Coastal Protection Strategies to Minimize Transportation Network Disruption from Sea Level Rise

Ilia Papakonstantinou
Post-doctoral researcher, Engineering Division, New York University Abu Dhabi, Abu Dhabi, UAE

Alain T. Siwe
Research Associate, Engineering Division, New York University Abu Dhabi, Abu Dhabi, UAE

Aaron C.H. Chow
Research Scientist, Engineering Division, New York University Abu Dhabi, Abu Dhabi, UAE

Samer M. Madanat
Professor, Engineering Division, New York University Abu Dhabi, Abu Dhabi, UAE

ABSTRACT: As sea levels rise, there has been an increase in research focused on the protection of shoreline infrastructure and transportation systems that may increasingly suffer from permanent capacity and accessibility reduction. This paper focuses on Abu Dhabi, UAE, a city vulnerable to inundation due to its insular geography, aiming to identify protection strategies that will minimize transportation network delays. The model considers hydrodynamic interactions and traffic assignment. The results show some shoreline portions are critical, and their protection leads to lower congestion, while there are combinations of shoreline protection that worsen the congestion levels. The results also show that in some cases, the marginal effects of protecting one precinct may yield a better reduction of congestion than multiple other precincts. This research can provide a general framework for the protection of transportation infrastructure against sea level rise.

1. INTRODUCTION

Sea level rise (SLR) may have considerable impact on coastal regions threatening countries with long coastlines or islands. Dangendorf et al. (2019) identified a persistent acceleration in global mean sea level since the 1960s.

Nazarnia et al. (2020) review and analyze research works on the impact of SLR on coastal infrastructure, considering the type of infrastructure and the adaptation method suggested. There are several papers that examine the effects of SLR on a variety of aspects and this shows the importance of the phenomenon; for example, Hummel et al. (2018) focus on how wastewater infrastructure in coastal areas will be affected by marine and groundwater floods. Traffic networks are even more vulnerable to inundation as seas rise, motivating the need for robust coastal adaptation plans. This proven increase of sea level rise threatens transportation networks, as floods may reduce links' capacity, as well as decreasing accessibility (ease of reaching destinations or activities distributed in space) due to isolation or inundation. Increased congestion due to inundated links can create higher loading elsewhere in the network as traffic may reroute to available links, thus increasing congestion on these links, which would increase travel times considerably (Chang et al., 2010). Lu and Peng (2011) consider how accessibility is reduced for several sea levels and describe the corresponding vulnerability of the network. Sun et al. (2022) discuss the relationship between transportation equity and SLR protections, and measure the accessibility and mobility (a measure of how far one can go in a given amount of time) of disadvantaged communities compared to others.

Another group of studies map the areas vulnerable to inundation, according to hydrodynamics and how they impact coastal transportation networks (Knowles, 2010). Monioudi et al. (2018) assess potential operational disruptions of the critical transportation infrastructure to climate change focusing on Caribbean small island developing states. Renne et al. (2021) attempt to qualify SLR impacts using visualization tools and comparing the before- and after-effects. Their approach increased the understanding of the audience, which helps to motivate decision makers to become more aware of the impacts of SLR. Other studies attempt to maximize the protection of flooded areas, considering strategies that include levee installation. A synthesis of literature related to the resilience of transportation systems is attempted by Zhou et al., (2019).

To avoid network disruptions due to SLR, preventive actions and adaptation plans are necessary (Nicholls and Cazenave, 2010), including installation of levees across shorelines, that protect the lands from floods. An approach related to this research is attempted by Papakonstantinou et al. (2019A), who consider levee installation on different parts of a shoreline in the San Francisco Bay Area, and the resulting hydrodynamic interactions, and identify protection combination scenarios that lead to lower delays, under budget constraints. Papakonstantinou et al. (2019B) continued to investigate the effects of the various decision makers in the area and the strategies that they may adopt against sea level rise, on the transportation network performance, employing game theory to represent different entities. Madanat et al. (2019) showed that a county's traffic congestion may be alleviated not by protecting its own coastlines, but by protecting other counties' shorelines, and they specify explicit strategies that yield the lowest congestion levels, depending on the available budget. Suh et al. (2019) focused on the road network of the San Francisco Bay area, using homogeneous sections to be protected with levees against SLR, and determined the high-risk regions considering hydrodynamic interactions. Sun et al. (2020) extended the work by integrating the public transportation system and allowing it to interact with other systems when different protection strategies were applied. The inclusion of the public transportation system helped the authors to identify transportation equity challenges against sea level rise (Sun et al., 2021).

The research in this field is increasing, but a holistic approach including hydrodynamic interactions and their interaction with coastal protection strategies, and their combined effect on traffic flow for Persian Gulf cities such as Abu Dhabi has never been examined before. The current paper aims to minimize the total delays in the transportation network by protecting the relevant parts of the shoreline, considering the effect of the protection on the hydrodynamics in the area. The protection strategy considered is levee construction across parts of the shoreline. Our model considers that each levee installed may impact inundation in other areas of the study location, and additionally, the transportation network interactions, which may result in delays in areas that initially may seem distant, due to queue spillback or traffic rerouting. We employ the transportation simulator used by UAE government agencies, therefore yielding a high level of realism. This connection also allows for our results and policies to be considered by the government when planning future infrastructure.

2. CASE STUDY

Abu Dhabi is one of the United Arab Emirates, located in the Persian Gulf, with a low elevation (most of the city is lower than 5 m above mean sea level) and is constituted of a system of coastal mangrove islands, as shown in the map of Figure 1. These characteristics render the city highly susceptible to inundation due to SLR.

The transportation network of interest consists of the streets in the entire emirate of Abu Dhabi, including locations away from the coast. For our research, the corridors along the coastline and the central business district (CBD) located on the main island are of primary importance, together with the bridges connecting it to the mainland and other islands.

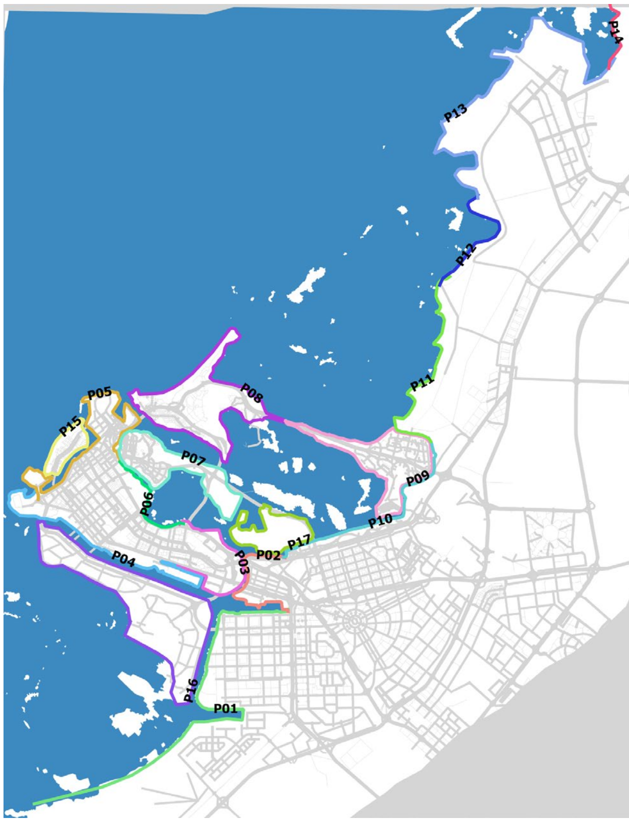

Figure 1: Map of the study area and precinct numbering across Abu Dhabi shoreline

As seas rise, the city could adapt to protect its infrastructure and transportation network by installing levees across parts of the shoreline. The combination of the parts that are protected affects the hydrodynamic response in the channels, and this results in different inundated areas.

The coastal hydrodynamics model used for the analysis is a combination of three separate models: one to model the tidal water levels and storm surge; one to calculate a representative wave set-up, and one for the wave run-up. The tidal water levels are predicted using a two-dimensional shallow water Reynolds Averaged Navier Stokes (RANS) model, modified from the Arabian Gulf Community model by Deltares (http://www.agmcommunity.org, Deltares, 2021). Descriptions of these models are described in greater detail in Chow and Sun (2022).

Given the complex coastline of the city of Abu Dhabi, it is necessary to consider the protection of different sections of its shoreline. The partition of the shoreline was informed by the precincts along the coast in the Urban Structure Framework of the Abu Dhabi 2030 Plan. This allowed us to identify the overall pattern of the city and name the partitions matching their corresponding precinct. We performed further refinement to divide the main Abu Dhabi Island, to group other islands and to define the boundary between some precincts. As a result, we consider 17 precincts according to the map in Figure 1.

2.1. Traffic Network Model

Using the results of the hydrodynamic simulations as inputs, we predict the inundations of links in the transportation network from flooding that will result from different protection strategies, and we simulate the impacts on the traffic flow pattern. We explore several cases, starting from cases where only one precinct is protected, to quantify the marginal transportation network effects from that protection action.

To predict inundation, we overlay the water levels with the topography. This is done by comparing the peak water level of the hydrodynamic simulation against the topographic elevation from the Digital Surface Model, purchased from LandInfo at a 12m resolution. We identify the areas that are flooded by comparing the water elevation to the height of the roads at each region of the network.

The flooded roads are removed from the network and the reduced network is then used as an input for the traffic simulation. The simulations are performed using the transportation network of 2040, which includes the changes in the supply and demand that will take place in the interim years, according to the Abu Dhabi Integrated Transport Center. This projected network was the closest in time to the 0.5m SLR projection in 2040 as described above. For the traffic simulations, we use the Strategic Transportation Evaluation and Assessment Model (STEAM), a regional strategic simulator that does not only consider the transportation network but also changes in land use, and other strategic decisions. STEAM is based on CUBE software, which is a widely used transportation simulator. STEAM uses the traditional four step modeling approach: trip generation, trip distribution, mode choice and traffic assignment. This platform is not accessible to the public, but it is granted to organizations in collaboration with the Integrated Transportation Center (ITC) of Abu Dhabi.

The metrics that we consider refer to mobility, including Vehicle Hours Traveled (VHT) and Vehicle Kilometers Traveled (VKT), that are network-wide values, Volume to capacity (V/C) Ratio, the ratio of cars along each street to its capacity, used to indicate congestion along individual street, and VHT per vehicle, also used as a network congestion measure. For comparison of different scenarios, we use percentage changes instead of absolute numbers, using as reference the base case of protecting all precincts. The metric used to quantify accessibility is the Number of vehicles on the network, which, if lower than the case of no inundation, shows a reduction in accessibility, as commuters opt out of taking a trip due to the very high travel times.

2.2. Results

For notation purposes, case P01 denotes that only Precinct 1 is protected, with all others not protected. Case P_None denotes no precinct is protected and case P_All denotes all precincts are protected. Different protection strategies are explored, aiming to identify their impacts in terms of hydrodynamic and traffic interactions, and identify the ones that may be beneficial. Focusing first on only the hydrodynamic impacts, we observe that protecting one precinct may affect the flooding in multiple other precincts. Most protection strategies reduce the inundation within the protected precinct effectively, except for P10 (Raha Beach), where the inundated area is only reduced by only 17%. Levee installation in some precincts leads the water to be pushed to other parts of the shore and increases the inundation in other precincts. For example, protecting P01 (Mussafah) increases the inundated area in P02 (Bain al-Jesrain) by 22%. This could potentially inundate the transportation network within P02 and therefore have consequences for congestion.

Even though the hydrodynamic effect of protecting individual precincts on other precincts is very clear, this is not the case for traffic network effects. For the traffic network, the protection of combinations of precincts is usually more effective in improving accessibility and mobility. Below, we present the most interesting outcomes of the traffic simulations, which we identified by inspecting each protection scenario and its effects on the overall network VKT, VHT and V/C ratio. The protection scenarios are denoted as follows:

- No protection (P_None),
- protecting all precincts (P_All),
- protecting only Precinct 7 (P07)
- protecting only Precincts 7 and 8 (P07P08),
- protecting only Precincts 8 and 9 (P08P09),
- protecting only Precincts 1, 2, 3, 5, 8, and 9 (P01P02P03P05P08P09),
- protecting only Precinct 1 (P01),
- protecting only Precincts 1,2 and 3 (P01P02P03), and
- protecting only Precincts 1, 2, 3 and 16 (P01P02P03P16).

First, we investigate and compare the two extremes: the case where all precincts are protected by levees (P_All) and the case where no precincts are protected (P_None), as shown in Figures 2a and 2b respectively. When all precincts are protected, all bridges that connect the main Abu Dhabi island to other lands remain operative, while in the case of no protection only one of the four bridges is accessible, mainly because of flooding of their approaches and entrance points, even if the decks are not inundated. This closure of bridges creates a major bottleneck on Sheikh Zayed bridge, the only operative bridge, so congestion levels network wide increase vastly. Also, there is a considerable loss in accessibility: in P_None many of the links are cut, either flooded or isolated, as neighboring links are inundated. The transportation network in Figure 2a appears smaller than in Figure 2b. Commuters whose origin or destination is the east part of Abu Dhabi, like Saadiyat Island (P08) or Reem Island

(P07), have lost accessibility and cannot perform their trips. This loss of accessibility is the reason why the number of vehicles in the network is lower, approximately 30%. Interestingly, the total network VHT is higher by more than 20% because of rerouting and congestion. Finally, the VHT per vehicle, a clear sign of congestion levels, is more than 70% higher in P_None compared to P_All.

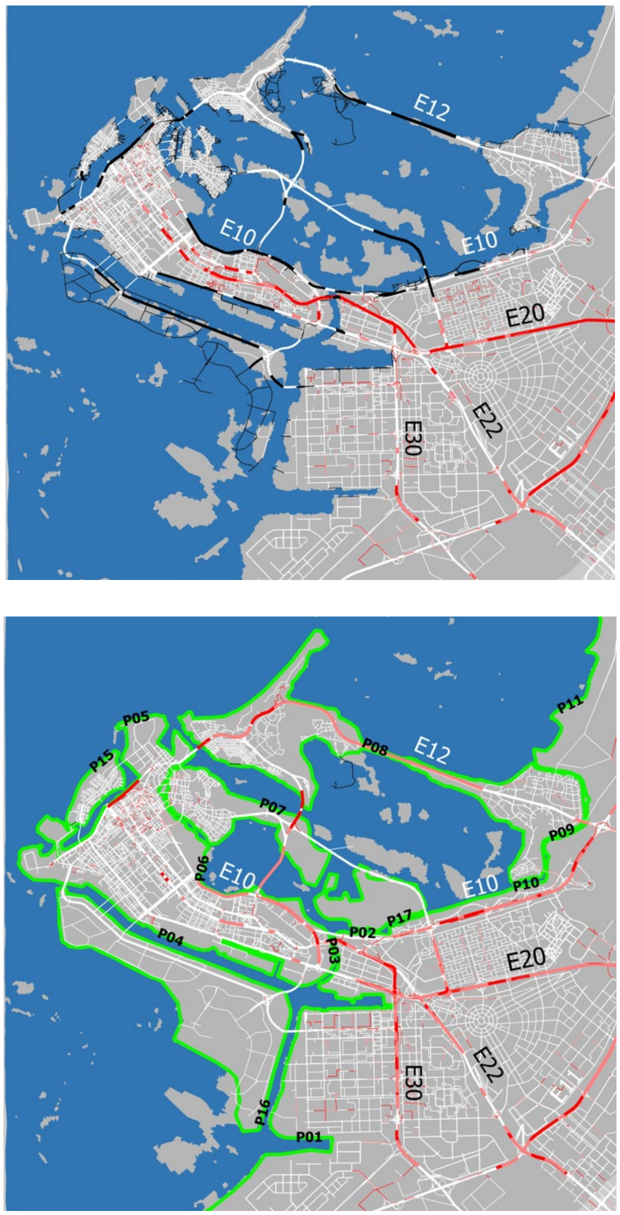

Figure 2: (a) Congestion map of P_None, no precinct protected. (b) Congestion map of P_All, all precincts protected. Green outlines show the levees around protected precinct boundaries. Color key to transport links: Black = inundated; White = not congested (V/C < 0.8); Pale Red = congested (V/C >0.8); and Dark red links = severely congested (V/C =1.0).

Obviously, P_All is the best-case scenario for protecting the transportation network, but it is also very expensive, as it assumes that levees would be constructed around all precincts of Abu Dhabi. On the other hand, P_None is the most inexpensive, but at the same time the least effective case. Thus, we explore a range of cases to determine protection strategies that can lead to satisfactory levels of accessibility and mobility on the network with lower costs than the case of full protection. Figure 3 shows percentage change in overall network VHT per vehicle resulting from each protection scenario relative to P_All, and Figure 4 shows the percentage change in vehicles from each protection scenario relative to P_All.

We present first the protection scenarios which cause more traffic delays than the case of no protection (P_None). While counter-intuitive, such cases exist, and this occurs when a combination of precincts that contain the eastern corridor that links Reem Island (P07), Saadiyat Island (P08) and Yas Island (P09) with the mainland are protected. When protecting only Reem Island, P07, the congestion levels expressed as VHT per vehicle are higher than not protecting any precinct (P_None, Figure 3). The reason is that the eastern islands of the city remain completely inaccessible to the mainland of Abu Dhabi. This is illustrated by Figure 4 which shows a significant increase of vehicles in circulation compared to P_None, while still lacking access to either the Abu Dhabi main island or the mainland. We can see that Sheikh Zayed bridge is operational, but the route to the Abu Dhabi CBD in the main island, through Saadiyat and Yas Islands, is closed. The insular parts of the west side of the city remain accessible only from downtown, as Sheikh Zayed bridge remains open. This means that there is only one way (Sheikh Zayed bridge) to the CBD from any starting point, which creates a bottleneck, and this explains the high increase in percentage of VHT per vehicle for this case. In the case of P07P08, Saadiyat Island becomes accessible to Abu Dhabi Island, but not to the mainland via the eastern corridor. Hence, all traffic must reroute via Sheikh Zayed Bridge in the south of Abu Dhabi island in order to reach the mainland. From Figure 3, this scenario results in the worst (highest) value of VHT per vehicle indicating the worst network-wide congestion. For the protection of both Saadiyat and Yas Island (case P08P09), there is still accessibility for the island parts of the network in the east, but there is only one bridge connecting downtown to the mainland (Sheikh Zayed bridge) so all vehicles in the eastern islands heading to the CBD must reroute through Sheikh Zayed bridge, which thus becomes a bottleneck, and is the reason for the very high percentage of increase in VHT per vehicle in this case. Figure 3 shows that the percentage of increase in VHT per vehicle is highest for the case of protecting Saadiyat and Reem Island (P07P08), and slightly lower for the combination of Saadiyat and Yas Islands (P08P09) and the protection of each island separately. In terms of the percentage change of VHT per vehicle, these scenarios yield worse results than the case of no protection. This occurs because all these protection combinations keep limited routes to the main island open: either only through Sheikh Zayed bridge or both Sheikh Zayed and Sheikh Khalifa bridges. These cases present the highest congestion levels of all examined cases.

We now move to cases where we address the western corridor and precincts of Abu Dhabi. These involve the precincts around the three main bridges that connect the main island to the mainland: P01 (Mussafah), P02 (Bain-al-Jesrain) and P03 (Grand Mosque District), and an additional corridor via Hodariyat Island (P16). When only Mussafah (P01) is protected, even though the immediate shoreline of Mussafah is protected, the hydrodynamic model shows that inundation water enters the precinct from the west affecting both accessibility and mobility in the west of Abu Dhabi. The rest of the network is like the case of no protection. The eastern regions of Abu Dhabi are also heavily affected in terms of connectivity, and a high number of commuters there will have lost their accessibility. This leads to higher travel times, which in this case is caused by the hydrodynamics and not the dynamics of the transportation network. Figure 3 shows that the percentage change of VHT per vehicle for P01 is worse than the case of no protection (P_None).

In contrast, in the scenario of protecting P01 (Mussafah), P02 (Bain-al-Jesrain) and P03 (Grand Mosque District), the bridges that connect the CBD to the mainland remain operative, as the levees protect their approaches. Figure 3 shows that the change in congestion levels (relative to the reference case) decreases from approximately 90% in case P01 to 31% in the current case. Sheikh Zayed bridge is no longer a bottleneck, as there are alternatives to and from the CBD. Another difference is in the number of vehicles on the road: for scenario P01 there were around 30% fewer vehicles on the network compared to the P_All case, while in the case of P01P02P03, this percentage is 24%, showing an improvement in accessibility. The total VHT are almost the same compared to the P_All case, while for P01 there was an increase of approximately 30%. Case P01P02P03P16 protects Mussafah, Bain al-Jesrain, Grand Mosque District and Hodariyat island. The addition of protecting P16 results in a large reduction in congestion levels, down to 20% above P_All. Connectivity from the CBD to the mainland remains as before with the addition of Hodariyat island. The eastern islands remain disconnected.

Finally, when protecting the entire northern and eastern portion of Abu Dhabi Island (P01P02P03P05P08P09), the eastern islands are connected to the mainland, and the bridges on the south side of Abu Dhabi Island are in operation. This scenario introduces the most redundancy in the traffic network. Figure 3 shows a significant improvement compared to only protecting the eastern island corridor, the result of increasing network redundancy. Figure 4 shows that this scenario results in the smallest decrease in the number of vehicles able to resume their participation in the traffic network.

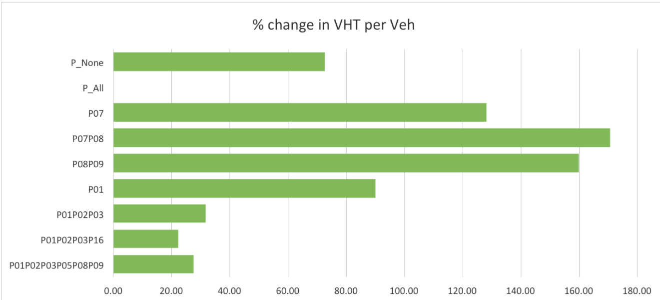

Figure 3: Percentage change in VHT per vehicle for the different protection scenarios.

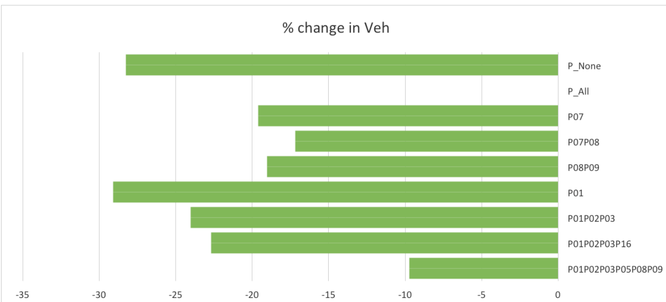

Figure 4: Percentage change in vehicles for the different protection scenarios.

3. CONCLUSIONS

This research aims to determine optimal strategies to protect the Abu Dhabi shoreline against sea level rise, in terms of the transportation network performance. By observing the network maps, the total VHT and the number of vehicles, we find that, while there may be accessibility to a particular part of the city (there is at least one open route, and high VHTs), travel times become so high that commuters will be unable or unwilling to realize their trip (leading to a low number of vehicles on the roads). We also find that, when two of the three bridges that connect the island of Abu Dhabi to the mainland around it are closed, congestion levels are high, because the remaining bridge acts as a bottleneck leading to high travel times. This means that it is critical to protect precincts which contain the approaches to these bridges. In the same vein, when protecting the corridor that connects the main island to the eastern islands and the mainland, while the other bridges are inundated, commuters are left with only one path from and to the CBD and this creates a different bottleneck, again increasing the travel times. Finally, if the precincts that contain the approaches to the bridges that connect the main island to the mainland are protected, the addition of the neighboring precincts will yield a larger marginal improvement to congestion.

This methodology can be applied in different regions at risk from sea level rise. Without the need of running simulations for other regions, there are some insights that can be generalized and extended to other shorelines. First, for areas with islands and peninsulas which connect to each other through bridges, there is solid evidence that protecting the entrances of those bridges decreases congestion levels. This conclusion is also supported by Sun et al. (2020). Another beneficial strategy found in this work that can be implemented elsewhere is to protect links that create corridors that do not have many alternatives for rerouting.

This study assumes that the only strategy to protect infrastructure is levee installation. This assumption can be relaxed in future work, as different protection strategies can be applied such as elevation of highways, or placement of barriers on bridge approaches. Additionally, natural barriers could be implemented to dampen the wave run-up on the shoreline. For example, mangroves grow with ease around Abu Dhabi, controlling the impact of the waves on those areas. Another limitation of this paper is the absence of land use changes in the modeling that will possibly occur over a long-time horizon as rising seas will mandate relocations of residential and commercial areas. Additionally, the effects of inundation on other infrastructure, such as airports, hospitals or industrial areas, or other networks such as electricity and water networks should be considered before implementing any protection strategy. Finally, we did not include public transit in our transportation modelling system as a large majority of trips in Abu Dhabi are undertaken by cars and public transit only accounts for 2.2% of the total trips made daily (Abu Dhabi Department of Municipal Affairs and Transport, 2015). The situation may be different in other cities, limiting the transferability of our results to other locations.

4. REFERENCES

Abu Dhabi Urban Planning Council 2007, Plan Abu Dhabi 2030, Urban Structure Framework Plan.

Abu Dhabi Department of Municipal Affairs and Transport, 2015. Abu Dhabi Travel Patterns: Highlights of the 2015 survey results. Abu Dhabi, 32pp.

Chow, A.C.H., Sun, J., 2022. Combining sea level rise inundation impacts, tidal flooding and extreme wind events along the Abu Dhabi Coastline. *Hydrology*, 9, 143.

Dangendorf, S., Hay, C., Calafat, F.M., Marcos, M., Piecuch, C.G., Berk, K. and Jensen, J., 2019. Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, *9*(9), pp.705-710.

Elevation of Abu Dhabi https://elevation.maplogs.com/poi/abu_dhabi_united_arab_emirates.306820.html

Hummel, M.A., Berry, M.S. and Stacey, M.T., 2018. Sea level rise impacts on wastewater treatment systems along the US coasts. *Earth's Future*, *6*(4), pp.622-633.

Knowles, N., 2010. Potential inundation due to rising sea levels in the San Francisco Bay region. San Francisco Estuary and Watershed Science, 8(1).

Lu, Q.C. and Peng, Z.R., 2011. Vulnerability analysis of transportation network under scenarios of sea level rise. *Transportation research record*, 2263(1), pp.174-181.

Madanat, S.M., Papakonstantinou, I. and Lee, J., 2019. The benefits of cooperative policies for transportation network protection from sea level rise: A case study of the San Francisco Bay Area. *Transport Policy*, *76*, pp. A1-A9.

Monioudi, I.N., Asariotis, R., Becker, A., Bhat, C., Dowding-Gooden, D., Esteban, M., Feyen, L., Mentaschi, L., Nikolaou, A., Nurse, L. and Phillips, W., 2018. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. *Regional Environmental Change*, *18*(8), pp.2211-2225.

Nazarnia, H., Nazarnia, M., Sarmasti, H. and Wills, W.O., 2020. A systematic review of civil and environmental infrastructures for coastal adaptation to sea level rise. *Civil engineering journal*, *6*(7), pp.1375-1399.

Nicholls, R.J. and Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, 328(5985), pp.1517-1520.

Papakonstantinou, I., Lee, J. and Madanat, S.M., 2019A. Optimal levee installation planning for highway infrastructure protection against sea level rise. *Transportation research part D: transport and environment*, *77*, pp.378-389.

Papakonstantinou, I., Lee, J. and Madanat, S.M., 2019B. Game theoretic approaches for highway infrastructure protection against sea level rise: Co-opetition among multiple players. *Transportation Research Part B: Methodological*, *123*, pp.21-37.

Renne, J.L., Hoermann, S. and Koleini, A., 2021. Visualizing sea level rise impacts to transportation infrastructure using virtual reality. *Journal of Transport Geography*, *93*, p.103077.

Suh, J., Siwe, A.T. and Madanat, S.M., 2019. Transportation infrastructure protection planning against sea level rise: Analysis using operational landscape units. *Journal of Infrastructure Systems*, *25*(3), p.4019024.

Sun, J., Chow, A.C. and Madanat, S.M., 2020. Multimodal transportation system protection against sea level rise. *Transportation Research Part D: Transport and Environment, 88*, p.102568.

Sun, J., Chow, A.C. and Madanat, S.M., 2021. Equity concerns in transportation infrastructure protection against sea level rise. *Transport Policy, 100*, pp.81-88.

Sun, J., Chow, A.C. and Madanat, S.M., 2022. Tradeoffs between optimality and equity in transportation network protection against sea level rise. *Transportation Research Part A: Policy and Practice, 163,* pp.195-208.

Zhou, Y., Wang, J. and Yang, H., 2019. Resilience of transportation systems: concepts and comprehensive review. *IEEE Transactions on Intelligent Transportation Systems*, *20*(12), pp.4262-4276.