Interacting Infrastructure Disruptions Due to Environmental Events and Long-Term Climate Change

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Abstract  Climate change places additional stress on critical infrastructure systems as demand for resources (e.g., water and electricity) increases and environmental disruptions (e.g., flooding and wildfires) become more frequent and severe. Interconnected infrastructure systems may be particularly vulnerable, as disruptions in one system can cascade to other systems and increase the severity of impacts. To ensure continued functionality, infrastructure systems must be designed or adapted to account for changing environmental conditions, with consideration for the interactions between systems. For this study, we examine the dependencies between shoreline protective infrastructure and transportation infrastructure in the context of sea level rise in the San Francisco Bay Area. Shoreline modifications implemented in one location can cause hydrodynamic feedbacks that exacerbate flooding and associated disruptions elsewhere. On the other hand, the decision not to implement shoreline protection can cause local flooding of roadways that leads to traffic feedbacks and system-wide travel delays. We compare the magnitude of these feedbacks, in terms of vehicle hours traveled (VHT), across a range of county-level shoreline scenarios to characterize the effects of one county's shoreline adaptation decisions on its neighbors. Our results show that VHT increases by as much as 7.2% due to hydrodynamic feedbacks and 10.7% due to traffic feedbacks. Comparing these effects for each scenario allows for targeted decision-making about adaptation approaches that account for both the local effects of flood disruptions and the regional network effects driven by infrastructure interactions.

Plain Language Summary  As sea levels rise, coastal communities are considering how to adapt their shorelines to protect themselves from flooding. When one community builds a seawall to protect itself, it may cause increased flooding for its neighbors. On the other hand, if communities do not take action to protect their shorelines, flooding of critical infrastructure systems such as roadways will occur, forcing drivers to find alternate routes. This can lead to longer travel times locally, for drivers who typically use the now-flooded roads, but also regionally, as these drivers are forced onto other roads that may not have enough capacity to support the higher traffic demand, thus causing additional congestion. In this analysis, we apply a set of computational models to examine the impact of shoreline protection strategies on travel times in the San Francisco Bay Area. We find that travel times can increase by as much as 10.7% for the scenarios considered here, leading to longer delays for commuters.

1. Introduction

Climate change is altering the magnitude and frequency of environmental disruptions of infrastructure systems, with important implications for human safety and well-being. Storms of increasing intensity, more severe wildfires, and more frequent coastal high-water events have all created massive disruptions to communities throughout the world in recent years (Friedman & Schwartz, 2017; McGrath, 2019; Mooallem, 2019). The evidence is clear that this trend will continue (IPCC, 2014; Sweet & Park, 2014; Vitousek et al., 2017), and infrastructure systems must evolve to become "climate-ready." Climate readiness consists of two distinct, but interrelated factors. First, infrastructure systems must be prepared to handle the resource requirements of future conditions, including, for example, water resource infrastructure with capacity to address future drought conditions (Grant et al., 2013) or power infrastructure with the capability to
support future cooling needs during heat waves (Auffhammer et al., 2017; Miller et al., 2008). Second, in order to be climate-ready, infrastructure systems must be able to withstand future environmental events of increasing intensity, duration, and frequency. An emerging example of this requirement lies in the need for coastal communities to adapt their infrastructure in view of increasingly frequent and disruptive coastal flooding events (Moftakhari et al., 2015; Vitousek et al., 2017).

An often overlooked aspect of long-term infrastructure decision-making is the interaction of various infrastructure systems, particularly when the systems are developed or maintained by different organizations (Madanat et al., 2019). A frequently cited example of the cascading impacts of infrastructure interactions followed Superstorm Sandy, when disruption of the electrical grid meant that fuel could not be pumped to fill generators, which were intended to be the backup source of electricity (Kunz et al., 2013). Studies of infrastructure interactions in the past decade have included the threat of intentional attacks on infrastructures systems (Mendonça & Wallace, 2006; O’Rourke et al., 2003; United Nations Counter Terrorism Committee Executive Directorate and United Nations Office of Counter-Terrorism, 2019) and, increasingly, how natural hazards create cascading disruptions through interconnected infrastructure systems (Dueñas-Osorio & Kwansinski, 2012; Hasan & Foliente, 2015; Pescaroli & Alexander, 2016).

The challenge of planning for infrastructure interactions is compounded when considering long-term climate change, since the planning time horizons for different infrastructure systems are frequently different and may or may not align with the timescales for changes in environmental conditions. Formally integrating analyses of multiple infrastructure systems allows for the disparate timescales of short-term events and long-term change to be bridged and to better inform decision-making in a changing environment.

The present study is designed to examine a particular vulnerability for coastal communities: the interaction between shoreline protective infrastructure and other regional networked infrastructure systems in the context of sea level rise (SLR). Shoreline protection meant to eliminate flooding in one location can exacerbate flooding elsewhere, such that decisions made about one shoreline segment have implications for others. This phenomenon has been observed in rivers (Doorn, 2015; Heine & Pinter, 2012), shelf systems (Song et al., 2013; Zhu et al., 2018), and tidal embayments (Holleman & Stacey, 2014; Lee et al., 2017; Lopes & Dias, 2015; Picado et al., 2010; Wang et al., 2018). In many systems, however, shoreline protection decisions are made with only consideration of the local threats of inundation, and regional interactions, either due to environmental physical processes or the cascading impacts on other infrastructure systems, are not usually considered. When they are considered (Papakonstantinou et al., 2019a, 2019b), they do not analyze the difference between the impacts attributable to the physical processes and those associated with cascading transportation effects.

In the study presented here, we formally integrate detailed shoreline scenarios, coastal inundation modeling, and traffic disruption models in order to quantify the impact of constructing shoreline protection on regional traffic, measured in terms of total vehicle hours traveled (VHT). We compare the increase in VHT due to regional shoreline adaptation and associated hydrodynamic feedbacks, which may lead to additional flooding and disruptions on local roadways, with the increase in VHT due to regional transportation disruptions, which may produce delays that affect local traffic flow. The results of this analysis allow us to isolate the processes that contribute to traffic delays to inform targeted SLR adaptation strategies that account for regional infrastructure interactions.

2. Data and Methods

We focus our analysis on the interaction between shoreline and transportation infrastructure in the San Francisco Bay Area, where dense development and the threat of future flooding due to SLR provide an ideal setting in which to test our approach. Our goal is to assess the relative importance of regional hydrodynamics and traffic dynamics, as well as their interactions, in establishing VHT, with implications for shoreline adaptation strategies at the county level. To do so, we simulate the hydrodynamic and traffic systems for paired county-level shoreline scenarios in which one county (County A) protects its shoreline while another county (County B) does not. For each shoreline scenario, we then compare (1) the change in VHT in County B that results from the reduction in flood disruptions to the transportation network in County A (traffic effect), and (2) the change in VHT in County B that results from the increase in flood disruptions to the transportation network in County B due to the shoreline action taken by County A (hydrodynamic effect). This allows us to
isolate the relative impacts of the hydrodynamic and traffic processes on travel disruptions in the region. The following sections provide more detail about the study area and the modeling approach, which combines hydrodynamic modeling of coastal inundation resulting from various shoreline configurations with agent-based modeling of subsequent traffic disruptions.

### 2.1. San Francisco Bay Setting

The San Francisco Bay Area is a highly urbanized coastal region comprised of nine counties with a total population of over 7 million people. Probabilistic projections of SLR at the San Francisco tide gauge suggest a likely range of 0.3–1.0 m by 2100 (Griggs et al., 2017). Flooding induced by SLR threatens residential and commercial zones and critical infrastructure facilities, including electrical substations, wastewater treatment plants, and hospitals (Heberger et al., 2011; Hummel et al., 2018). The transportation network is also susceptible to SLR, as many heavily trafficked transportation corridors are located at or near the shoreline (Figure 1).

Figure 1. Map of San Francisco Bay Area with regional transportation network. The focus of this paper is on interactions between San Mateo, Santa Clara, and Alameda Counties in South San Francisco Bay.
Efforts to adapt to SLR are already underway in the Bay Area. The majority of these efforts are occurring at the local or subregional scale (defined as a shoreline segment that spans multiple cities) in communities that face the most imminent threat of flooding due to SLR. Some examples include the SAFER Bay project along San Francisquito Creek in San Mateo and Santa Clara counties and the Sea Change project in San Mateo County (County of San Mateo, 2020; San Francisquito Creek Joint Powers Authority, 2020). While local shoreline improvements can provide benefits for residents and infrastructure within the project boundaries, changes in the shoreline can also affect nearshore tidal dynamics and cause regional adjustments in water levels (Holleman & Stacey, 2014; Wang et al., 2018). These regional interactions can lead to additional flooding in areas that are not protected.

2.2. Hydrodynamic Modeling

The U.S. Geological Survey’s Coastal Storm Modeling System (CoSMoS) for the San Francisco Bay Area serves as the basis for the hydrodynamic simulations (P. Barnard et al., 2009; P. L. Barnard et al., 2014). The CoSMoS model uses a nested approach to downscale wave and wind fields derived from global climate models (GCMs) to the regional scale. The CoSMoS model simulates flooding resulting from a variety of SLR and storm scenarios using present-day topography and bathymetry, including existing shoreline infrastructure such as levees, berms, and seawalls. The model has been modified in previous studies to quantify how potential shoreline adaptation strategies implemented at the county level will influence bay-scale hydrodynamics, potentially leading to increased flooding in other counties (Wang et al., 2018).

Physically, county-to-county hydrodynamic interactions are created due to the dynamics of the tides in San Francisco Bay. These interactions are particularly strong in South San Francisco Bay (Figure 1), including the counties of San Mateo, Santa Clara, and Alameda. As in many coastal estuaries (van Rijn, 2011), the tides in South San Francisco Bay are amplified due to the dimensions and shape of the basin (Holleman & Stacey, 2014). Under current conditions, the tides are amplified by as much as 60% at the southern tip of the Bay in Santa Clara County, but if the shorelines of the estuary are allowed to move landward as sea levels rise, the amplification could be reduced to 35% or 40% (Holleman & Stacey, 2014). As a result, decisions regarding whether to maintain shorelines where they are or allow them to migrate upland influence regional water levels, with implications for flooding in other jurisdictions.

To better resolve the CoSMoS model predictions for some critical transportation access points in these counties (such as the San Francisco-Oakland Bay Bridge), we refined the horizontal resolution of the computational grid to about 50 m and modified some of the coastal shoreline leve protection scenarios (so that levees, for example, do not cut across local creeks). Finally, we adjusted the time series forcing at the landward boundary using water level and current data from the TPXO-8 global tide model (Egbert & Erofeeva, 2002) to enhance model stability with the new model grid. We restrict our analysis to the interactions between the three South San Francisco Bay counties with 0.5 m of SLR above a 2010 baseline, which falls within the likely range of SLR projections for 2070 in San Francisco and is thus relevant for decision-making and adaptation planning purposes (Griggs et al., 2017). We map the inundation that would occur at high tide during a spring tide cycle, which persists for approximately two weeks each month. This results in permanent flooding in some low-lying areas and shorter-duration (minutes to hours) but frequent (multiple days per month) flood disruptions at higher elevations.

2.3. Traffic Modeling

To predict traffic redistribution in the Bay Area, we use the Multi-Agent Transport Simulation (MATSim) model. MATSim (Horni et al., 2016) is an activity-based traffic simulation platform that performs large-scale traffic assignment by defining the scoring function for each agent to achieve user equilibrium (Popovici et al., 2012). The modeling framework of MATSim requires a travel plan (daily activity chain) of commuters and a connected network, consisting of highways and arterial roads, to perform the traffic assignment.

For this study of the San Francisco Bay Area, we assume a static transportation network reflecting current roadway infrastructure. The travel plan of commuters is based on the vehicular travel information from Pozdnoukhov et al. (2016). Since running MATSim with the entire population of commuters is computationally prohibitive, a random sample of 463,938 agents, which represents 16% of the commuting population in 2050, is used for travel demand. Accordingly, the road links in the transportation network are scaled down to
### Table 1

*Change in Flooded Area and Flooded Roadway Mileage for Paired County Scenarios*

| Scenario | County A (taking action) | County B (response) | Δ Flooded area (%) | Δ Flooded mileage (%) | Δ Flooded area (km²) | Δ Flooded mileage (km) |
|----------|--------------------------|---------------------|--------------------|-----------------------|---------------------|------------------------|
| 1        | Santa Clara              | San Mateo           | 3.7                | 11.4                  | 2.2                 | 18.2                   |
| 2        | Santa Clara              | Alameda             | 2.8                | 1.8                   | 2.6                 | 0.5                    |
| 3        | San Mateo                | Santa Clara         | 1.3                | 6.1                   | 0.8                 | 4.0                    |
| 4        | San Mateo                | Alameda             | 2.8                | 4.0                   | 2.7                 | 1.2                    |
| 5        | Alameda                  | Santa Clara         | 3.1                | 11.8                  | 1.8                 | 7.7                    |
| 6        | Alameda                  | San Mateo           | 4.0                | 11.2                  | 2.4                 | 17.9                   |

16% of their original capacities to correctly match the scaling of the travel demand. This ensures that the traffic simulation reflects and preserves actual delays of the original transportation system. Proportional scaling of demand and capacity is consistent with the piecewise linear shape of the highway traffic fundamental diagram (Daganzo, 1997). Under different shoreline protection strategies, the hydrodynamic interactions produce transportation network disruptions that, in turn, lead to changes in traffic flow patterns. The results of the traffic flow patterns are then used to quantify the impact of SLR on the transportation network, using VHT as the metric.

#### 2.4. Scenarios

To examine the coupling between shoreline protection and transportation, we focus our analysis on South San Francisco Bay, where previous analyses have found strong interactions in both the hydrodynamic and traffic systems (Suh et al., 2019; Wang et al., 2018). Under current conditions, commuters rely on major north-south corridors (US Highway 101 and Interstate 880) to travel between San Francisco or Oakland and Silicon Valley and east-west corridors (State Route 237, San Mateo Bridge, Dumbarton Bridge) to travel from the Peninsula to the East Bay (Figure 1). All three South Bay counties have low-lying lands along their shorelines. Transportation infrastructure in San Mateo County is generally closer to the shoreline, while marshes and salt ponds provide a buffer for roadways in Santa Clara and Alameda counties.

We consider the six scenarios shown in Table 1, where one county (County A) takes action to protect its shoreline and another (County B) does not. The decision to create a physical barrier to flooding (a wall or levee) in County A is considered to turn “on” hydrodynamic interactions, leading to additional flooding in County B. The decision not to take protective action, thus allowing expanded areas of inundation in County A, turns “off” hydrodynamic interactions so that County B experiences no additional flooding. The second type of interaction involves regional traffic dynamics, where turning “on” traffic interactions means that roadways in County A experience flooding, affecting traffic congestion in County B. Turning “off” the traffic interactions means that roadways in County A are not disrupted due to flooding, thus preventing traffic delays from propagating into County B.

With these definitions, we can define three plausible scenarios for county-to-county interactions; comparisons of these scenarios allow us to separately evaluate the impacts of hydrodynamics, traffic dynamics, and their interactions on regional VHT (Figure 2). We denote these scenarios as Causeways (Hydrodynamic interactions off, Traffic interactions off = $H_{on}T_{off}$), Free Inundation (Hydrodynamic interactions off, Traffic interactions on = $H_{off}T_{on}$), and Walls (Hydraulic interactions on, Traffic interactions off = $H_{on}T_{off}$). In the Causeways case (Figure 2a), both the hydrodynamic and traffic interdependencies between County A and County B are inactive. That is, County A does not take protective action at its shoreline and allows inundation to progress landward with SLR, but at the same time roadways in County A are not disrupted by that inundation (as if they were all elevated as causeways). As a result, there is no negative impact from the action (or inaction) of County A on other counties in the region. In the Free Inundation case (Figure 2b), County A still does not take protective action at its shoreline, but now roadways in County A are disrupted by the increased inundation. This scenario represents a case where County A takes no protective action, and the resulting inundation leads to deleterious regional effects on traffic congestion. The Walls case (Figure 2c) involves County A taking action to protect its shoreline with a seawall or levee, thus also ensuring no disruption to the roadways in County A. This case therefore causes no regional disruptions due to traffic dynamics, but it does create negative hydrodynamic interdependencies.
For each scenario, we run the CoSMoS and MATSim models to calculate the VHT for $H_{off} T_{off}$, $H_{off} T_{on}$, and $H_{on} T_{off}$. VHT is then tabulated for the roadways in County B (the unprotected county) to isolate the impacts of County A’s actions on traffic congestion in County B. Although from a decision-making perspective the Free Inundation case may be considered the base case for comparison (i.e., the impact of taking no action), we wish to focus here on the interaction between shoreline infrastructure (walls or levees) and transportation infrastructure (roads, bridges, and causeways) and the potential for nonlinear interactions between them. Therefore, to deconvolve the impacts of shoreline infrastructure and transportation infrastructure, we will use the Causeways case as our base case, since it represents no negative interdependencies for either the hydrodynamics (created when walls or levees are constructed as part of the shoreline infrastructure) or the traffic congestion (created when the transportation infrastructure is disrupted by inundation). In the calculations that follow, we use the percent change of VHT induced by each mechanism (hydrodynamics or traffic), computed as follows:

$$\Delta VHT_{\text{hydro}} = \frac{H_{on} T_{off} - H_{off} T_{off}}{H_{off} T_{off}}$$

$$\Delta VHT_{\text{traffic}} = \frac{H_{off} T_{on} - H_{off} T_{off}}{H_{off} T_{off}}$$

Comparing the Walls case ($H_{on} T_{off}$) to the Causeway case ($H_{off} T_{off}$) isolates the impact of shoreline infrastructure development on regional traffic congestion ($\Delta VHT_{\text{hydro}}$). Similarly, the difference between the Free Inundation case ($H_{off} T_{on}$) and the Causeway case ($H_{off} T_{off}$) isolates the regional impact of traffic dynamics on congestion ($\Delta VHT_{\text{traffic}}$). A positive $\Delta VHT_{\text{hydro}}$ indicates that shoreline construction in County A will cause additional flooding and further disruption to the transportation network in County B. A positive $\Delta VHT_{\text{traffic}}$ indicates that disruptions to roadways in County A will propagate through the transportation network to cause additional traffic delays in County B. Implementing shoreline protection in County A will cause hydrodynamic effects ($\Delta VHT_{\text{hydro}}$) but mitigate traffic effects ($\Delta VHT_{\text{traffic}}$). Thus, comparing these values for each scenario allows for an assessment of the costs and benefits of County A’s decision on County B. At the regional scale, these results demonstrate which county-level interactions are strongest and highlight how local and regional hydrodynamic and traffic effects impact the performance of the transportation system.

3. Results

We first present the results of the hydrodynamic modeling to quantify the direct effects of shoreline infrastructure in terms of flooded area and flooded roadway mileage. We then discuss the results of the traffic modeling, which demonstrate how the effects of flooding propagate through the transportation network.
3.1. Hydrodynamic Interactions

The extent of inundation and flooded roadways are shown for each scenario in Figure 3. Table 1 summarizes the change in flooded area and change in flooded roadway mileage for each of the paired county scenarios. In all scenarios, County B typically experiences an increase in flooded area of 1–4% due to the actions of

**Figure 3.** Extent of inundation and flooded roadways for each shoreline protection scenario, including (a) no South Bay protection, (b) Alameda is protected, (c) San Mateo is protected, and (d) Santa Clara is protected. The black lines show the weirs that were added to the model to simulate shoreline protection. The roadway links that experience flooding are highlighted in red.
The largest increases occur in San Mateo, with 3.7% and 4.0% more flooded area due to protection in Santa Clara and Alameda, respectively. San Mateo also experiences increases in flooded roadway mileage as a result of protection in Santa Clara (11.4% increase) and Alameda (11.2% increase). Santa Clara experiences a similar increase when Alameda protects its shorelines (11.8%), but smaller effects due to protection in San Mateo (6.1%). Roadways in Alameda exhibit the smallest increase in flooding due to protection in neighboring counties (1.8% from Santa Clara and 4.0% from San Mateo). The roadways in Alameda County are generally located further inland, behind marshes and salt ponds, which provide some additional protection from the effects of flooding.

### 3.2. Traffic Interactions

Table 2 shows the change in VHT due to hydrodynamic and traffic effects for each of the six paired county scenarios. Random sampling of commuters for the MATSim simulations using 16% of the total commuting population results in a standard error of approximately 3%. As a result, changes in VHT less than ±3% are not considered significant. We therefore focus our discussion on scenarios that produce significant differences compared to the base scenario.

When Santa Clara roadways are disrupted and regional traffic interdependencies are included (Free Inundation), 65 km of roads, including parts of two major highways (Highway 101, which connects San Francisco, San Mateo, and Santa Clara, and Highway 237, which runs along the Santa Clara shoreline and connects Alameda and San Mateo; Figure 1), are inundated. This causes a moderate increase in VHT in San Mateo (3.7%). Hydrodynamic interactions resulting from shoreline protection in Santa Clara (Walls) cause additional flooding of 18.2 km of roads in San Mateo, including parts of Highway 101. Roads in Alameda are not impacted. Despite this increase in flooding along roadways, the change in VHT is within the margin of error for both Santa Clara (−0.1%) and Alameda (−0.2%). Thus, providing protection along the San Mateo shoreline produces regional traffic benefits due to a reduction in flooding on internal roadways, with minimal costs in terms of hydrodynamic effects on roadways in other counties.

When San Mateo roadways are allowed to inundate (Free Inundation), 160 km of roads are impacted, including Highway 101 and the western approach to the San Mateo Bridge connecting San Mateo and Alameda counties. This has a large effect on VHT in Santa Clara (10.7%) and a small but significant effect on VHT in Alameda (3.2%), highlighting the importance of these roadways in the regional transportation network. When the San Mateo shoreline is protected (Walls), hydrodynamic interactions cause additional flooding of 4.0 km of surface streets in Santa Clara and very little additional flooding (1.2 km) in Alameda. The change in VHT is also within the margin of error for both Santa Clara (−0.1%) and Alameda (−0.2%). Thus, providing protection along the San Mateo shoreline produces regional traffic benefits due to a reduction in flooding on internal roadways, with minimal costs in terms of hydrodynamic effects on roadways in other counties.

Inundation in Alameda (Free Inundation) impacts 29.4 km of roads, mainly surface streets. This leads to insignificant changes in VHT in Santa Clara (0.8%) and San Mateo (0.4%). On the other hand, when Alameda protects its shoreline (Walls), flooding of an additional 7.7 km of surface streets occurs in Santa Clara, along with flooding of parts of Highway 101 and the western approach to the Dumbarton Bridge.
connecting San Mateo and Alameda, totaling 17.9 km of impacted roads. This causes a significant increase in VHT in Santa Clara (7.2%). Impacts on VHT in San Mateo (−1.5%) are not significant. The interaction between Alameda and Santa Clara highlights the hydrodynamic interdependencies triggered by shoreline infrastructure development, which cascade to create impacts on the transportation infrastructure in adjoining jurisdictions. In contrast to protecting San Mateo, protecting the Alameda shoreline produces regional costs due to hydrodynamic interactions while providing little benefit in terms of avoided traffic effects.

4. Discussion and Conclusions

4.1. System Interactions

Comparing the inundation and traffic results for the scenarios, we can see the importance of using a systems approach that accounts for multiple infrastructure systems and their internal and external connections. In the shoreline system, the internal connections are driven by the hydrodynamic feedbacks between the tides and the shoreline configuration. In the transportation system, the internal connections are a function of the traffic network topology and flow pattern. The interactions between the flood hazard and the infrastructure network define the overall impact on the system and may lead to new insights that are not visible merely by considering the systems separately. For example, when Santa Clara protects its shoreline, an additional 18.2 km of roadways are flooded in San Mateo, but the change in VHT is not significant. Thus, while the hydrodynamic feedbacks seem large, the impact on traffic is small. In contrast, when Alameda protects its shoreline, an additional 7.7 km of roads are flooded in Santa Clara, and VHT increases by 1,636 hr. A moderate hydrodynamic feedback thus produces a significant increase in travel delays. This suggests a potential chokepoint in the transportation system in Santa Clara, as the system is not able to adjust as readily to accommodate loss of capacity on certain road segments. These insights are useful to decision-makers who wish to identify critical links within the transportation system that exacerbate traffic congestion and could be prioritized for mitigation actions.

Modeling the shoreline and transportation systems together also allows us to separate the hydrodynamic and traffic effects on travel delays, which promotes more robust planning that can target each effect individually. Previous analyses have focused on quantifying the overall effect of flooding on travel delays, without attributing the delays to specific causes (Papakonstantinou et al., 2019a, 2019b). As a result, it was not clear whether the regional impacts of each shoreline protection scenario were due to feedbacks in the hydrodynamic system resulting from shoreline modifications or in the transportation network resulting from regional traffic flow pattern changes. Our results suggest that both effects play a role in defining regional travel delays and that the relative strength of the effects varies by location, depending on the specific arrangement and structure of the transportation system in relation to the flood hazard zone. For example, because Alameda’s major transportation corridors are located further inland and are less prone to flooding, the impact of free inundation in Alameda results in negligible regional traffic effects. San Mateo’s roadways, on the other hand, are located in the flood zone and, if not protected, experience substantial flooding that results in regional travel delays for Alameda and Santa Clara.

4.2. Implications for Planning

Modeling the interactions between infrastructure systems and their regional feedbacks can facilitate more comprehensive regional cost-benefit analyses. A particular shoreline adaptation project may have a favorable benefit-cost ratio locally, within the project’s geographic scope, but may cause unintended impacts in other jurisdictions, thus requiring additional investment to mitigate negative effects. In the context of this study, the cost of exacerbating flooding on roadways in other jurisdictions can be compared with the benefit of reducing flooding on local roadways to evaluate the efficacy of county-level protection strategies. If the benefits outweigh the costs, as is the case when San Mateo protects its shoreline, a project may be viewed more favorably from a regional planning perspective, as it will not require large investment to mitigate negative external effects.

More broadly, this analysis demonstrates that long-term infrastructure planning requires an integrated and holistic approach that accounts for the infrastructure interactions across scales (local to regional) and sectors. Modifications made to one system will not only affect the physical processes it governs (e.g., shoreline infrastructure and flooding) but will also affect other interacting networks and cause cascading impacts (whether positive or negative) to propagate through these systems. It does not make sense for the regional...
transportation authority to develop SLR adaptation plans without also considering how the shoreline might be modified over the coming decades, since the spatial distribution of flooding in the transportation network is inextricably linked to the shoreline configuration. Overcoming limitations to coordinated management of interacting infrastructure networks, including different ownership structures (public versus private) and planning horizons, is critical to effectively mitigate future hazards. This can be achieved through sustained, integrated assessment and planning efforts that cross jurisdictional and sectoral boundaries and promote a regional vision for SLR adaptation (Lubell, 2017).

4.3. Limitations

In this study, we used simplified but representative models of the shoreline infrastructure and transportation system to examine the interdependence between hydrodynamic and traffic effects and the relative magnitude of their interactions. The results are based on a single representative simulation of the hydrodynamic and traffic models for each scenario. Uncertainties in the hydrodynamic model include inaccuracies in land surface elevation and vertical land motion due to subsidence and/or uplift. Uncertainties in the traffic model stem from the demand side, which relies on surveys of actual commuters in the San Francisco Bay Area, and agent sampling, which is used to randomly select a subpopulation of agents to model (in this case, 16% of all agents, as described in section 2.3). For our simulations, we estimate that changes in VHT less than ±3% are within the uncertainty of the model. When evaluating and selecting likely flood mitigation alternatives for implementation, decision-makers may wish to perform a more thorough assessment of uncertainty in the calculated ΔVHT values to ensure that the selected alternatives are robust to variations in demand and commuting behaviors. In this case, repeated stochastic simulations of the system could be performed to estimate the range of potential costs and benefits association with each alternative.

This analysis considers only the impacts on travel delays in the transportation network. While the results could prove useful for decision-makers as they evaluate potential shoreline alternatives for flood mitigation, impacts on other infrastructure systems, critical facilities, and residential and commercial properties will also factor into these decisions and may tip the scale toward a different mitigation alternative. The integrated infrastructure modeling approach presented in this study can be replicated for other infrastructure systems to provide a more complete analysis of potential interdependencies between networks and across scales, from local to regional.

Finally, we have only considered one SLR scenario (50 cm) and a static network of roadways and commuters in this analysis. The actual impacts on the region will depend on the rate at which SLR progresses, the extent of disruptions to the transportation system, the behavioral adjustments that commuters make in response (e.g., living closer to work or switching to other transportation modes), and any associated modifications made to the transportation network (e.g., floodproofing of existing roads or construction of new roads). Our ability to understand and model the coupling between changing physical systems resulting from natural disasters and human response is still in a nascent stage but presents a ripe area for future research that could enhance the effectiveness of adaptation planning.

Overall, our results highlight the interdependencies that exist between the shoreline protective infrastructure, which determines flooding, and the transportation network, which experiences disruptions as a result of flooding. These interdependencies occur both at the local scale, where protective infrastructure like levees and seawalls can directly mitigate flooding of neighboring roads, and at the regional scale, where decisions about shoreline protection in one community can exacerbate flooding and traffic delays in other areas. Thus, decision-makers must account for the choices of others, both across infrastructure systems (shoreline and transportation) and across geographies (counties), when formulating strategies to mitigate the impacts of SLR on lives and livelihoods. If interdependencies are ignored when developing SLR adaptation strategies and shoreline infrastructure plans, projects may result in unanticipated negative consequences for other communities, and potential benefits may be overestimated.

Data Availability Statement

The data used in this analysis is available through the Zenodo data repository at the following link (http://doi.org/10.5281/zenodo.3978456).
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