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A Critical Review of Climate Change on Coastal Infrastructure Systems

Gregory J. Howland Jr.

A CRITICAL REVIEW OF CLIMATE CHANGE ON COASTAL INFRASTRUCTURE SYSTEMS

THESIS

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Abstract

Coastal regions have seen some of the most telling signs of climate change over the past few decades. In response to these and other threats, the Department of Defense (DoD) released a report detailing the impacts of climate change on its installations in January 2019. However, the report was determined to be largely inadequate, and the Government Accountability Office recommended that the DoD further incorporate guidance on climate projections into planning and facility standards. As a result, the U.S. Air Force has increased their interest in developing its climate adaptation portfolio, but it is lacking in tools and understanding on how its facilities will be impacted. In this study, critical review of the literature regarding climate change's impact on coastal infrastructure is performed. Through this critical review, we investigate which infrastructure systems are evaluated, how they are investigated, and what aspects should DoD infrastructure managers be aware of. The goal of this study is to find what research exists, what adaptation measures are successful, and what holes need to be filled by future research. The compiled information will inform civilian and military managers on how to invest time and money in future research as efficiently as possible. This research aims to provide the Air Force and other large organizations insight into existing information on adapting infrastructure to climate change.

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Greg Howland

Table of Contents

Page

Abstract v
Table of Contents vii
List of Figures ix
I. Introduction 1
1.1 Background 2
1.2 Problem Statement 4
1.3 Research Questions 6
1.4 Organization/Purpose of Remaining Chapters 7
II. Literature Review 8
2.1 Background 8
2.2 Coastal Flooding Context 12
2.3 Coastal Flooding Analysis 17
2.4 Coastal Flooding Impacts/Adaptations 24
III. Comprehensive Literature Review Methods 31
3.1 Gathering Literature 31
3.2 Collecting Data 32
IV. Results 36
4.1 Scale Analysis 38
4.2 Infrastructure Sectors Analysis 42
4.3 Research Outcome Analysis 47
V. Discussion 50
5.1 Discussion on Scale 51

5.2 Identifying Infrastructure in Need 53

5.3 Focusing on Infrastructure Adaptation 57

VI. Conclusion 61

References.. **Error! Bookmark not defined.**

Appendix A: List of Articles Reviewed...70

Appendix B: Questionnaire...86

List of Figures

Page

Figure 1: Display of likely global average sea level rise ...**Error! Bookmark not defined.**

Figure 2: Modeling framework to describe potential flooding 20

Figure 3: Scale of Study with Infrastructure Types. 38

Figure 4: Literature Attributed to Infrastructure System by Region................................. 42

Figure 5: Histogram of Publishing date based on Research Focus................................... 47

Figure 6: Electric power plants and substations exposed to storm surge. 54

Figure 7: Interdependencies between Infrastructure Systems 55

List of Tables

Page

Table 1: U.S. Military Installations Vulnerable to Climate Change 9

Table 2: Flooding Impacts to Hampton Roads, VA, Transportation 25

A CRITICAL REVIEW OF CLIMATE CHANGE ON COASTAL INFRASTRUCTURE SYSTEMS

I. Introduction

A news article released in 1912 warned that burning coal for electricity could affect the global climate (Sadeghi, 2021). The prediction at that time was that it would take centuries to see major changes in the climate. Since 1912, the interest in climate change has grown exponentially with little action, and the predictions have become increasingly dire. In the 21st century, climate change has become an important but controversial topic. There has been a significant push to predict the effects of climate change in many different fields of study. Climate's impact on coastal infrastructure is one of the focus areas going into the future. To that end, this research will investigate existing studies of coastal infrastructure impacts of climate change.

Over the last two decades, coastal regions have seen some of the most telling signs of climate change. Stronger storms and higher tides have become the norm for the east coast of the United States. These factors have spurred a lot of research into the nature of storm surge and sea-level rise (SLR). There are a lot of questions about how these factors will affect the future of our coasts. This research will specifically examine the effects of climate change on coastal infrastructure. A comprehensive review of the academic literature showed the potential vulnerability of coastal infrastructure and what holes in the research need to be filled. The compiled information will inform civilian and military managers on how to invest time and money in future research to adapt to coastal climate change.

1.1 Background

The Office of the Undersecretary of Defense for Acquisition and Sustainment released the "Report on Effects of a Changing Climate to the Department of Defense" in January 2019. The report outlines some of the climate threats that the Department of Defense (DoD) is facing and details the current efforts of the DoD to improve infrastructure resiliency (Report on Effects…, 2019). The report acknowledged a threat but left much to be desired in the evaluation and adaptation to that threat. The following research will synthesize the existing research and present it to coastal enterprises, one of the largest of which is the U.S. Air Force, to identify risks to coastal infrastructure. In particular, the U.S. Air Force (A.F.) has seen a significant impact of climate change at coastal installations and is interested in learning as much as possible to adapt to future scenarios.

The climate change report to the DoD outlines recurrent flooding hazards and mentions a handful of recent mitigation examples across the Air Force. The report also says that 20 A.F. bases currently deal with recurrent flooding (page 5). That number could potentially climb to 25 (Report on Effects…, 2019) under future climate projections. However, the Government Accountability Office (GAO) launched an investigation to verify some of the statements in the report and found some large oversights. Most importantly, the GAO found that the assessment of vulnerability to climate change effects was primarily based on past events, not future projections (Maurer, 2019). They also found that while the DoD said bases were implementing climate projections and considerations in master planning, many were not. Those bases attributed the lack of guidance and instruction on how to implement such standards for their failure. GAO recommended that the DoD incorporate guidance on climate projections into planning and facility standards as a way forward (Maurer, 2019).

The GAO report showed that the DoD needed to devote more time and effort into accounting for climate change in infrastructure policy. Looking deeper into changing coastal priorities due to new climate variability showed a significant breadth of research but little synthesis. SLR values vary from source to source, with a general scientific consensus of between 0.5 to 1 meter of SLR by the end of this century (Horton et al., 2014). SLR has two significant implications on coastal infrastructure. First, SLR can cause extensive recurrent, or nuisance, flooding when the addition of SLR to high tides causes flooding during the higher tides of the year. This can affect transportation significantly as seen in the case study performed on the Hampton Roads, Virginia, area (Sadler et al., 2017). Sadler et al. (2017) show that SLR can have significant impacts on the transportation network of metropolitan areas. Second, the addition of SLR to mean higher high water (MHHW), or mean high tide level, causes a compounding effect that significantly increases potential flooding caused by storm surge. Storm surge is the rise in water levels due to the massive force of storms pushing water into the coast as they make landfall (Merrifield et al., 2021). These two flooding mechanisms have different effects on infrastructure. The consequences of these flooding mechanisms range from minor disturbance to massive damage.

A comprehensive review was important in this field of research to synthesize the current literature and create a platform to guide future research. Climate change related research needs to be adapting quickly to make sure that knowledge is gained and shared as quickly as possible to combat the climate crisis. This review combines current ideas in different fields and regions to create a broad idea of how to move forward. For the most part, the current literature focuses heavily on defining flooding scenarios with great clarity but lacks detailed analysis on how to combat flooding events at the required scale. Adaptation planning is an area of need for the Air Force as well as other coastal entities. Ultimately, this research is about finding the best way to get helpful information into the hands of decision-makers.

1.2 Problem Statement

Coastal infrastructure is at increasing risk of inundation due to recurrent flooding and storm surge. Roads, buildings, utility networks, and groundwater are susceptible to rising sea levels. There has been research on why and how the sea is rising, but this study focuses on the research done on how the rising sea will affect coastal infrastructure systems. Some places are already experiencing recurrent flooding due to high tide conditions (Sweet et al., 2021). These flooding mechanisms only stand to worsen in the coming decades. Many of the country's most prominent urban areas are right on the coast, thus putting a large portion of the infrastructure portfolio at risk. These enormous urban areas have also pulled large government entities into their outskirts. In particular, the U.S. Air Force has numerous installations and annexes along both the East and West coast, Alaska, and Hawaii. This topic has begun to draw the attention of top-level military and government officials. The Air Force already has a large backlog of infrastructure spending, and future coastal climate change poses the potential to increase the required infrastructure spending significantly. There are some cases where coastal flooding could cause bases to be unable to complete their mission entirely. The A.F. needs to evaluate the risk and nature of the challenges brought on by SLR and the factors associated with it. There is a large amount of research that needs to be conducted to get to this point. However, the A.F. could significantly decrease this research burden by relying on existing regional SLR studies. For example, Li et al. (2013) studied the effects of hurricane impact on the inundation of Naval Station Norfolk. They examined the potential impacts of tropical storms combined with tidal levels to predict the impact on the station. Since this Naval station is very close to Langley Air Force Base, their research could be very useful to planners at Langley.

This study has two primary goals. First, find what research exists, what adaptation measures are successful, and what holes need to be filled by future research.

Second, create a database that A.F. stakeholders can use to find coastal research that has been conducted near their installation. Synthesizing the current literature is an essential step to efficiently moving forward with coastal infrastructure understanding and protection. Large entities, like the A.F., require better knowledge of which dangers present the most considerable risk to their infrastructure portfolio. Many studies show that typical facility designs for flooding (100-year storm) have become essentially obsolete. One such study shows that critical infrastructure may see flooding up to three times that of a 100-year storm (Fant et al., 2020). This could put more facilities than previously expected at severe risk of inundation. Installation planners need to be aware of this type of information so that proper adaptation measures can be considered in design phases. Similar issues can be found across the infrastructure portfolio as well. There has been little research that defines the risk caused to systems like sewer and electric when it comes to recurrent flooding. These are all important factors that must be faced over the next century.

1.3 Research Questions

What research on coastal flooding impacts to infrastructure has already been completed? The government can often be late to conduct research, especially regarding infrastructure. This problem is not a popular one, but it will become an increasingly expensive and crucial subject for all coastal entities as time goes on. That is why the government needs to rely on existing research. This research is essential to ensure that the government and other interested parties are starting with a strong baseline of information in tackling infrastructure adaptation.

Where are the holes in the research, both regionally and intellectually? One of the primary advantages of synthesizing the literature into a review is that it makes the holes in the research more easily identifiable. One of the major takeaways from this study is that there will be a more straightforward path for future researchers to make the literature more robust. Additionally, the synthesis will show the regional density of research. It will help identify portions of the U.S. coast that have not received the share of research that might be needed. Certainly, there are different complexities based on the region of the coast. Each region has its own unique challenges.

1.4 Organization/Purpose of Remaining Chapters

Following this introduction there will be an explanation of the literature review, methods, results, discussion, and conclusion. The literature review will summarize the main themes of the literature studied for this thesis. The methods will detail the process used to collect the data related to this review. The results and discussion will be an analysis of the data collected during this review and a commentary on how that information can be used to push the research forward. Lastly, the conclusion will be a wrap up of the main takeaways from this research.

II. Literature Review

The following literature review is intended to both shed light on the issue of climate change affecting coastal infrastructure as well as identify the primary themes of the literature in the coastal infrastructure field. These themes were identified through a mixture of systematic evaluation and subjective placement after reading. The four categories below represent the in depth background of the military's concerns with coastal infrastructure followed by the three primary themes that were identified within the literature.

2.1 Background

The Department of Defense (DoD) report on climate change from 2019 was significant because it was the first such document published by the DoD to address the implication of climate change on DoD infrastructure. This document is a key part of the motivation to conduct the research contained in this thesis. The authors describe the intent of the report with the following statement, "The effects of a changing climate are a national security issue with potential impacts to Department of Defense (DoD) missions, operational plans, and installations" (*Report on Effects…,* 2019). The DoD report specifically identifies several climate-related threats to infrastructure and outlines how those threats might impact installations across the services. The climate threats identified are recurrent flooding, drought, desertification, wildfires, and thawing permafrost. The

DoD used responses from 79 military installations across the United States (U.S.) to assess the current risk these climate hazards pose and how these hazards might affect these installations in the future (*Report on Effects…,* 2019). While this report looks across the DoD at all potential climate change impacts, this literature review focuses on climate impacts to infrastructure, not just in the military domain.

The DoD report talks specifically about the causes and implications of recurrent flooding. The report states:

> [Recurrent flooding] vulnerabilities to installations include coastal and riverine flooding. Coastal flooding may result from storm surge during severe weather events. Over time, gradual sea level changes magnify the impacts of storm surge, and may eventually result in permanent inundation of property. Increasing coverage of land from nuisance flooding during high tides, also called "sunny day" flooding, is already affecting many coastal communities. (*Report on Effects…,* 2019, pg 5)

This statement defines the parameters used to consider recurrent flooding in this literature review. The flooding mechanisms described above proved to be the most prominent within the literature as well. Sea-level rise (SLR) is also explicitly mentioned as a cause for concern. The report also detailed that 20 out of 36 surveyed USAF installations currently report problems with recurrent flooding. It also states that the number could increase to 25 within 20 years (see Table 1). The description above shows the need for climate change-related research and policy for the USAF.

Table 1*: This table provides a summary of current and future (20 years) vulnerabilities to military installations (Report on Effects…, 2019, pg 5).*

		Recurrent Flooding		*Drought*		*Desertification*		*Wildfires*		*Thawing Permafrost*	
Service	# Installations	Current	Potential	Current	Potential	Current	Potential	Current	Potential	Current	Potential
Air Force	36	20	25	20	22	4	4	32	32	-	-
Army	21	15	17	5	5	2	2	4	4	1	1
Navy	18	16	16	18	18	-	-	-	7	-	-
DLA	2	2	2	-	2	-	-	-	-	-	-
DFAS	1	-	-	-	1	-	-	-	-	-	-
WHS	1	-	-	-	-	-	-	-	-	-	-
Totals	79	53	60	43	48	6	6	36	43	1	1

The DoD report also mentioned some of the mitigation and adaptation measures that military installations have already implemented to counteract the effects of CC. The document primarily references DoD policies that require certain actions from installations. These policies largely require disaster planning, climate projection adaptation, and updated facility criteria (Report on Effects…, 2019). The report claims that many of these adaptations are already in effect and provides numerous implementation examples. The report also detailed current and future research attempts to quantify DoD exposure to SLR.

In response to the DoD Climate Change report discussed above, the Government Accountability Office (GAO) launched an investigation into some of the claims in the report. The GAO report found that base-level authorities were not executing the mitigating policies proposed by the DoD (Maurer, 2019). To make this determination, the GAO contacted 23 installations that were surveyed in the DoD report. They found that 8 of the 23 bases had not implemented severe weather planning as part of their infrastructure planning. Only 11 of the 23 bases had factored in weather events to improve the resilience of the facility. However, even in these cases, the adaptation was based on historical events and not climate projections. The primary finding of this GAO report is that even the bases that are trying to plan for future climate events are using old information to do so (Maurer, 2019). This is a critical issue moving forward and one of the primary concerns for coastal infrastructure systems moving forward. Infrastructure design uses codes and criteria that are based on a historical average. The climate-related rules that have been in place for so long are becoming increasingly unreliable, thereby creating the need for climate projections to be developed and refined to allow infrastructure adaptation well into the future.

In January 2021, President Biden signed Executive Order (EO)14008 (2021) to place an emphasis on climate change throughout the U.S. government. Specifically, the first section of the EO promises to put the "climate crisis at the center of United States foreign policy and national security" (EO 14008, 2021). This sort of emphasis shows clear objectives to further U.S. capabilities in combating adverse climate impacts. The EO goes on to mandate net-zero carbon emissions for the United States by 2050. To accomplish this, the administration plans on supporting new clean infrastructure development throughout the country. Additionally, the EO charges the Secretary of Defense with identifying the potential threats that the climate crisis poses to national security. Identifying how infrastructure can be impacted in coastal communities is an important aspect to national security because of the great deal of coastal assets that the DOD employs to protect this nation.

2.2 Coastal Flooding Context

It is important to gain an understanding about the context of the problem facing coastal infrastructure. The challenges are numerous, and the driving factors are measured at extreme scales. Sea-level rise, storm surge, increased rainfall, erosion, land subsidence, and saltwater intrusion are all climate change related factors that may cause problems in coastal environments. Due to the ambiguity around SLR, realistic projections are imperative for constructive analysis. One real issue surrounding SLR from a broader public point of view is the lack of clarity from mainstream news organizations. While these reports are not scientific and do not represent scientific literature, they do provide an interesting look into how climate change is viewed in society. Popular news outlets such as the *New York Times* and *Forbes* provide varied and unsubstantiated claims about SLR projections. One *Forbes* article shows that the coastal U.S. may see 2-7 ft of SLR and portrays up to 10 ft in the article (Dobson, 2019). A *Times* article claims that Miami, FL, may see 3 ft by 2060 (Flavelle and Mazzei, 2021). Lastly, an article in *The Atlantic* claims that near-term SLR may not be as bad according to some scientists but may exceed 26 ft by 2300 (Meyer, 2019). There is a significant amount of variation in SLR numbers being reported by news agencies which contributes to a significant amount of confusion around SLR in the public domain. Even the scientific community has some variation based on the projection tools provided by the National Oceanic and Atmospheric Administration (NOAA) and the International Panel on Climate Change (IPCC) (Horton et al., 2014). Taking a broad view towards the coastal flooding literature showed that while there is variation in the scientific community surrounding SLR projections, the culmination of the data shows that there is a reasonable range of confidence to which many scientists would agree.

Horton et al. (2014) provide a detailed analysis of the existence and magnitude of SLR. Their research focuses on synthesizing the various climate change projections into a consensus range from climate experts. Setting a likely range of SLR relative to the year 2100 was important to assess the validity of SLR claims within the literature. Horton et al. acknowledges a range of SLR predictions and solicits the input of experts in the field of climate science. The authors sought input from researchers who had published at least six peer-reviewed papers on SLR. The authors received 90 useable responses. The respondents were asked to give their expert opinion on likely ranges of SLR for 2100 and 2300 based on representative concentration pathways (RCPs) 3 and 8.5. These RCPs are scenarios that are based on potential greenhouse gas (GHG) emission levels in the future. RCP 3 is a lower emission scenario, and RCP 8.5 is a high emission scenario. They synthesized the experts' opinions using statistical methods and reported likely and very likely ranges of SLR. The results showed a likely range of 0.75 to 1.5 m of SLR for RCP 8.5 by 2100 and 0.25 to 0.5 m for RCP 3.0 by 2100 (see figure 1). It verifies the assumption that there is SLR, and there is a general magnitude to be expected by the year 2100. Their analysis provides the baseline to measure potential claims of SLR levels for other research.

One of the most significant flooding contributors associated with SLR is storm surge (Neumann et al., 2014). Storm surge is a rise in water brought on by tropical storms pushing water into the coast. The combination of storm surge and SLR is the most prominent flooding risk to coastal regions. A significant amount of research has been conducted to try and predict the effects climate change will have on storm frequency and intensity. Knutson (2021) reviewed this research and found that there is no scientific evidence to prove that storms will increase in frequency, but there is an indication that storms will become more severe on average over the next century. There is still significant debate on the effects of climate change on tropical storms and hurricanes, but the combination of SLR and potentially more intense storms means that severe flooding events will become more common on the coasts of the U.S.

Recording and evaluating flooding events is also an important aspect of understanding how coastal regions may be affected. Haigh et al. (2017) provides a detailed assessment of past storm surge events in the United Kingdom. Although not specifically applicable to the U.S., their data showing the increasing frequency and severity of these storms is very relevant. The authors take a broader look at flood events by including reports from various media outlets that may not have been recorded at a national level. Their analysis covers the years from 1915 to 2016. They recorded every storm event and gave it a rating from nuisance to disaster. This increased the event database from 59 to 329 events, thereby providing a more holistic view of the flooding occurrence and showing a significant increase in small-scale flooding events in the area. The main takeaway from their research is that there are more flooding events than those that get national coverage; therefore, when researchers set out to find all instances of coastal flooding, the number of events can skyrocket. A similar study conducted on a state-by-state level in the U.S. could be very impactful.

Flooding that can be attributed to climate change is certainly one of the most dangerous coastal infrastructure threats. The coastal infrastructure category consists of many types of infrastructure, and all types have different exposure based on the flooding or climate change mechanism they face. The infrastructure types discussed in the following critical review are built infrastructure, transportation, water/storm/sewer, and energy. Climate change impacts infrastructure beyond just coastal flooding, and the other effects can compound flooding issues. For example, Fant et al. (2020) discuss the vulnerability of electricity transmission to higher temperatures. They diagnose the broader impacts of climate change on electric transmission and distribution. SLR is one component of their study, but the authors study a broad range of climate-related impacts. They also quantify the financial implications of these climate stressors as well. They set up the problem in a few different contexts. They base their analysis on two representative concentration pathways (RCPs) that are potential carbon emission scenarios going forward. One moderate RCP and one extreme RCP were chosen for each study. Under each RCP, they defined a proactive response, a reactive response, and no adaptation strategy. They found that climate change is expected to decrease grid performance in the future, increasing the cost by as much as 25% (Fant et al., 2020).

There are other utility networks that may be at increased risk to SLR as well. For instance, Johnston et al. (2014) describe the threats to water-based infrastructure. Although their study is conducted in Scarborough, Maine, their findings are widely applicable. Sewer infrastructure failure poses an environmental risk to inhabitants in the area, and many of the components of this system are in low-lying areas, which makes them more vulnerable. Freshwater distribution is underground, but flooding-related washouts can damage the lines and allow outside material to get into the system. This poses a health concern and leads to boiling mandates or potential water outages. Lastly, stormwater infrastructure is more susceptible to losing capacity with SLR. This causes more flooding and prolongs the flooding event (Johnston et al., 2014).

Other studies offer additional insights into the effects of flooding. Najafi et al. (2021) focused on the effects of storm surge on the airport on the island of Saint Lucia in the Caribbean. The authors focused on the interconnectedness of infrastructure systems. They specifically examined how the airport would function based on different flooding scenarios using a network analyses framework. The scenarios were based on model replications of hurricane Mathew from 2016. They modeled how the airport operations would function if certain aspects of the infrastructure were interrupted in different flooding scenarios. They found that basic infrastructure systems like runway/aprons and backup power for the control tower became the highest risk items in the network during increased severity events. Their study is unique because it focuses on a coastal airport. While not in the contiguous U.S., the study is valuable because it directly relates to Air Force needs in the coastal sector. Because the study is based on interconnectivity at the airport, it also provides a microcosm for other coastal infrastructure systems. While their study was completed at a small airport, many inferences can be made at a larger scale, such as a coastal city.

The threat to coastal infrastructure is serious, and the context for that threat is required to make accurate assessments. Knowing the details about SLR, storm surge, and infrastructure exposure is important to assess the risk to coastal areas.

2.3 Coastal Flooding Analysis

Coastal flooding analysis applies to research that simply details a relevant aspect of flooding mechanics or projections. Generally, the portion of the literature that focuses on flooding analysis is intended to increase the understanding of flooding and how it may threaten coastal infrastructure. These articles create the foundation for understanding how flooding may propagate in the future and promote research into how to develop mitigation strategies to protect infrastructure. They tend to dive much deeper into the nature of how SLR affects flooding scenarios or mechanisms. They do not define the specific impacts of the flooding mechanism or how to solve it. While those outcomes are beneficial, there is knowledge to be gained in more detailed research into the actual flooding scenarios. Some of the articles in this section provide the most information regarding affected infrastructure, but they stop short of defining real impacts and leave it for future research.

The real advantage of analyzing flood plains is that it allows for a broader study of actual flooding mechanisms. For example, Habel et al. (2020) define specific flooding areas based on three different flooding mechanisms. The researchers had to find detailed tide, groundwater, and stormwater network data to create a coastal flooding model to define the multi-mechanism flooding. The analysis is very in-depth, and none of the impact/adaptation papers go into such detail about their respective infrastructure. The authors are setting up future researchers to have more information about flooding extent to allow their research to better define impacts and adaptations with greater effectiveness than otherwise.

The Habel et al. (2020) study focuses on recurrent flooding concerns in Honolulu, HI. The critical outcome of this research is outlining the multiple ways in which SLR can cause flooding in a coastal city. The first mechanism is traditional coastal flooding in which water comes over the beach and starts to flood infrastructure. Second, storm drain backflow is caused by storm drains becoming unable to discharge water properly and subsequently beginning to back-up and cause flooding at the inlet. Lastly, groundwater inundation is when coastal water seeps into the groundwater and causes the water table to rise above ground level (Habel et al., 2020). The study takes SLR projections and overlays them on Honolulu to find the total area flooded and location-specific flooding. The findings were that SLR would cause significant flooding around the city and that coastal and groundwater inundation mechanisms will have the highest impacts. Groundwater inundation is not an obvious flooding mechanism, and the identification of this flooding pathway is an important finding for future flooding research.

An important factor in how floods impact a coastline is the morphology of the coastline. The shape of the coast and its land use play a large part in dictating how an area might flood. Bilskie et al. (2014) analyze the coast of Alabama and Mississippi to see how flooding might change based on SLR and storm surge in three different time periods (1960, 2005, and 2050). They used Hurricane Katrina tides to model storm surge and combined them with projected SLR to test shoreline effects. The conclusion is that if coastal development keeps trending upward, it will affect how floods distribute across the region. The study found that flooding intensity increased overall as development increased (Bilskie et al., 2014). The combination of SLR and coastal development will lead to more flooding and more intense flooding in previously flooded areas. Understanding coastal morphology and it impacts flooding under a changing climate is an important step to combatting those changes. Bilskie et al. (2014) describe the potential threats to coastal infrastructure based on morphology and make recommendations to continue the research by finding the impacts of flooding to justify mitigation or mitigation research.

Modeling flooding based on multiple mechanisms is a difficult task. In the literature, most papers that address floodplain analysis use historical storms to create different flooding scenarios. Using historical scenarios of storm surge and adding SLR to the previously recorded levels allows researchers to take historic floodplains and find the additional area that SLR would impact. Khanam et al. (2021) do a great job of detailing the process to create their flooding model, and this model is representative of similar research done in the literature. Figure 2 shows the different portions of the model that Khanam et al. (2021) used to simulate flooding. Based on events like hurricanes Florence, Sandy, and Irene, they combined several different scenarios with future SLR projections to create a broad range of possible flooding zones and infrastructure exposure. This leads to a discussion of scenario-based modeling and how it is presented in the literature.

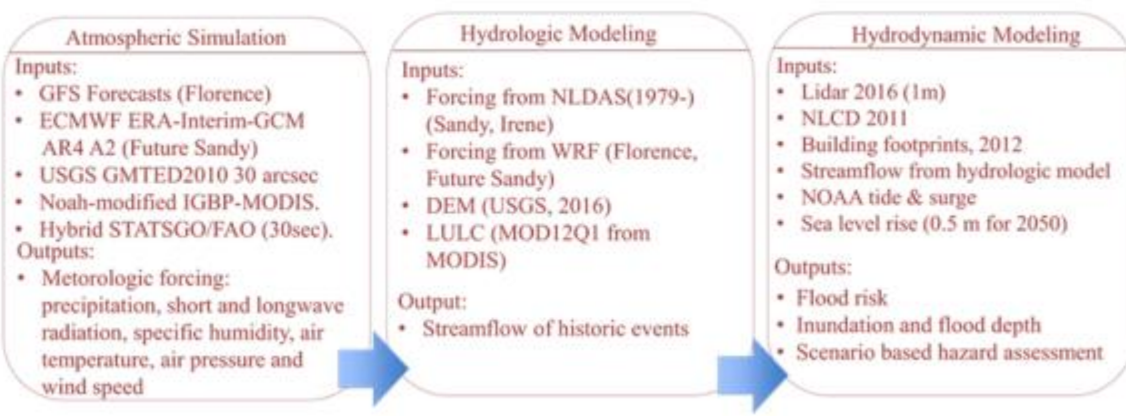


Figure 1: Modeling framework to describe potential flooding based on historical events (Khanam et al., 2021)

Figure 2 shows that based on events like hurricanes Florence, Sandy, and Irene, the authors combined several different scenarios with future SLR scenarios to create a broad range of possible flooding zones and infrastructure exposure. This leads into the discussion of scenario-based modeling and how that modeling is presented in the literature.

Scenario-based modeling is the primary framework used in the literature to predict coastal flooding. Due to the long history of recorded storms, there is a plethora of data to access that allows researchers to find tidal and surge elevation numbers along the entire coast of the U.S. The historical events for a given area that cause the most significant flooding are typically worst-case events or some of the worst events that have occurred. Shen et al. (2019) present an example of using worst-case historical events to describe potential future scenarios. The authors use historical hurricane data to produce storm surge and rainfall characteristics to evaluate the effectiveness of stormwater infrastructure. Hurricanes are typically extreme scenarios for coastal flooding, and the nature of analyzing coastal flooding leads researchers to these worst-case scenarios. While this method is understandable, there is a more subtle pathway for flooding than massive tropical storms. Tidal flooding is a scenario that is much less violent or dramatic but still can cause serious problems. A smaller proportion of the literature uses tidal flooding scenarios to model coastal flooding. The work by Sadler et al. (2017) is one of the few studies that uses a tidal scenario with SLR and without storm surge. To clarify, the paper does have storm surge scenarios, but they offer various flooding pathways.

They look at how recurrent flooding due to just tides may increase significantly over the next century, thereby causing serious impacts to transportation systems (Sadler et al., 2017).

Many of the coastal flooding analysis articles set out to define potential flood boundaries and report threatened infrastructure. It is crucial to define the exposure of certain infrastructure systems to identify the possible impacts. Most of the articles do this by using historical scenarios to model how the impacts might worsen with SLR. Another significant impact is the addition of SLR to tidal cycles. Many regions face more "sunny day" flooding events simply because SLR has made the high tides reach some flooding threshold (*Report on Effects…,* 2019). SLR poses a significant threat to transportation in the future. Bloetscher et al. (2014) outline how SLR-induced tidal flooding may impact roadways in Florida. Specifically, the authors project sea levels out to the year 2100. The SLR used in this process was based on peer-reviewed literature, and the authors chose to create a range of 2-5 ft for SLR in 2100 based on that literature. Their study also described the effects of the porous Florida soil on how SLR increases groundwater levels. The study used LiDAR data (detailed elevation data) to compare sea level to low elevation roads. By making this comparison, the authors were able to label vulnerable roadways in various places in Florida (Bloetscher et al., 2014). This is an interesting case because it shows that there can be significant impacts to coastal flooding that are completely unique to a region. The porous soil in Florida poses a difficult challenge that other regions may not face and shows the importance of considering regionality for those seeking guidance.

Energy infrastructure is also at tremendous risk in coastal systems since a large portion of the U.S. energy production takes place on the Gulf Coast. Bradbury et al. (2015) studied the effects of storm surge and sea-level rise on energy infrastructure. They examined historical hurricane data along the Texas and Louisiana coast and combined storm surge with SLR projections for 2100. They separated the region's three main energy infrastructure types: petroleum, natural gas, and electric. They were able to identify how many facilities in each category were at risk based on the storm intensity. They found that the largest incremental increase in affected facilities due to SLR was in lower intensity storms. Their work represents a benchmark energy paper for analyzing flooding risk in the Gulf region. However, their paper intentionally avoids generating any impact statement or damage estimates. The authors recommend that future research be conducted on the risk to the infrastructure systems by combining damage estimates to their study (Bradbury et al., 2015). The damage profile for the Gulf Coast energy production is large. The infrastructure in the Gulf Coast supplies a significant amount of the U.S. with fuel and has compounding economic effects.

The knowledge gained from these articles creates a holistic look at how coastal flooding occurs and what coastal infrastructure may be at risk. It also provides specific references for recommendations of future studies. A large part of this thesis is creating a path forward for researchers to fill in the gaps in coastal infrastructure reliability.

2.4 Coastal Flooding Impacts/Adaptations

The most impactful portion of the literature are those papers that define impacts and recommend adaptation strategies. The obvious desired outcome of the research in this field is to provide actionable information to decision-makers and create reasonable adaptation measures to prevent destruction on U.S. coasts. There is certainly a need for this information. However, the majority of research articles did not go as far as defining impacts or recommending solutions to these coastal problems. The data coming out of the articles in this section is quantitative and actionable. For example, Sadler et al. (2017) provide meaningful impact data and Shen et al. (2019) provide data to make design decisions to address flooding issues. Both of these studies are close to a Naval base and an Air Force base as well. These types of studies are crucial to quantifying and addressing climate change impacts on coastal infrastructure.

Sadler et al. (2017) is one of the best examples of providing clear and meaningful impact data on a specific region. Their study takes SLR projections and combines it with tidal data from the Hampton Roads, VA, area. The focus is mostly on tidal nuisance flooding, but the authors also examine 100-yr storm surge conditions. Specifically, they are focused on flooded roadways causing transportation interruption. This flooding primarily causes impacts to transportation in the form of freight and commuters but can have significant economic effects. The unique part of this study is that they quantify the severity of flooded roads based on the known traffic data. They lay out which roadways face recurrent flooding, under what scenarios, and total annual traffic (Sadler et al., 2017).

Table 2. Table showing significant flooding events by scenario and traffic volume (Sadler et al., 2017)

Point	Location	City	Roadway elevation (m)	Storm surge elevation (m)	Year of predicted flooding: SLR+ MHHW	SLR+ 99%-tide	SLR + 99%-tide + SS	AAWDT
1	Intersection of I-264 and Kempsville Road	Norfolk	2.9	2.4	>2100	2080–2100	Present	198,000
2	I-64 near Mill Creek	Norfolk	2.0	2.4	2080	2060–2080	Present	146,000
3	Intersection of I-264 and Brambleton Avenue	Norfolk	2.0	2.4	2080	2060–2080	Present	131,000
4	Intersection of I-264 and Broad Creek	Norfolk	2.8	2.4	>2100	2080–2100	Present	123,000
5	I-264 near Eureka Park	Virginia Beach	3.0	2.2	>2100	2080–2100	Present	111,000
6	I-264 connection South of Berkley Bridge	Norfolk	3.0	2.4	>2100	2080–2100	Present	107,000
7	Intersection of I-264 and E Main Street	Norfolk	3.0	2.4	>2100	2080–2100	Present	105,000
8	Intersection of I-64 and W Bay Avenue	Norfolk	2.3	2.2	2080–2100	2060–2080	Present	93,000
9	I-64 W before Hampton Roads Bridge Tunnel	Norfolk	2.7	2.2	2080–2100	2080–2100	Present	88,000
10	Intersection of Independence Boulevard and Garrett Drive	Virginia Beach	2.6	2.3	2080–2100	2080–2100	Present	76,000

The data in Table 2 a tremendous tool for decision-makers to use to make adaptation decisions. While Sadler et al. (2017) do not provide any adaptation recommendations, they lay out the impact of flooding in a clear and concise way. Additionally, road adaptation is fairly simple and tied mostly to either abandonment or elevating the pavement surface with erosion protection (Johnston et al., 2014). The research by Sadler et al. (2017) is the benchmark for transportation-related studies. They go into great detail about the flooding risk, as well as providing quantifiable impacts. Lastly, their research is in a very military-heavy region, making it extremely valuable to military installation planners in that area.

A great complement to Sadler et al. (2017) is the research by Shen et al. (2019), who provide adaptation measures to solve roadway flooding problems in the Norfolk, VA, area. They describe the combined effects of storm surge and rainfall on stormwater systems in coastal areas by using historical data from hurricanes. The authors model the storm surge events using relevant software and model the rain event with a specific lag. The authors claim that the peak rain event typically does not come until after the peak tide event. The combination of these two events has significant effects on the efficiency of the stormwater system. An interesting portion of their study is the modeled discharge of the stormwater system. As the storm tide hits the landmass, the stormwater system starts discharging water at -2 m^3/s or intakes water from the ocean. This event is followed shortly by peak discharge in the period. The model shows that water is being forced back into the city from the ocean, thus causing flooding right before the intense rainfall makes landfall. The peak flood area occurs right around that time when peak discharge is observed. Their study effectively details the potential stressors on a stormwater system in a coastal zone, and the authors provide their model as an adaptation measure to design future stormwater systems and upgrades.

Providing relevant adaptation strategies is another desired outcome of the coastal infrastructure field. The two articles previously discussed in this section do a fantastic job providing impacts and presenting pathways to adaptation, but there have been other research efforts that provide clear adaptation recommendations. A good example of this the research by Johnston et al. (2014), who provide a framework to assess coastal vulnerability to SLR. In this case, the framework was used to assess Scarborough, ME. Their research is unique in the fact that it assesses a variety of infrastructure types. The authors use different potential flooding scenarios based on historic storm surge and 2 feet of SLR. They use GIS software to identify critical infrastructure within Scarborough and overlay flooding scenarios to find affected areas. A unique factor about their work is that it discusses the specific risks to each infrastructure type from coastal flooding. The detailed explanation of risk based on infrastructure type is useful going forward. The authors also provide detailed adaptation recommendations and strategies based on specific locations impacted by the flooding scenarios. This is certainly a unique aspect of their research; they go down to the detail of recommendations for specific road sections.

There is also a good portion of the literature that covers SLR induced failure on sewage infrastructure. This is a fascinating infrastructure problem because some of the most essential components of these systems are often built at very low elevations. After all, sewer systems are primarily gravity fed. Two research effort rise to the top of this genre within the literature. Both provide adaptation measures or impact statements and they focus on opposite coasts as well.

First, Hummel et al. (2018) describe the risk to U.S. coastal wastewater systems. Wastewater treatment plants are at high risk of SLR because they are built-in lowest elevation areas to aid in sewage flow. There are a lot of benefits about being at the lowest elevation for the operation of the facility, but it does leave the facility vulnerable to SLR (Hummel et al., 2018). The authors take a closer look at San Francisco Bay, CA. They assess risk based on two flooding mechanisms: marine and groundwater. They used GIS software to find the depth at which SLR would cause flooding at wastewater treatment facilities. They also quantified the population impacted by the loss of each treatment facility based on the area serviced by each facility. One of the largest takeaways from their research is the exponential increase from the population affected directly by flooding to those impacted by the loss of services. Lastly, the authors provide recommendations for threatened wastewater plants to build floodwalls, pumping stations, or relocate to higher ground based on the flooding model (Hummel et al., 2018). Their research excels because it includes an analysis of flooded infrastructure, impacts to the system, and potential recommendations.

Second, Allen et al. (2019) outline the risks of failing sewer infrastructure on the community from an emergency management context, with special emphasis on the second-order effects and the implications of a damaged water system on public health. The authors detail what damage may be assessed to the systems and what various water failures can cause public health implications. The primary discussion of the paper is a tabletop exercise that forecasts a severe hurricane in 2035 based on SLR projections for that year. This exercise posed the combined effects of storm surge and SLR to threaten the community wastewater systems. The exercise concluded that SLR raises the risk to municipal water infrastructure. SLR increases the flooding extent, which could affect the clean water supply to critical health infrastructure and causes sewage overflow into the community, thus causing disease. Although they did not offer physical infrastructure adaptation techniques, they recommended an emergency management overhaul to better prepare coastal municipalities for flooding scenarios. They used their 2035 storm model to advise creating new hospital evacuation measures and choose new evacuation routes to avoid flooded transportation corridors (Allen et al., 2019).

To bring in an example of built infrastructure research and adaptation, Frazier et al. (2010) assesses a large area of built infrastructure and its economic susceptibility to CC related threats. They focus on the socioeconomic impact of storm surge and SLR on Sarasota County, FL. Their research examines contemporary storm surge effects from recent hurricanes, and the authors apply potential SLR scenarios to those storm surge events. They studied the extent of flooding, as well as the socioeconomic value of the inundated area. To get a more detailed picture of the socioeconomic impact, they considered population, land use, critical facilities, and parcel value. They provide images of current storm surge danger and storm surge with 120 cm of SLR to show the expansion of the at-risk area (Frazier et al., 2010). They concluded that SLR will significantly increase storm surge impacts. Their research is a good reference for the effects of SLR on residential and commercial infrastructure. It is one of the few studies in the infrastructure category that provides economic impact estimates.

The research by Frazier et al. (2010) is unique because it is one of the few papers that recommends policy changes as an adaptation strategy. The authors claim that better land-use planning could significantly decrease the exposure of coastal infrastructure. However, the authors acknowledge that Sarasota, FL, has a high reliance on coastal tourism as an economic driver (Frazier et al., 2010). This is an interesting problem because this same issue can be said for a large majority of the U.S. coastline. This is where policy changes in support of CC related threats become a murky issue. It becomes very difficult for policymakers to make decisions because the potential threats they are trying to avoid will often impact the economic stability of the coastal area.

Conclusion

Most importantly, adaptation and impact research provides planners and decision-makers with actionable information. The end goal of all of this research is aimed at making coastal infrastructure more resilient to climate change. The data contained in these articles is what drives the decisions being made in the field. The synthesis of this type of information is what will have the most impact going forward because it will allow a broader audience to view this essential research going on in other geographic areas. All of this research can be duplicated and applied to any coastal ecosystem as long as the correct data is available. Many of the studies in this section provide specific recommendations about specific pieces of infrastructure or offer the opportunity to make design decisions based on these models.

III. Comprehensive Literature Review Methods

This study is a comprehensive literature review to understand the research around coastal flooding and infrastructure. Articles and reports from various publishing sources and regions were systematically collected to represent the literature. There were a number of qualifiers required to accept the literature into the review. Predominantly, the studies had to address climate change projections in conjunction with some infrastructure assessment. Also, this research focused specifically on the United States coastline, therefore most foreign studies were overlooked. However, there were additional articles in the literature review as well to provide context for climate change projections as well as specific studies that would be beneficial to the USAF, i.e., island airport studies.

3.1 Gathering Literature

While gathering the literature for review, it was crucial to make sure that there was a thorough evaluation of the greater research database. Access to a range of scholarly search engines through the Air Force Institute of Technology library. The primary databases that were used to collect literature for this thesis were Scopus, Google Scholar, Science Direct, and the American Society of Civil Engineers online library. These sites did not provide access to every article on the topic, but it is reasonable to assume that it covers the large majority of related literature. The terms used in the search were important as well. Using combinations of climate change, sea-level rise, storm surge, infrastructure, coastal flooding, inundation, and military proved useful for finding the target articles. The most beneficial method was to use Boolean logic to download large numbers of articles then sort through them as needed. The logic applied was (climate change OR sea level rise) AND (coastal OR infrastructure OR military) and (flooding OR storm surge OR inundation).

A total of 456 potentially relevant journal articles were downloaded using the methods described above. Once the articles were flagged as relevant the next step was to filter out those articles that were obviously not relevant to this study based on title. A closer look at each abstract was required to further digest the meaning and relevance of the article. Over 200 abstracts reviewed narrowed the number of articles down to around 116 articles. Of those 116 articles there were a small number that did not apply directly to this research based on intricacies of the topic studied or the fact that it was based in another country. The final number of articles completely reviewed for this study was 93.

3.2 Collecting Data

Cataloging data from the articles was another important step in the review process. The online survey software Google Forms allows the user to input various types of information repeatedly and stores the data in a spreadsheet. Tracking location, scale, focus, and other metrics through this software allowed more cumulative analysis of the information. This method creates a local, regional, and national picture of the climate related coastal flooding research in the U.S. based on the reviews input into the system. The Google Form questions used to collect the information are based on information that can answer a few basic questions about the article as well as more detailed information about the nature and value of the research.

The information questionnaire is intended to get the most pertinent information out of an article in a way that can be analyzed at a larger scale. Simple information such as title, author and publishing dates are collected for identification. Next, scale and location data are input. The scale of the study (city, state, country, etc.) is recorded to study the extent of articles in the field that research at these different levels. Also, tracking the general location of the study provides the data required to do geographical analysis. To track the location coordinates were taken based on the general area of a specific study. These were not precise points, for example if a study was conducted in New York City a point somewhere in the five boroughs was selected to represent that study. Also, the temporal scale of each study was tracked in the scale section as well. This is a measure of how far into the future the article projects climate change or sea level rise.

The next section of the questionnaire is related to data and methods. Intended to record the methods and data used by the authors of each study. It also records the type of infrastructure that the article focused on. This is one of the most important pieces of information for the analysis. Also, this section was used to record what modes of failure were used in the analysis. The important information was if the study included storm surge, SLR, rainfall, etc. or any combination of failure modes. Following the data and methods is the context section. This section records data about each article that describes why the analysis was conducted, and how it can be useful to the literature review. Primarily, the focus of the analysis for each study was the most important part of the context. Damage reduction, infrastructure reliability, transportation disruptions, and economic impacts were the primary focuses recorded with an option for other inputs to be recorded as well. Also, the extent of sea level rise used in the study was recorded here, whether by representative concentration pathways (RCPs) or low, intermediate, and high designations. Adaptation recommendations were recorded in the context section as well. Lastly, relevant quotes and interesting figures were recorded to be referenced later in the process, as well as a quick note about the relevance of the article for this thesis. A complete list of the questions used in this research can be found in Appendix B.

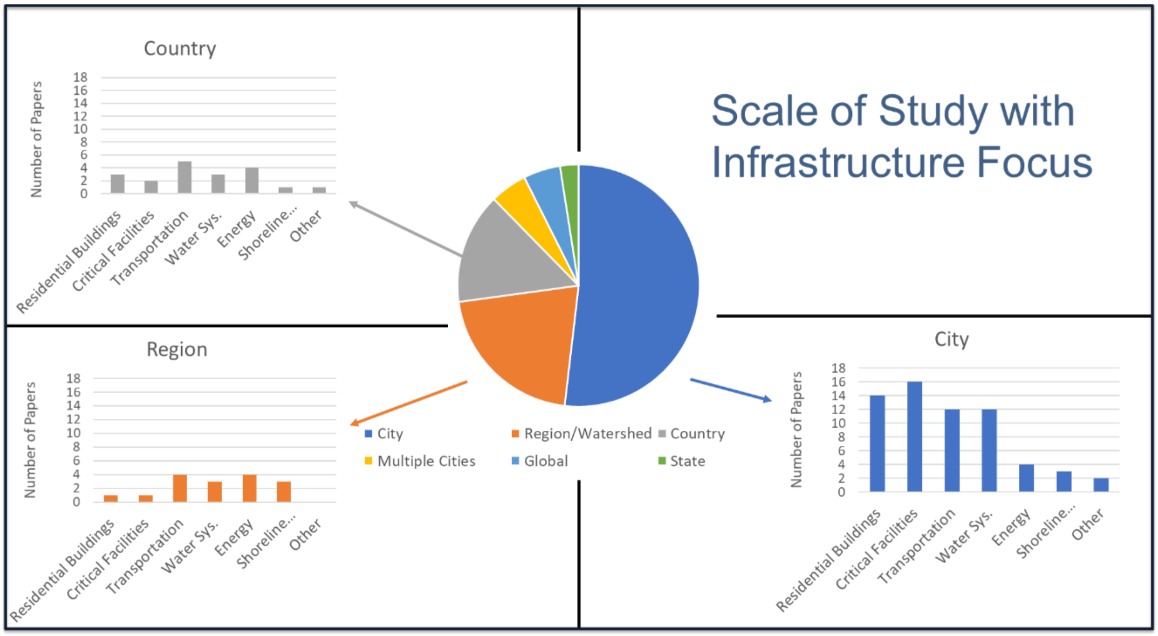
Lastly, the themes generated in the literature review were developed by a combination of systematic analysis and deductive reasoning. The themes discussed in the literature review were informed by the patterns of the literature reviewed in this analysis. Collecting the data revealed that there was a distinct difference between the content and applicability of each article. The subjective part of identifying those themes was using the content of the paper to relate it to other groups of paper in the research. After the review was complete the three main themes discussed in the literature review chapter rose to the top.

IV. Results

Climate change’s effects on coastal ecosystems are diverse. The intention of this review was to take a wide look at the literature surrounding coastal flooding and climate change and synthesize it by identifying trends and finding gaps that need to be filled. Those gaps may be intellectual gaps, geographical gaps, etc., but the importance of identifying focus areas for the future is paramount. The data presented in this section was selected to showcase some of the important results of this review.

Some of the simple metrics to discuss first are temporal scale and recommended solutions. Temporal scale is the metric used to identify how far out each study projected sea-level rise (SLR) impacts. This number was overwhelmingly the year 2100. 65% of the papers included in this review projected climate change impacts out to year 2100; this year is common as a projection for SLR from the oldest papers in this review to the most recent papers. Primarily this projection was used to provide a useable value for SLR. Another interesting fact is that while 65% of the papers project out to 2100, no other timeframe was mentioned by more than 5% of the papers. However, although 2100 is a nice round number that represents the turn of the century, is it a suitable basis for projection? Should literature surrounding infrastructure be focused on a point 80 years from now or should they focus more near term? Should they be focused even further out? Theoretically, the life-cycle for most infrastructure is less than 50 years so most infrastructure built today will have run its course by then.

Solutions and recommendations are another vitally important part of this review. In general, research is done to further knowledge on a topic so that decisions can be made with a better understanding of the consequences. While research that furthers our knowledge about the nature of flood events in the future and how it may affect infrastructure systems is important, there is certainly a need for more specific research to identify mitigation strategies for these flooding metrics. About 25% of the studies in this review offered no mitigation strategies for effects of coastal flooding. Most of the papers that did mention solutions only did so with minimal effect and concluded by recommending further research into those mitigation strategies. This is another big step in the research that needs to be overcome to see real usefulness in real-world decision-making.



4.1 Scale Analysis

Figure 2: Break down of the scale of each article and histograms of how those breakdowns relate to infrastructure types.

The scale of the study shown in Figure 3 reflects the level of detail evaluated and the corresponding outcomes of the research. The more detailed smaller studies typically have a more detailed conclusion of their research. However, larger studies at the national level typically are looking at much larger patterns and general impacts. Both of these extremes are important to the overall section of literature, but they are important in different ways. City level studies provide real actionable results that are easily repeated in other cities, while national scale studies provide actionable data for the smaller studies to use in their analysis. The regional scale is a blend of both of these previous mentioned sizes, taking slightly more general data and evaluating it over a slightly larger area to finding picture impacts for a specific region. These are maybe the most useful studies for state level planners and policy-makers. Having a bit more diversity in a study but still being focused enough to make detailed decisions is a great technique for studies moving forward.

52.4% of the studies were at the city scale. This was an expected outcome, and it comes with both positives and negatives. Having these localized studies make up the bulk of the research is problematic in the fact that there is less knowledge about the big picture coastline data. The positives associated with this are the detailed knowledge of effects on cities. Cities receive the most attention because of the more severe consequences in higher population centers on the coast. More detailed studies are important at the city scale because the data volume is huge, and the data granularity is small. Intricate societal and infrastructure networks in cities require a more detailed evaluation to determine impacts to drive adaptation planning. There are a lot of great city-level papers in this study, but one of the most interesting was a review of city-level infrastructure policies and how they affected climate readiness (Singh et al., 2021). Specifically, the study compares New York City, Tokyo, and Rotterdam to see how different countries with similar issues approach this subject, and how New York could potentially improve their approach to be more resilient in the future.

The larger scale national studies are typically studying more broad implications of climate change to coastal flooding, and they take up 13.1% of the total. The larger studies shy away from the more specific impacts of coastal flooding and are more often finding trends of climate impacts on flooding mechanisms. In general, these studies are adding to the knowledge base of flooding projections over the next 100 years. While there is not likely any fine resolution data coming out of these studies, there are data that can be used as building points for the smaller scale research. These national studies are laying the framework for how coastal flooding can be evaluated at a more actionable level for stakeholders. An example of a national scale study is the research conducted by Azevedo de Almeida et al., (2016). Their study takes a broad approach of defining flooding mechanisms, impacts, and adaptation measures relative to civil infrastructure. The study focuses on broad ideas that can relate to any coastal region but is defined well enough to be useful at the smaller scales.

The middle ground between the two previous scale studies discussed is the regional scale. This scale is defined by a study that can be as small as multiple cities to as large as a coastal region such as the Gulf of Mexico. The regional scale category certainly has the largest range of size and most variability of analysis. The research at this scale is much more focused than the national scale but is often broader and more general than the city level. However, there can often be outcomes at this scale that offer high resolution data for stakeholders to use in making decisions. They also provide a much needed link between more general flooding projections and specific impacts to coastal areas. Another key aspect of the regional scale papers is studying the relationship between multiple coastal communities in a region and the potential large scale impacts climate threats may have to different systems. For example, Dismukes et al. (2018) evaluate the potential impact of climate change on energy infrastructure on the Gulf Coast and detail the potential impact of losing the vast amount of natural gas and oil production that is focused in that area. Using historical events as a baseline to add climate projections shows this could be a high-risk area (Dismukes et al., 2018).

Figure 3 shows that the city-level studies are heavily weighted towards the built infrastructure systems as opposed to more broad systems like energy and shoreline infrastructure. Residential and critical facilities are the most heavily researched while transportation and water systems are slightly less researched but still relatively high compared to the other categories. This is not surprising given the more local scale of these infrastructure systems. Coastal flooding studies done in cities are understandably more focused on buildings and transportation issues than a larger scale study would be. Additionally, municipal water systems are much more local than other infrastructure systems like energy. Most sanitary and drinking water systems are contained within a municipality as opposed to energy which has a very wide network of transmission lines interconnected across the country. That is also why the larger studies tend to be more focused on more geographically widespread infrastructure systems like energy and shoreline infrastructure.

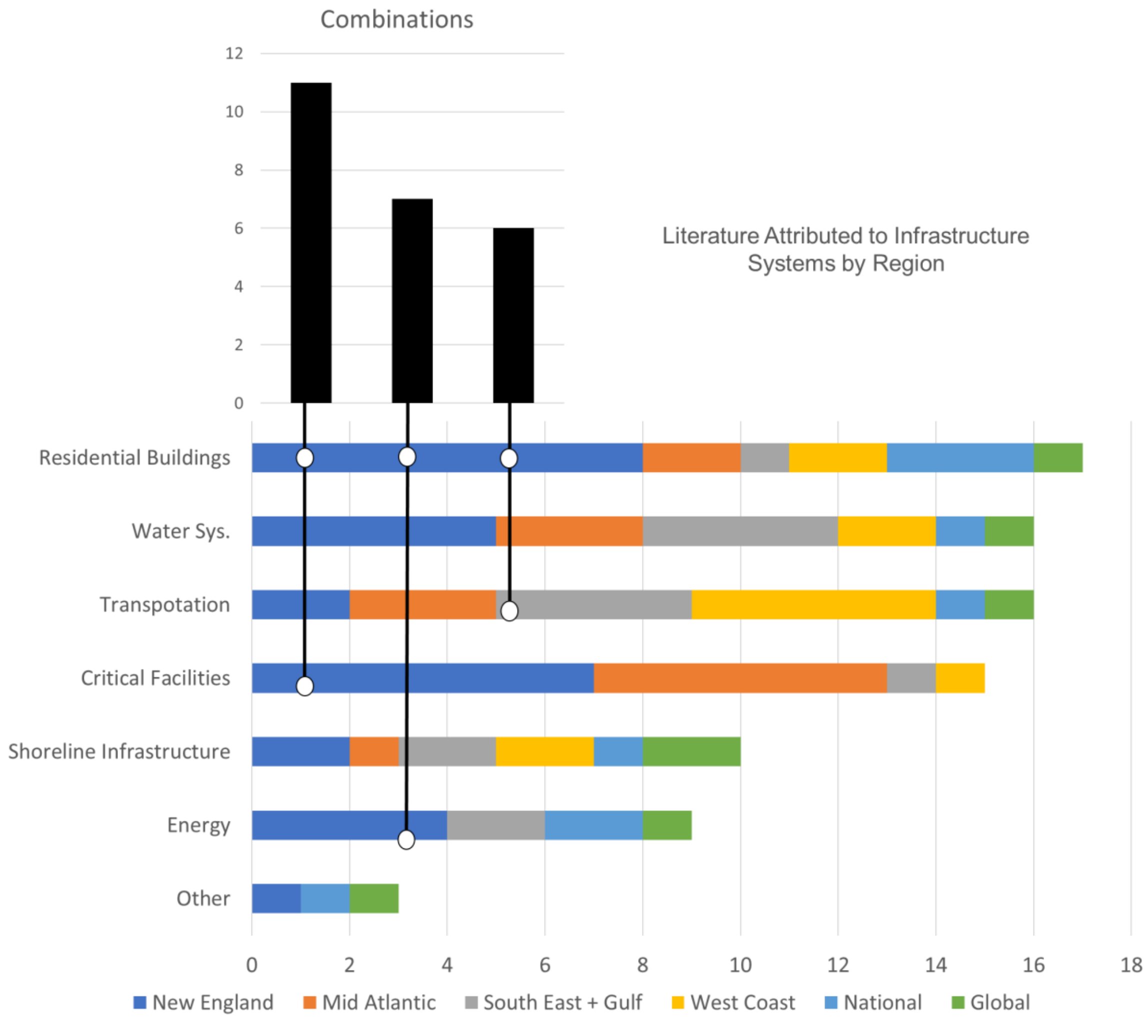


Figure 3: *Each bar represents the type of infrastructure studied and how many times that infrastructure type is focused on in the literature. The colors represent the region of the study, and the most combined infrastructure types are shown in the top left.*

4.2 Infrastructure Sectors Analysis

Infrastructure focus is an important metric of this literature analysis. Gathering data about the types of infrastructure that were studied and how they were studied is very informative. One of the desired outcomes of this thesis is defining how and where to focus research in the future. Knowing the focus of previous research is instrumental in making those decisions. Figure 4 shows that the majority of the research is split between residential (17) and critical built infrastructure (15), transportation (16), and water-related municipal infrastructure (16) to include drinking water, sanitary sewer, and storm sewer. Shoreline infrastructure and energy fall behind with a noticeable gap between them and the categories previously mentioned. This shows that larger infrastructure systems that typically stretch beyond one city or municipality seem to get less focus despite the broad importance of those infrastructure types. Energy-related studies are the least researched of the major categories (9) despite being one of the most fundamentally important infrastructure systems to modern society.

The geographic location of each study is also a very important aspect to record. Like infrastructure type, location of study can also show where certain infrastructure sectors are well researched and which regions may need more focus going forward. The biggest take away from Figure 4 from a geographical standpoint is that the Northeast U.S. has the most studies in nearly every category. The overall focus of the literature clearly shows that the Northeast has seen the most research. This is not necessarily surprising given that the region has one of the largest coastal population densities in the country with cities like Boston and New York City. The other evident areas of focus are the Mid-Atlantic and Southeast. Both are very important regions of the U.S. with high population densities as well. It is also quite clear that based on the research count that the East coast is a focus of the literature. The West coast has some representation in most categories, but transportation unsurprisingly is the biggest sector of concern. The literature on the West coast was predominantly focused on San Francisco because of a number of unique challenges they face related to SLR.

There were also a fair number of studies that focused on two different categories. Most prominently, critical buildings and residential buildings were often paired together for obvious reasons. Although the scale and importance of these types of buildings are very different, they face very similar threat profiles and failure modes. However, there are typically very different outcomes related to flooding in these two building types. The second most common pairing was water systems and energy systems. This combination is a little more interesting to decipher. The relationship between energy and water systems is not quite as evident as the residential and critical infrastructure comparison. In Tonmoy et al. (2014), the authors use a systems dynamic approach to estimate the impact and interdependency of municipal system outages. This is an example of research that examines a combination of systems to determine a more realistic picture of vulnerability for a region. Many of these combination papers look at a similar problem with different intricacies associated with each study. The idea of cascading effects of infrastructure systems is an important theme in this genre and will be discussed later.

The next most common combination of infrastructure was water systems and transportation. This combination is quite obvious given that storm water systems and transportation systems are closely linked. When discussing flooding in transportation networks, especially roads, storm water management cannot be left out. In fact, this combination alludes to the research of multi-mechanism flooding and the nature of widespread flooding in a coastal area. SLR is much more than just water rising directly from the ocean and flooding areas near the water. Higher sea levels reduce and even reverse storm drain flow; they also raise groundwater levels to points above ground in a process called ground water inundation (Habel et al., 2020). Road and storm water systems are so closely linked in that if there is any storm water backflow the first areas that will be inundated are roadways. The effect of SLR on drainage systems can be explained as,

> "Functionality of gravity-flow drainage depends partially on elevation differences between drainage and receiving outflow areas (i.e., ocean waters). In low-lying coastal areas, high tides decrease these elevation differences and can slow or reverse the rate of drainage. During extreme tide events in Honolulu, reversal of flow has impacted basements and low-lying streets." (Habel et al., 2020)

Habel et al. (2020) studied multi-mechanism flooding potential of SLR and quantified how SLR can cause flooding in multiple ways. Stormwater systems can also be overrun by storm surge as well, which often makes flooding worse and prolongs the effects of the storm.

Lastly, there were a number of studies that studied more than two infrastructure systems. However, there were very few studies that made the leap to study more than two infrastructure systems in the same paper. Out of the 93 papers only eight studied three or more infrastructure systems, and only three papers studied four infrastructure systems at once. This is a very small portion of the literature and is likely due to the complexity in researching that many different infrastructure systems at once. This complexity is driven by the systems of systems idea. Infrastructure systems are tied together and the more systems that are being evaluated at once develop an increasingly complex network of infrastructure links that becomes challenge to quantify. The level of data and detail required to complete those more complex studies may be the hindrance to the number of studies conducted at that level.

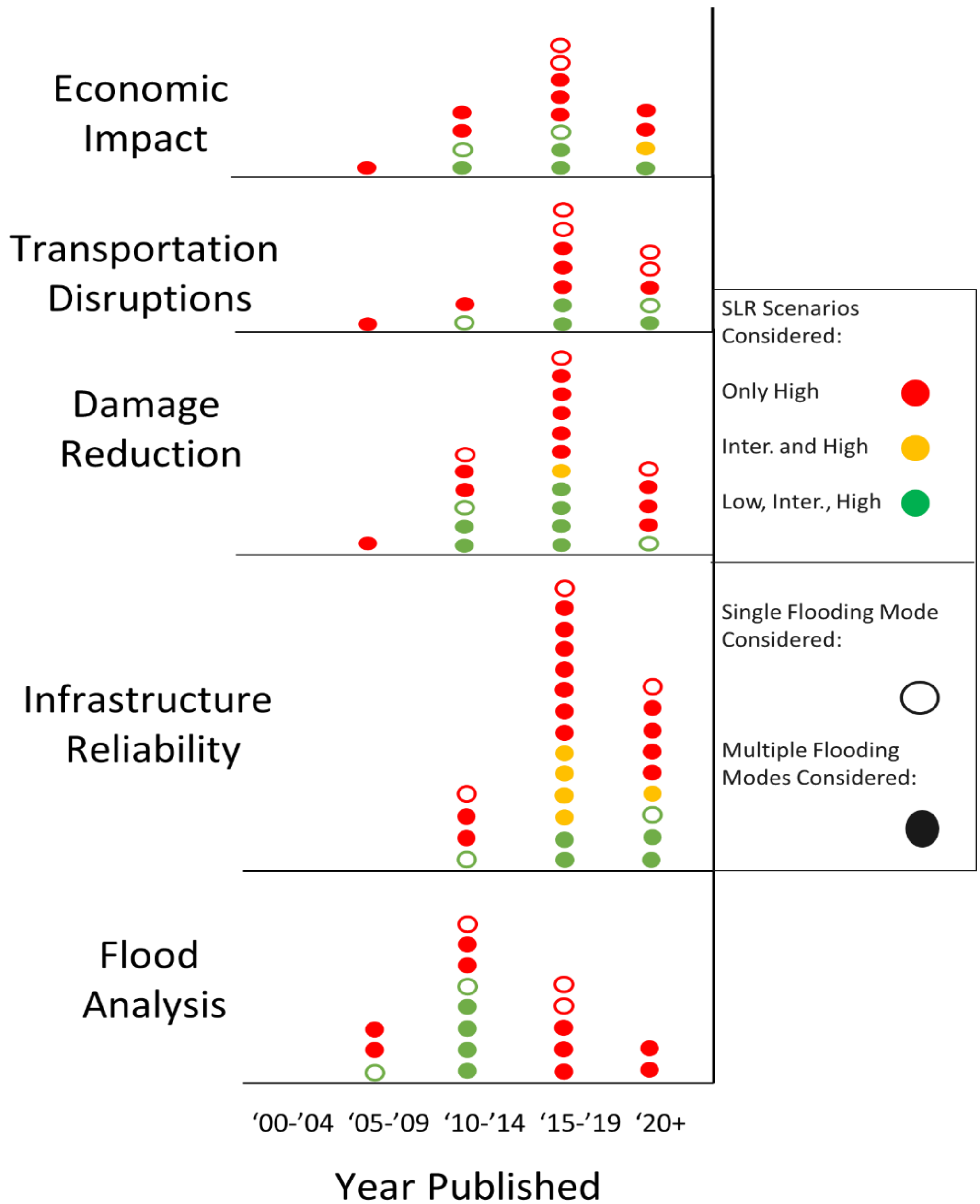


Figure 4: The focus of the literature as histograms of the publishing year. Each point (studies) is categorized by the SLR scenarios used as well as the number flooding modes considered in the study.

4.3 Research Outcome Analysis

Each article researched has a specific set of factors that are interesting. Figure 5 shows a number a combination of some of those factors. This figure is meant to identify some themes in the literature as well as identifying the timeframe. Additionally, a few insights about the nature of the study are included to provide insight into the extent of the work. Identifying the different SLR levels associated with each study is important to find the intent of the study as well as point out potential issues. All the studies shown as red only examined the worst-case scenario of SLR. There are two ways of looking at this sort of research. First, planning for the worst-case scenario defines the maximum extent of potential damage. This is an important metric to have when engineering for solutions. However, there is something to be said for using a profile of scenarios to define the threat. Having multiple SLR scenarios represented could potentially improve the efficiency of engineering solutions. Another important metric that was well represented in these studies was how broad the flooding modes where that were studied. For example, a study that only looked at flooding from SLR inundation is indicated by a symbol that is not filled in, but a study that combine SLR inundation and storm surge is indicated by a filled-in symbol. Most of the studies are solid circles, meaning that the large majority of studies looked at multiple flooding modes to conduct their analysis. This is important because coastal flooding is a very diverse event and the different flooding modes can affect each other significantly.

Another important observation drawn from Figure 5 is the timeline of different studies and the associated analysis. The flooding analysis section has the earliest mean of the focus areas. This particular focus is based on defining flooding extents and how flooding modes change under SLR. Flood analysis typically looks only at how the flood propagates and does not dive into specifics on infrastructure consequences. The relative timeline of these studies is understandably the earliest because they provide some of the basis for evaluating flooding moving forward. The other focus areas represent a natural progression from the flooding analysis studies to the research and focusing on other areas. Damage reduction and infrastructure reliability have received the most attention in the most recent years. Simple deduction would say that damage reduction and infrastructure reliability are closely linked and represent the biggest focus of the research moving forward. This is likely due the need to optimize infrastructure designs to balance resilience and cost.

V. Discussion

This section will focus on the themes discussed in the results section above. The goal is to analyze the data collected in this review to provide insights into the literature and how research can be improved for the future. A retrospective look at previous work is important from time to time to make sure that re-vectoring is not needed, and if it is to do it as efficiently as possible. The future of coastal flooding is uncertain and defining the consequences of climate change is an important factor in making improvements to infrastructure planning. Planning and mitigating infrastructure impact due to coastal flooding is the end goal of producing literature on this topic. Conglomerating and analyzing the literature can help refocus the path forward to achieve this goal.

One of the first points that needs some further exploration is the overwhelming idea of using the year of 2100 as a projection for the future, which is used by governing bodies such as the International Panel on Climate Change and the National Oceanic and Atmospheric Administration. There are certainly pros and cons to this metric as well as confusing decisions. Now, this is not necessarily a bad thing, but it does raise some questions about the validity of that measurement and why it was chosen. Such a large portion of the literature focuses on that year that it seems prudent to evaluate that milestone year. The design life of different types of infrastructure is anywhere from 20 to 100 years. So, 2100 is certainly going to be a relevant year for some infrastructure types.

It is certainly relevant to plan for SLR implications in coastal areas right now. However, it may be prudent to look past the year 2100 and evaluate long-term planning.

5.1 Discussion on Scale

A very important aspect of this research for a federal organization such as the Air Force is the scale of each study. As shown in the results section, most studies conducted in this field were at the city scale. While the city scale is very important because it focuses on more specific and measurable impacts, the lack of regional and national scale studies may be a problem. While the impacts may not be as detailed, there is merit in looking at larger regions from a system mentality to gain big picture insights. Economic impact studies and widespread municipal infrastructure are both focus areas that require a wide look to gain to the whole picture. An economic study broken down by department looking at all coastal regions through the lens of potential economic impact using statistical methods would be a beneficial study to determine where the greatest financial risk lies. An economic study could also be useful in conversations with decision-makers as economics are easily translatable to diverse backgrounds.

Understanding the interconnectedness of certain systems also makes a good case for larger studies. A good example of this is the electric grid. Electric networks are very susceptible to flooding and are typically very interconnected across larger regions. For example, Khanam et al. (2021) focus on the effects of several different SLR and storm surge scenarios to determine the flooding at critical nodes in the electric infrastructure.

Their study is an important example because they found that by using climate change projections and geographic modeling that the Federal Emergency Management Agency (FEMA) flood predictions were significantly inadequate during specific flood scenarios. Although their study was localized and only focused on substations, increasing the scale and examining at a bigger region with even more critical infrastructure, such as production plants, would provide a clearer picture of the threat and vulnerabilities to that system. Lack of big picture data is certainly one of the biggest holes in this research area and given the giant infrastructure footprint of the Air Force it is important to make sure that these effects are anticipated.

Another important aspect along this line of thinking is the nature of the localized studies. Most of the coastal infrastructure studies were at the local scale. This level of research is the most detailed and important for adaptation planning. To make the decision-making knowledge as widely available as possible, the most important standard of localized studies is replicability. There are many cities around the U.S. that need coastal research done and making research replicable lowers the barrier to entry for other researchers investigating cities. This is not always a an easily accomplished task, but as research and data become more accessible and manageable across the country more informed decisions can be made. This is especially important for the smaller coastal communities that do not have the same resources as the big coastal cities. It provides manageable frameworks that significantly reduce the resource burden to other cities that need similar research.

From a scale perspective, the easiest way for stakeholders such as the Air Force to progress the literature is to invest in more regional studies that focus on how utility systems interact between different parts of the coast. The focus would be on how to make different infrastructure systems more resilient so that critical infrastructure is less critical and the majority of the system can still function or bounce back quickly after an adverse event. Additionally, it is important that investments in local studies produce repeatable products. If stakeholders decide that new research is required in one region, it is important to make sure that research can be used somewhere else with different data.

5.2 Identifying Infrastructure in Need

Of the major infrastructure sectors that were tracked in this research, the energy sector received the least attention. Only nine of the articles reviewed focused on the energy infrastructure. This is an interesting discussion point considering how important the energy grid is to modern life and how interconnected the system is with other infrastructure. Regarding the energy infrastructure in the Texas and Louisiana region of the gulf coast, (Bradbury et al., 2015) stated that, “Sea-level rise by 2050 could increase the number of electric power substations exposed to inundation caused by [Category]-1 hurricanes by 35%, from 711 to 958 facilities.” They defined the affected critical electrical components and how different flooding scenarios would relatively affect each component. Figure 6 shows that there is a very significant number of electric components impacted based on the hurricane type. All these critical components represent both economic liability and failed operability. Bradbury et al. (2015) is an example case study regarding how different coastal flooding scenarios could have enormous impacts on coastal energy infrastructure.

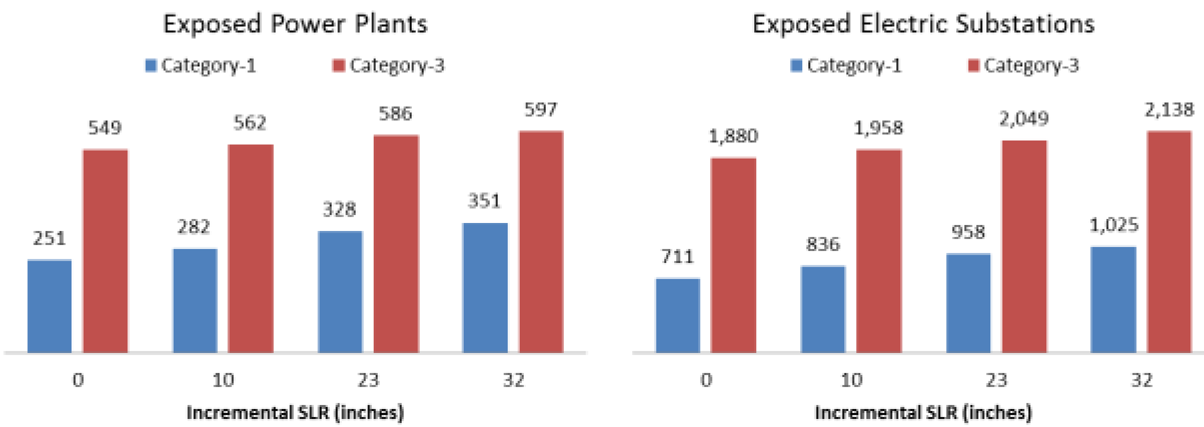


Figure 5: Excerpt from Bradbury, et al., "Total number of electric power plants (left) and substations (right) exposed to storm surge under four SLR scenarios and different categories of hurricane". Projected to the year 2050.

Infrastructure effects are a vitally important category of the studies in this review. Building on the discussion about the energy grid implications, cascading effects are a very important consideration when talking about infrastructure failure. Energy is an example of an interconnected system where failure could cause the failure of other systems. For example, Zhu et al. (2021) modeled the ability for the Manhattan transportation network to operate during power outages and showed how cascading failures can affect a system of systems. Their study showed significant impacts to the ability to evacuate a city due to transportation issues, but the effects of losing power had more wide-reaching impacts than transportation. There are also many impacts on other systems from losing different utilities as well. Figure 7 shows some of the basic relationships between systems based on SLR implications. There needs to be more research about how communities can make their infrastructure networks more resilient to interruptions. To take effective steps toward that end, there needs to be more clarity on how that resilience can be achieved.

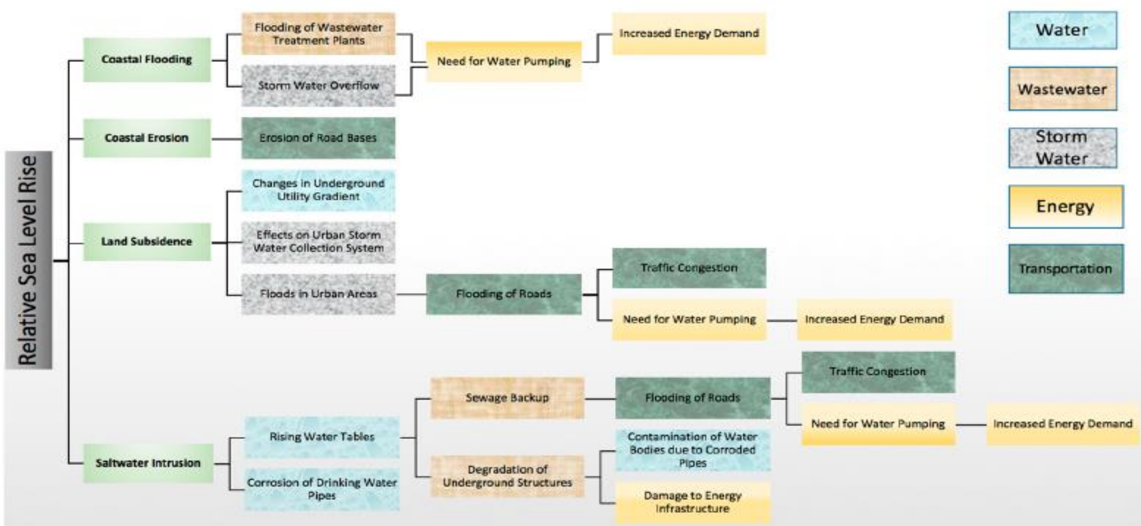


Figure 6: Interdependencies between Infrastructure Systems: Cascading impacts of seal level rise on infrastructure systems. (Azevedo de Almeida et al., 2016)

Multi-mechanism flooding is another way of presenting the entire picture of how SLR can affect flooding in an area in different ways. SLR can cause or enhance flooding through multiple mechanisms. As mentioned in the results section, storm surge and SLR combine to cause greater flood magnitude and potentially induce flooding through different avenues. Habel et al. (2020, showed that flooding can propagate through storm water systems, elevated ground water tables, and direct marine flooding. These problems are very pertinent to many coastal regions around the U.S., and each region has a unique threat profile based on its geographical area. This is important information for infrastructure planners. Defining the greatest threat and updating thresholds for future design is paramount for future resilience to flooding events. The literature shows that importance with a focus on multi-mechanism flooding. 75% of the papers used in this review looked at some combination of SLR and storm surge. This number shows that this is one of the most important topics moving forward and should be quantified in coastal areas. Researching this combination is important for setting new precedents and defining design standards for flooding expectations. Khanam et al. (2021) used projected SLR and storm surge to model inundation for a number of scenarios. They compare the modeled data to the FEMA flood thresholds in that area. This is a very interesting analysis because the FEMA flood plain is often used in infrastructure design to determine the level of flood mitigation required for a facility. Their study found that there were a significant number of areas where the modeled flooding was very different from the FEMA levels

(Khanam et al., 2020). This is another example of why the engineering community should consider changing design standards to a projection basis and not a historical one.

Accurate vulnerability data is needed to adequately protect infrastructure in the future. The Air Force needs to ensure that infrastructure planners are working with the best data available. That means using the knowledge that has been provided in the literature to create a threat profile for base infrastructure. The best way to define future vulnerability is to update design standards (Unified Facility Criteria) to project into the future instead of using historical data. Multi-mechanism flooding will be a key aspect to creating forward-looking flood predictions. Additionally, energy infrastructure is so important to every aspect of society that the Air Force needs to invest in research in this sector. Generating energy vulnerability data and mitigation strategies for each coastal base should be a priority for the Air Force. While the research is potentially lacking, there are certainly good reference studies that can be used to conduct a progressive analysis, including Bradbury et al. (2015) and Khanam et al. (2020). Accurate data is the only way to combat climate hazards efficiently.

5.3 Focusing on Infrastructure Adaptation

To wrap up this discussion, it is important to talk about how the research can evolve into its most useful form and create advantages for stakeholders. Based on Figure 5, most of the research is only considering the worst-case scenario of SLR and/or hurricane level storm surge. There are certainly some pros and cons to this mentality.

Worst-case scenarios create a design standard that equates to the most robust infrastructure systems possible and show the broadest implications of climate change to involve the most infrastructure in a given area. However, a portfolio of climate impacts allows for more efficient planning. Examining multiple scenarios from low to high impact gives decision-makers the most flexibility to adapt at various levels depending on relative infrastructure criticality.

Defining future infrastructure impact is important but using that information in a meaningful way is probably the most difficult challenge. In terms of this review, the natural progression of the research seems like it is towards focusing on infrastructure reliability and damage reduction. Those two focus areas have been the most popular in the most recent time block of Figure 5. The transition from projecting floods to projecting the impact of floods is evident. The next logical step is to research how to control those impacts. The end goal should be to create steadfast mitigation strategies as efficiently as possible. Taking reliability, damage, and economic capability into account is how realistic mitigation strategies can be made. Much of the literature has not yet approached how to effectively mitigate climate effects on infrastructure, but there are a few that have made a good effort, specifically Azevedo de Almeida et al. (2016).

Additionally, the literature showed that adaptations were difficult to present at a large scale. The papers that focused on implementing real adaptation strategies were typically at a small scale. Even among the city scale the adaptation studies were at smaller cities in general. Increasing the scale of an adaptation research study severely increases the difficulty required to complete the study. Because there is so little relevant adaptation research most of the effort is on the researcher to develop the plan of attack for their desired area, and often applying that added burden can make the task of attacking the mitigation of coastal flooding in bigger cities too daunting for researchers to approach. However, this effort is required to take a step forward in this field. The only way to overcome this hurdle is to prioritize adaptation research and devote more resources to completing the necessary studies. More resources allow for more hands to divide the work and it incentivizes more researchers to join in.

Mitigation and adaptation are the key to making progress in this field. “There are three approaches for adaptation of coastal areas in dealing with the sea level rise impacts on water infrastructure: (1) Protection, (2) Accommodation, and (3) Retreat” (Azevedo de Almeida et al., 2016). This is a very important distinction. Protection is simply building barriers around important infrastructure nodes. Those barriers can be physical barriers such as seawalls and green barriers such as dunes or vegetation. Both can be effective to different degrees. Accommodation is letting the water in and diverting it away from important infrastructure as effectively as possible. An example of accommodation is enhancing municipal storm water systems to more effectively distribute water under SLR conditions. Lastly, retreat is the act of moving infrastructure away from the coast or to a safer position (Azevedo de Almeida et al., 2016). These are the primary avenues for developing adaptation strategies, but most of the papers that recommend adaptation strategies only provide a short simple explanation of potential options. This is more of a suggestion for future research as opposed to a comprehensive recommendation to decision-makers.

The future of coastal infrastructure research needs to be diving into the detailed ways in which infrastructure can manage future risks. The same detail that has been used to analyze both flooding scenarios and potential infrastructure impacts needs to be provided to mitigation strategies as well. Investing in adaptation research is going to pay dividends in the future, but the problem is that this information is needed now. Having an effective arsenal to combat climate change impacts is very important and the scientific community is the only one that can deliver.

VI. Conclusion

The risk to coastal infrastructure is increasing due to climate change. Many organizations need to take notice of these threats. The U.S. Air Force needs to be aware of the projected impacts of climate change. As an organization with a large amount of coastal infrastructure, the Air Force must find the best way to deal with flooding in the future. To do this, it needs to invest in research focused on SLR-induced flooding mitigation strategies. There is a framework to build from, so the Air Force does not need to start from scratch. However, only 25% of the articles in this study provided adaptation recommendations. Detailed explorations into mitigation and adaptation strategies for coastal infrastructure will be imperative to plan for the future.

Additionally, there are a few other areas that may need improvement for the Air Force to have a clear picture of the issue. First, the energy sector is under-researched with only nine studies. There needs to be more research to define the impacts of SLR-induced flooding on the energy grid. Research into how components may be affected by more frequent flooding and how outages may affect other regions and/or other infrastructure systems is necessary. There also needs to be further research into the desired life expectancy of infrastructure and how that life-cycle will be affected by climate-related hazards. Greater clarity on how long infrastructure is expected to last will allow for more comprehensive planning to ensure that infrastructure is as capable as possible to handle future scenarios.

When planning for infrastructure to combat climate change, it is essential to be looking forward. That is why there needs to be serious consideration about evaluating design standards related to coastal flooding. The current model of looking at historical data to project future needs is not sustainable under the climate change scenarios presented in the literature. There will have to be changes that reflect different climate conditions in the future to ensure that infrastructure is capable of lasting its intended life span as efficiently as possible.

Finally, global populations focused around coastal areas continue to grow. By 2100, as many as 630 million people worldwide may be affected by coastal flooding compared to 250 million right now (Kulp et al., 2019). This is a problem that will continue to grow in severity over time and the consequences of not planning for the future could be drastic. Civil infrastructure is required for modern life and climate change has the potential to radically affect how that infrastructure operates.

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Appendix A: List of Articles Reviewed

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Appendix B: Questionnaire

Sea Level Rise impact on Coastal AF Infrastructure LitReview

G Howland

General Info
1. Paper Title
2. First Author
3. Year Published
4. Journal Name

Scale Info

5. Size of the study
    - City
    - State
    - Coastal Areas
    - Multiple Cities
    - Region/Watershed
    - Other
6. Location Descriptor
7. Latitude
8. Longitude
9. Time Period (Current Benchmarking)
10. Temporal Scale (How far out are they projecting)

Data & Methods

11. Infrastructure Studied

Check all that apply.

- Residential Buildings
- All other Buildings
- Roads
- Sewer/Storm
- Energy
- Other:

12. Where are they getting their data from

13. What methods are they using to conduct analysis?

14. Did they use any relevant software?

Context

15. What is the focus of the analysis?

Check all that apply.

- Damage Reduction
- Infrastructure Reliability
- Transportation Disruptions
- Economic Impacts
- Other:

16. What RCP Pathway was considered?

Check all that apply.

- 1.9
- 2.6
- 3.4
- 4.5
- 6
- 7
- 8.5

17. Did they recommend a solution?

18. List Interesting figures/tables (i.e. Figure 1, etc.)

19. Any Relevant Quotes?

Qualitative Review

20. Rate the Paper

- Excellent
- Good
- Average
- Poor

21. Final Thoughts

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14. ABSTRACT

Coastal regions have seen some of the most telling signs of climate change over the past few decades. In response to these and other threats, the Department of Defense (DoD) released a report detailing the impacts of climate change on its installations in January 2019. However, the report was determined to be largely inadequate, and the Government Accountability Office recommended that the DOD further incorporate guidance on climate projections into planning and facility standards. As a result, the U.S. Air Force has increased their interest in developing its climate adaptation portfolio, but it is lacking in tools and understanding on how its facilities will be impacted. In this study, we perform a critical review of literature, focused on climate change's impact on coastal infrastructure. Through this critical review, we investigate what infrastructure systems are evaluated, how they are investigated, and what aspects should DoD infrastructure managers be aware of. The goal of this study is to find what research exists, what adaptation measures are successful, and what holes need to be filled by future research. The compiled information will inform civilian and military managers on how to invest time and money in future research as efficiently as possible. This research aims to provide the Air Force and other large organizations insight into existing information on adapting infrastructure to climate change.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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