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Sea Level Rise Impacts on Wastewater Treatment Plants and their Social Vulnerability Differences

THESIS

David S. P. Robinson, Captain, USSF

AFIT-ENV-MS-23-M-226

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

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in Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

David S. P. Robinson, M.S.C.E.

Captain, USSF

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THESIS

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Abstract

Many of the United States' major cities that have a high population are located along the coast. The number of people residing in low-elevation coastal areas, below 10 meters, is increasing. Coastal areas may be affected by various short- and long-term climate hazards, such as sea level rise (SLR). Climate change induced SLR will threaten residents and infrastructure in low-lying coastal areas. A household's capacity to respond to hazards is highly dependent on its socio-demographic situation which determines its social vulnerability. Wastewater treatment facilities are a particularly critical piece of infrastructure often located in low-lying areas due to gravity-fed collection systems. Additionally, flooding of these infrastructure systems can lead to the spread of disease and contamination of water sources. In this analysis, we utilized a geographic information system to assess the exposure of wastewater infrastructure to sea level rise projections in the conterminous United States. We then paired these inundation estimates against the Center for Disease Control's Social Vulnerability Index (SVI) to investigate inequities in infrastructure impact. An analysis of variance (ANOVA) was performed to compare the SVI of populations near wastewater treatment plants that were inundated to those that were not inundated at sea level rise projections. Of the 1,040 wastewater treatment plants within two kilometers of the coast in the United States, 394 treatment facilities are in danger of inundation at 10 feet of sea level rise. Interestingly, the results of the ANOVA tests revealed some statistical differences in social vulnerability indexes of impacted populations and infrastructure against non-impacted populations.

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I. Introduction

The number of people residing in low-elevation coastal areas, below 10 meters above sea level, continues to increase [1], while at the same time, coastal areas continue to be affected by various short- and long-term climate hazards, such as sea level rise [2]. Sea level rise, resulting from climate change, will threaten residents living in low-lying coastal areas, meaning coastal communities will experience more persistent and more frequent flooding. Climate change projections show sea temperature increases and melting ice caps leading to regional sea level rise, resulting in flooding, coastal erosion, and shoreline retreat [3]. Additionally, projected rainfall intensification results in an increase in flood risk in low-lying coastal areas [4]. These flood risks directly affect infrastructure vulnerability, especially infrastructure in low-lying coastal areas [5, 6]. As such, it is important to investigate how different infrastructure systems will respond to sea level rise and recurrent flooding.

Wastewater treatment plants are particularly vulnerable to coastal impacts of climate change as they are usually located at lower elevations, making them more susceptible to coastal flooding [7, 8]. The Department of Homeland Security (DHS) considers wastewater systems as critical infrastructure [9]. According to the DHS, there are more than 16,000 publicly owned wastewater treatment systems in the United States; 75 percent of the U.S. population has its sanitary sewage treated by one of these wastewater systems [10]. Accordingly, disruption to wastewater treatment plants can lead to economic impacts and severe public health and environmental effects. The lack of redundancy in wastewater treatment plants heightens these impacts [9].

The amount of sea level rise is projected to vary across the world to include relative sea level rise changes across the United States with higher rates in the equatorial regions compared to polar regions [11]. Therefore, wastewater treatment plant disruptions might vary by region. Approximately 40% of the U.S. population live in counties located on a coast, creating a strong economic dependency on coastal communities [12]. Due to climate change, America's coastal properties, infrastructure, and ecosystems face increased risks from ongoing sea level rise. Socially vulnerable individuals are also more likely to be adversely affected as they have fewer resources to protect against and recover from flood damage or property loss. Studies show, however, that socioeconomic and educational factors can impede individuals' abilities to prepare for, respond to, and cope with the risks of climate change [12]. This is true from other studies to include COVID-19 in the United States, [13], climate-sensitive hazards [14], COVID-19 in England [15], and urban tree canopy [16], among other studies. Socially vulnerable populations near climate change-affected wastewater treatment plants may have less sustainable and resilient socioeconomic capabilities for coping with sea level rise.

In this study, sea level rise impacts on critical infrastructure (wastewater treatment facilities) are analyzed in conjunction with social vulnerability to understand differences in socioeconomic impacts of infrastructure inundation. This study uses a geographic information systems (GIS) to assess the exposure of coastal wastewater treatment plant infrastructure (from [17]) against sea level rise projections from the National Oceanic and Atmospheric (NOAA) and the Center for Disease Control's Social Vulnerability Indexes (SVI). The census block SVI information provides information on potentially how disadvantaged groups might be impacted by the inundation of neighboring wastewater treatment facilities. Through the combination of variables in the GIS, this study answers the following question: What are the social vulnerability differences in sea level rise impacts on wastewater treatment plants?

II. Background and Literature Review

2.1 Sea Level Rise Trends

Sea level rise in the twenty-first century compared to the twentieth century has been faster [18] and sea level rise will continue to accelerate in the 21^{st} century [19]. Coastal areas are highly susceptible to sea level rise and the effects have been evaluated in multiple capacities. Behera et al. [3] studied sea level rise with increasing rates using GIS, vulnerability assessment modeling and risk categorization, and analytical hierarchy process. The result was a risk analysis of increased sea surface temperature and thermal expansion of seawater and melting of glaciers on land and ice. Additionally, their risk analysis showed social vulnerability mapping of coastal populations to help policy planners to focus on an area having greater vulnerability and to optimize the utilization of resources. Bera and Maiti [20] found that low elevation and low slopes that are characteristic of many coastlines contribute to a greater rate of sea level rise. Hadipour et al. [2, 1] studied spatial multi-criteria decision analysis (SMCDA) and found coastal areas are expected to have higher risks due to flooding. Worldwide coastal population is growing with an estimated 200 million residents in 1990 and a projected 600 million residents by 2100 [18]. Therefore the total population exposed to coastal flooding could increase by three times by the year 2070 [21].

Worldwide coastal populations living below 10 meters, or 33 feet comprise 2% of the land but 10% of the population [22]. In the United States, 4.2 million people are susceptible to flooding at 3 feet of sea level rise and 13.1 million people are susceptible to flooding at 6 feet of sea level rise by the year 2100 are projected [23]. Climate change-induced sea level rise necessitates analysis of coastal risks to develop adaption strategies aimed at managing those impacts [24].

Wastewater treatment plants are especially vulnerable to sea level rise because they are commonly located at low elevations and next to a waterbody that receives a discharge of treated water [25]. Additionally, flooding of wastewater treatment plants can lead to the spread of disease and contamination of water sources, therefore it is important to assess wastewater treatment plants and their surrounding communities. Despite research on vulnerable populations of sea level rise, existing research is limited in its understanding of the social vulnerabilities of these populations and their support infrastructure.

2.2 Social Vulnerability Indexes

Social vulnerability was first introduced in the 1970s to understand interactions between social and natural systems that give rise to hazards, i.e., sea level rise, and disasters [14]. Alternatively, social vulnerability describes the differential impacts of environmental threats on people and places where the people live. As opposed to physical vulnerability, the ability of systems to absorb or withstand impacts, social vulnerability accounts for a social construct that highlights the uneven social capacity for preparedness, response, recovery, and adaptation to environmental hazards. There are two items to understand the vulnerability of a place 1) attributes of the hazards exposure, which includes frequency, severity, and areal extent and 2) sensitivity of the population to impacts [14]. The sensitivity of a population is their social vulnerability, which is defined as the social, economic, and demographic characteristics, which affect a community's ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards. There are multitude of SVIs developed in the literature, discussed in the following section. However, this study adapts the CDC's social vulnerability index based on its use across a wide variety of applications including natural disasters and COVID-19 response.

The CDC's Agency for Toxic Substances and Disease Registry (CDC/ATSDR) defines social vulnerability as the potential negative effects on communities that are caused by external stresses, i.e., natural, or human-cause disaster, or disease outbreaks, on human health [26]. Understood in this way, reducing social vulnerability may decrease both humans' distress and economic loss. CDC/ATSDR social vulnerability indexes are based on 15 variables from the United States Census Bureau's data to identify communities that might need assistance before, during, or after a disaster. The index is updated every two years to identify at-risk groups in times of crisis [27]. The CDC/ATSDR social vulnerability indexes lists four themes: 1) socioeconomic status, 2) household composition and disability, 3) minority status and language, 4) housing type and transportation, and final summary index. Multiple studies have used the CDC's social vulnerability assessments. Cunningham et al. [28] used the CDC's social vulnerability indexes to identify vulnerable populations needing additional mental health assistance post-hurricane. Flanagan et al. [29] showed the potential value of the social vulnerability indexes by exploring the impact of Hurricane Katrina on local populations to decrease both human suffering and the economic loss that are related to providing social services and public assistance after a disaster. Moreover, Lehnert et al. [30] explored the relationship of heat related emergency departments visits with the CDC's social vulnerability data to demonstrate the spatial and statistical relationship of social vulnerability to heat related health outcomes. Al Rifai et al. [31] used the CDC's social vulnerability indexes to find the distribution of social vulnerability indexes across U.S. states and the average number of COVID-19 cases, deaths, tests, and vaccinations to use social vulnerability indexes as a valuable tool that can be used for resource allocation and health policy design to combat COVID-19 or other diseases. The CDC's social vulnerability indexes is a well-established metric to study social vulnerabilities of a population in an area.

The overlap of social vulnerability and infrastructure is a growing field to understand infrastructure and environmental justice concerns. For example, Fekete and Rhyner [32] found emerging vulnerabilities due to growing dependency on critical infrastructure show different implications with identifying groups and their vulnerabilities to disaster risks need changes within common indicators of social vulnerability and their dependencies with critical infrastructure. Novak et al. [33] presented a framework for different disinvestment actions based on a developed Disinvestment Vulnerability Index (DVI), which identifies socially vulnerable populations impacted by disinvestment by setting up criteria for roadway necessity. Similarly, Karakoc et al. [34] proposed an important measure of transportation infrastructure that is driven by social aspects of resilience, using a multi-criteria decision analysis technique to determine the final importance ranking. Social vulnerabilities have been incorporated into the analysis of infrastructure to help decision-makers for investment and restoration activities.

2.3 Sea Level Rise and Social Vulnerability

Many studies have analyzed sea level rise risks [35] and social vulnerability consequences using many methods. Social vulnerability is defined by social, economic, and demographic characteristics that influence a community's ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards [36, 14, 37, 38, 39, 40]. While organizations like the CDC have their own SVI, many studies developed their own social vulnerability indexes to reach more targeted goals (e.g., [41, 37, 42, 43, 44, 45]). For example, Emrich and Cutter [14], studied social vulnerability based on race/ethnicity, wealth, housing type and tenure, education and employment, age, gender, and health, and gender and family structure to natural hazards from floods, hurricanes, and sea level rise, among others.

Previous research has applied these SVIs to flooding and sea level rise risk evaluations, just not considering wastewater treatment plants. For example, Chakraborty et al. [46] quantitatively examined coastal hazards and developed a spatial representation of the hazards to social vulnerability indexes. Hardy and Hauer [47] studied the sea level rise scenarios and population projections scenarios using the Hamilton-Perry method. The Hamilton-Perry method is a cohort-component method used for sub-county population projections with smaller data requirements than traditional cohort-component methods. This method uses data from the two most recent censuses and only projects population by age and sex using cohort-change ratios (CCR) [48]. Finally, Koks et al. [39] analyzed hazard and social vulnerabilities information using flood risk management strategies.

One of the main benefits of social vulnerability indexes is their versatility in pairing natural or manmade risks with the social aspect. Lianxiao and Morimoto [40] studied social vulnerability influences the distribution of resources and power that are necessary for disaster preparedness and countermeasure. Bera et al. [20] studied Sundarbans, an UNESCO world heritage site, to assess the degree of vulnerability of its coastline using physical and social variables to find social vulnerability based on the surrounding area to calculate its risk. To accurrately represent the relative level of risk among places both the spatial reprentation of the hazard and the social vulnerabilities are required [14]. Social vulnerabilities are needed as a significant component of engineering decision-making of flood risk reduction [1]. Regional environmental assessment of social vulnerability to natural hazards has become increasingly urgent for risk management and sustainable development [42]. Additionally, recent federal objectives have prioritized environmental justice considerations in planning and management of infrastructure projects, further driving the need for social vulnerability assessments as part of future disaster planning.

III. Methodology

3.1 Study Area

This study focuses on the conterminous United States for analysis of wastewater treatment plants. Analysis was completed across the total study region and across three coastal regions, Figure 1. The western United States included the states of California, Oregon, and Washington; The southeastern United States spanned from Texas to North Carolina. The northeastern United States spans from Virginia through Maine. Vermont does not have a coastline and is, therefore, excluded from the northeast area of interest. Additionally, the study analyzed three smaller case studies within each of the regions based on high density of wastewater treatment facilities: the San Francisco Bay Area, the state of Louisiana, and the Delaware River estuary across the states of Delaware, Pennsylvania, and New Jersey.

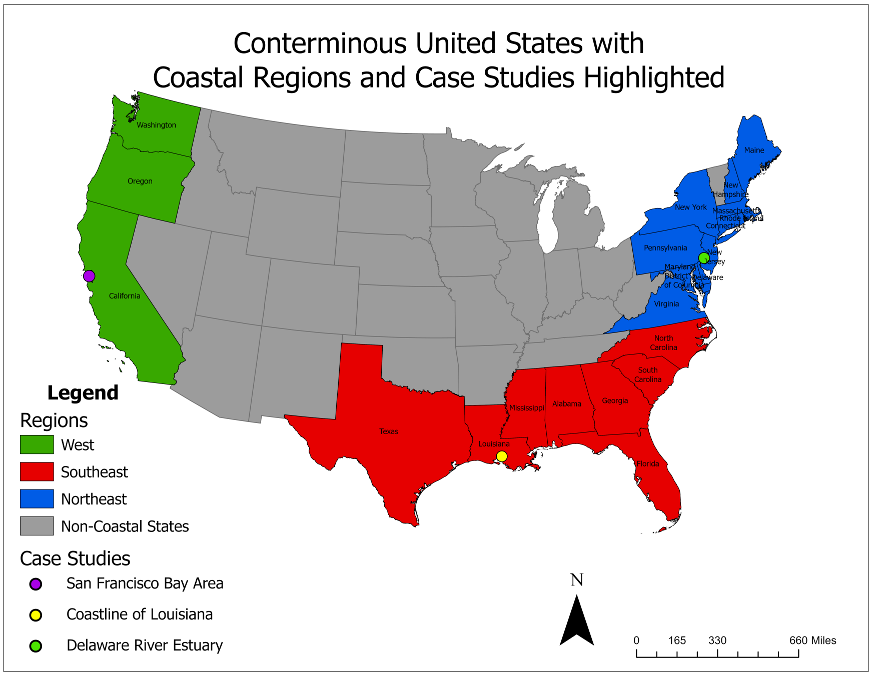

Figure 1: The conterminous United States coastline was investigated nationally and across three regions: west, southeast, and northeast.

3.2 Data Collection

Four main data sources were needed for the analysis. First, geospatial vector shapefiles of specific sea level rise projections are available NOAA's Office of Coastal Management [49]. These shapefiles are based on LiDAR collection data and range from 1-10 foot (0.3 – 3.0 m), with multiple shapefiles per state. Second, Hummel et al. [17] compiled a list of 1,040 wastewater treatment plants within two kilometers of the coast based on Environmental Protection Agency with the west region having 205, southeast having 404, and the northeast having 431 wastewater treatment plants. The wastewater treatment plant data contain characteristics of the wastewater treatment plants to include whether the wastewater treatment plants are public or federal and major or minor wastewater treatment plants. Next, the Center for Disease Control's Agency for Toxic Substances and Disease Registry's (ATSDR) Geospatial Research, Analysis, and Services Program (GRASP) provide data on social vulnerability indexes

[50] across four categories and at a combined metric for census tracts in the United States. Finally, census tract spatial extents were available through the United States Census Bureau [51]. Data were aggregated and processed using ArcGIS Pro v3.0 and the R programming language v4.1.1.

3.3 Data Analysis

Using ArcGIS's geoprocessing tools, wastewater treatment plants were assigned to census tracts based on location of the treatment facility. The upstream sewer system was not considered in the assigning of facilities to a census tract. Inundation of facilities at each of the sea level rise assessments was assessed based on a simple overlap of the sea level polygons with the wastewater treatment location. Using the concurrent location data, social vulnerability indexes and the level of inundation (if applicable) were assigned to each wastewater treatment facility. Following spatial evaluation and combination of data, data were exported to RStudio for statistical analysis. Analysis of Variance (ANOVA) tests were performed to evaluate difference in means of social vulnerability indexes across all sea level rise scenarios. These ANOVA tests were conducted at the three different study scales: national, the three regions, and the three local case studies to identify any statistical differences in SVI between flooded and non-flooded wastewater treatment plants. In this analysis, the significance thresholds α were 0.05 and 0.1.

3.4 Challenges

NOAA shapefiles of sea level rise are very large due to their detailed representation of the United States coastline and its elevation. As a result, these data were not able to be merged to allow for ease of data manipulation. Therefore, each sea level rise polygon for every sea level projection had to be treated individually against the wastewater treatment plant. Additionally, NOAA's sea level rise projections were missing parts of the conterminous United States, specifically the northwestern coast of the state of Washington, which contained only one wastewater treatment plant within two kilometers of the coast.

IV. Results and Analysis

4.1 Sea Level Rise Projection Impacts

Figure 2 shows that the total number of wastewater treatment plants and population inundated are closely coupled, with the trend increasing steadily after three feet of sea level rise. Across the United States, an estimated 394 wastewater treatment plants will be inundated at 10 feet of sea level rise. The southeast region has the largest number of vulnerable wastewater treatment plants (160), followed by the northeast region (155), and the west region (79). The total population inundated at 10 feet of sea level rise is approximately 11 million [52], approximately 3.6% of the 2020 conterminous United States population. Three different scales of analysis were completed to evaluate these trends and their impacts on social vulnerability: national, regional, and local case studies.

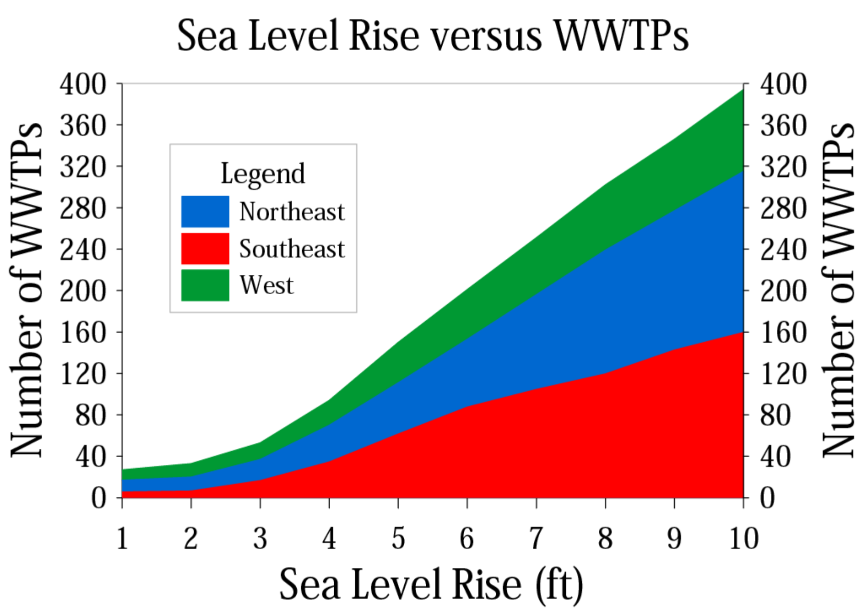

Figure 2: Sea Level Rise impacts in terms of the number of wastewater treatment plants (WWTPs) increase dramatically after three feet of sea level rise.

4.2 National Scale Analysis

A national scale analysis compared the SVIs of inundated wastewater treatment plants of non-inundated treatment plants at each of the ten sea level rise scenarios (1-10 ft). An analysis of variation compared each of the four themes and the overall SVI between the two categories. Significance at the 0.05 and 0.10 levels was assessed; see Figure 3.

The four themes, socioeconomic status (theme 1), household composition and disability (theme 2), minority status (theme 3) language, housing type and transportation (theme 4), and summary values had different responses to sea level rise impacts of wastewater treatment plants. The dark red represents a p-value below 0.05 and the light red represents a p-value between 0.05 and 0.10. The lower sea level rise typically results in statistical differences in means, which is largely due to the small sample size. Theme 4 or housing type and transportation were statistically different within 0.1 for all sea level rise scenarios except sea level rise of 2 feet. Additionally, sea level rises of 1, 3, and 7 feet were statistically different means for social vulnerability indexes besides minority status and language, i.e., theme 4. All social vulnerability indexes that were statistically significant, i.e., red, or light red, the impacted wastewater treatment plants were less socially vulnerable.

Figure 3 highlighted boxes indicate significantly different means of social vulnerability indexes between wastewater treatment plants and not inundated wastewater

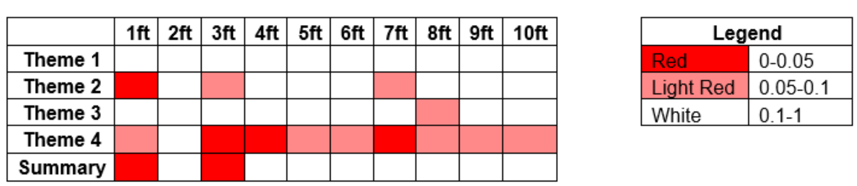

Figure 3: Highlighted boxes indicate significantly different means of social vulnerability indexes between, inundated wastewater treatment plant and not inundated wastewater treatment plants.

treatment plants. 2 feet of sea level rise is not significantly different due to multiple factors, such as similar means, small sample size, and non-uniform shaped census blocks. Additionally, these census blocks were considered inundated when the wastewater treatment plants were inundated, regardless of the shape or size of the census block.

4.3 Regional Scale Analysis

The test was completed on nationwide, west, southeast, northeast regions to find statistical difference in means for social vulnerability indexes. The ANOVA for the west region resulted in no social vulnerability indexes being statistically different at any sea level rise scenario. The ANOVA for the southeast region resulted in being statistically different in sea level rise scenarios of four through seven feet for all social vulnerability indexes, i.e., socioeconomic (Theme 1), household composition and disability (Theme 2), minority status and language (Theme 3), housing type and transportation (Theme 4), and summary (Theme 5). The ANOVA for the northeast region resulted in two indexes, i.e., socioeconomic status (Theme 1) and household composition and disability (Theme 2), being statistically different at sea level rise scenario at one foot. Additionally, the direction of all the statistically significant ANOVA tests indicates the inundated social vulnerability of wastewater treatment plants were less socially vulnerable compared to wastewater treatment plants.

Figure 4, A, shows the west region's wastewater treatment plants when inundation will occur if inundation does occur. There are up to 79 wastewater treatment plants that will be inundated at ten feet of sea level rise. The location of high inundation occurs at the San Francisco Bay area, which include the cities of San Francisco, San Jose, and Oakland. Figure 4, B, shows the interquartile range (IQR) and the median of the summary social vulnerability index. The IQR is the range of data from

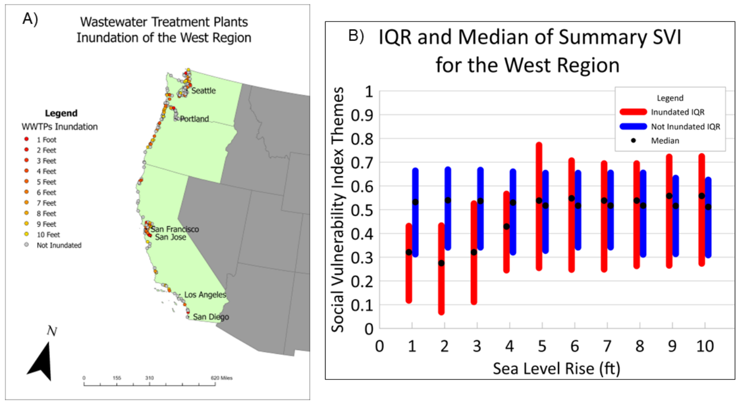

Figure 4: A, west region wastewater treatment plants (WWTP) inundation by sea level height. Figure 4, B, wastewater treatment plants social vulnerabilities' interquartile range (IQR) and median of inundated and not inundated wastewater treatment plants versus sea level rise.

the 25th to the 75th percentiles of data with the median being the 50th percentile. The median of the sea level rise scenarios is approximately 0.5 and for inundated wastewater treatment plants is lower for sea level rise scenarios 1-4 feet.

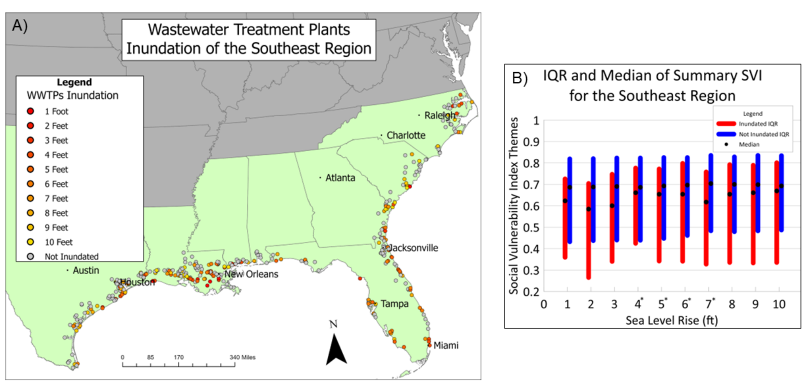

Figure 5: A, southeast region wastewater treatment plants (WWTP) inundation by sea level height. Figure 5, B, wastewater treatment plants social vulnerabilities' interquartile range (IQR) and median of inundated and not inundated wastewater treatment plants versus sea level rise.

Figure 5, A, shows the west region's wastewater treatment plants when inundation will occur if inundation does occur. There are up to 160 wastewater treatment plants that will be inundated at ten feet of sea level rise. The location of high inundation occurs at the state of Louisiana's coastline, which include the city of New Orleans. Figure 5, B, shows the interquartile range (IQR) and the median of the summary social vulnerability index. The median of the sea level rise scenarios is approximately 0.65 and for inundated wastewater treatment plants is lower for all sea level rise scenarios. Additionally, the sea level rise scenarios of 4-7 feet, annotated by an asterisk, were statistically significant difference in means based on the ANOVA test.

Figure 6, A, shows the west region's wastewater treatment plants when inundation will occur if inundation does occur. There are up to 155 wastewater treatment plants that will be inundated at ten feet of sea level rise. The location of high inundation occurs at the Delaware River estuary, which includes the states of Delaware, Pennsylvania, and New Jersey. Figure 6, B, shows the interquartile range (IQR) and the median of the summary social vulnerability index. The median of the sea level

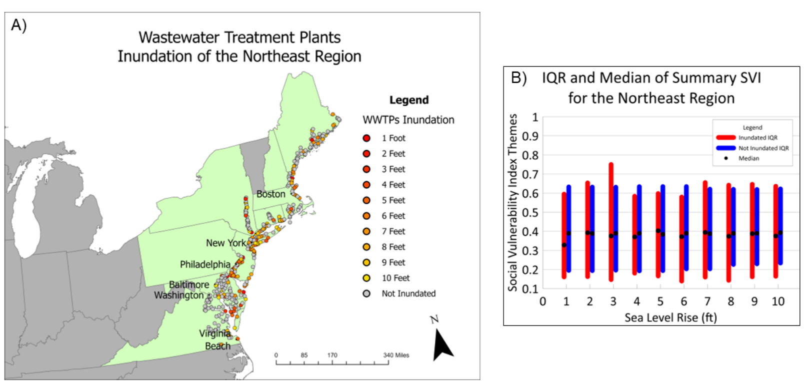

Figure 6: A, northeast region wastewater treatment plants (WWTP) inundation by sea level height. Figure 6, B, wastewater treatment plants social vulnerabilities' interquartile range (IQR) and median of inundated and not inundated wastewater treatment plants versus sea level rise.

rise scenarios is approximately 0.38 and for inundated wastewater treatment plants is lower for all sea level rise scenarios.

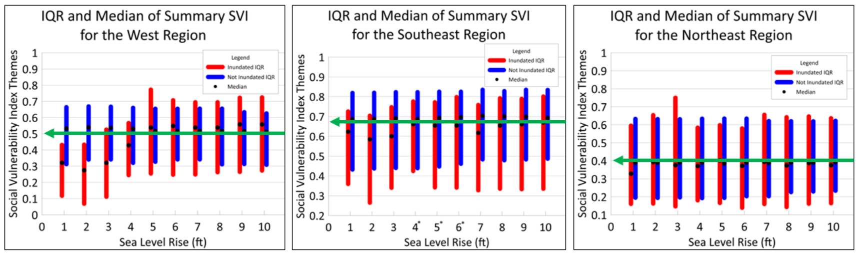

Figure 7: Regional comparison of the three regions' IQR and medians are shown in this figure. The Southeast is the most socially vulnerable, followed by the West, and the Northeast regions as described above.

4.4 Local Case Study Analyses

As expected, the number of wastewater treatment plants inundated increases around cities, including San Francisco, CA; New Orleans, LA; and Philadelphia, PA. These three cities were chosen for further analysis as local case studies: the San Francisco Bay area, Louisiana's Coastline, and the Delaware River estuary. Figure 7 shows the maps of the summary social vulnerability index for the three case studies against the wastewater treatment plant locations. In a general comparison of the three case studies, the San Francisco Bay Area and the Delaware River are less socially vulnerable, i.e., lighter in color, than Louisiana, i.e., darker in color. Additionally, Figure 7 shows the inundation of wastewater treatment plants that will be inundated based on the DSRL database projection of the three regions [53]. The approximate sea level rise for the three regions is 1 foot for San Francisco Bay Area and Louisiana's coastline and 2 feet for the Delaware River estuary by 2065. In Figure 7, the red wastewater treatment plants indicate inundation by 2065, which results in five, four, and four wastewater treatment plants being inundated for the San Francisco Bay Area, Louisiana's coastline, and the Delaware River estuary, respectfully.

Only one ANOVA analysis was statistically significant in the San Francisco Bay Area, household composition and disability (Theme 2) at the sea level rise scenario of 6 feet. However, with no other statistically significant results, we can conclude that this observation might be due to sample size. Along the Coast of Louisiana, two of the social vulnerability themes showed statistical significance between 7-10 feet of sea level rise: household composition and disability (theme 2) and minority status and language (theme 3). Upon further examination, the difference was counter to what one might expect with inundated wastewater treatment facilities being less socially vulnerable than wastewater treatment unaffected facilities between seven and nine feet. However, the direction of the difference in means reverses for sea level rise of ten feet with the household composition and disability indicator showing inundated wastewater treatment plants of being more socially vulnerable than unaffected locations for the coast of Louisiana. Finally, the ANOVA analysis for the Delaware River estuary shows no statistical significance across all social vulnerability indexes and all sea level rise scenarios. In general, despite a few statistically significant categories, the local scale studies showed no overall correlation between those plants affected by sea level rise and their social vulnerability compared to unaffected locations. The results of this study indicate there is relatively equal inundation of the wastewater treatment plants regardless of region, i.e., 37%, or location, i.e., 50%, at ten feet of sea level rise.

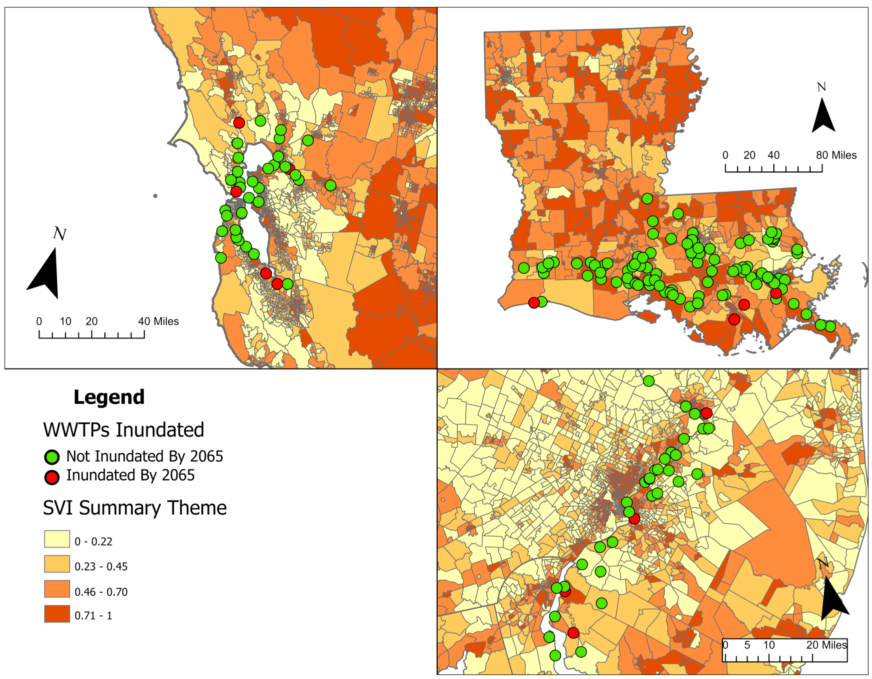

Figure 8: Social vulnerability is higher in Louisiana than the other two case study locations, however, there is minimal statistical significance on social vulnerability correlated with impacted wastewater treatment plants across each study.

V. Discussion

5.1 Inundation of Wastewater Treatment Plants

Projected sea level rise will impact up to 11 million people based on 2020 populations. Accompanying the population impacted are the critical infrastructures that support society. This study evaluated wastewater treatment plants and their local community social vulnerability. While the number of wastewater treatment plants vary by region, with nearly 400 wastewater treatment plants impacted at 10 feet of sea level rise, 160 in the southeast region alone. Wastewater treatment plants perform an essential community service by purifying and removing contaminants from sewage before returning it into the environment. In the case of sewer overflows, raw sewage is discharged directly into the environment, causing significant environmental and public health impacts. Inundation of these wastewater treatment plants could have similar public health implications and populations with a higher vulnerability would not recover as quickly.

Social vulnerability refers to the potential negative effects on communities that are caused by external stress on human health. Furthermore, the reduction of social vulnerability can decrease both human suffering and economic loss [26]. CDC's social vulnerability indexes can be used to help emergency response planners and public health officials identify and map communities that will likely need assistance before, during, and after hazardous events [50] to reduce social vulnerability.

This study found based on ANOVA analysis that there is minimal statistical difference in local social vulnerability between inundated and not affected wastewater treatment plants at all scales and sea level scenarios. For the minimal comparisons that were significant, the coastal wastewater treatment plants that are inundated are in general less socially vulnerable communities than those plants that are not affected.

Additionally, coastal regions are not homogeneous in that there are differences in social vulnerability between regions. Therefore, if a hazardous event, i.e., sea level rise, were to occur and affect a local wastewater treatment plant, the people living near an inundated wastewater treatment plant are more capable to deal with the hazard, i.e., less socially vulnerable, than those that are not affected by sea level rise.

5.2 Climate Change and Social Vulnerability

This study's findings align with other findings of less socially vulnerable people live near coasts at the national [54, 52], regional [14], local [45], and international scales [37]. This finding is likely due to the desire and attraction for people to live near coasts and cope with the vulnerabilities it may have, e.g., buying insurance or putting their house on stilts.

The findings of this study indicate there is relatively equal inundation of the wastewater treatment plants regardless of region, i.e., 37%, or location, i.e., 50%, at ten feet of sea level rise. Additionally, regions with lower social vulnerability, i.e., southeast region, and regions with higher social vulnerability, i.e., northeast region, are affected equally by sea level rise. Therefore, many wastewater treatment plants, e.g., Figure 7, have locations in highly vulnerable areas, i.e., susceptible to sea level rise, which have low social vulnerability. Therefore, it is important to understand social conditions on a case-by-case basis to evaluate community impact of sea level rise.

5.3 Limitations of this Study

This study assumed a uniform sea level rise. However, sea level rise is not uniform with areas lower in latitude experiencing more sea level rise [11] and regional differences dictating relative sea level rise including ground subsidence and other factors.

Therefore, the southern conterminous United States is experiencing higher rates of sea level rise than the northern conterminous United States. Additionally, this study did not consider how sea level rise implications of operations, such as maintenance of the wastewater treatment plants. Some limitations that may affect operations from sea level rise include increased salinity in air [55], inundation of network links, e.g., pipes [56], imperviousness of land cover [57], presence of ocean barriers [58], and disruption of service [5, 59]. Additionally, this study was constrained to data regarding infrastructure parallel to wastewater treatment, which limited conclusions of this study.

VI. Conclusions

Sea level rise puts low-lying coastal infrastructure, such as wastewater treatment plants, at significant risk. The results of this study indicate that a nation-wide sea level rise of 10 feet would inundate nearly 400 wastewater treatment facilities. Flooding of a wastewater treatment facility would result in the inability to treat wastewater and potential hazardous overflows in neighboring communities. The neighboring communities surrounding wastewater treatment plants vary in their social vulnerability, which is indicative of a community's ability to recover from a disaster. We assessed the relative statistical difference in social vulnerability of the community surrounding inundated and non-inundated wastewater treatment plants. Following multiple analysis of variance tests, we conclude that there is no widespread statistical difference in social vulnerability of populations that are inundated at the national, regional, or local scale. While there is no statistical difference in the impacted population, communities with higher vulnerability have wastewater treatment plants that are susceptible to sea level rise and need to be analyzed on a case-by-case basis. The analysis of social vulnerability indexes in conjunction with infrastructure impacts open new insights into how communities are affected. Moreover, precautionary measures may need to be taken for the people living in low-lying areas that may be affected by sea level rise.

While the current study focused on wastewater treatment plants, there are other infrastructure systems impacted by sea level rise and other coastal hazards from climate change. Therefore, future research could study social vulnerabilities of other infrastructure types, including bridges, electric power infrastructure, or other public infrastructure. The study of additional infrastructure types will enable a better understanding of the impact of hazards on communities and their potentially disproportionate ability to respond to disasters. For example, military facilities' infrastructure, which are essential to national security, are also at risk to sea level rise [25]. There are more than 1,700 military installations worldwide coastal areas that may be affected by sea-level rise, which are vital due to their support of DoD readiness and operations [60]. The communities that support these installations have different levels of adaptive capacity, as defined by social vulnerability. Alternatively, electric power substations are a critical infrastructure and sea level rise increases the vulnerability of these systems to flooding [61]. Understanding the impacted populations from sea level rise could give insights into the inequitable distribution of resilience and adaptation efforts in infrastructure systems. Therefore, social vulnerability indexes or other socio-economic indicators should be an essential factor in assessing vulnerabilities to climate change across infrastructure.

Appendix A. Appendix

NAME	coords_x1	coords_x2	F10_feet_i	F9_feet_in	F8_feet_in	F7_feet_in	F6_feet_in	F5_feet_in	F4_feet_in	F3_feet_in	F2_feet_in	F1_feet_in	TOTPOP	THEME1	THEME2	THEME3	THEME4	THEMES
ANCHOR BAY WWTF	-123.5731609	38.80300105	0	0	0	0	0	0	0	0	0	0	4165	0.5847	0.4494	0.6612	0.4698	0.5767
WOODLAND STP	-122.740365	45.90401562	0	0	0	0	0	0	0	0	0	0	8189	0.564	0.8772	0.4524	0.9358	0.7912
DERBY WPCF, CITY OF	-73.08619878	41.31646534	0	0	0	0	0	0	0	0	0	0	6296	0.8392	0.6465	0.7723	0.771	0.8534
EAST HAMPTON WPCA	-72.54641997	41.56418253	0	0	0	0	0	0	0	0	0	0	5678	0.1874	0.1622	0.2942	0.1489	0.1042
ALDERWOOD STP	-122.317429	47.87836837	0	0	0	0	0	0	0	0	0	0	5373	0.0971	0.0473	0.6711	0.0557	0.0513
HOQUIAM STP	-123.9207686	46.97359456	1	1	1	1	1	0	0	0	0	0	3733	0.6403	0.8315	0.4351	0.731	0.7224
KITTERY WWTF	-70.75472147	43.09638018	0	0	0	0	0	0	0	0	0	0	3593	0.1289	0.1252	0.1933	0.3987	0.1284
HAVRE DE GRACE WWTP	-76.09860896	39.53138105	0	0	0	0	0	0	0	0	0	0	2122	0.6051	0.575	0.2993	0.8345	0.6501
VANDERBURGH COVE SD#1	-73.92424126	41.87367489	0	0	0	0	0	0	0	0	0	0	2708	0.1886	0.6282	0.4172	0.8202	0.4865
MCNEIL ISLAND SPECIAL COMMITMENT CENTER WWTP	-122.6620942	47.19533144	0	0	0	0	0	0	0	0	0	0	5311	0.422	0.8792	0.2521	0.7804	0.6074
FERNANDINA BEACH, CITY OF	-81.46329679	30.65764416	1	1	1	1	0	0	0	0	0	0	6943	0.1093	0.5273	0.1248	0.3227	0.166
SUMMERLAND SD WWTP	-119.5966528	34.41923903	0	0	0	0	0	0	0	0	0	0	4102	0.2596	0.1722	0.6135	0.68	0.3993
WALDPORT WWTP	-124.0572635	44.42699474	1	1	1	1	1	0	0	0	0	0	3317	0.7289	0.6635	0.0808	0.8	0.6519
GARDEN CITY WPCP	-81.16871717	32.11724662	1	0	0	0	0	0	0	0	0	0	1996	0.5349	0.6607	0.8062	0.5946	0.6811
NEW BALTIMORE (T) SD STP	-73.78961851	42.4463314	0	0	0	0	0	0	0	0	0	0	3271	0.2818	0.2114	0.0555	0.2041	0.1145
ELLIS CREEK WATER RECYCLING FACILITY	-122.5819147	38.20907903	1	1	1	1	1	1	1	1	1	1	4628	0.1949	0.3185	0.5418	0.354	0.2751
VAN HOESEN ST OVERFLOW	-73.80039851	42.4752914	0	0	0	0	0	0	0	0	0	0	4135	0.1655	0.3711	0.1558	0.3365	0.1737
JACKSON CO WCID NO. 2 - WWTP	-96.6146078	28.82883145	0	0	0	0	0	0	0	0	0	0	5075	0.4318	0.8427	0.6386	0.8628	0.732
PORT ISABEL WWTP	-97.22314066	26.06262163	0	0	0	0	0	0	0	0	0	0	4327	0.6867	0.4296	0.8719	0.8029	0.7866
LYNN BAYOU WWT	-96.62944835	28.62384608	0	0	0	0	0	0	0	0	0	0	2656	0.4781	0.741	0.3162	0.3012	0.433

Figure 9: This is an example of 20 WWTPs data, which was used in this study. Items shown in the table include the WWTP's name, the sea level rise of inundation, and the SVI themes associated with the WWTPs.

Bibliography

1. Vahid Hadipour, Freydoon Vafaie, and Norman Kerle. An indicator-based approach to assess social vulnerability of coastal areas to sea-level rise and flooding: A case study of Bandar Abbas city, Iran. *Ocean & Coastal Management*, 188:105077, April 2020.

2. Vahid Hadipour, Freydoon Vafaie, and Kaveh Deilami. Coastal Flooding Risk Assessment Using a GIS-Based Spatial Multi-Criteria Decision Analysis Approach. *Water*, 12(9):2379, August 2020.

3. Rashmisikha Behera, Abhipsa Kar, Manas Ranjan Das, and Prachi Prava Panda. GIS-based vulnerability mapping of the coastal stretch from Puri to Konark in Odisha using analytical hierarchy process. *Natural Hazards*, 96(2):731–751, March 2019.

4. Thomas K. J. McDermott. Global exposure to flood risk and poverty. *Nature Communications*, 13(1):3529, December 2022.

5. Carmela De Vivo, Marta Ellena, Vincenzo Capozzi, Giorgio Budillon, and Paola Mercogliano. Risk assessment framework for Mediterranean airports: a focus on extreme temperatures and precipitations and sea level rise. *Natural Hazards*, 111(1):547–566, March 2022.

6. Yu Han and Pallab Mozumder. Building-level adaptation analysis under uncertain sea-level rise. *Climate Risk Management*, 32:100305, 2021.

7. Thomas R. Allen, Thomas Crawford, Burrell Montz, Jessica Whitehead, Susan Lovelace, Armon D. Hanks, Ariel R. Christensen, and Gregory D. Kearney. Linking Water Infrastructure, Public Health, and Sea Level Rise: Integrated Assess-

ment of Flood Resilience in Coastal Cities. *Public Works Management & Policy*, 24(1):110–139, January 2019.

8. Michelle A. Hummel, Matthew S. Berry, and Mark T. Stacey. Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coasts. *Earth's Future*, 6(4):622–633, April 2018.

9. Patricia Cleveland. Water and Wastewater Sector-Specific Plan - 2015. page 56, 2015.

10. Cyber and Infrastructure Security Agency (CISA). Water and Wastewater Systems Sector | CISA, June 2022.

11. National Aeronautics and Space Administration (NASA). Sea Level Change Observations from Space, 2022.

12. Environmental Protection Agency (EPA). Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. page 101, September 2021.

13. Natalie Coleman, Xinyu Gao, Jared DeLeon, and Ali Mostafavi. Human activity and mobility data reveal disparities in exposure risk reduction indicators among socially vulnerable populations during COVID-19 for five U.S. metropolitan cities. *Scientific Reports*, 12(1):15814, September 2022.

14. Christopher T. Emrich and Susan L. Cutter. Social Vulnerability to Climate-Sensitive Hazards in the Southern United States. *Weather, Climate, and Society*, 3(3):193–208, July 2011.

15. Amy J. Stevens, Anna M. Ray, Ahimza Thirunavukarasu, Ella Johnson, Lucy Jones, Anna Miller, and James W.T. Elston. The experiences of socially vulnerable groups in England during the COVID-19 pandemic: A rapid health needs assessment. *Public Health in Practice*, 2:100192, November 2021.

16. Weiqi Zhou, Ganlin Huang, Steward T.A. Pickett, Jing Wang, M.L. Cadenasso, Timon McPhearson, J. Morgan Grove, and Jia Wang. Urban tree canopy has greater cooling effects in socially vulnerable communities in the US. *One Earth*, 4(12):1764–1775, December 2021.

17. Michelle Hummel, Matthew Berry, and Mark Stacey. Sea Level Rise Impacts on Wastewater Treatment Systems along the U.S. Coasts [data], 2018. Artwork Size: 72148737 bytes Pages: 72148737 bytes Version Number: 2 Type: dataset.

18. Minnu Abraham, R. S. Mahendra, Venkata Ravibabu Mandla, Chaithanya Sudha Merugu, and Veerendra Satya Sylesh Peddinti. Geospatial-Based Coastal Risk Assessment of Gujarat Coastline. In Sireesh Saride, B. Umashankar, and Deepti Avirneni, editors, *Advances in Geotechnical and Transportation Engineering*, volume 71, pages 41–57. Springer Singapore, Singapore, 2020. Series Title: Lecture Notes in Civil Engineering.

19. Jeremy Rohmer, Daniel Lincke, Jochen Hinkel, Gonéri Le Cozannet, Erwin Lambert, and Athanasios T. Vafeidis. Unravelling the Importance of Uncertainties in Global-Scale Coastal Flood Risk Assessments under Sea Level Rise. *Water*, 13(6):774, March 2021.

20. Rakesh Bera and Ramkrishna Maiti. An assessment of coastal vulnerability using geospatial techniques. *Environmental Earth Sciences*, 80(8):306, April 2021.

21. Anamaria Bukvic, Guillaume Rohat, Alex Apotsos, and Alex de Sherbinin. A Systematic Review of Coastal Vulnerability Mapping. *Sustainability*, 12(7):2822, April 2020.

22. Moslem Imani, Chung-Yen Kuo, Pin-Chieh Chen, Kuo-Hsin Tseng, Huan-Chin Kao, Chi-Ming Lee, and Wen-Hau Lan. Risk Assessment of Coastal Flooding

under Different Inundation Situations in Southwest of Taiwan (Tainan City). *Water*, 13(6):880, March 2021.

23. Mathew E. Hauer, Jason M. Evans, and Deepak R. Mishra. Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, 6(7):691–695, July 2016.

24. Gianluigi Di Paola, Angela Rizzo, Guido Benassai, Giuseppe Corrado, Fabio Matano, and Pietro P. C. Aucelli. Sea-level rise impact and future scenarios of inundation risk along the coastal plains in Campania (Italy). *Environmental Earth Sciences*, 80(17):608, September 2021.

25. Jeffrey Peterson. Coastal Storm and Sea Level Rise Risks to Critical Infrastructure. In *A New Coast*, pages 57–69. Island Press/Center for Resource Economics, Washington, DC, 2019.

26. Center for Disease Control (CDC). CDC/ATSDR Social Vulnerability Index (SVI), October 2022.

27. Center for Disease Control (CDC). Getting to Know GRASP | Place and Health | ATSDR, August 2022.

28. Stephen Cunningham, Steven Schuldt, Christopher Chini, and Justin Delorit. A simulation–optimization framework for post-disaster allocation of mental health resources. *Natural Hazards and Earth System Sciences*, 21(12):3843–3862, December 2021.

29. Barry E. Flanagan, Edward W. Gregory, Elaine J Hallisey, Janet L. Heitgerd, and Brian Lewis. A Social Vulnerability Index for Disaster Management. *Journal of Homeland Security and Emergency Management*, 8(1), January 2011.

30. Erica Adams Lehnert, Grete Wilt, Barry Flanagan, and Elaine Hallisey. Spatial exploration of the CDC's Social Vulnerability Index and heat-related health outcomes in Georgia. *International Journal of Disaster Risk Reduction*, 46:101517, June 2020.

31. Mahmoud Al Rifai, Vardhmaan Jain, Safi U. Khan, Khurram Nasir, Dongshan Zhu, Rhythm Vasudeva, Carl J. Lavie, Sunita Dodani, Laura A. Petersen, and Salim S. Virani. Social vulnerability and COVID-19: An analysis of CDC data. *Progress in Cardiovascular Diseases*, page S003306202100102X, September 2021.

32. Alexander Fekete and Jakob Rhyner. Sustainable Digital Transformation of Disaster Risk—Integrating New Types of Digital Social Vulnerability and Interdependencies with Critical Infrastructure. *Sustainability*, 12(22):9324, November 2020.

33. D.C. Novak, J.F. Sullivan, K. Sentoff, and J. Dowds. A framework to guide strategic disinvestment in roadway infrastructure considering social vulnerability. *Transportation Research Part A: Policy and Practice*, 132:436–451, February 2020.

34. Deniz Berfin Karakoc, Kash Barker, Christopher W. Zobel, and Yasser Almoghathawi. Social vulnerability and equity perspectives on interdependent infrastructure network component importance. *Sustainable Cities and Society*, 57:102072, June 2020.

35. Department of Homeland Security (DHS). Methodology for Assessing Regional Infrastructure Resilience - Lessons Learned from the Regional Resiliency Assessment Program June 2021. page 118, June 2021.

36. Susan L. Cutter, Bryan J. Boruff, and W. Lynn Shirley. Social Vulnerability to Environmental Hazards *: Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, 84(2):242–261, June 2003.

37. A. Fekete. Validation of a social vulnerability index in context to river-floods in Germany. *Natural Hazards and Earth System Sciences*, 9(2):393–403, March 2009.

38. Lam Thi Mai Huynh and Lindsay C. Stringer. Multi-scale assessment of social vulnerability to climate change: An empirical study in coastal Vietnam. *Climate Risk Management*, 20:165–180, 2018.

39. E.E. Koks, B. Jongman, T.G. Husby, and W.J.W. Botzen. Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. *Environmental Science & Policy*, 47:42–52, March 2015.

40. Lianxiao and Takehiro Morimoto. Spatial Analysis of Social Vulnerability to Floods Based on the MOVE Framework and Information Entropy Method: Case Study of Katsushika Ward, Tokyo. *Sustainability*, 11(2):529, January 2019.

41. Sigridur Bjarnadottir, Yue Li, and Mark G. Stewart. Social vulnerability index for coastal communities at risk to hurricane hazard and a changing climate. *Natural Hazards*, 59(2):1055–1075, November 2011.

42. Yi Ge, Wen Dou, Zhihui Gu, Xin Qian, Jinfei Wang, Wei Xu, Peijun Shi, Xiaodong Ming, Xin Zhou, and Yuan Chen. Assessment of social vulnerability to natural hazards in the Yangtze River Delta, China. *Stochastic Environmental Research and Risk Assessment*, 27(8):1899–1908, December 2013.

43. Christian Kuhlicke, Anna Scolobig, Sue Tapsell, Annett Steinführer, and Bruna De Marchi. Contextualizing social vulnerability: findings from case studies across Europe. *Natural Hazards*, 58(2):789–810, August 2011.

44. Cuong Viet Nguyen, Ralph Horne, John Fien, and France Cheong. Assessment of social vulnerability to climate change at the local scale: development and application of a Social Vulnerability Index. *Climatic Change*, 143(3-4):355–370, August 2017.

45. Alex de Sherbin and Guillem Bardy. Social vulnerability to floods in two coastal megacities: New York City and Mumbai. *Vienna Yearbook of Population Research*, 1:131–165, 2016.

46. Jayajit Chakraborty, Graham A. Tobin, and Burrell E. Montz. Population Evacuation: Assessing Spatial Variability in Geophysical Risk and Social Vulnerability to Natural Hazards. *Natural Hazards Review*, 6(1):23–33, February 2005.

47. R. Dean Hardy and Mathew E. Hauer. Social vulnerability projections improve sea-level rise risk assessments. *Applied Geography*, 91:10–20, February 2018.

48. David A. Swanson, Alan Schlottmann, and Bob Schmidt. Forecasting the Population of Census Tracts by Age and Sex: An Example of the Hamilton–Perry Method in Action. *Population Research and Policy Review*, 29(1):47–63, February 2010.

49. National Oceanic and Atmospheric Administration (NOAA). Sea Level Rise Data Download, June 2022.

50. CDC/ATSDR SVI Fact Sheet, 2021.

51. United States Census Bureau. TIGER/Line Shapefiles, 2022. Section: Government.

52. Climate Central. See your local sea level and coastal flood risk, June 2022.

53. Department of Defense Regional Sea Level (DRSL). DRSL Database, October 2022.

54. Climate Central. About us | Climate Central, July 2022.

55. Y.A. Shirazi, E.W. Carr, G.R. Parsons, P. Hoagland, D.K. Ralston, and J. Chen. Increased operational costs of electricity generation in the Delaware River and Estuary from salinity increases due to sea-level rise and a deepened channel. *Journal of Environmental Management*, 244:228–234, August 2019.

56. Jiayun Sun, Aaron C.H. Chow, and Samer Michel Madanat. Equity concerns in transportation infrastructure protection against sea level rise. *Transport Policy*, 100:81–88, January 2021.

57. Rahman Davtalab, Ali Mirchi, Rebecca J. Harris, Mark X. Troilo, and Kaveh Madani. Sea Level Rise Effect on Groundwater Rise and Stormwater Retention Pond Reliability. *Water*, 12(4):1129, April 2020.

58. Paul Chinowsky and Jacob Helman. Protecting Infrastructure and Public Buildings against Sea Level Rise and Storm Surge. *Sustainability*, 13(19):10538, September 2021.

59. Aaron N. Yesudian and Richard J. Dawson. Global analysis of sea level rise risk to airports. *Climate Risk Management*, 31:100266, 2021.

60. Margaret Tucker and G James Herrera. Military Installations and Sea-Level Rise. page 2, July 2019.

61. David Yates, Byron Quan Luna, Roy Rasmussen, Dick Bratcher, Luca Garre, Fei Chen, Mukul Tewari, and Peter Friis-Hansen. Stormy Weather: Assessing

Climate Change Hazards to Electric Power Infrastructure: A Sandy Case Study. *IEEE Power and Energy Magazine*, 12(5):66–75, September 2014.

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14. ABSTRACT

Many of the United States' major cities that have a high population are located along the coast. The number of people residing in low-elevation coastal areas, be-low 10 meters, is increasing. Coastal areas may be affected by various short- and long-term climate hazards, such as sea level rise (SLR). Climate change induced SLR will threaten residents and infrastructure in low-lying coastal areas. A household'scapacity to respond to hazards is highly dependent on its socio-demographic situation which determines its social vulnerability. Wastewater treatment facilities area particularly critical piece of infrastructure often located in low-lying areas due to gravity fed collection systems. Additionally, flooding of these infrastructure systems can lead to the spread of disease and contamination of water sources. In this analysis, we utilized a geographic information system to assess the exposure of wastewater infrastructure to sea level rise projections in the conterminous United States. We then paired these inundation estimates against the Center for Disease Control's Social Vulnerability Index (SVI) to investigate inequities in infrastructure impact. An analysis of variance (ANOVA) was performed to compare the SVI of populations near wastewater treatment plants that were inundated to those that were not inundated at sea level rise projections. Of the 1,040 wastewater treatment plants within two kilometers of the coast in the United States, 394 treatment facilities are in danger of inundation at 10 feet of sea level rise. Interestingly, the results of the ANOVA tests revealed some statistical differences in social vulnerability indexes of impactedpopulations and infrastructure against non-impacted populations.

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