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Highway Infrastructure Protection against Sea Level Rise: Policy Recommendations for Cooperative and Competitive Decision-Makers

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Abstract

This research investigates the influence of decision-maker behaviour on policies that are likely to be adopted for the protection of highway infrastructure against inundations resulting from sea level rise. We analyse two different types of games to represent decision-maker behaviour, and use the San Francisco Bay Area shoreline with a scenario of a 0.5m sea level rise as a case study. In our model, the objective of the decision-makers (the counties bordering the SF Bay Area) is to minimize the traffic delay caused by inundations in the transportation network that lies in the geographical boundaries of their counties. Our model considers hydrodynamic interactions, traffic flow patterns changes as a result of inundations, and budget constraints on the protection costs. The hydrodynamics in the Bay Area are affected by the shoreline protection strategy: protection of the shoreline of a county may lead to increased inundations in another, unprotected, county. Furthermore, closure of a highway link in one county affects traffic delays in other counties due to traffic re-routing. Thus, protection decisions made by a county have potential impacts on several other counties, and therefore counties must take into account other counties' actions. Both competitive (Nash) and cooperative games are analysed. It is shown, through several examples, that cooperation among counties increases benefits (reduction of

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Vehicle Hours Travelled) for all participants in most cases. In some cases, cooperation also reduces protection costs.

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Keywords: Nash Equilibrium; Cooperative Games; Sea level rise; Protection of shoreline infrastructure; Transportation networks

1. Introduction

According to forecasts (Rahmstorf, 2007), sea-level in 2100 will possibly rise by 0.5-1.4 meters compared to 1990 levels. The resulting shoreline inundations will affect the coastal highway infrastructure and disrupt transportation systems causing delays, trip cancellations and accessibility reduction. Due to network effects, inundation of a link may lead to increased delays throughout the transportation system (Nicholls et al., 2007; Koetse and Rietveld, 2009; Chang et al., 2010). Thus, identifying policies to minimize these consequences and increase resilience against Sea-Level Rise (SLR) is vital for the protection of transportation networks.

The literature contains a large body of research focused on evaluating the risk of exposure and vulnerability of infrastructure and quantifying the levels of impact of future sea level rise. Some of the research is related to land use and properties or business: Geisler and Currens (2017) describe barriers to prevent water from entering inland areas and suggest proactive and adaptive policies. Song et al. (2016) develop a framework to evaluate the impacts of SLR on business, including infrastructure and apply it in Bay County, Florida.

For the case of transportation infrastructure, Dawson et al. (2016) assess the costs related to the railway disruption from SLR on a part of the London – Penzance railway. Habel et al. (2017) suggest that SLR will impact $5 billion of taxable real estate and 48 km of road network in Hawaii. Some works are specifically related to the performance of transportation network under inundations. Suarez et al. (2005) evaluate the impacts of coastal flooding on the road network on the Boston Metropolitan area, considering changes in land use and population, and find that delays and lost trips will be doubled. Demirel et al. (2015) examine how the EU road network will possibly react to transportation infrastructure disruptions due to sea level rise. The authors develop a general framework for policymakers, which can be used to assess the results of inundations of transportation infrastructure. Asadabadi and Miller-Hooks (2017) quantify the effect of accounting for stochasticity in climate impact predictions on infrastructure protection planning. They perform experiments under different predictions and conclude that there are significant cost savings when there is improved accuracy in predictions.

Some papers in the literature specifically focus on levee installation for protection against SLR. Haddad et al. (2015) calculate the optimal levee location and size that optimizes the net benefit of flood control. Peng and Song (2018) evaluate the policy of levee installation to protect Miami, Florida against flooding, using cost-benefit analysis. Lee et al. (2018) present a framework for levee budget allocation among counties around the San Francisco Bay Area to minimize the total traffic delay resulting from SLR inundations.

The literature does not consider the interaction among different decision-makers in the context of infrastructure protection in the face of SLR. Coastal flooding occurs in areas that do not necessarily fall under the jurisdiction of a single decision-maker. The protection strategy selected by a decision-making agency can increase flooding in areas outside its jurisdiction. In this paper, we adopt game theory approaches to simulate the interactions between the decision-makers and identify policies that may reduce such negative externalities.

Game theory concepts have been used widely in the field of transportation. Possible applications of Nash and Stackelberg games in different transportation problems were discussed by Fisk (1984). Bell (1999) considers a game theory approach with user pessimism about the expected network performance and later, in Bell (2004) the vehicle routing problem is analyzed with game theory. Kita (1999) considers a non-cooperative game among pairs of merging and through cars on a highway. In the area of connected vehicles, Talebpour et al. (2015) adopt a game theory approach for the flow of information. Adler and Blue (2002) suggest a game among drivers that follow a guidance system, information service providers, and network managers.

In the above cases, the games are between the network users and the authorities, or only between network users. There is an additional part of literature where the games occur between authorities, which is relevant to our problem. In the rail industry, Hsu et al. (2010) discuss the game between high speed and conventional rail and solve for the prices of the two services based on Nash equilibrium. In Medda (2007), the author considers the transportation public and private sectors as players, to solve for the risk allocation among them. Fragnelli (2000) discusses the cost allocation between the agents that should pay for the maintenance of infrastructure. Bergantino and Coppejans (2000) use a similar approach, considering the ship-owners as players to allocate maritime infrastructure costs. In Özener and Ergun (2008), the authors allocate shipping costs to shippers when they collaborate in logistics network. Matsubayashi et al. (2005) also use cooperation games for cost allocation among agents aiming to build hub-spoke networks, accounting for congestion. In the context of cost allocation, Littlechild and Owen (1973) have published related work where they consider cooperation among airlines for the building cost component of the fees paid when using airports.

In this paper, we model the problem of transportation network protection in inundation-susceptible regions which fall under the jurisdiction of multiple agencies as games among the decision makers. The present paper extends our previous work (Lee et al 2018), which approached the problem from the perspective of a centralized decision-maker, allocating limited protection resources to achieve a system-optimal solution in the San Francisco Bay Area. In reality, the lack of coordination and conflicts of interest among the decision-makers makes the problem more suitable to a game-theoretic approach.

In this paper, the objective of the decision-makers is to minimize the total delay occurring in the transportation network from inundation events. The decision-makers' actions affect inundation in the counties of other decision-makers, and the traffic delays, resulting from inundation and motorists' rerouting in the network, vary according to these actions.

The paper is organized as follows. First, we present the geographical area under consideration and its characteristics. Then we discuss two different game theoretical approaches that we examine for the decision-making interactions. We then highlight some practical insights obtained from the implementation of the different approaches. We conclude with observations regarding the relative merits of the two types of decision-making strategies.

2. Methodology

We consider players who represent coastal communities vulnerable to inundations due to SLR; each can decide whether to build a levee at each levee candidate site along its shoreline or to invest funds to build levees along other counties' shorelines. Levee installation along the shoreline of a county affects the inundation levels on other counties. Drivers react to the existence of cut links by rerouting, which depends on the links that are inundated and can affect areas that are beyond the inundated counties. Thus the decision of each county directly affects the traffic congestion levels in other counties. We quantify the benefits as reduced Vehicle Hours Traveled (VHTs) compared to the default scenario where there is no new levee installation.

The players may decide to act either competitively or cooperatively with each other. In the first case, their actions lead to a Nash equilibrium, that is the steady state where no player has an incentive to change their action (Nash 1951). For each possible levee installation strategy, the expected benefit (in VHTs) for every player is compared to the strategies that correspond to changing this player's decision, when all the other players' actions, remain constant.

In the second case, some players form a team or teams and collaboratively invest in protecting the shorelines that yield the best benefit for their coalition. The non-cooperating players act competitively, so the problem can be defined as a mixed-competitive-and-cooperative game. Cooperation is only possible if none of the participants in the coalition suffers a reduction in benefit, relative to that of the corresponding Nash equilibrium, and the summation of the coalition members' benefits is higher than the pure Nash scenarios. Players are allowed to build levees on the shoreline of another county if the latter does not have a sufficient budget to install the levee. Players whose shoreline will be protected, independently of whether they contribute funding or not, have the right to approve or refuse the levee installation. Players that do not have a budget or do not receive funding for a levee do not participate in the cooperation, and thus their benefit could be lower than that under Nash equilibrium. When a cooperation strategy is suggested, the total levee installation cost should be distributed among the participants not according to their shoreline length, but according to the benefit they gain from their participation. For this, we use the Shapley value that divides the total surplus created by cooperation among the players (Shapley, 1953).

3. Findings

This paper uses the San Francisco Bay Area, shown in Figure 1, as a case study. This area is interesting because of its long shoreline that is exposed to inundations (Knowles, 2010; Ellen and Wieczorek, 1988), its high population of around 7 million (US Bureau of the Census, 2010), and the existence of several decision-makers (counties), who according to their policies may create different dynamics and influence the future of the Bay. The expected SLR has led to different levels of action among the local communities, with some at advanced levels of planning (Stacey et al., 2017).

Fig. 1. Map of the San Francisco Bay Area Counties, generated on QGIS (www.census.gov).

We consider the counties around the Bay as decision-makers and investigate the dynamics among their decisions. Each county can decide whether or not to build a levee along its shoreline, and also has the option to invest funds to build levees along other counties' shorelines. The levee combinations produced by these decisions yield different hydrodynamics in the Bay. A hydrodynamic prediction, using the DeltaRes simulator (DeltaRes, 2015) with CoSMoS ((Barnard et al., 2014) is performed to identify the areas that will be inundated under a certain protection scenario. We consider a sea level rise of 0.5m, which is projected to occur in 2054. In fact, sea level rise cannot be accurately predicted, as ice sheets may be inherently unstable (Bamber, 2009). An estimation of the range of the possible sea level rise is 0-3.3m (Bamber, 2009) and considering 0.5m can be a safe assumption within this range according to the Intergovernmental Panel on Climate Change's A2 scenario (Stocker, 2014). For the inundated areas, we assume that the corresponding highway links are cut permanently, and we obtain the resulting traffic flow pattern, using User Equilibrium. The analysis is done with the expected highway traffic demand in 2054 (California Statewide Travel Demand Model, 2014). The network used includes only freeways and major arterials.

The counties along the Bay shoreline that are considered as players are Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, and San Mateo. San Francisco county is not considered as a player, because its shoreline is always protected due to its importance, as explained in Lee et al. (2018). Thus, the total number of players is eight. For every combination of counties' levee protections, we identify the links that are inundated and the resulting traffic flow pattern. This allows us to compute the difference in Vehicle Hours Traveled (VHTs) between that combination and the case of zero protection (i.e., where no county is protected). Each protection scenario has an associated levee installation cost. This cost is expressed in shoreline length because it is reasonable to assume that it is linearly related to the length of the levee.

As explained earlier, the decisions of participants affect the resulting congestion in the counties of other participants because the existence of levees on the shoreline of a county may lead to increased inundations in other counties. The resulting highway link inundations have effects on traffic delays beyond the affected counties, as motorists change their routes, leading to increased congestion in counties further away from the inundation.

For every combination of counties' levee protections, we identify the links that are inundated and the resulting traffic flow pattern by User Equilibrium, using the expected highway traffic demand in 2054 (California Statewide Travel Demand Model, 2014). Each protection scenario has an associated levee installation cost, expressed in shoreline length. We consider that counties either have no budget or have a limited budget, equal to that needed to build a levee on their own shoreline. This case is interesting, because in some scenarios, even though counties are economically capable of protecting themselves, they choose to leave their shoreline unprotected and instead invest their budget in protecting other counties, which yields higher benefit for them. This reveals how important cooperation can be.

First, we identify a case with the highest difference in total benefit between Nash and cooperation strategies. In Figure 2 the budget scenario Q is {Napa, Alameda}, meaning that counties Napa and Alameda are the ones that invest funds. In this case, the Nash equilibrium is {Napa, Alameda}: when all counties act competitively, the result would be to protect Napa's and Alameda's shoreline.

There are several possible cooperation strategies where the levee scenario {Marin, Solano, Santa Clara} is the one that yields the highest benefits. In Figure 2, it is obvious that for the funding counties (Napa and Alameda) as well as for all the counties that will receive protection (Marin, Solano, Santa Clara) the benefits of this cooperation scenario are higher or equal to those of the Nash equilibrium, and this is why the cooperation is possible. This result is not obvious: policymakers would probably not think that if Napa and Alameda had a budget to invest, protecting Marin, Solano and Santa Clara would be the best solution in terms of traffic delay minimization. This represents a very high improvement compared to the Nash equilibrium (178,834VHT/hr).

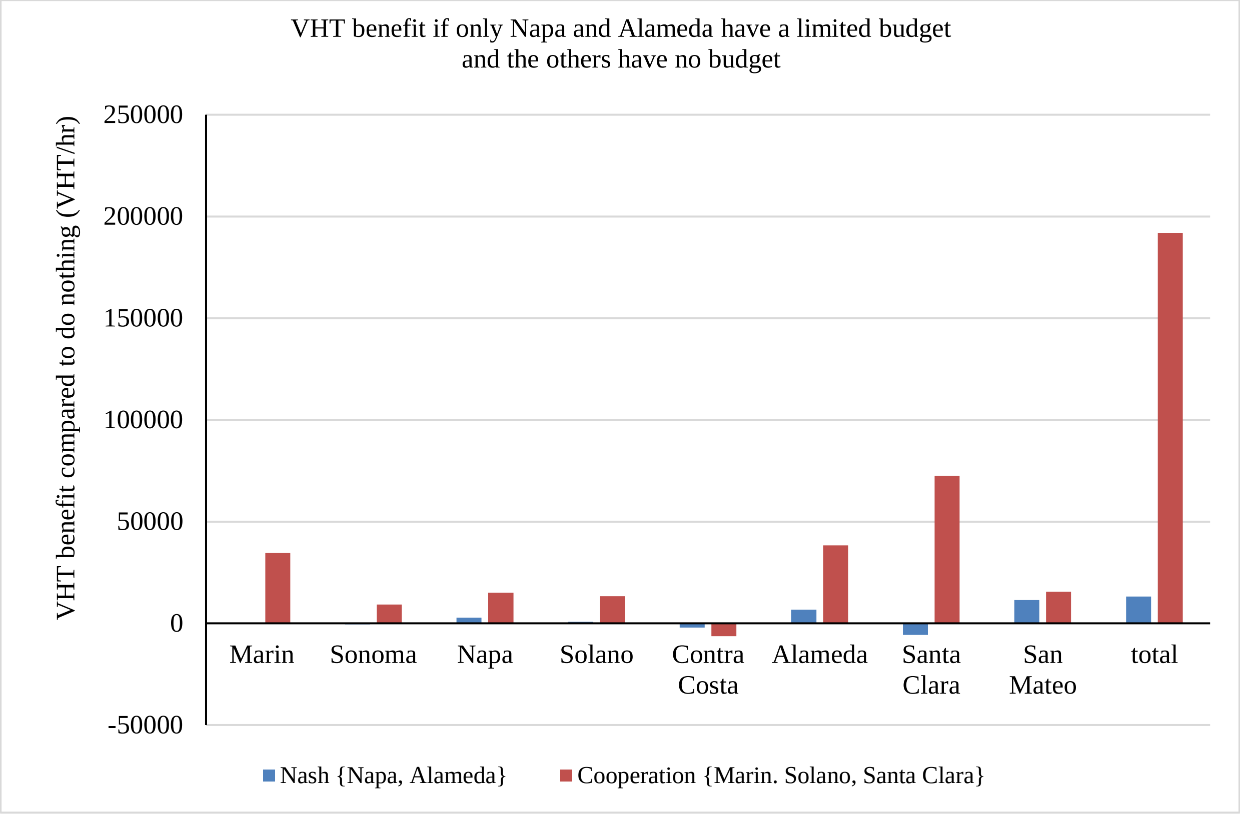

Fig. 2. VHT benefit for Nash and Cooperation strategies, when Napa and Alameda are funding with a limited budget.

Additionally, in this case is that not only does cooperation yield higher benefits for both funding counties and overall, but it also involves lower costs in comparison to the Nash case for both counties, as represented in Figure 3.

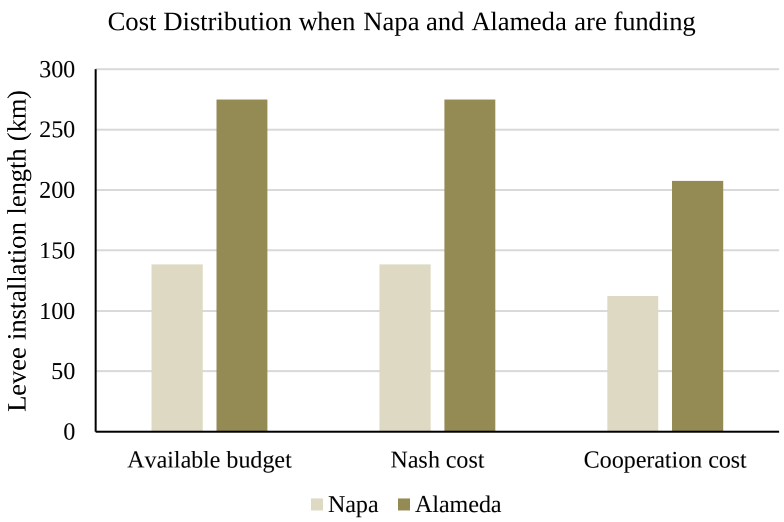

Fig. 3. Cost distribution when Napa and Alameda are funding, with a limited budget

For each funding scenario, there can be several possible cooperation scenarios. There is a subset of the possible cooperation scenarios for which the benefit of the funding counties is maximum and another subset where the benefit of all counties is maximum. For example, for the scenario where Napa and Alameda are the funding counties under budget constraint, which was analytically described in Figures 2 and 3, the case that yields the highest benefits for the funding counties (64,386VHT/hr) is coalition 1, to protect Marin and Solano, where the total benefit for all counties is 154,800VHT/hr, as seen in Table 1. However, for coalition 2, to protect Marin, Solano and Santa Clara, the total benefit increases to 191,996VHT/hr, but in that case the benefits for the funding counties are lower (53,288VHT/hr). Thus, the funding counties will choose to implement coalition 1, even though coalition 2 would be better for all counties in the Bay Area.

TABLE 1 VHT benefits when Napa and Alameda are funding, under a limited budget. Coalition 1 yields the highest benefits for the funding counties and Coalition 2 yields the highest benefits for all counties.

Levee Scenario	VHT Benefits compared to do nothing										
	Marin	Sonoma	Napa	Solano	Contra Costa	Alameda	Santa Clara	San Mateo	Total for funding counties	Total for all counties	Cost
Nash {3,6}	-182	-482	2767	705	-2038	6664	-5775	11504	9431	13161	414
Cooperation1 {1,4}	34129	10255	15292	13769	-3537	49093	36606	-809	64386	154800	241
Cooperation2 {1,4,7}	34562	9314	15042	13319	-6363	38245	72396	15480	53288	191996	320

Naturally, there may also be a subset that includes cooperation scenarios that yield the optimal benefit both for the funding counties and for the total of counties. For the cases where this occurs, choosing a strategy from this subset is optimal for both the funding counties and the system optimal. However, as this is not always the case, there should be incentives for the funding counties to move from the strategy that maximizes their own benefits to the one that maximizes the overall benefit.

Another interesting result is the case where Marin, Santa Clara, and San Mateo are the funding counties. The shorelines of these three counties are the ones whose protection is the most critical according to the Pareto frontier in Lee et al. (2018), and they are responsible for the highest percentage of VHT reduction. In this case, the Nash equilibrium is to protect Marin, Santa Clara, and San Mateo. The optimal cooperation scenario, under budget constraint, is the same: to protect only their own shorelines. This is a rational decision as these are the most critical counties and do not benefit from leaving their shorelines unprotected and protect other counties' shorelines. If however the budget constraint is removed, the optimal cooperation strategy is to protect additionally Solano, Contra Costa and Alameda.

There is also chance that for a specific funding scenario, no cooperation strategy is possible, because no combination is better than the Nash equilibrium. For example, when Marin and Alameda are the only funding counties, as represented in Figure 4, the Nash equilibrium is to build a levee along Marin and Alameda shorelines. Even if the two counties have no budget constraint, they only choose to implement this Nash strategy and not a cooperation combination. This insight is compatible with the fact that this is a Pareto optimal strategy. In Figure 4 we compare it with the system optimal protection strategy found in Lee et al. (2018) and we see that for Marin the benefit is lower, and Contra Costa's benefit is reduced, which is why full protection cannot be a suggested cooperation. In this case, decision-makers can be sure that this strategy is the best solution.

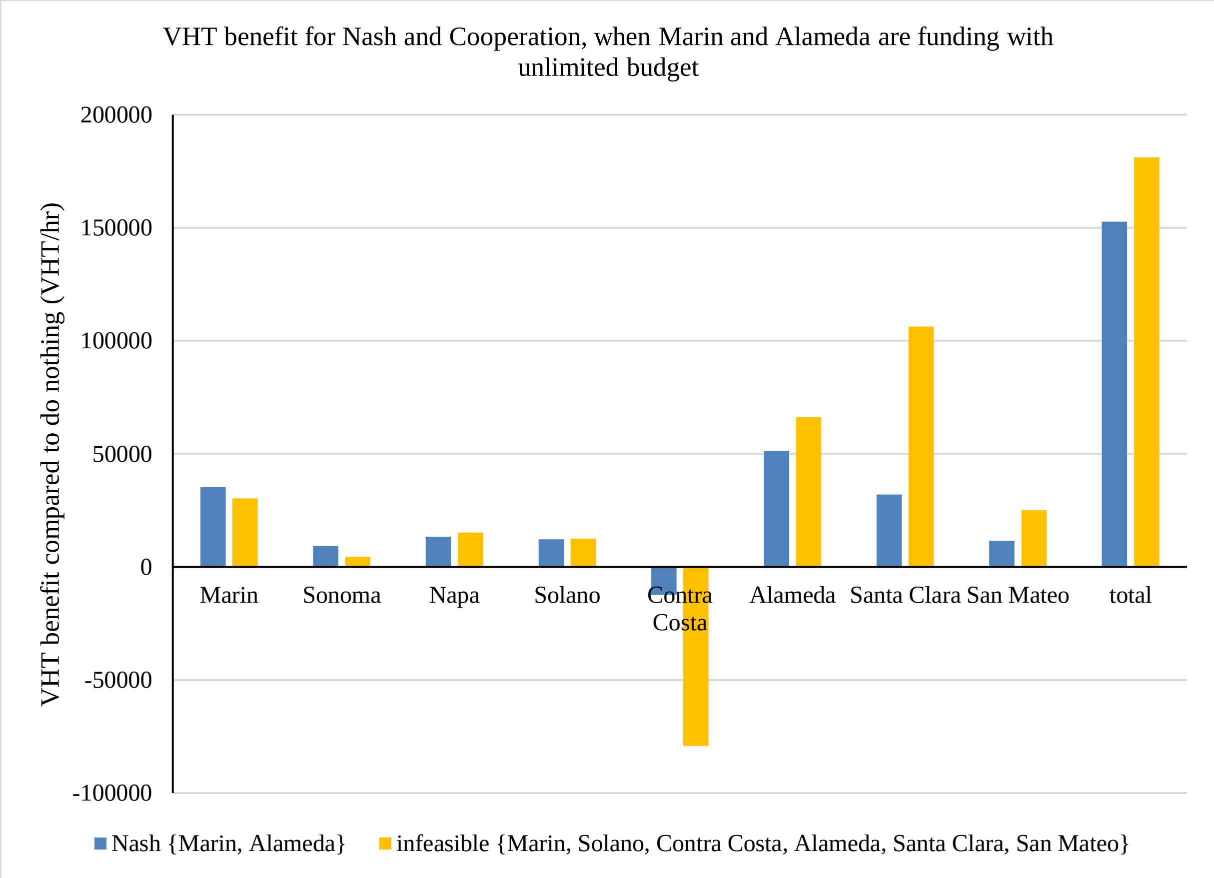

Fig. 4. VHT benefit for Nash and Cooperation, when Marin and Alameda are funding with unlimited budget.

4. Conclusions and Future Work

There are four conclusions:

1. Cooperation is beneficial for counties in most cases. It is shown that, for counties whose shoreline is not critical, cooperation can multiply their VHT benefits relative to Nash equilibrium, because instead of investing their budget to protect their shoreline, they can contribute to the protection of other more critical shorelines that lead to a reduction of their own traffic delays.
2. The extent to which cooperation is more beneficial than a Nash equilibrium varies, depending on the coalition of funding counties, the available budget and the impact of each levee on other counties.
3. Cooperation can be cost saving compared to Nash equilibrium.
4. The cooperation strategies that maximize the VHT benefit of funding counties do not necessarily maximize the overall VHT benefit in the Bay. Thus, it is suggested that incentives are given to funding counties to move to strategies that maximize the total benefit for the entire SF Bay Area.

This research has several possible extensions. Realistically, each county can take action at a different point in time. This creates different levels of actions, where counties that act ahead of others can be considered as leaders and counties that act later can be seen as followers, since at the time they act, there is a specific levee installation policy already in place. Additionally, counties can be categorized into different hierarchical levels according to their societal engagement in the Bay Area and influence on other counties. These formations of county levels either depending on time of action or on engagement, allow us to consider this situation as a multi-level Stackelberg game. This is the subject of ongoing work by the research team.

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