors consist of the communities that use the infrastructure and may be directly affected by flooding and the policymakers who make important adaptation decisions. Communities have differential levels of awareness, vulnerability, and adaptive capacity, which may be based on socioeconomic class or racial biases and thus raise important considerations of environmental justice, procedural, and distributive equity. Policymakers include elected/administrative officials, non-governmental organizations, and others, who have opportunities to engage in political leadership in response to community needs.

In the context of the governance structure, the users/actors engage in three key interactions that enable climate change adaptation: learning, cooperation, and bargaining (Lubell 2013). Learning refers to understanding the severity of the problems, their environmental drivers, and interdependencies, along with key aspects of the governance system such as the institutional rules in place and the preferences of other stakeholders (Fischer and Maag 2019; Lubell et al.

2016; Heikkila and Gerlak 2013). Cooperation refers to the joint actions needed to effectively implement policies (Bardach 1998) or the levels of resource investment or consumption needed to provide public goods or sustainably use common-pool resources, respectively (Ostrom 1990). Bargaining means agreeing on the distribution of the costs and benefits of the various policy choices, since even within the set of potentially mutually beneficial policies, there are many possible allocations of costs and benefits (Hardin 1982; Libecap 1989; Knight 1992).

In the context of sea-level rise adaptation, learning, cooperation, and bargaining combine to determine adaptation strategies categorized in terms of protection, accommodation, and retreat, which might be implemented at the community or individual household level. Protection strategies may often be “gray” infrastructure like seawalls or levees or “green” infrastructure such as restored wetlands; in either case, the shoreline remains at its current location even as sea-level rises. Accommodation approaches might include reshaping the built environment to “live with water,” for example by elevating households. With accommodation, communities remain in place, but the effective shorelines are allowed to progress upland as seas rise. Retreat means moving human development to some other place and allowing natural processes to be restored at the site. The mix of adaptation strategies that might be adopted in a place depends on many different environmental and social variables; there is not a uniform solution (Beagle et al. 2019). To the extent policy actors can effectively interact to implement appropriate adaptation strategies, there should be a reduction in vulnerability and increased adaptive capacity and resilience.

Students of Ostrom’s SES framework will notice that our framework does not reference the long list of “second-tier” concepts that are often associated with “first-tier” concepts of the resource system, resource units, governance system, and actors (Hinkel et al. 2015). For example, a second-tier concept related to the resource system is “human-constructed facilities.” While many of our concepts can be translated into the original SES framework, we intentionally focused on a small number of concepts to avoid inflating the long list already included in the SES framework. In addition, the coupled environmental infrastructure models provide a more precise description of how the resource units and resource system combine to create collective action problems. We then sought to translate the governance challenges into the language of real-world policy stakeholders, with the hope of providing an actionable target list for ongoing planning.

The remainder of this section provides more specific results about each component of the diagnostic framework that we analyze with our combination of environmental infrastructure models and social science methods.

3.1 Resource units: inundation and disruptions of infrastructure capacity

The collective action problems that arise from environmental and infrastructure interdependencies associated with sea-level rise impose social costs on communities throughout the region. In the case of sea-level rise, these costs can be conceptualized as resource units that are vulnerable to climate change impacts: the amount of land area inundated and how flooding disrupts the capacity of critical infrastructure systems such as transportation and wastewater. Figure 2 presents the inundated land area for three sea-level rise scenarios (50 cm, 100 cm, and 150 cm), derived from the CoSMoS model simulations assuming no shoreline management actions. The respective total area of inundation for each scenario is 304 km^2, 565 km^2, and 691

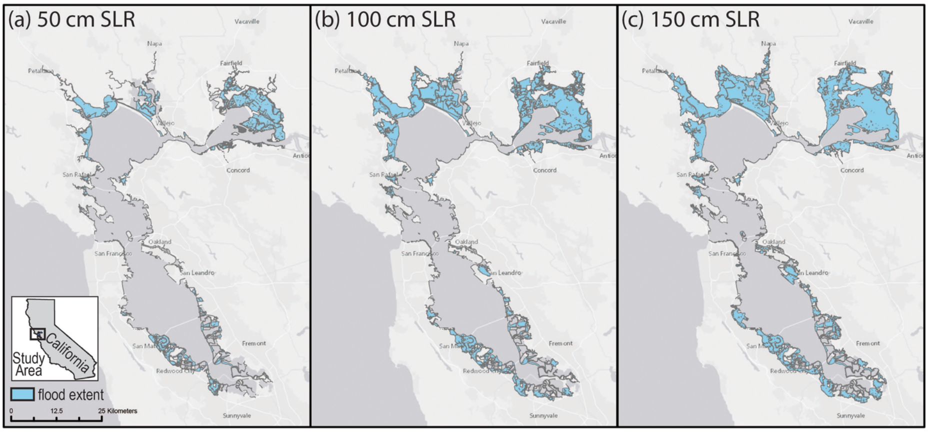

Figure 2 Projected flooding for three sea-level rise scenarios. Maps of new inundation (shown in blue) in the San Francisco Bay Area under three sea-level rise scenarios using the CoSMoS hydrodynamic model. Each scenario includes a specified mean sea-level (current sea level +50cm, +100cm, and +150cm shown in these panels; simulations were done in 25 cm increments) and superposes tidal water surface variability. The offshore boundary condition consists of the specified mean sea level plus the 8 largest constituents of the astronomical tides; the model resolves the propagation of the tidal signal into and through San Francisco Bay. Regions shown as inundated are submerged at the highest high tide in a tidal month.

km^2, with local spatial heterogeneity depending on a combination of topology and hydrodynamics.

How sea-level rise will affect the amount of inundated land and infrastructure capacity varies over space and time. For example, Hummel et al. (2018b) grouped SF Bay communities according to similar vulnerabilities, with some communities facing high levels of flooding, while also featuring critical infrastructure facilities and lower socioeconomic status. Such communities may be considered disadvantaged and require consideration from an equity and environmental justice standpoint (e.g., Felsenstein and Lichter 2014).

While the amount of inundated land is one type of resource unit, flooding also disrupts another critical type of resource unit: the capacity of the wastewater and transportation infrastructure systems. Within the wastewater network, flooding at wastewater treatment plants can cause partial or total loss of treatment capacity, leading to discharge of untreated sewage to SF Bay and posing a hazard to human and ecosystem health. The impacts of these disruptions also extend regionally, as residents living further inland but located within the service areas of these plants will lose access to effective wastewater services. Figure 3 shows the magnitude of flood impacts at wastewater treatment plants in SF Bay, depicting the percentage of each facility's physical footprint that is vulnerable to flooding across a range of sea-level rise scenarios (Hummel et al. 2018a). The magnitude of flood impacts at these facilities will increase over time and is heterogeneous across the region.

The capacity of the transportation infrastructure is another critical resource unit for the region. Flooding of shorefront highways or intersections reduces the ability of the infrastructure to support traffic flows. As links and nodes of the transportation network (infrastructure system) are disrupted, individual responses and choices about transportation mode and route define the regional traffic flows and infrastructure capacity (resource units). The next section demonstrates how the capacity of traffic infrastructure is related to the networked structure of the transportation system.

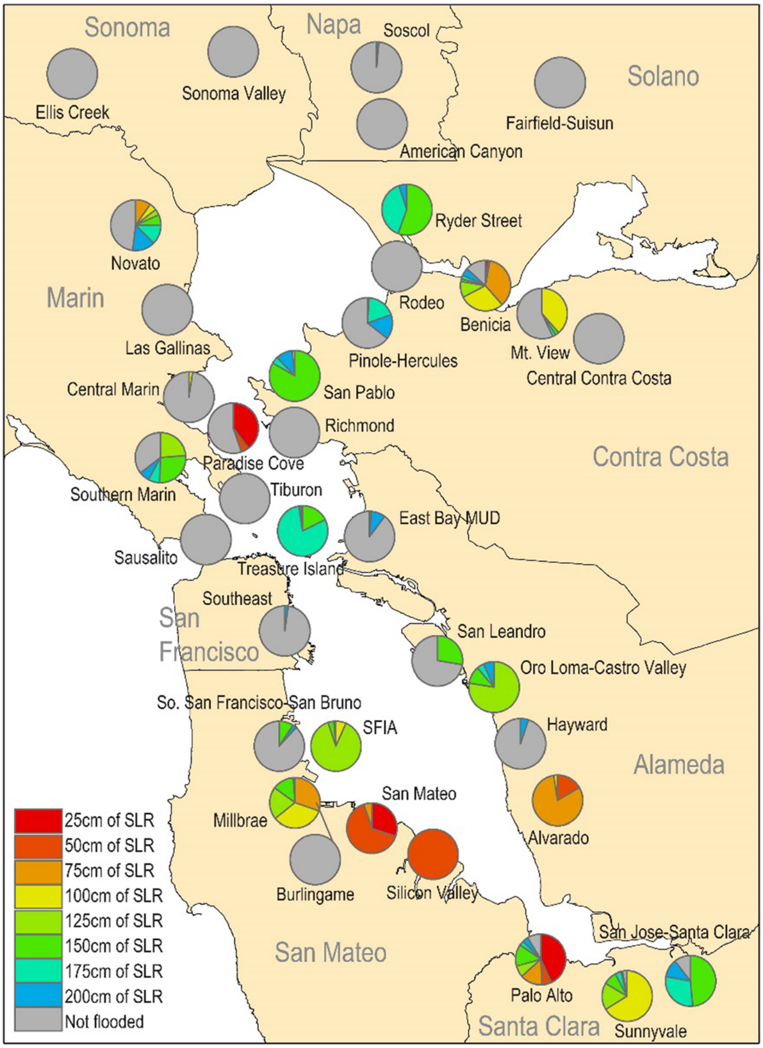

Figure 3 Wastewater infrastructure vulnerability to sea-level rise. Using the tidal inundation projections for sea-level rise scenarios in increments of +25 cm, the inundated area of a wastewater facility's footprint is calculated. The fractional inundation of each facility is represented by a pie chart, with complete inundation represented by a chart filled with color; portions that are never flooded (out to the maximum sea level considered, +200 cm) are shown in gray. The colors show the lowest sea level at which the fraction is inundated; for example, the red portion shows the fractional area inundated at +25cm of sea level, the red-orange shows the additional area inundated at +50 cm, the orange shows the additional area inundated at +75 cm, and so on.

3.2 The resource system: cascading impacts and the creation of vulnerability and adaptation interdependencies

Interdependence is at the heart of cooperation problems—the benefits and costs experienced by one actor depend on the actions of others. Vulnerability and adaptation interdependencies emerge from processes that are shaped by the structure of environmental and infrastructure

systems. These dynamical interdependencies can be resolved using the coupled environmental infrastructure models to define the cascading impacts of environmental disruption.

Figure 4 demonstrates vulnerability interdependence based on the traffic delays created by the inundation of bayfront roadways with 1 m of sea-level rise. While flooding under this scenario is limited to areas along the bayshore, as the capacity of the transportation infrastructure is reduced locally, traffic is rerouted into other adjacent portions of the network, creating congestion that further reroutes traffic across the network, and potentially continues to propagate into traffic delays throughout the network. It should be noted that commuters from some census tracts may experience improved traffic conditions (i.e., negative delays) due to the regional redistribution of traffic flows away from their local streets and highways. The cascading of traffic delays from a local infrastructure disruption to regional congestion and delays compromises the resource unit (traffic capacity) in census tracts that do not border the bay or experience any direct flooding. In the case of transportation, vulnerability interdependence reveals how the structure of the infrastructure system and the processes that cascade through the system are intertwined with the resource unit of traffic capacity.

To illustrate adaptation interdependence, Figure 5 illustrates how protective actions taken by one jurisdiction influence vulnerability to flooding in other jurisdictions (Wang et al. 2018). In this case, shoreline scenarios are developed by assuming that each of the Bay Area's 9 counties act individually to protect their shoreline. The color and direction of the arrows indicate the effect that implementing protective infrastructure (e.g., a seawall or levee) along one county's shoreline has on other counties in the region. Adaptation interdependence is similar to watershed flooding, where upstream flood management infrastructure may have downstream consequences (Tobin 1995; Criss and Shock 2001). Other work on coastal embayments (Holleman and Stacey 2014; Wang et al. 2018; Hummel and Stacey 2021) has demonstrated that for tidal systems, this interaction is more geographically complex and is frequently bi-directional.

Figure 5 also demonstrates the long-term evolution of adaptation interdependence. Early actions taken at current sea levels will have little to no regional consequence, but with higher sea levels, actions throughout the region are interdependent. Importantly, this temporal change in the dynamic regional interactions means that individual actions taken in the near term may miss opportunities for coordination that would be justified by the interdependencies that emerge later.

3.3 Governance system: structural barriers to adaptation

The disruption of infrastructure capacity due to inundation and the interdependencies caused by cascading effects define the collective action problems faced by the governance system and users. Here we summarize the major barriers to sea-level rise that emerge from the structure of the governance system and the current activities seeking to overcome them.

3.3.1 Network governance in polycentric systems

The governance system for sea-level rise adaption is a polycentric, multi-level system featuring many public and private actors participating in multiple planning venues and adaptation projects. There has been rapid growth in the number of forums and planning processes and involved actors at different levels of geographic scale (Figure 6). The growth has increased the

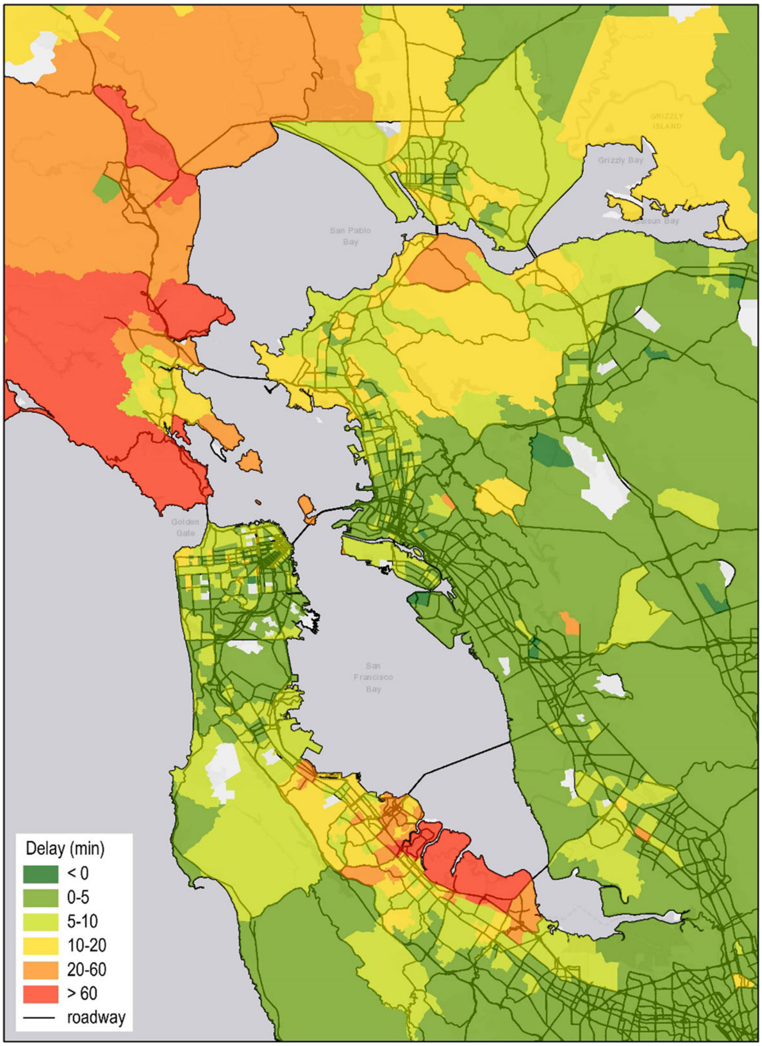

Figure 4 Regional traffic delays caused by local disruptions. MATSim computations of current traffic dynamics are compared to those for +100 cm of sea level by using projected inundation (Figure 2) to disrupt the transportation infrastructure network (reducing the capacity of links in the network). The resulting travel-time increases for all trips that originate in each census tract in MATSim are averaged to produce the shown traffic delay map.

overall complexity of the polycentric governance system and is consistent with the "punctuated equilibrium" theory of the policy process (Baumgartner and Jones 2009).

The increasing complexity of the governance system creates the core challenge of network governance: how to coordinate adaptation planning, decision-making, and implementation across the multi-level system. Because vulnerability and adaptation interdependencies involve local decisions whose impacts cascade regionally, the governance network must effectively build cross-scale interactions (Cash et al. 2006). There is currently not a single central agency or institutional arrangement with comprehensive responsibility for sea-level rise and climate adaptation planning in SF Bay. Research on

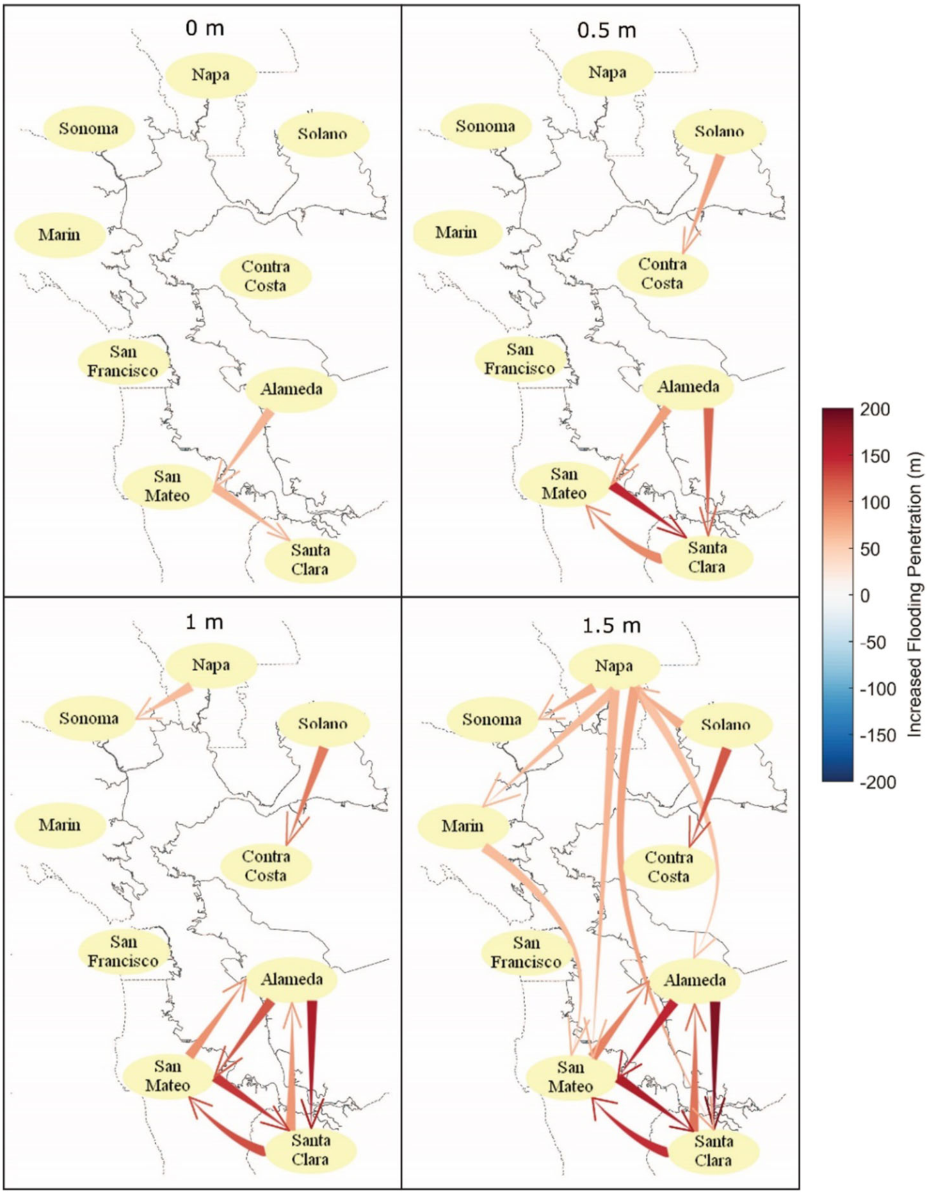

Figure 5 Adaptation interdependencies between San Francisco Bay counties. Analysis on a county-by-county basis explores how shoreline intervention in one county influences others. Using the CoSMoS hydrodynamic model, each county shoreline is switched between "accommodation" (or unprotected) (no intervention to provide protection and rising waters can freely inundate new areas) and "protected" (deliberate intervention to maintain shorelines where they are today through development of a seawall or levee). When a county shoreline is switched from unprotected to protected, the impact on inundation in other counties is computed, and the change in the extent of inundation is presented in this figure, with red colors indicating increased inundation. The metric for new inundation shown here is the "penetration" of flooding into a county, which is defined as the newly inundated area divided by the length of the shoreline.

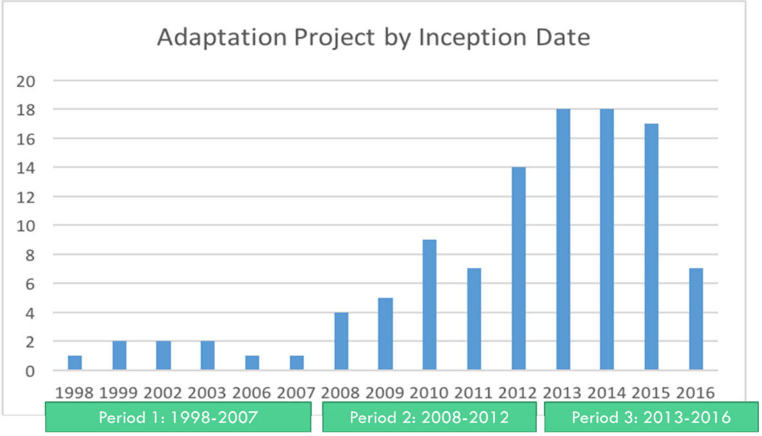

Figure 6 Number of adaptation policy forums from 1998 to 2016. The policy forums were identified from an inventory curated by the UC Berkeley Climate Readiness Institute. Online archives from each forum were investigated to determine the date of establishment. In period one, a small number of existing policy forums started to consider climate change and sea-level rise alongside their existing responsibilities for water management or other environmental issues. In period 2, there is a rapid growth of new policy forums in response to emerging salience of sea-level rise. In period 3, there is a steady state of new institutional growth, which has continued through the time of this writing. Note the data was collected in 2017, hence the creation of more recent forums is not depicted.

network governance has identified three possible modes for coordination: shared governance, lead organization, or network administrative organization (Provan and Kenis 2008). Shared governance involves organizations coordinating their activities, either informally or formally, without nominating a specific leader. In the lead organization model, an existing agency takes the lead in organizing the network for joint action. The network administrative organization model establishes a new administrative agency with authority to influence the decisions of the other actors.

SF Bay stakeholders currently face a Catch-22 in network governance: they recognize the need for coordination but cannot agree on the network governance mode to achieve it. The San Francisco BCDC is frequently mentioned as a potential lead agency. Established in 1965, BCDC is a unique regional agency that issues development permits in SF Bay (Smith and Pendelton 1998). As one interview respondent described the institutional advantages of BCDC, “I think BCDC is really interesting because it has the right jurisdiction, it covers the Bay and all 9 counties, has the right geography…one option for the SF Bay Area is to give BCDC more authority and more tools to deal with climate adaptation.” BCDC has led several sea-level rise planning efforts associated with their Adapting to Rising Tides program and in 2019 initiated a highly visible regional planning process called Bay Adapt: Regional Strategy for a Rising Bay. Hence, BCDC has developed the cross-scale relationships needed to address vulnerability and adaptation interdependencies. However, stakeholders worry that BCDC is constrained by a geographic jurisdiction limited to 100 feet beyond the mean high tide line, a reputation for emphasizing regulatory compliance that challenges local autonomy, and an associated history of political conflict. Hence, whether Bay Adapt will provide an enduring lead agency solution versus paving the way for additional institutional change remains an open question.

3.3.2 Regional adaptation planning for sea-level rise

Associated with the evolving structure of network governance is the lack of a single regional plan that identifies how actors will work together to address the key interdependencies. “There are no voices for the SF Bay Area. And that’s one of our challenges…is to bring all of the land managers in the SF Bay Area, the different jurisdictions over vulnerable lands in the SF Bay Area, together to co-plan and to plan together. And that’s because there really is that kind of gap. Question is who’s going to fill that gap and how’s it going to get filled,” lamented one interview respondent. Instead, there are several relevant regional plans that address aspects of sea-level rise under pre-existing legal mandates, such as the regional transportation plan (Plan Bay Area 2040), BCDC’s San Francisco Bay Plan that guides their permitting decisions, the basin plan for the San Francisco Bay Regional Water Quality Control Board, and the portfolio of green infrastructure and coastal habitat restoration projects being considered by San Francisco Bay Restoration Authority. These additional regional plans are complemented by a wide range of vulnerability analysis and adaptation planning at the county, local government, and special district levels. However, there is substantial variance in the extent and quality of local plans. Regional plans must develop processes and incentives to align the range of planning efforts across the multi-level, polycentric system.

How sea-level rise planning occurs depends heavily on the type of network governance institutions that emerge. In theory, such a plan must incentivize local actors to consider how their decisions affect other actors and regional goals. Under a lead agency model, BCDC would be the most likely candidate to develop a regional plan, and the “joint platform” being developed by the Bay Adapt process may become the focal point for coordination at the regional and local levels. However, the Bay Adapt process may only be an intermediate step towards the development of a new agency with greater authority, which would also produce a plan. Even if Bay Adapt is widely accepted as a legitimate regional plan, additional shared governance is required via the alignment of other plans promulgated by local governments, special districts, regional agencies, and state/federal agencies with SF Bay programs. Hence, regional adaptation planning will always be a collection of plans produced by multiple actors in the polycentric system, potentially orchestrated by a regional plan (Bartelings et al. 2017; Dhanaraj and Parkhe 2006).

3.3.3 Developing the climate science enterprise

To solve collective action problems, scientific knowledge is needed to link knowledge to action by understanding the involved interdependencies, potential solutions, and future uncertainties about the extent of sea-level rise and extreme climate events (Cash et al. 2003). The production of science itself occurs in a polycentric system that has been described as a science enterprise (Delta Stewardship Council 2013, p.3): “the collection ofscience programs and activities that exist to serve managers and stakeholders in a regional system. The elements of anenterprise range from in-house programs within individual agencies or other organizations to large-scale collaborative scienceprograms funded by governments. Included in thisdefinition is academic research, recognizing that academic researchers often operate independently of management andstakeholder entities.”

Stakeholders expressed a desire for a more centralized and collaborative science enterprise. “One of the things that everyone recognizes…would be a tremendous asset, would be a central repository of information. The question has been who should take that on. There is a need to

centralize this," said one respondent. The SF Bay climate science enterprise has witnessed the development of some central sources of knowledge used by many stakeholders. In 2018, the Ocean Protection Council updated the "State of California Sea-level Rise Guidance" to consider the range of future sea-level rise and storm scenarios that might occur in SF Bay. In 2019, the San Francisco Estuary Institute (SFEI), a non-governmental research organization, developed the San Francisco Bay Shoreline Adaptation Atlas. The Adaptation Atlas introduced the concept of operational landscape units, which are geographic areas with similar physical features that are suited to different types of adaptation options. Many organizations are now using operational landscape units as core planning elements. The preliminary results of the environmental infrastructure models in this article have also been presented to many Bay Area stakeholders, who are especially interested in how the concepts of adaptation and vulnerability interdependencies justify the need for regional planning.

However, the availability of science does not guarantee its usability as knowledge for decision-making (Cash et al. 2003). Interview respondents stressed the need for professional assistance to translate the best available science into their local planning contexts; as one county planning official exclaimed "Enough with the proliferation of portals!" Instead, as one respondent commented, "They need a collaborative approach—they need a sustained collaborative approach, which means scientists and boundary organization professionals who understand and care about the needs of decision makers, engage with those decision makers over time, in an iterative fashion, to go internalize what our needs are, and then customize products and processes that will help us meet our needs." The Bay Adapt process is exploring the development of a "climate science services center" that engages in the co-production of actionable science for stakeholders (Vogel et al. 2016; Moss et al. 2013). A climate science service center not only serves as a data and research clearing house for the best available science, but also includes boundary-spanning and translational experts to directly interact with stakeholders (Kirchhoff et al. 2013; McNie 2012; Miles et al. 2006). The translational experts would assist stakeholders in identifying, translating, and analyzing relevant scientific data and information for appropriate integration into planning and decision-making. The center would seek to integrate and coordinate the range of research efforts currently being developed by NGOs, government agencies, and universities. A climate science service center requires a formal organizational structure, staffing, and sustained funding.

3.3.4 Fragmented permitting

Collective action for sea-level rise adaptation requires a portfolio of on-the-ground infrastructure projects that account for patterns of interdependency. Projects in the form of green or gray infrastructure may require obtaining permits from multiple agencies: local government, the BCDC, the Army Corps of Engineers, the Regional Water Quality Control Board, the California Department of Fish and Wildlife, the US Fish and Wildlife Service, the National Marine Fisheries Service, and others. Many projects also require a full environmental review under the 1969 National Environmental Policy Act or the 1970 California Environmental Quality Act. Obtaining these permits requires substantial time and understanding, which delay or block project implementation, increase costs, or produce conflicting recommendations. Describing the permitting of green infrastructure, one respondent said "Because right now, I mean, we basically, we get treated the same as someone putting up a Wal-Mart. We got to jump through the same hoops, and it takes years and hundreds and hundreds of thousands of dollars to get permits."

Alleviating fragmented permitting requires strategic coordination among multiple agencies, and potentially the development of new administrative procedures for integrated permitting (Rabe 1995). One respondent asked, "Is there a way…to increase the geographic scope, the collaborative approval, and accelerated approval of larger scale resource protection strategies?" In 2019, state and federal agencies formed the Bay Restoration Regulatory Integration Team (BRRIT) to coordinate permitting around multi-benefit habitat restoration projects eligible for funding from the San Francisco Bay Restoration Authority. Inspired by the collaborative model of the Dredged Material Management Office https://www.spn.usace.army.mil/Missions/Dredging-Work-Permits/Dredged-Material-Management-Office-DMMO/, the BRRIT is a team of dedicated staff from six state and federal agencies who work together to review an integrated permit pre-application that complies with the permit requirements of each individual agency. By coordinating throughout the permitting process, the BRRIT seeks to accelerate the time frame for acquiring permits.

3.3.5 Insufficient funding

Fully implementing all gray and green infrastructures needed to enhance adaptive capacity will require substantial funding for which there is a current shortage of identified sources. Funding is an omnipresent point of discussion. "And unfortunately, it's going to be very expensive," said one respondent, while another worried, "No there won't be enough money, I mean that's clear." For example, the cost estimates for the goal of restoring 100,000 acres of wetlands is approximately $1.43 billion over 50 years (Save the Bay 2018) and up to $5 billion for the Embarcadero Seawall Program. While these financial figures are large by themselves, they represent only a portion of the needed infrastructure investments; Hirschfeld and Hill (2017) estimate adaptation costs as high as $453 billion for 2.0 meters of sea-level rise depending on shoreline management goals. All stakeholders agreed that a "funding portfolio" including federal, state, local, and private sources will be needed to meet all potential adaptation investments. Adaptation investments could potentially be targeted in geographic regions predicted to be most vulnerable to infrastructure disruptions, or where local adaption actions have the highest regional benefits.

There has been some progress on funding: Measure AA (2016) established a parcel tax to fund $500 million over 20 years for shoreline protection in SF Bay; SB1: The Road Repair and Accountability Act (2017) funds some transportation projects related to sea-level rise adaptation; and Proposition A (2018) in San Francisco authorized a $425 million general obligation bond to finance the first phase of the Embarcadero Seawall Program. In 2021, the state of California has a projected $75.7 billion budget surplus, and Governor Gavin Newsom's proposed budget calls for over $200 million of spending for sea-level rise. US President Joe Biden's "American Jobs Plan" also calls for investments in climate resilience, although how much federal funding will arrive in California remains uncertain at the time of this writing. While the recent increases in state and federal funding are hopeful, the full price tag for needed infrastructure investments is unknown and is likely to exceed currently available funds. Hence, a key point of discussion in the Bay Adapt plan is developing strategies for seeking, in the words of one respondent "Federal money, local money, and private money, all of it."

3.4 Users and actors: behavioral barriers to adaptation

The values, beliefs, attitudes, and behaviors of resource users and actors are also potential barriers to collective action. These individual-level, behavioral factors interact with the

structure of governance systems. As with the description of structural governance system barriers, here we summarize the main behavioral barriers related to collective action and current activities that are underway to address them.

3.4.1 Community engagement

Individual community members are the most fundamental aspect of social vulnerability, and the capacity to govern climate adaptation depends on community engagement. Community members need to perceive the risks and recognize that local community vulnerabilities and adaptation actions are affected by the decisions of other jurisdictions. One respondent remarked, “So the challenge was…how can we assure the public, listen, we care, we know about this issue, there is a risk, we don’t know the exact amount of risk, the sooner we start, the sooner we can work on it, and the better off you are.” Community members also need to participate in various types of political activities to communicate their preferences to elected officials and administrative decision-makers. If elected and administrative officials do not perceive community support, they are less likely to engage in the necessary collective action. Respondents highlighted the importance of local community knowledge for climate adaptation, “There’s a lot of understanding, wisdom, knowledge, that comes out of communities because people are dealing with the issues of environmental change and environmental impact on a daily basis.”

Sea-level rise is a challenge to community engagement because it is currently perceived as a “slow moving natural disaster” that is not immediately visible, where the costs of adaptation are short-term and more certain while the benefits are long-term and uncertain. The “psychological distance” of sea-level rise also increases when people perceive it to affect others who are not like themselves or in geographically distant places (Spence et al. 2012). Engaging disadvantaged communities is further constrained by a lack of capacity to effectively participate in planning, more attention being paid to other short-term priorities, and a history of distrust with political actors. Like in many other coastal regions, disadvantaged communities in the Bay Area are disproportionately exposed to flood risks (Hummel et al. 2018b).

Most sea-level rise planning efforts recognize the importance of community engagement and have taken steps to engage them. Adapting to Rising Tides is a bottom-up process that starts with the formation of stakeholder working groups. Bay Adapt has explicitly included community-based organizations in leadership and advisory groups and is also developing a public communication strategy. The short-term but highly visible Bay Area: Resilient by Design Challenge included equity and integration of local knowledge as key principles. However, the effectiveness of existing community engagement strategies remains subject to debate, and there is no single effort to coordinate the portfolio of community engagement across the many planning processes that are occurring in SF Bay. Any overarching engagement strategy must consider the needs of disadvantaged communities, including the necessity of trust-building and early engagement.

3.4.2 Political leadership

Consistent and visible political leadership from elected officials and executive administrators at all levels of government is needed to advance planning and implementation of sea-level rise adaptation. Elected officials play a key role in enacting policies (legislation, ordinances, etc.) that authorize and fund adaptation projects. Political leaders also increase the salience of issues and signal the legitimacy of climate adaptation planning to stakeholders and communities.

Political leadership around sea-level rise has been historically uneven, because California political leaders have traditionally paid more attention to climate mitigation, or water scarcity/supply due to drought and the long history of conflict over California water management. Some respondents attributed uneven political leadership to the lack of focusing events, “We need the day after tomorrow to hit – there are super storms all over North America, and the people are like we have to do something. I don’t know, it’s just not on people’s agendas. It’s not on legislators’ agendas.” However, there are recent signs that California political leaders are paying more attention to climate adaptation and sea-level rise.

In the legislative branch, leadership comes from legislative member organizations that focus attention on issues of common interest to members (Ringe et al. 2013). In 2019 and 2020, the CA Assembly’s Select Committee on Sea-level Rise and the California Economy held two hearings to discuss sea-level rise vulnerability and regional solutions. The Bay Area Caucus is another potential venue for directing specialized attention to sea-level rise issues. The legislative attention was at least partially spurred by reports from the Legislative Analyst’s Office on potential legislative strategies for addressing sea-level rise (Petek 2019, 2020). In 2021, the Alliance of Regional Collaboratives for Climate Change Adaptation is tracking 31 climate adaptation bills being deliberated in the California legislature.

In the executive branch, the Governor of California can use powers of oversight, agenda-setting, and intergovernmental coordination to focus attention and policy action on sea-level rise. “And the more that the Governor’s office says it’s important, the more we get state participation,” observed one respondent. Upon taking office in 2019, California Governor Gavin Newsom’s administration catalyzed more intergovernmental coordination and funding for sea-level rise, coastal adaptation, and climate adaptation financing. Newsom’s actions have included signing climate change adaptation legislation, issuing executive orders for state agencies to consider adaptation, writing line items for climate adaptation into the state budget, and creating interagency workgroups.

4 Discussion: the benefits of applying the SES diagnostic framework

Our translation of the SES diagnostic framework has epistemological, theoretical, and practical benefits. Climate adaptation is an example of what the US National Science Foundation (NSF 2021) calls convergence research, which “is a means of solving vexing research problems, in particular, complex problems focusing on societal needs. It entails integrating knowledge, methods, and expertise from different disciplines and forming novel frameworks to catalyze scientific discovery and innovation.” The SES framework provides epistemological benefits because it organizes convergence research and enables a multidisciplinary analysis of the interactions among the most important system components (Cumming et al. 2015; Pahl-Wostl 2009; Hinkel et al. 2015). Such cross-disciplinary knowledge convergence does not occur when scientists limit the analysis to the components of the system that are within disciplinary boundaries. In addition, the integration of natural and social sciences is a challenge for the SES framework itself (Partelow 2018). Leslie et al. (2015) argue that analyses that rely solely on either natural science or social science approaches risk missing key process and variables and arriving at incorrect conclusions. By putting environmental, infrastructure, and social analyses on equal footing, our approach applies the principles of convergence to address a weakness in SES research.

Theoretically, any synthetic framework should identify how system components are related to the theory of collective action and the complex interdependencies that create collective action problems in the first place (Hinkel et al. 2015). While previous papers point out the importance of cooperation for climate change adaptation (Adger 2003), the coupled environmental infrastructure models used here characterize the vulnerability and adaptation interdependencies that give rise to collective action problems, which in turn provides a theoretical motivation for the qualitative analysis of the governance system and users/actors.

Practically, diagnostic frameworks endeavor to provide lessons for decision-makers (Moser and Ekstrom 2010). The quantification of interdependencies connects sea-level rise collective action problems to scales and impacts that are considered by decision-makers, specifically how sea-level rise will affect different types of communities and infrastructures. During our policy engagement, we have directly witnessed stakeholders using the results of the coupled environmental infrastructure models to articulate the narrative that SF Bay must act collectively to address the threat of sea-level rise. The analysis of governance barriers provides an actionable list of issues that should be addressed in subsequent adaptation planning. These practical benefits are further enhanced because our translation of the diagnostic framework uses language that is familiar to policy stakeholders.

The concept of diagnosis seeks to avoid panaceas and uncover the case-specific configuration of variables that impede or facilitate cooperation (Partelow 2018). Once the problem is diagnosed, the analysis proceeds to recommend institutional solutions that have a particular fit to the specific problems (Ostrom and Cox 2010), and the potential barriers to achieving those solutions (Eisenack et al. 2014). The precise configuration of collective action problems and governance barriers depends on the economic, political, and environmental history of a particular region like our SF Bay case study. Cascading impacts and associated vulnerability and adaptation interdependencies are likely to appear in other coastal regions, along with governance barriers. However, the severity of these barriers, and the mix of potential solutions, is likely to vary across social-ecological systems. The analysis here thus establishes some target research questions that can be empirically explored via comparative research.

5 Conclusion: extending the SES diagnostic framework to other regions and climate adaptation issues

Our translation of the SES diagnostic framework conceptually integrates hydrodynamic and engineering models with social science to demonstrate how the environmental and infrastructure dynamics of sea-level rise creates regional collective action problems, which are being addressed by an increasingly complex set of polycentric governance arrangements. The evolving institutional arrangements pose structural and behavioral governance barriers that are clearly recognized by stakeholders. Our analysis demonstrates how the SES diagnostic framework can be translated into the vernacular of policy stakeholders, to provide a basis for the development of common understanding of governance barriers and deliberation over policy solutions. We describe some of the steps that Bay Area stakeholders are taking to overcome these barriers, which can serve as examples for other regions facing similar challenges. However, the SF Bay Area is still in the midst of institutional change, and much work remains to fully overcome the governance barriers.

Table 1 Solution concepts for sea-level rise governance barriers

Governance system structural challenges	Proposed solution concepts
Network governance	• Climate Adaptation Vision or Commission (e.g., Delta Vision, Governor's Commission for a Sustainable South Florida, Western Water Commission) • Shared governance ("stay in your own lane") • Lead agency (BCDC or another existing agency) • New "network" administrative agency (e.g., Delta Stewardship Council) • Institutional consolidation: special districts, regional governing boards
Regional adaptation planning	• Vision Plan and next step recommendations • Update existing regional (SB375, Plan Bay Area, SF Bay Plan, other) and local plans (general plans, congestion management plans, local climate adaptation plans) • Overall regional climate adaptation or sea-level rise adaptation plan • Separate but linked new plans for specific issues (sea level rise, temperature, drought)
Climate science enterprise	• Climate science services center (data and assistance/guidance) hosted at agency, university, NGO, or consortium • Create centralized web portal for all climate science information • Internal independent science review board • External National Academy of Science review panel (e.g., Committee on Independent Scientific Review of Everglades Restoration Progress)
Fragmented permitting	• Create new integrated permitting strategy for green infrastructure • Expand scope of Long-Term Management Strategy for Dredging and associated Dredged Materials Management Office • Informal Communication Networks • Regional Advanced Mitigation Planning • Habitat Conservation/Natural Communities Conservation Plan • Expand permitting authority of existing regional agencies like BCDC
Insufficient funding	• Regional/local: parcel taxes, increases in fees, special taxation districts • State: transportation and bond money, special legislation • Federal: special legislation, WRDA, transportation funding • Public-private partnerships
Users/actors behavioral challenges	**Proposed solution concepts**
Community engagement	• Community-based adaptation meetings (e.g., adapting to rising tides) • Partnerships with established institutions (schools, museums, non-profits, utilities, airports) • Developing marketing and communication campaign with digital, traditional, alternative media • Citizen science and in situ visualizations • Educational venues • Climate leadership training programs (outreach staff, community leaders, consultants) • Partnerships with non-profits that have links to citizens
Political leadership	• Create state and federal legislative caucus groups focused on climate adaptation • Governor-sponsored regional climate adaptation dialog sessions • Legislative staff outreach task force • Climate leadership network for elected officials

Note: Cell entries are the policy options developed from Regional Solutions Focus Groups. The underlined options are where the most progress is currently being made

A crucial question going forward is the extent to which the climate adaptation diagnostic framework applies to sea-level rise in other regions, and to other types of climate adaptation issues like wildfire, extreme heat, and extreme weather in which

collective action problems emerge. In most coastal regions, flooding and sea-level rise will be subject to vulnerability and adaptation interdependencies, which necessitate regional cooperation. Such interdependencies also exist for any climate impacts that cascade across communities and land management boundaries. For example, the traffic disruptions and smoke dispersal from wildfires are examples of vulnerability interdependence because a fire in one community spreads smoke and traffic congestion to other communities. Likewise, adaptation interdependence occurs when one community successfully implements fire-risk reduction practices, which then lowers the risk of fire spreading to other communities. The exact structure of those interdependencies requires detailed quantitative modeling of the sort reported in this article to inform and interpret the social science analysis of governance and decision-making.

Similarly, all regions will feature polycentric governance arrangements, although again the exact structure of the associated networks requires local analysis. For example, the Southeast Florida Regional Climate Change Compact provides a central coordination forum in the Miami region but still requires individual cities and counties to formulate their own plans. Similarly, wildfire planning and response requires multi-level coordination among local communities, state agencies, federal agencies, and other stakeholders. As with SF Bay, we expect such polycentric systems to face barriers associated with network governance, planning, funding, science, permitting, community engagement, and political leadership. However, the relative priority of those barriers and availability of solutions will vary across contexts. From a comparative perspective, the structure of macro-political institutions and political culture in different countries will be important contextual variables (Lubell and Edelenbos 2013).

Our analysis highlights what should now be an obvious research need but deserves additional emphasis: comparative studies over space and time. Resilience is a dynamic and long-term process, and we have not observed the co-evolution of governance and climate change impacts over a long enough period to understand the potential outcomes. The same point can be made for comparative observations in different geographic contexts; case studies are accumulating but without a common theoretical framework or empirical approach (Hinkel et al. 2015). The SES diagnostic framework is one possible theoretical foundation, though other alternatives merit consideration for related applications (Anderies et al. 2004; Pahl-Wostl 2009).

Appendix. Solution concepts for sea-level rise governance challenges

The interviews identified a range of possible solutions for the governance challenges identified by our diagnostic approach. The semi-structured interviews and three sub-regional focus groups deliberated about which solutions would be most effective. Table 1 summarizes the solution concepts considered for each challenge. The underlined solutions are those considered most viable by the focus groups, and the ongoing activities associated with each preferred solution concept are discussed in the body of the paper. Note all descriptions of governance activities are current at the time of writing this paper (December 2020), but we expect that many more changes will occur by the time this article is published. For a more in-depth discussion of all considered solution concepts, see Lubell (2017).

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Mark Stacey, lead researcher on hydrodynamic and transportation model integration
Michelle Hummel, development of analytical methods and results for hydrodynamic and transportation models

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