ABSTRACT OF THESIS

SECURITIZATION OF CLIMATE CHANGE:
A GIS CASE STUDY OF SEA LEVEL RISE IN SEATTLE, WASHINGTON

In the post-Cold War political environment, climate change has received mounting attention from the security establishment as a potentially destabilizing force, threat multiplier, and existential danger. This securitization of climate change has focused on national and international scales. Recently, however, subnational scales, particularly cities, have been found to play an important role in maintaining security. My study employed geographic information systems (GIS) to model future projections of sea level rise (SLR), a key component of climate change, to investigate possible impacts to security at the city level. Using Seattle, Washington, my GIS model showed that 21st century projections of low, medium, and high probabilities of SLR would disrupt numerous sectors of critical infrastructure and key resources, inundate several square kilometers of land, and displace thousands of residents. My results indicate sea level rise may pose a significant threat to the security of Seattle and the rest of the United States.

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THESIS

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requirements for the degree of Master of Arts in Integrative Studies
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Table of Contents

List of Figures

List of Tables

List of Abbreviations

CIA	Central Intelligence Agency
CIKR	Critical infrastructure and key resources
CO_2	Carbon dioxide
DHS	Department of Homeland Security
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FCC	Federal Communications Commission
GHG	Greenhouse gas
GIS	Geographic information systems
GMSL	Global mean sea level
GRACE	Gravity Recovery And Climate Change
HP	High probability
HSPD7	Homeland Security Presidential Directive 7
IPCC	Intergovernmental Panel on Climate Change
LMSL	Local mean sea level
LP	Low probability
MHHW	Mean highest high water
MHVM	Multi-hazard vulnerability map
MP	Medium probability
MSL	Mean seal level
NAO	North Atlantic Oscillation
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum 1988
NIC	National Intelligence Council
NIPP	National Infrastructure Protection Plan
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
PCB	Polychlorinated biphenyls
PDO	Pacific Decadal Oscillation
SLR	Sea level rise
TEU	Twenty foot equivalent unit
UN	United Nations
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
VLM	Vertical land movement
WMO	World Meteorological Organization
WSDOT	Washington State Department of Transportation

1 Introduction

Over the past two decades, climate change has emerged as a significant issue within the discourse of numerous academic and professional fields. The prospect of global climate change with consequent environmental alterations threatens to profoundly transform all aspects of life. For decades, physical scientists had been hypothesizing that human releases of carbon dioxide (CO_2) and other greenhouse gasses (GHGs) would affect the global climate system, but it was not until the late 1980s that government officials and social scientists began to consider the implications of the scientists' projections, and governments across the globe began taking an interest in the potential implications of climate change. The creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 marked a noteworthy step toward governmental participation in the climate change discourse. At the time of this writing, 195 countries are participating members of the IPCC (IPCC, 2013).

There are several reasons for governments to consider the effects of climate change, ranging from economics, environmental and social impacts, energy, and threats to national security. The latter of these – security – is one of the least, and most recent, to be explored. National security policy is largely influenced by domestic politics (Jordan, Taylor, Meese, & Nielsen, 2009), which since World War II has evolved from concerns over the threat of communism and international nuclear war to those of decentralized terrorist networks. The traditional security establishment historically focused on climate change in terms of armed conflict because it dominated the national security discourse (Barnett, 2011). The earliest and perhaps most widely accepted context in which the traditional security establishment considered climate change is that of a threat multiplier with potential to increase the likelihood of conflict over geostrategic resources (e.g., land, water, fossil fuels, etc.) at local, national, and international scales (Dabelko, 2009).

One reason offered for the reluctance of the traditional security establishment to recognize climate change as a threat *per se* is the absence of enemies (Gilman, Randall, & Schwartz, 2011).Yet others claim climate change may represent a new security threat because it has the capacity to devastate society and humanity as a species (Barnett, 2011). Campbell et al. (2007) even concluded that climate change may eventually present a greater national security challenge than violent extremism.

The post-Cold War perceptions of security have become more comprehensive and no longer limited to the narrow lenses of foreign policy, espionage, and violent conflict (Caudle, 2009). The expansion of the security discourse has led to the conceptual framework of "securitization," which some claim is an objective framework while others claim it is a subjective, socially driven concept (McDonald, 2008; van Munster, 2012). In simple terms, securitization is an examination of "how security problems emerge, evolve, and resolve" (Balzacq, 2010, p. 56). Within this new thinking, climate change might pose a wider array of challenges than just precipitating conflict or multiplying threats. One of these challenges is the effect of rising global sea levels in the 21st century.

1.1 Research Problem

Although the traditional security community has begun to consider the importance of the environment and climate change, it has continued to frame the discourse within traditional notions of geostrategic interests, regional stability, and even terrorism. Hence, the focus remains on national level implementation of foreign policy based on national interests related to climate change. Researchers who explore the nexus between climate change and security at the subnational level tend to do so only in less developed countries (Buhaug, Gleditsch, & Theisen, 2010; Werz & Conley, 2012). Furthermore, the subnational studies tend to place the emphasis on conflict such as civil war or ethnic clashes (Barnett & Adger, 2007; Buhaug et al., 2010). There have been extremely few studies at the subnational level in developed countries, especially the United States; hence, there remains a gap in understanding how climate change may impact security within developed nations at the subnational level.

In the United States, subnational security is a multilayered effort ranging from local to national institutions and is frequently described as "homeland security" (Gaines & Kappeler, 2012). This concept and discourse is separate from the federal government agency of the same name (Department of Homeland Security (DHS)) and seeks to convey the idea that individuals and communities are free of threats to their well-being. Homeland security is a distinctly American concept, and though there is no single U.S. government definition of homeland security (Morag, 2011), most academic definitions focus on safeguarding the United States, its people, vital interests, and way of life (Bullock, Haddow, & Coppola, 2013). Additionally, policy makers and experts agree that it is a coordinated effort involving all levels of government (Reese,

2013) as well as non-governmental organizations (NGOs) and private-sector entities (Bullock et al., 2013).

There is also agreement that local governments are a central component of maintaining homeland security (Gaines & Kappeler, 2012). According to White (2009), there is substantial support for the localization of homeland security services, largely because local offices are more adept at recognizing and solving local problems. Nevertheless, localized homeland security activities primarily focus on terrorism, most often from a law enforcement and emergency management perspective (White, 2009).

Just as the security establishment has recently emphasized the importance of local institutions in protecting the homeland, so too have climate change advocates recognized that cities are at the forefront in mitigation and adaption to climate vulnerability (Rosenzweig, Solecki, Hammer, & Mehrotra, 2011). Local institutions are fundamental to structuring the risks and vulnerabilities to climate hazards, facilitating or hindering collective responses, and shaping the outcome of those responses (Agrawal, 2010). Yet there has been a lack of initiative from the local security apparatus to consider the profound effects that climate change may have on the security environment.

Thus two questions emerge. First, what are the potential effects of climate change at the local level? Second, are the potential effects at the local level significant enough to warrant the securitization of climate change? My research is an effort to answer these questions by using sea level rise (SLR) as a proxy for climate change (Parker, 1992). I submit the hypothesis that if sea level rises enough by the end of the 21st century to negatively impact the people, vital interests, and way of life in the United States, then climate change is a threat to homeland security. Conversely, my null hypothesis must be that climate change is not a threat to homeland security because rising sea levels by the end of the 21st century will have no effect on the people, vital interests, and way of life in the United States.

Identifying the impact of SLR on people (i.e., population patterns) is a more objective endeavor than identifying and quantifying vital interests and way of life. To operationalize the concepts of vital interests and way of life, I will use sovereign territory (i.e., land resources) and critical infrastructure/key resources (CIKR). According to the DHS (n.d.), CIKR are vital to the security, economy, and health of the United States and its people.

1.2 Overview of Research

Testing my null hypothesis requires an interdisciplinary approach consisting of two sets of research methods. The first is an integrative literature review summarizing the current state of knowledge in political science, climatology, and geospatial science. The second method is a case study employing geospatial modeling of 21st century projections of SLR in Seattle, Washington. According to Yin (2003), the case study can be a comprehensive research strategy useful for contributing to the understanding of complex phenomena. Using remote sensing and geographic information systems (GIS), my objective is to identify and quantify vulnerable land, population, and critical infrastructure/key resources.

There are several benefits of the case study approach at the local, or municipal, level. First, the research question can be analyzed in a manageable unit of study. Using a larger study area, such as a state or country, would not allow for the detail and specificity of a municipal level analysis. Second, the city may be seen as the foundational functional unit of society, an intact urban ecosystem, whereby it exhibits all of the aspects of national society writ small. Third, the case study allows a researcher to apply and integrate the concepts, theories, and perspectives of the various disciplines needed to understand a functioning urban ecosystem.

Locational data for the study was obtained from the National Oceanic and Atmospheric Administration (NOAA), the Puget Sound Lidar Consortium, King County GIS, the City of Seattle, and the Federal Communications Commission (FCC). These data, consisting of lidar images, shapefiles, and geodatabases, were then processed and analyzed to visually represent the 21st century projections of SLR, and the impacts of these projections on land, population, and CIKR.

Lastly, because Seattle is just one of the many coastal cities likely to be affected by sea level rise over the next century, my case study provides insights and conclusions which will be useful for other coastal communities. Furthermore, if other cities in the United States are projected to experience results similar to those of Seattle, the security implications drawn from my research may be extrapolated to the national scale.

2 Review of Literature

2.1 Climate Change

The climate is a complex system involving the atmosphere, land surface, snow and ice, large bodies of water, and living things. It evolves overtime because of internal dynamics (i.e., natural causes) and external forcing factors including anthropogenic causes. In essence, climate change is a "change in the state of the climate that can be identified […] by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" (IPCC, 2007, n.p.).

Climate change as a result of CO_2 and other GHG emissions was an idea proposed in the late 19th century by Svante Arrhenius. According to Bolin (2007), 19th century breakthroughs in the comprehension of atmospheric conditions, solar radiation, and carbon dioxide's effects on temperature led to what we currently know as the greenhouse effect. Yet as industrialization occurred, there was little societal concern for the exponential increase in carbon dioxide and other GHG emissions until the mid 20th century.

In a landmark effort beginning in 1958, Charles David Keeling began taking high-accuracy measurements of atmospheric CO_2 concentrations on Mauna Loa in Hawaii, which because of its high elevation provided measurements not influenced by local conditions, resulting in the master time series documenting the changing atmospheric conditions (Keeling, et al., 1976). The ongoing observations from Mauna Loa provided scientists with decades of a nearly continuous record of changing concentrations of GHGs. Keeling concluded that rising CO_2 concentration was "clearly in response to increasing amounts of industrial CO_2 in the air on a global scale" (Keeling, et al., 1976, p. 550).

By the 1980s, the trends observed in global climate change had become well accepted in the scientific community. Reflective of many of the conclusions drawn by various disciplines at the time, Houghton and Woodwell (1989, p. 36) wrote in an article for Scientific American:

> The world is warming. Climatic zones are shifting. Glaciers are melting. Sea level is rising. These are not hypothetical events from a science fiction movie; these changes and others are already taking place, and we expect them to accelerate over the next years as the amounts of carbon dioxide, methane, and other trace gass accumulating in the atmosphere through human activity increase.

In 1988, the year prior to Houghton and Woodwell's article, the Intergovernmental Panel on Climate Change was created by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). Climate change had become a topic of concern for numerous nations. The IPCC was created to provide the world with the current state of knowledge in climate change, specifically in areas of environmental and socioeconomic impacts.

The IPCC Assessment Reports remain extremely authoritative because they were written by the world's foremost experts in their respective fields. In fact, there were 152 lead authors who contributed in 2007 to The Fourth Assessment Report (AR4). The IPCC reports are some of the most frequently cited literature on the subject of climate change.

Many scientists now believe the world could experience a 4°C increase in global temperatures by the end of the 21st century (New, Liverman, Schroder, & Anderson, 2011). A temperature increase of this magnitude is thought to pose tremendous challenges to agriculture, ecosystem stability, human migration, and coastal settlements (Panda, 2012). A rapidly shifting climate is projected to lead to more frequent extreme weather events, changing precipitation patterns, desertification, and rising sea levels. The probability and uncertainty of rising sea levels has generated considerable concern in recent years (New, et al., 2011; Nicholls, et al., 2011).

2.1.1 Sea Level Rise

Among the central topics reviewed by the IPCC in *Climate Change 2007* were changes in ocean climate. The report concluded that oceans are warming, salinity is changing, biogeochemistry is shifting (e.g., inorganic carbon and pH), and as a result, global mean sea level (GMSL) is rising. The AR4 offered two reasons for the rising sea levels: thermal expansion and melting land ice (i.e., glaciers and continental ice sheets). Over the 20th century, SLR was estimated at 1.7 mm/yr. However, between 1993 and 2003, SLR was estimated at 3.1 mm/yr (IPCC, 2007). This estimate only accounted for global mean sea level. In 2009, Prandi, Cazenave, and Becker used satellite altimetry and coastal tidal gauge measurements to calculate coastal sea level. They found that tidal gauges revealed a trend of 3.3 mm/yr and satellite altimetry a trend of 3.4 mm/yr.

After the release of the IPCC AR4, Cazenave et al. (2009) provided the scientific community with an updated sea level budget using advanced modeling to account for the ocean mass increase due to melting polar ice sheets. Using satellite altimetry from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, Cazenave et al. estimated that land ice contribution to SLR between 2003 and 2008 was 2.1 mm/yr. This amount was significantly more than what was observed from 1993-2003.

Church et al. (2010) also concluded that the land ice contribution to SLR based on data from this new technology was significant. Church and his colleagues further stated the "Antarctic and Greenland Ice Sheets are the biggest concern for longer-term sea-level rise" (2010, p. 411). They posited that ice sheets are experiencing dynamic changes, including melting at a rate faster than snow accumulates.

Though there is much agreement on the factors contributing to SLR, there is not a firm consensus on the projected increases during the 21st century. In response to the voluminous literature on SLR estimations, Fletcher (2009) conducted a thorough review and focused on the following 21st century projections: the IPCC's (2007) estimate of 0.18 m to 0.59 m; Pfeffer, Harper, and O'Neel's (2008) estimate of 0.8 m to 2 m; and Rahmstorf's (2007) estimate of 0.5 m to 1.4 m. However, in a more recent study, Vermeer and Rahmstorf (2009) used newer climate models to project a low estimate of 0.75 m and a high estimate of 1.9 m for 21st century SLR. Table 1 summarizes some of the commonly cited sources for projected sea level rise over the next 100 years.

Though global mean sea level is projected to increase through the 21st century and beyond, there is considerable spatial variability in global sea level. A team of researchers used satellite altimetry to map the global variability in ocean topography and found that some areas experience much faster than average rate sea level rise, while others actually experience a slower than average increase rate in sea level rise (Yin, Griffies, & Stouffer, 2010).

There are several global and local factors responsible for the variability in sea level (Meyssignac & Cazenave, 2012). Among these are thermal expansion due to local temperature changes, land ice loss, reshaping of hard earth surfaces which leads to gravitational and deformational effects, salinity, and winds. Additionally, interannual sea level variability is largely dependent on the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO) (Fenoglio-Marc & Tel, 2010; NAS, 2012). Local SLR variation for the study area, Seattle, is discussed in detail in the research methods section below.

Table 1 Commonly cited projections of sea level rise for the 21st century

Source	21st Century Low Estimate	21st Century High Estimate
IPCC (2007)[a]	0.18 meters	0.59 meters
Rahmstorf (2007)[b]	0.5 meters	1.4 meters
Pfeffer et al. (2008)[c]	0.8 meters	2.0 meters
Vermeer and Rahmstorf (2009)[d]	0.75 meters	1.9 meters

Note.
[a]Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate Change 2007: Impacts, Adaptation, and Vulnerability.* Cambridge: Cambridge University Press.

[b]Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. *Science, 315*(5810), 368-370.

[c]Pfeffer, W. T., Harper, J. T., & O'Neel, S. (2008). Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science, 321*(5894), 1340-1343.

[d]Vermeer, M., & Rahmstorf, S. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences of the United States of America, 106*, 21527 - 21532.

2.2 National and Homeland Security

"We will respond to the threat of climate change, knowing that failure to do so would betray our children and future generations…" This statement was offered by President Obama at his 2013 inaugural address (Stevenson & Broder, 2013). A simple deconstruction of the statement reveals two key points to be inferred. First is the use of the word "threat." According to the Mirriam-Webster dictionary (2013), threat entails "an expression of intention to inflict evil, injury, or damage" or "an indication of something impending." Second is the reference to a betrayal of future generations, which implies the notion of security. Security is the "quality or state of being secure;…freedom from danger…fear, or anxiety" (Mirriam-Webster, 2013). Thus taken together and in context, climate change is perceived by President Obama as a threat to the security of our nation. Yet, how is it a threat? What aspect of our security does it threaten?

The notion of security has evolved significantly in recent decades and, indeed, there are numerous types of security. Buzz words and terms abound in the media and academic literature such as energy security, food security, and even the nebulous term human security. Since the September 11, 2001 terrorist attacks, two commonly heard terms are national security and homeland security. Though they may appear to be similar terms, there are practical differences. For operational use within this review, national security will imply our nation's efforts to protect our strategic interests throughout the world, primarily in an international context with defense and intelligence apparatus; homeland security will entail our nation's efforts to protect our domestic assets, including physical, economic, and social welfare from terrorism and natural disasters.

In the wake of the 9/11 attacks, the United States began to differentiate between national and homeland security (Morag, 2011). Though the U.S. pioneered this approach, some countries since have adopted a somewhat similar strategy. Yet most other democracies continue to use one strategy and security apparatus to address threats arising from internal and external sources (Morag, 2011).

2.2.1 Post-Cold War Security

For nearly a half century the United States focused national security efforts toward the singular goal of preventing the spread of the Soviet Union and communism. This strategy known as "containment" focused on the use of American aid as well as the threat of American coercion to deter Soviet expansion in other countries (Rosati & Scott, 2011). However, in the aftermath of the Cold War, the traditional notions of security began to evolve. No longer did the term national security solely mean military security. During the beginning of this shift, Romm (1993) described the burgeoning policy debate on national security from a nonmilitary perspective. Romm called for a post-Cold War security transformation and brought to the forefront emerging security challenges such as domestic drug use and international drug trafficking, global environmental problems, American dependence on imported oil, and the decline of the U.S. economic competitiveness.

Romm also built upon the sentiment of previous commentators such as Matthews (1989, para. 1) who wrote in the article *Redefining Security* that new global conditions warranted a "broadening definition of national security to include resource, environmental and demographic issues." The shift from nuclear threats to global environmental issues was no less concerning to Smil (1997) who believed that both concerns could result in a truly global spatial reach as well as social and economic devastation.

The fundamental transition in redefining concepts of national security has not been completely resolved. Indeed, as long as new threats continue to emerge, ideas of national security will continue to evolve. In the article *National Security Strategies: Security from What, for Whom, and by What Means*, Caudle (2009) also attributed the current transformation to the post-Cold War threat environment. By examining how various states defined national security, Caudle found that definitions differ from country to country and even institution to institution.

However, a key observation among the various definitions is the absence of a military threat. Ultimately, Caudle settled on a definition put forth by Evans that:

> [N]ational security entails the pursuit of psychological and physical safety, which is largely the responsibility of national governments, to prevent both direct and indirect threats and risks primarily from abroad from endangering the survival of these regimes, their citizenry, or their ways of life. (as cited in Caudle, 2009, pp. 8-9).

This broad definition allowed for the consideration of a wide array of phenomena to be of national security interest. It recognized the wellbeing of citizens and their government as well as threats to physical and psychological safety.

As noted above, Matthews' (1989) call to broaden the notions of national security was successful because Caudle, writing two decades later, recognized the trend toward broader approaches to national security in the strategic planning documents of many countries. At the national government scale, the transformation can best be seen by these "strategies" to protect national security. A strategy – or strategic planning – as defined by Bryson (1988, pg. 74) "is a disciplined effort to produce fundamental decisions and actions shaping the nature and direction of an organization's (or other entity's) activities within legal bounds." Many governments as well as public and private organizations have adopted the practice of strategic planning.

2.2.2 Post-9/11 Security

Beginning in 2001, shortly after the 9/11 attacks, the United States diverged from a conventional security strategy by creating the Office of Homeland Security (Gaines & Kappeler, 2012). Then, as a result of the Homeland Security Act of 2002, the Department of Homeland Security (DHS) was created in 2003. The Netherlands, the United Kingdom, Canada, Finland, and Switzerland have integrated national military defense and domestic/homeland security strategies. Conversely, the United States has two separate strategies, the *National Security Strategy* and the *National Strategy for Homeland Security*. Though these documents were complimentary, they distinguished between the security of the nation (i.e., foreign affairs) and that of the homeland (i.e., domestic affairs).

Although the most recent *National Security Strategy*, published in 2010, was more inclusive than previous editions, it continued to place a significant emphasis on traditional notions of national security. This was clearly communicated in the Foreword by President Obama as he stated, "as we face multiple threats – from nations, nonstate actors, and failed states – we will maintain the military superiority that has secured our country, and underpinned global security, for decades" (para. 2). It is clear that other issues, such as climate change, while mentioned in the document, were of much less importance to the White House than conventional military, intelligence, and diplomatic concerns. Furthermore, the document does not provide an actual definition of national security. Thus the reader is left to infer what is implied throughout the document.

Similarly, the *National Strategy for Homeland Security* (2007) focused on more traditional aspects of security, specifically applied to the threat of terrorism to the homeland. In this document, the White House offered an explanation of homeland security as "a concerted national effort to prevent terrorist attacks within the United States, reduce America's vulnerability to terrorism, and minimize the damage and recover from attacks that do occur" (p. 3). Yet, the definition provided by the White House seemed to contradict the overall tenor of the strategy. For instance, significant attention was given to natural catastrophes such as Hurricane Katrina and pandemic disease. This paradox is further illustrated by the admission that "certain non-terrorist events that reach catastrophic levels can have significant implications for homeland security" (p. 3). Non-terrorist events could erode citizens' confidence in the federal government and increase the vulnerability to attack.

The vague content of the *National Strategy for Homeland Security* left ample room for interpretation. For this reason, Bellavita (2008) submitted that there are no less than seven defensible definitions of homeland security found in the security literature. Bellavita's seven definitions are:

1. **Terrorism** – coordinated effort by the government and private sector to mitigate terrorist acts.
2. **All Hazards** – prevent and disrupt terrorism and prepare for natural and technological hazards.
3. **Terrorism and Catastrophes** – governmental efforts to respond and recover from terrorism and catastrophic events that affect security
4. **Jurisdictional Hazards** – political jurisdictions determine the threats to homeland security based on perceived risks
5. **Meta Hazards** – mitigation and prevention of threats and social trends that disrupt the American way of life.
6. **National Security** – governmental efforts to protect sovereignty, territory, the population, and critical infrastructure.
7. **Security *Über Alles*** – justification by government officials to curtail American civil liberties and freedom in furtherance of national security.

Bellavita asked the question, “is agreeing on one definition the only way” to promote a unified homeland security effort (p. 2)? Ultimately, Bellavita did not accept any singular definition of homeland security, but proposed that the security environment is akin to an ecosystem. In essence, it may be thought of as “a continuously evolving social construction, a reality shaped by social processes” (as cited by Bellavita, 2008, p. 22), and this interpretation is consistent with the contention put forth by Jordan et al. (2009) that the national political discourse, driven by societal trends, strongly influences security policy. Within Bellavita’s ecosystem analogy, various definitions and conceptions may be more active throughout society depending on circumstances. A terrorist attack may invoke a security sentiment that reverts to traditional military and intelligence paradigms. Conversely, another natural catastrophe such as Hurricane Katrina, may summon a strategy for natural hazards.

2.2.3 Securitization of Climate Change

Within the ecosystem analogy, climate change may present new challenges to homeland security which require flexible approaches. Barnett (2003) systematically explored emerging connections between climate change and security. Barnett’s justification for including climate change with other security issues hinged on the definition offered by Soros that security is “the assurance people have that they will continue to enjoy those things that are most important to their survival and well-being’’ (as cited in Barnett, 2003, p. 7).

Climate change may be seen to have both direct and indirect effects on a nation’s security. Direct effects primarily include physical threats to sovereign territory such as that of sea level rise resulting in loss of land. In this regard, countries with a substantial portion of sovereign territory with elevations close to sea level will experience devastating impacts. For instance, Bangladesh could lose 10.9% of its territory with a 45 cm rise in sea level (Barnett, 2003). Indirect effects are those undermining the legitimacy of governments, such as individual and collective economic wellbeing, food and water availability, evolving disease vectors, state wealth and military capability, and exacerbation of inequalities. Therefore, giving climate change the status of a security issue necessitates a policy response equal to that of traditional notions of security, such as war.

Rather than grouping climate change impacts into direct versus indirect effects as Barnett did, Matthew (2011) listed three criteria by which climate change may impact security. Climate change may be considered a security concern if it weakens national power, contributes to state failure, or results in or exacerbates violent conflict. In this framework, threats posed by climate change are all considered direct, so long as they fall within one of the three criteria above.

Interestingly, Matthew, like Barnett, viewed rising sea levels as the most looming existential threat to the territorial sovereignty of many nations, especially island nations. Other phenomena such as glacial lake outburst floods may cause similar large scale devastation in non-island places like Nepal. Hence, the possibility of sovereign territorial disruptions may be the biggest challenge as a result of global climate change for many nations.

Similar to Barnett, Dabelko (2009) used the terms "direct" and "indirect" for classifying potential effects of climate change on security. The categorization of a climate change related phenomenon as direct or indirect was based on that phenomenon's potential to challenge "state capacity" and the fundamental welfare of populations at a large enough scale to affect state stability (2009, p. 16). Further underpinning Dabelko's notion of the climate-security nexus was a traditional view of security threats in terms of political/military violence, especially at large scales.

The view that climate change is a security threat gained substantial traction within the intelligence community in recent years. The National Intelligence Council (NIC) issued a report in 2008 titled *Global Trends 2025: A Transformed World* in which a global climate change scenario was explored. The scenario, *October Sunrise*, hypothetically introduced an extreme weather event drastically affecting the New York Stock Exchange and Wall Street with economic ripple effects reaching the entire country. In October 2012, the NIC scenario was nearly realized when Superstorm Sandy devastated the Eastern Seaboard causing the New York Stock Exchange to close, placing 375,000 New York residents in flood zones. This was the first unplanned closure of the Stock Exchange since the September 11, 2001 terrorist attacks (Esterl, Mann, Fleisher, & Strasburg, 2012).

In 2009, the Central Intelligence Agency (CIA) also recognized the threat of climate change and opened the Center on Climate Change and National Security (CIA, 2009). The center was charged with investigating how changing environmental factors can affect political, economic, and social stability in terms of U.S. national interests. Unfortunately, this initiative was shut down in 2012 and virtually all of the work conducted by the CIA center remains classified and unavailable for public disclosure.

Also in 2009, the White House issued an Executive Order – *Federal Leadership in Environmental, Energy, and Economic Performance* – which mandated federal agencies to consider the risks of climate change and develop mitigation strategies for both short term and long term operational and mission capabilities. As a result of the Executive Order, numerous agencies developed strategies and guidance to address how environmental issues such as climate change will impact their organization. Among these agencies was the DHS, which published the *Department of Homeland Security Strategic Sustainability Performance Plan* (2012). This plan detailed the department's assessment of internal operations in the areas of environmental, economic, and fiscal sustainability. The DHS stated that the concept of sustainability has become a central "value system" that "guides mission operations and supporting projects" (DHS, 2012, p. 2). To address climate change, a detailed appendix is included in the plan titled *Climate Change Adaptation Road Map*.

The *Road Map* is important because it was the first federal security document to focus exclusively on climate change as a threat to domestic security. Though some literature discussed above may have mentioned climate change implications for the homeland, they focused on outside threats to the homeland. A fundamental DHS charter is to focus on threats within the homeland. Consequently, the road map offered a course of action for how the department will plan, prepare, and respond to climate change related security concerns. Among these concerns were impacts on CIKR, natural disasters, and severe weather events.

2.2.4 Critical Infrastructure and Key Resources

The federal government effort to protect the nation's critical infrastructure began in 1998 under the Clinton administration with *Presidential Decision Directive No. 63* (Moteff, 2011). The directive called for protection of both physical and cyber infrastructure with a heavy emphasis on the latter. In the wake of the physical damage caused by the 9/11 terrorist attacks the federal government bolstered policies and implementation strategies for protection of physical infrastructure. In 2003 the Bush administration released *Homeland Security Presidential Directive 7* (HSPD 7) which built upon previous infrastructure protection policy and charged the newly created DHS with coordinating the national effort to protect CIKR.

The 2003 HSPD 7 adopted definitions of critical infrastructure and key resources from previously drafted documents. The official U.S. government definition of critical infrastructure is found in the USA PATRIOT Act of 2001. It defines critical infrastructure as "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" (section 1016(e)). The DHS put the definition into more common terms by stating it "is the backbone of our nation's economy, security and health. We know it as the power we use in our homes, the water we drink, the transportation that moves us, and the communication systems we rely on to stay in touch with friends and family" (DHS, n.d.). The U.S. government definition of key resources was established in the Homeland Security Act of 2002 and "means publicly or privately controlled resources essential to the minimal operations of the economy and government" (section 2(9)).

The *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* (2003) outlined specific aspects of infrastructure and assets (i.e., resources) that were of high importance to the White House. This strategy, drafted in the aftermath of 9/11, focused on reducing vulnerability from terrorism. There is little mention of natural disasters perceived as future threats to CIKR; rather they are discussed as something from which the nation may learn to reduce terrorism vulnerability. However, in 2005, Hurricane Katrina devastated New Orleans and other parts of the southern United States resulting in one of the deadliest natural disasters in U.S. history. Afterward, the U.S. Senate Committee on Homeland Security and Governmental Affairs (2006) concluded that our nation as a whole, and government at all levels, was unprepared for the large scale natural catastrophe.

After Hurricane Katrina the DHS underwent a shift in philosophy from terrorism centricity and adopted an all-hazards approach to homeland security (Perry & Lindell, 2007). This shift was evident in the DHS *National Infrastructure Protection Plan (NIPP)*, first released in 2006 and later updated in 2009. The NIPP still placed a large emphasis on hardening the nation's infrastructure and resources to reduce terrorism vulnerabilities, but it also recognized the significant impacts that natural disasters can have on CIKR. Accordingly, it called for mitigation strategies that can address both concerns. To accomplish this, the document designated sector-specific agencies assigned to eighteen specific CIKR sectors, shown in Table 2.

Much of the federal effort to protect CIKR is focused on the prevention of terrorism. Yet in comparing the threat of environmental hazards to that of terrorism the former is much more prevalent than the latter in the U.S. For instance, in 2012, there were 47 presidential disaster declarations and 16 presidential emergency declarations, all of which were natural disasters

(FEMA, 2013). In 2013, at the time of this writing, there were 27 disaster declarations, all of which were environmental, and four emergency declarations, one of which was a result of an act of terrorism – the Boston Marathon bombing (FEMA, 2013). The most commonly occurring natural disasters in the two years mention above were hurricanes, severe storms, flooding, tornadoes, and wildfires.

Coastal areas are particularly vulnerable to many of the natural hazards mentioned above, including hurricanes, severe storms, and flooding. Because a large portion of the U.S. population lives near coastal areas much of the nation's critical infrastructure, especially energy and transportation, is located near the coast (Dell, et al., 2013; Schwartz, et al., 2013). Furthermore, coastal critical infrastructure tends to geographically concentrate as a result of resource location, agglomeration economies, community preferences (i.e., zoning and land use), and economic efficiency (Parfomak, 2005).

Table 2 Agencies designated for sectors of critical infrastructure and key resources

Designated Sector-Specific Agency	**Critical Infrastructure and Key Resources Sector**
Department of Agriculture Department of Health and Human Services	Agriculture and Food
Department of Defense	Defense Industrial Base
Department of Energy	Energy
Department of Health and Human Services	Healthcare and Public Health
Department of the Interior	National Monuments and Icons
Department of the Treasury	Banking and Finance
Environmental Protection Agency	Water
Department of Homeland Security *Office of Infrastructure Protection*	Chemical Commercial Facilities Critical Manufacturing Dams Energy Services Nuclear Reactors, Materials, and Waste
Office of Cybersecurity and Communications	Information Technology Communications
Transportation Security Administration	Postal and Shipping
Transportation Security Administration U.S. Coast Guard	Transportation Systems
Immigration and Customs Enforcement Federal Protective Services	Government Facilities

Note. Adapted from Department of Homeland Security. (2009). National Infrastructure Protection Plan. Washington, D.C.: Author.

The presence of a robust coastal critical infrastructure supports the nation's economy through industry, transportation and shipping, tourism, and much more. In 2000, coastal states in the U.S. contributed 75 percent of the nation's Gross State Product (Colgan, 2004). Accordingly, significant damage to coastal CIKR can result in the loss of billions of dollars for cities, counties, and states (FitzGerald, Fenster, Argow, & Buynevich, 2008). Critical infrastructure is also vastly interconnected and damage to one system can have ripple effects to many other systems which may impact large geographic areas (Lee II, Mitchell, & Wallace, 2004). Thus physical and economic disruptions to CIKR in coastal cities and states may have far reaching economic impacts on the rest of the country. A prime example of this impact is the ongoing recovery cost of Superstorm Sandy. Although future economic costs are difficult to estimate, the federal government has already approved $60.4 billion dollars in aid (Associated Press, 2012) much of which will go to repairing and rebuilding CIKR.

The potential for climate change to negatively affect coastal CIKR is tremendous. Rising sea levels, more frequent and intense storms, and flooding, which are projected to increase with climate change, are likely to increase the risks of damage from natural hazards. Much like infrastructure is interconnected, so are natural hazards. For instance, rising sea levels can increase the inundation potential of storm surges and tsunamis, resulting in damage further inland than previously experienced.

2.3 Geospatial Science

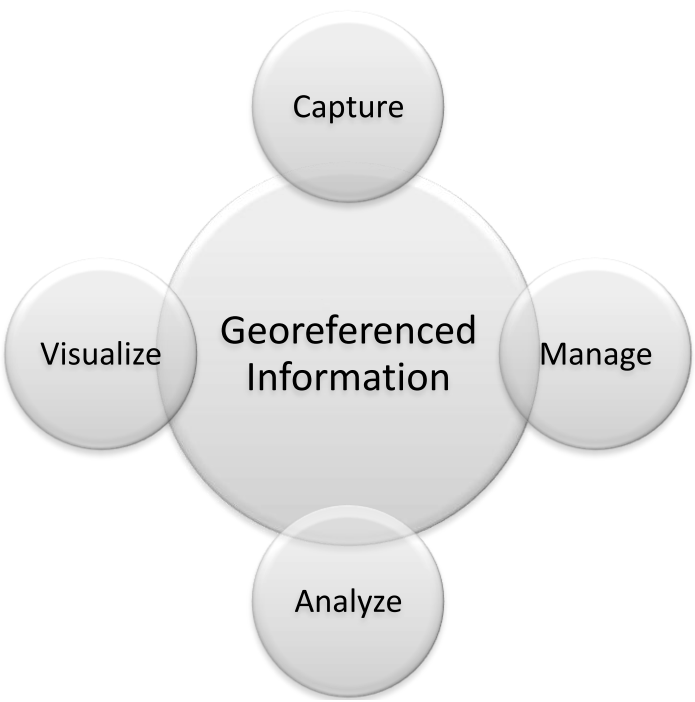
The notion that nearly "everything that happens, happens somewhere" (Longley, Goodchild, Maguire, & Rhind, 2005, p. 4) implies that almost all human and environmental activity has geographical implications. According to McGrew Jr. and Monroe (2009), geography is an "integrative spatial science that attempts to explain and predict the spatial distribution and variation of human activity and physical features on the earth's surface" (p. 3). The use of geography to explore complex problems has been noted throughout history (Holt-Jensen, 2009).

2.3.1 Geographic Information Systems

Beginning in the 1960s, the field of geography evolved to utilize emerging computational technologies (Coppock & Rhind, 1991). In the early 1960s, Roger Tomlinson, a Canadian researcher working with an interdisciplinary team, conceptualized a computer mapping system to store and analyze land use data in Canada (Tomlinson, 1999). Around the same time, Edward Horwood of the University of Washington began teaching a course on computer mapping of census data (DiBiase, 2012). In 1969, Ian McHarg, a landscape architect and planner, advocated the potential for advanced geographic techniques that employed map overlays (DiBiase, 2013). McHarg visualized geographic information by constructing layers based on information from various scientific disciplines (Goodchild, 2010). These early developments in the use of geographic information and technology led to the contemporary applications of geographic information systems (GIS).

A GIS incorporates hardware, software, and data for capturing, managing, analyzing, and visualizing geospatial data (ESRI, n.d.). Geospatial data refers to geographically referenced information related to the surface of the Earth. In essence, GIS is a suite of technological capabilities that attempt to examine where, what, when, and how information can be procured in a particular area and at multiple scales (Sui, 2008). The basic functions of a GIS are shown in Figure 1.

Figure 1 Basic capabilities of geographic information systems



2.3.2 Remote Sensing

One method of capturing information about the earth's surface is remote sensing. Remote sensing is the science of gathering information about objects from a distance, typically by utilizing aircraft or satellites (NOAA, 2013). The National Aeronautics and Space Administration (NASA, n.d.) described remote sensing as a process that detects and measures radiation of different wavelengths that are reflected or emitted from different objects or materials that can then be identified and categorized by class, type, substance, and spatial distribution. Additionally, advancements in remote sensing technologies in the past two decades have allowed precise measurements of topography and topographic changes over temporal and spatial scales resulting in an improved ability to assess, mitigate, and anticipate natural hazards (Necsoiu & Hooper, 2009). When used together, GIS and remote sensing technologies can be effective tools for assessing hazard vulnerability (Mahendra, Mohanty, Bisoyi, Kumar, & Nayak, 2011).

2.3.3 Geospatial Science for Modeling Sea Level Rise

Coastal areas are particularly vulnerable to a variety of natural hazards (NOAA, 2013). For this reason, a NOAA *Sea Level Rise and Inundation Community Workshop* listed geospatial modeling, storm surge modeling, and flooding/inundation modeling as priority tools for assessing vulnerability (Culver, Schubel, Davidson, Haines, & Texeira, 2010).

As early as the 1990s, remote sensing systems began offering new insights on many aspects of climatology and oceanography (Cazenave & Llovel, 2010). Additionally, satellite altimetry provided a new method to measure sea level rise in areas without tidal gauges (Prandi, Cazenave, & Becker, 2009). These advancements in remote sensing have allowed researchers to generate better estimates of overall sea level budget based on thermal expansion, cryosphere considerations, and circulation (Church, et al., 2010). Estimates of SLR are often combined with LiDAR (light detection and ranging) elevation data to accurately measure potential effects on land (Gesch, 2009). Specifically, the use of digital elevation models (DEM) created from LiDAR has become prominent in modeling SLR effects on land (Cooper, Beevers, & Oppenheimer, 2005).

The use of GIS for assessing the potential impacts of SLR on land is considered valuable because of the ability to overlay multiple data layers. With ever increasing availability of datasets, researchers have utilized GIS to estimate potential damage throughout the world. GIS has been used at multiple scales ranging from global to local. Li et al. (2009) conducted a global GIS analysis to quantify total inundated land area, land cover, and human population using 1m and 6m of SLR. Another team of researchers offered a comparative study of SLR in developing countries and estimated that hundreds of millions of people in the developing world are likely to be displaced (Dasgupta, Laplante, Meisner, Wheeler, & Yan, 2007).

Continental and national level GIS models have also been employed. For instance, a population estimation analysis was conducted for the 23 coastal states in the coterminous United States which found that 11.6 million people live below three meters of elevation (Lam, Arenas, Li, & Liu, 2009). Others have narrowed the focus to map socially vulnerable populations in the United States (Martinich, Neumann, Ludwig, & Jantarasami, 2013).

Improvements in technology as well as the need for information to inform subnational policy making led to studies at the regional and local scales. In the United States, GIS studies have examined Maui, Hawaii (Cooper, Chen, Fletcher, & Barbee, 2013), North America Atlantic Coast (Sallenger Jr., Doran, & Howd, 2012), the Gulf Coast (Thatcher, Brock, & Pendleton, 2013), the California coast (Cooley, Herrera, Gleick, & Moore, 2009), and the Pacific Northwest (Baron, Wood, Ruggiero, Allan, & Corcoran, 2010). Each of these studies focused on some particular aspect of physical, environmental, or social vulnerability in coastal communities.

Port cities are particularly important for coastal communities because of the economic value they provide to their respective nations. Thirteen out of twenty of the world's most populous cities are port cities (Hanson, et al., 2011). Hanson et al. used GIS to analyze and rank the world's largest port cities in terms of climate change and SLR impacts. At the city scale, another team of researchers performed a detailed and complex assessment of the port city of Copenhagen, Denmark (Hallegatte, et al., 2008). The study concluded that Copenhagen is not highly vulnerable, yet if left unprotected, could still experience economic losses in the billions of Euros. There are 12 key port cities (seaports) in the United States that rank among the world's top 100 in volume of containers (AMID, 2009). The combined ports of Seattle and Tacoma, Washington are among the top U.S. port cities in container volume.

There has been little GIS analysis of sea level rise for the City of Seattle. At the time of this writing, the extent of scholarly research employing GIS to model the effects of SLR in Seattle have been limited to university student undertakings. Petterson (2007) modeled SLR for three areas in the Puget Sound, including Seattle, Olympia, and Quartermaster Harbor. Petterson's analysis focused on social-ecological resilience framework to analyze and respond to sea level rise. Petterson limited his analysis of Seattle to Harbor Island, which is only a fraction of land that is likely to be inundated under various scenarios. Additionally, Mahr (2009) utilized

GIS to analyze the land within Seattle city limits. However, the projected levels of SLR in Mahr's analysis were higher than the levels that are supported by scientific literature on the subject. It is also likely that Mahr's estimates did not take into account local variation due to water temperature, vertical land movement, and cryosphere contributions. Thus, a more comprehensive GIS analysis of the City of Seattle is needed which reflects the current state of knowledge for 21st century SLR projections.

2.3.4 Hazard, Vulnerability, and Risk Mapping

There are two primary hazards that emanate from natural disasters such as rising sea levels: natural hazards and technological hazards (Smith, 2013). There are many definitions of natural and technological hazards, however, this study will rely upon Smith's (2013) adoption of definitions offered by the United Nations (UN). According to the UN (2007, n.p.), a natural hazard is a "natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage." A technological hazard originates from "technological or industrial conditions, including accidents, dangerous procedures, infrastructure failures or specific human activities, that may cause loss of life, injury, illness or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UN, 2007, n.p.).

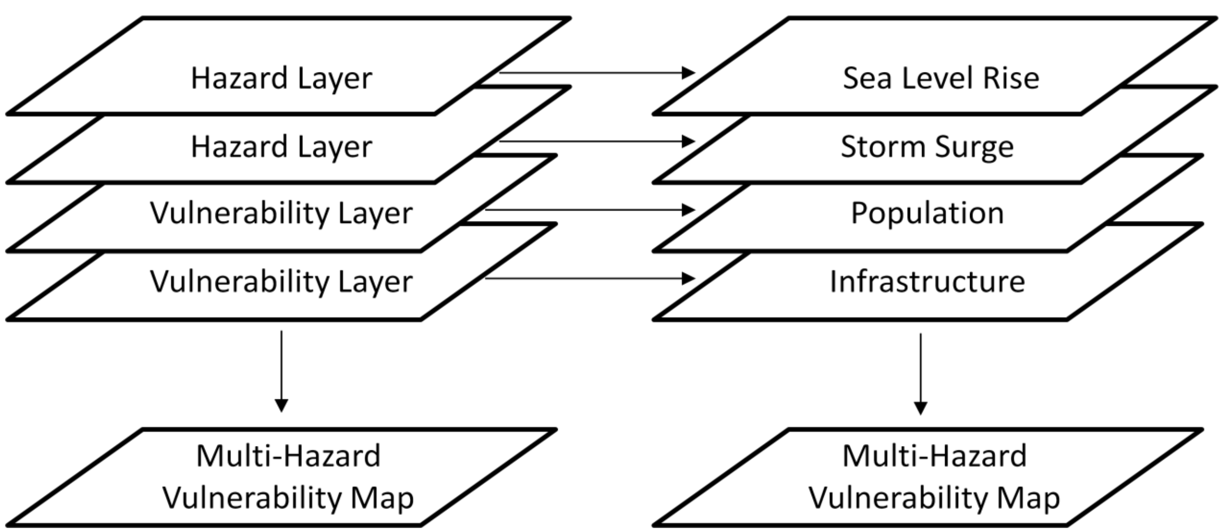
As part of the Disaster Mitigation Act of 2003, state and local governments are required to implement pre-disaster mitigation, which include the development of hazard maps (Waugh Jr. & Tierney, 2007). Hazard mapping is regarded as one of the most useful decision making tools for managing risks (Neri, Le Cozannet, Thierry, Bignami, & Ruch, 2013). Charrière, Bogaard, & Mostert (2012) posited that maps are well suited to communicate information about natural hazards because of their inherent spatiotemporal component. Hazard mapping has been used to communicate information about various natural hazards such as landslides (Dahal, et al., 2012), earthquakes (USGS, 2013), floods (FEMA, 2013), and coastal inundation (Saxena, Purvaja, Suganya, & Ramesh, 2013).

Vulnerability to a given hazard (in this case, rising sea level and storm surge) is partly a function of geography. According to Mahendra et al. (2011, p. 302), vulnerability is a "set of conditions and processes resulting from physical, social, economic and environmental factors that increase the susceptibility of a community to the impact of hazards." Physical factors such as infrastructure, social factors such as population, and economic factors such as land and structure value may influence vulnerability in a community (Cooper et al., 2013). Thus a Multi-Hazard Vulnerability Map (MHVM) incorporates vulnerability to understand the risk of a given hazard (Mahendra et al., 2011). Researchers have used remote sensing and GIS to conduct SLR vulnerability assessments for various aspects of coastal regions (Cooper et al., 2013; Gesch, 2009; Kumar et al., 2010; Mahendra et al., 2011).

Disaster risk denotes the possibility of negative effects in the future. It is an assessment based on the hazards and the vulnerabilities of exposed elements (Cardona, et al., 2012). Risk may also be seen as the "product of an event and the consequence of its occurrence" (National Research Council (NRC), 2009, p. 91). Similarly, Kasperson et al. (1988) and Smith (2013) explained risk assessments as estimations of the probability of a hazard and the magnitude of consequences.

The NRC (2009) concluded that hazard and risk maps are necessary tools for fostering public understanding of challenges to living in hazard areas. There are three primary objectives of hazard and risk maps: (a) improve risk perception by increasing knowledge and understanding, (b) promote personal risk framing through creating a personal view, and (c) establish credibility by providing objective information (Charrière et al., 2012, p. 13). A schematic of a MHVM is shown in Figure 2.

Figure 2 Elements of a Multi-Hazard Vulnerability Map



3 Study Area

The city of Seattle, shown in Figure 3, is a critical economic center in the Pacific Northwest region of the U.S. It is an economically, culturally, and environmentally diverse metropolis. Located along the I-5 corridor to Canada as well as its status as a port city, Seattle has a wide range of critical infrastructure systems and key resources. The economy is supported by a thriving business environment, suitable for both large and small businesses alike. Notable corporations in the Seattle area are Boeing, with a major commercial airplane factory, Starbucks headquarters, Safeco Insurance, and Russell Investments. Other industries such as biotechnology, biopharmaceuticals, large boat construction, commercial fishing, and information technology can also be found in Seattle. It is home to several higher educational institutions, including the University of Washington.

The city hosts numerous large public events each year, including sporting events in Major League Baseball, Major League Soccer, the National Football League, and the Women's National Basketball Association. It is home to Safeco Field (seating for 47,116 people) and CenturyLink Field (capacity of 72,000), both of which are located near the Elliot Bay waterfront.

Bordered by the Puget Sound on the west and Lake Washington on the east, the natural environment in and around Seattle is ecologically diverse. Seattle covers 91 square miles of land and contains 193 miles of waterfront (City of Seattle, 2012). The Greater Seattle Area has a population of about 3.2 million with approximately 620,000 living in the City of Seattle (United States Census Bureau, 2012). As a heavily urbanized area, Seattle has a high population density of 7,250.9 persons per square mile compared to the United States average of 87.4.

The Port of Seattle and those near it, such as the Port of Tacoma, are vital components of the United States economy. Seattle's Seaport is the sixth largest U.S. port in shipping volume of containers known as twenty-foot equivalent units (TEUs); the seventh largest North American port in TEUs; and fifty-seventh largest in the world in TEUs. In terms of dollar value of passing goods, it is the ninth largest U.S. port (Port of Seattle, 2011).

Figure 3 Study area: Seattle, Washington

Seattle is also a key hub for the Washington State Ferry System operating in the Puget Sound which is the largest ferry system in the United States and fourth largest in the world. In terms of number of vehicles carried, it is the largest in the world. More than 22 million riders transit the ferries each year (WSDOT, 2011). The ferries transport freight vehicles, passenger vehicles, bicycle commuters, and pedestrians – the majority of which pass through Seattle. The ferries offer a critical link between more affordable housing on the west side of the Puget Sound and vital employment centers on the east, especially Seattle. They are also major tourist attractions and icons in Washington. Some ferries offer ports of entry from British Columbia, Canada. Other than personal boats, the ferries are the sole link to Vashon Island and San Juan Islands.

Adding to Seattle's state, regional, and national importance are the highways that run through the city, which are critical for passenger and freight vehicles. The I-5 corridor through Seattle receives over 250,000 vehicles per day (WSDOT, 2008). The aging Alaskan Way Viaduct (State Route 99) receives over 100,000 vehicles per day (Seattle Department of Transportation, 2012). The city also has a high ridership transit system and promotes various forms of active transportation (e.g. bicycle commuting and walking).

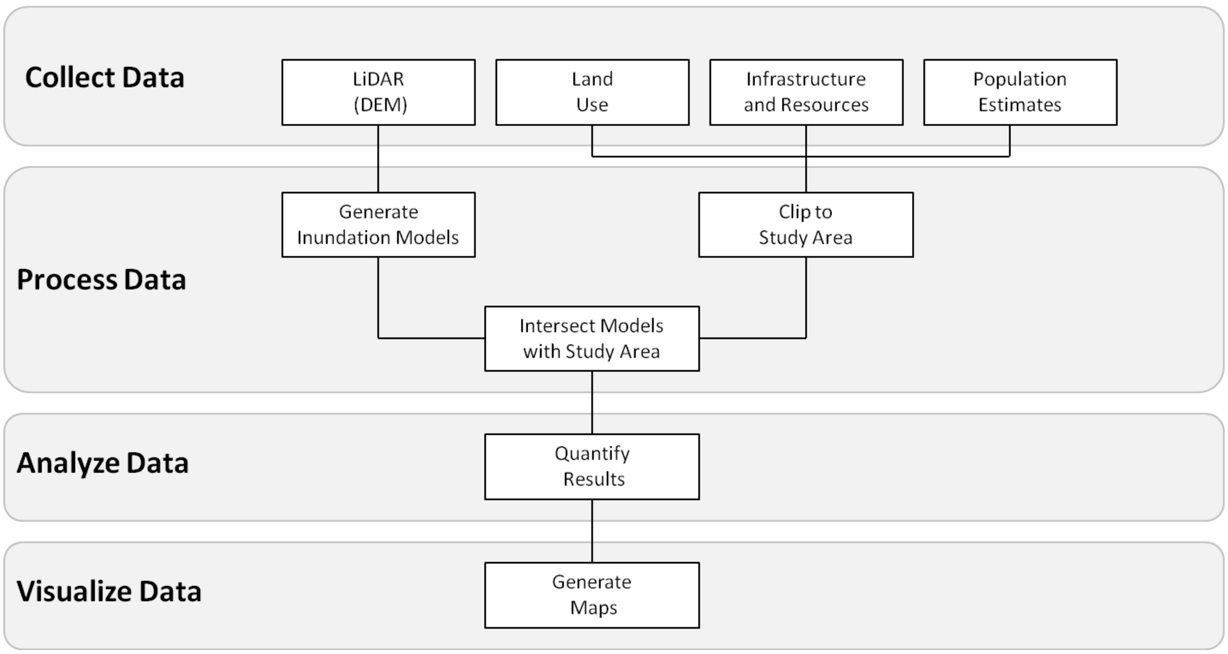
Much of Seattle's industrial infrastructure and activity is located along the Duwamish Waterway and in the Interbay neighborhood. These areas contain robust port facilities as well as various means of ground shipping and transportation including rail and trucking. There are several hazardous materials sites and petroleum tanks located on the manmade Harbor Island which is situated on the Duwamish Waterway delta in Elliot Bay (EPA, n.d.). Harbor Island is also the location of three Superfund cleanup sites containing metals, polychlorinated biphenyls (PCBs), tributyl tin, and petroleum products (EPA, n.d.).

As a densely populated urban area, Seattle has a dense network of utilities such as water and sewer systems, storm drains, communications, and electricity. Other CIKR includes public safety facilities such as police, fire, emergency medical services (EMS), and hospitals. These facilities and services, and myriad others, are essential to the everyday lives of residents and visitors of the city.

4 Research Methods

This study employed a GIS methodology consisting of four primary steps: (a) data collection, (b) data processing, (c) data analysis, and (d) geovisualization of results. A flowchart of this methodology is shown in Figure 4. The first three processes are explained throughout this research methods chapter. The fourth step, visualizing the data, is presented throughout the results chapter below.

Figure 4 GIS methodology flowchart



Based on the availability of data and the uncertainty of future events, primarily SLR, the analysis was conducted under the following considerations and assumptions:

- No consideration was given to geomorphic events such as coastal erosion, tsunamis, or sieche.
- With the exception of filling in sinks recognized by the LiDAR (see section 4.3 for a detailed explanation), complex ground-water hydraulics were not considered due to the large number of unknown and unpredictable variables such as precipitation, floods, and soil saturation.
- Storm surge events in the future were assumed to be consistent to those of the recent past, including record surge heights.

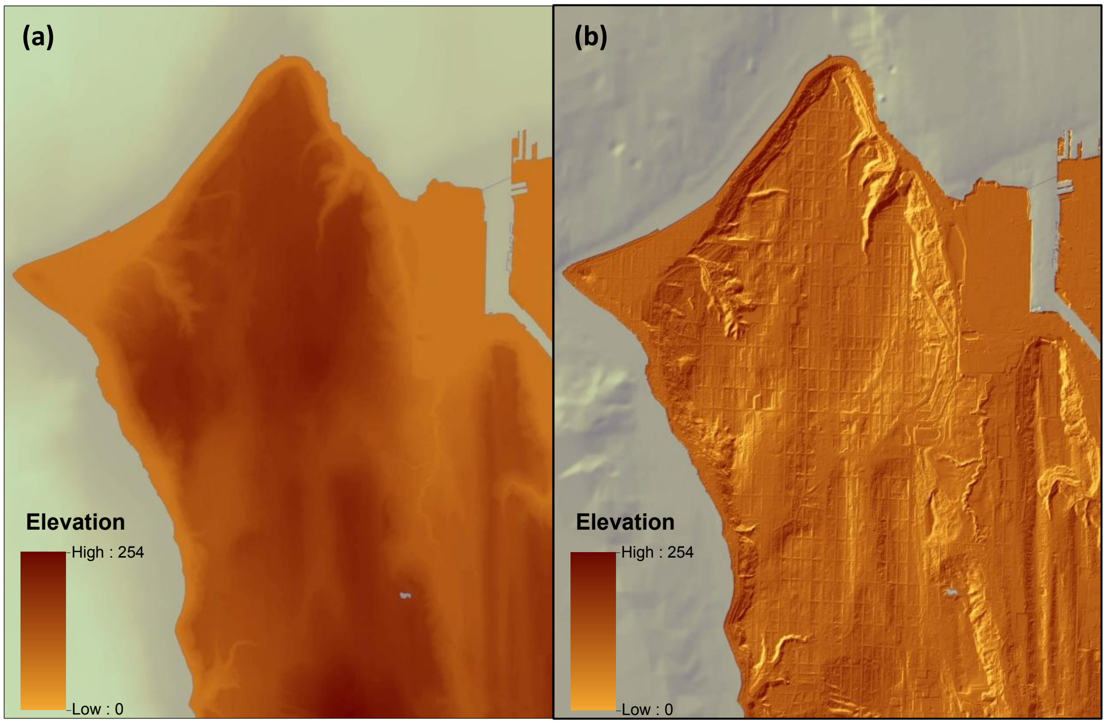
- GIS shapefiles representing structure locations (e.g., buildings or roads) were assumed to mark the center of the structure and are not reflective of the height of the structure.
- Future projections of population patterns or numbers were not considered. Population data was retrieved from 2010 Census results.
- Future mitigation and adaptation strategies were not considered.

4.1 Digital Elevation Modeling

Accurate representation of topography is paramount in modeling hydraulic inundation. For this reason, high resolution DEMs derived from LiDAR data are often used to simulate topographic properties of the real world (Hailea & Rientjes, 2005). LiDAR is a remote sensing method that uses light emitting pulsed radar from an aerial platform, most often airplanes and helicopters, to measure variable distances to the earth's surface (NOAA, 2013). The LiDAR data is then converted to xyz coordinates representing horizontal location and vertical values. This location and elevation data is then sampled at regularly spaced horizontal intervals and processed into digital raster form (USGS, 2012). Recent improvements in DEMs as well as relative availability of these data have led to greater empirical trust for accuracy as an elevation layer (NOAA, 2010).

Elevation data for this study was generated from LiDAR data retrieved from the Puget Sound LiDAR Consortium (PSLC) in the form a high resolution bare earth DEM. The PSLC is comprised of local agency staff and federal scientists dedicated to providing public domain high resolution LiDAR topography for the Puget Sound region. A bare earth DEM was chosen because, according to NOAA (n.d.), only points that hit the ground should be used for applications such as storm surge modeling and flood events. In a bare earth DEM manmade structures and vegetation have been removed and elevation values are interpolated based on surrounding elevation (PSLC, 2005).The PSLC bare earth DEM of Seattle has a horizontal resolution of six feet and a vertical accuracy of one foot. Using ArcGIS 10, a hillshade raster was generated from the bare earth DEM to show terrain relief of Seattle (Figure 3).

Figure 5 Comparison of DEM and hillshade



Note. (a) Bare earth digital elevation model (DEM) of the West Seattle neighborhood. (b) Hillshade image generated from the bare earth DEM.

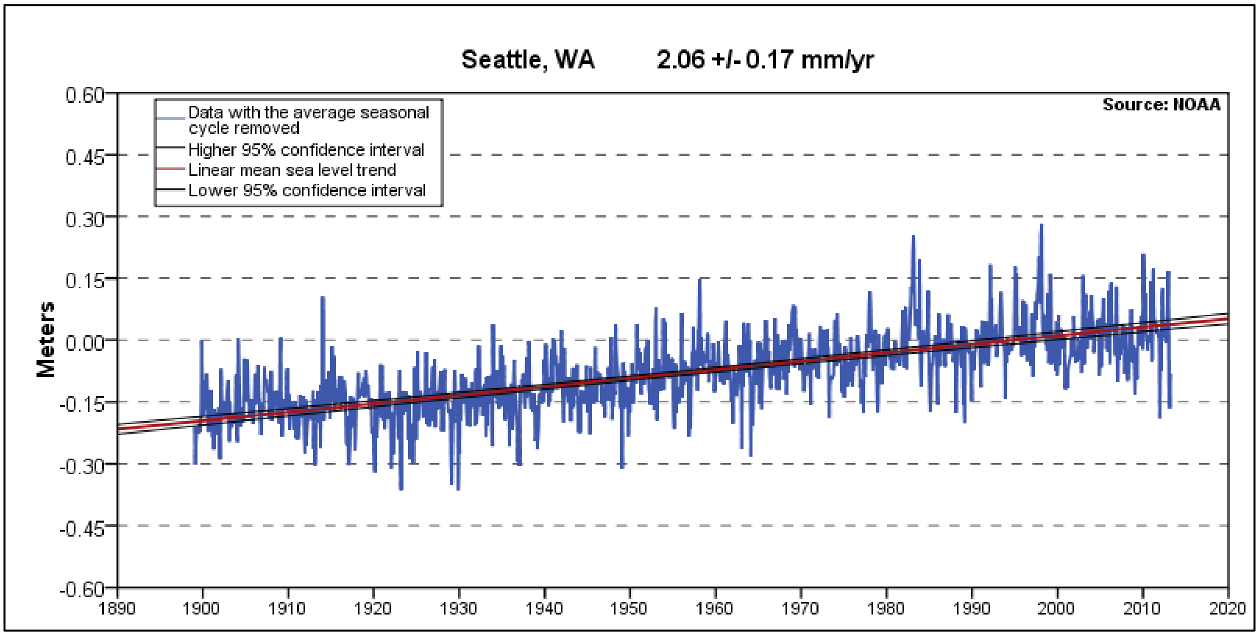
4.2 Sea Level Rise of Washington State and The Puget Sound

In 2010 there were 164 million people, slightly more than 50 percent of the nation's total population, living within coastal watershed counties (Burkett & Davidson, 2012). Recently researchers estimated that 20 cities (including Seattle) with populations greater than 300,000 and 160 cities with populations between 50,000 and 300,000 possess land area with elevations at or below 6 m and adjacency to the sea (Weiss, Overpeck, & Strauss, 2011). There are 15 coastal counties in Washington with a combined coastline of over 3,000 miles and a total coastal population of more than 4.5 million people (Washington State Department of Ecology, n.d.; NOAA, 2013).

Overall, coastal waters of Washington experience significant variability in sea level rise. This is primarily due to vertical land movement (VLM) caused by tectonic activity, water temperature, winter winds, especially during El Niño Southern Oscillation (ENSO) events, and Pacific Decadal Oscillation (PDO) phase changes (Mote, Petersen, Reeder, Shipman, & Binder, 2008; NAS, 2012).

Historically, the Puget Sound near Seattle has experienced an increase in local mean sea level (LMSL), which is a 19 year average of mean high and mean low water, with a trend of 2.06 mm/yr with a 95% confidence interval of +/- 0.17 mm/yr (NOAA, 2013). The NOAA time series in Figure 6, from 1898 to 2006, shows an increase equivalent to 0.21 m in the last 100 years. However, the future is less certain due to numerous environmental and anthropogenic factors such as earthquakes, melting land ice, and carbon emissions.

Figure 6 Mean sea level trend for Seattle, Washington



Note. Sea level trend based on sea level data at the Seattle tidal gage from 1898 to 2006. Source: National Oceanic and Atmospheric Administration. (2013). *Mean sea level trend: 9447130 Seattle, Washington*. Retrieved from NOAA Tides & Currents: http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9447130

Researchers at the University of Washington and the Washington Department of Ecology (2008) estimate that the Puget Sound may experience sea level rise between 0.16 m and 1.28 m by the end of the 21st century. Additionally, VLM in the Puget Sound basin results in land subsiding at an overall rate of about 2.0 mm/yr. Near Seattle, it has been observed that land is subsiding at a rate of about 1.4 mm/yr thereby increasing the observed effects of local sea level rise (Mote, 2001; National Wildlife Federation, 2007).

The National Academy of Sciences (NAS) Committee on Sea Level Rise in California, Oregon, and Washington (2012) built on previous estimations by the IPCC (2007), Mote (2008), and Vermeer and Rahmstorf (2009). The NAS estimations attempt to account for the sea level fingerprint created by melting ice in the cryosphere from Alaska, Antarctica, and Greenland. The NAS project the SLR on the coasts of Washington at the end of the 21st century to be between 0.5 m and 1.4 m, relative to levels in 2000. Table 3 compares the low and high estimates of SLR for the Puget Sound at the end of the 21st century.

Table 3 Comparison of 21st century SLR projections for the Puget Sound

Source	21st Century Low Estimate	21st Century High Estimate
Univ. of Washington & Washington Dept. of Ecology (Mote et al. 2008)[a]	0.16 meters	1.28 meters
National Academy of Sciences (2012)[b]	0.50 meters	1.40 meters

Note.
[a]Mote, P., Petersen, A., Reeder, S., Shipman, H., & Binder, L. W. (2008). *Sea Level Rise in the Coastal Waters of Washington State.* University of Washington Climate Impacts Group and Washington Department of Ecology. Retrieved from http://cses.washington.edu/db/pdf/moteetalslr579.pdf

[b]National Academy of Sciences. (2012). *Sea-level rise for the coasts of California, Oregon, and Washington: Past, present, and future.* Washington, D.C.: National Academies Press.

The projected sea level rise in the Puget Sound near Seattle is likely to be exacerbated by the frequent occurrence of storm surge events which can cause tremendous damage to coastal infrastructure (Walker, Figliozzi, Haire, & MacArthur, 2011). These storm surge events are a result of low pressure and high winds arising from mid-latitude cyclones, which move onshore from the Pacific Ocean and are most severe and frequent in the Pacific Northwest during the winter months (Finlayson, 2006). Additionally, storms also increase wave forcing and bring heavy rainfall which may lead to accumulation of local water level (Burkett & Davidson, 2012). It is uncertain whether climate change will have a direct effect on storm surge frequency or strength in the future (Knutson, et al., 2010); yet even if storm surge frequency remains similar to observations over the past several decades, the impact is expected to be amplified due to rising sea levels.

Although lower magnitude storm surges up to 0.4 m are frequent in the Puget Sound, there have been several noteworthy events in the past thirty years (NAS, 2012). On January 27, 1983, a record storm surge recorded by NOAA (Seattle, Puget Sound Station ID 9447130) reached 0.95 m above mean higher high water (MHHW), which is the 19-year average of the highest of two daily high tides. Furthermore, a series of six storms between 1997 and 2000 occurred as a result of El Niño (1997-98) and La Niña (1998-99) events which resulted in storm surges along the coast that topped 1.6 m (Allan & Komar, 2002) and reached 0.5 m above MHHW at the Seattle, Puget Sound tidal gauge. More recently, on December 17, 2012 the same tidal gauge recorded another storm surge of 0.95 m above the MHHW. Thus the worst case projected scenario for Seattle's shoreline at the end of the 21st century is a low probability/high impact SLR of 1.4 m plus a storm surge, judging by the past, of 0.95 m. Therefore, the SLR estimates used for this study are based on the NAS (2012) projections plus a storm surge of 0.95 m. These projections are summarized in Table 4.

Table 4 Sea level rise projections used for this research

High Probability	Medium Probability	Low Probability
1.45 m	1.90 m	2.35 m

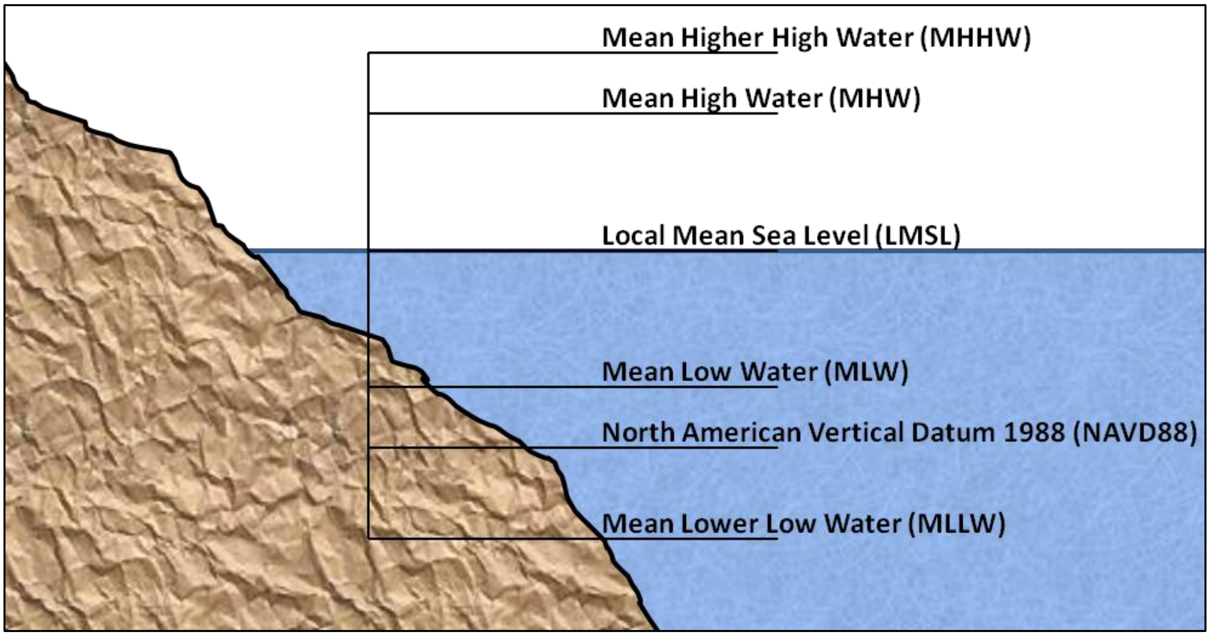
Note. The High Probability (HP) and Low Probability (LP) estimates were taken directly from NAS (2012) plus 0.95 m storm surge, however the Medium Probability (MP) is simply the mean the HP and LP, plus 0.95 m storm surge.

4.3 GIS Modeling of Sea Level Rise in Seattle

Modeling the three estimates of SLR onto the DEM required converting the vertical tidal datums from the Seattle, Puget Sound tidal gauge to the vertical orthometric datum of the DEM. In simple terms, datums are reference points that provide base values to measure vertical elevations (Slocum et al., 2009). In this case, datum conversion was necessary because local mean sea level does not indicate a zero-foot starting point for land elevation. Likewise, a z-value, or height, of zero on the DEM does not indicate LMSL. In other words, LMSL is not the origin point for land height estimates. A diagram comparing the common tidal datums with the orthometric North American Vertical Datum 1988 (NAVD88) is shown in Figure 7.

Tidal datums are water level averages at a tidal gauge over time (NOAA, 2013). Orthometric height is height above an imaginary surface approximated by mean sea level and determined by the earth's gravity (Fraczek, 2003). A tidal datum of MHHW was used as the inundation baseline for this study because it is the arithmetic mean of the higher high water tide occurring daily when there are two high tides (Washington Department of Ecology, 2012). That is to say, because MHHW is the current highest average for local sea level height, any future SLR will extend beyond the MHHW.

Figure 7 Comparison of tidal datums to orthometric datum NAVD88



Note. Adapted from National Oceanic and Atmospheric Administration. (2013). *Datums for 9447130, Seattle WA*. Retrieved from NOAA Tides & Currents: http://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=9447130&name=Seattle&state=WA

The NOAA VDatum tool was downloaded along with grid files for the Northwest to convert MHHW to the DEM datum of NAVD88. The height in meters was converted to height in feet for ArcGIS because the DEM altitude distance units were designated in feet (PSLC, 2005.). The VDatum conversion yielded a NAVD88 height for MHHW as 2.75 m (9.02 ft). Combining the NAVD88 height for MHHW with the 21st century estimates in Table 4 yields the actual SLR elevation modeled in the GIS software. Table 5 shows a comparison between the SLR projections, the actual elevation modeled after VDatum conversion, and the SLR projections in relation to LMSL.

Table 5 Comparison of SLR projections, vertical datum, and tidal datum

	High Probability	Medium Probability	Low Probability
SLR Projections[a]	1.45 m	1.90 m	2.35 m
Actual Elevation Modeled[b]	4.20 m	4.65 m	5.10 m
Height Above Local Mean Sea Level[c]	2.89 m	3.34 m	3.79 m

Note.
[a]SLR Projections are based on Table 4 figures. These numbers include a storm surge height of 0.95m.

[b]Actual Elevation Modeled was obtained by converting the MHHW to NAVD88 using NOAA VDatum. The conversion number, 2.75m, was added to the SLR Projections.

[c]Height Above Local Mean Sea Level indicates the height of the SLR projections above LMSL.

In ArcGIS, the "Reclassify" tool was used with the DEM to calculate an inundation raster based on the projected sea levels in Table 2. Each SLR extent, beginning with MHHW was assigned a new value from 1 to 4 (i.e., MHHW = 1, high probability = 2, medium probability = 3, low probability = 4). The derived raster revealed several areas of inland Seattle that were shown to be inundated, yet, they were not coterminous with the flooding from the Puget Sound. These are referred to as sinks. More specifically, a sink is an area recognized by the software as being lower than the inundation extent even though it may be geographically separate from the inundation. To correct for sinks in the surface raster, the "Fill" tool was employed. The "Raster Calculator" was used next to create individual rasters for each of the SLR projections in Table 5. Next, a "Raster to Polygon" function generated polygons of each of the SLR projections. Creating the polygon layers made it simpler to calculate the area of inundation by using the "Intersect" tool with a Seattle land area shapefile, followed by "Calculate Geometry." Lastly, the "Layer to KML" tool was used to convert the ArcGIS polygons into KML files to export and use in Google Earth.

4.4 Identification of Vulnerable Critical Infrastructure, Key Resources, and Population

The CIKR data for the study area was procured from the King County GIS Center, the City of Seattle, the Federal Communication Commission, and the U.S. Census Bureau. Because most of the CIKR data were in point, line, or polygon format, the "Clip" and "Intersect" tools were used most frequently to determine what facilities, structures, and resources were likely to be inundated at the projected SLR extents. Each category of CIKR was then quantified by calculating total quantity for points, linear distance for line features, and square area for polygons.

Because a principal goal of homeland security at all levels of government is to protect the American people, it was important to understand how much of the Seattle population may potentially be directly affected by SLR (DHS, 2003). Population estimations were obtained by first calculating the population density for each census block group that experienced inundation based on the models. The estimates of population density were obtained using 2010 Census data. Using Microsoft Excel, the population density for each block group was multiplied by block group area of inundation in square miles. This method of calculating affected coastal population is commonly used in other coastal inundation studies and assumes that census block group populations are uniformly distributed (Crowell, et al., 2010). Block groups are relatively homogenous areas containing between 600 and 3,000 people, and are the smallest census units released in tabulated data to protect confidentiality (Iceland & Steinmetz, 2003).

5 Results

Figure 8 shows the total areas of inundation within Seattle city limits based on the three projections of SLR at the end of the 21st century plus a storm surge of 0.95 m. The total inundated land area for the high probability (HP) scenario is 2.31 km^2, which is 1.06 percent of Seattle's land area. The medium probability scenario (MP) indicated that 4.53 km^2, or 2.08 percent, of Seattle's land area would be inundated. Lastly, the low probability (LP) scenario revealed an inundation area of 11.14 km^2, the equivalent of 5.12 percent of Seattle's land.

By observing the models of sea level inundation mentioned above, it is clear the majority of flooding under any SLR scenario occurred on Harbor Island, along the Duwamish Waterway, and north in the Interbay area. There was less inundation along the downtown area, but due to the high density of businesses and infrastructure located along the waterfront there were still significant impacts, especially in the low probability model. Figure 9 shows a larger scale image of the most heavily inundated area, the Duwamish Waterway, by exporting the ArcGIS files to Google Earth and changing the visual azimuth.

There was a mixture of commercial, industrial, residential, downtown, and major institution zoning areas inundated in all three SLR scenarios, which is shown in Figure 10. The chart in Figure 11 shows the breakdown of inundated areas by zoning class description. The category most heavily inundated was industrial land, primarily located on Harbor Island, along the Duwamish Waterway, and the Interbay area. Residential land experienced the next highest extent of inundation, followed by commercial land. Downtown zoning experienced the fourth largest extent of inundation. The zoning category with the lowest inundation extent was major institutions, which consist of hospitals, universities, and colleges. For each SLR scenario, there was a small amount of inundated land that did not contain zoning information within the GIS database.

The industrial areas located at Harbor Island and along the Duwamish Waterway are critical transportation hubs that integrate several modes such as roads, railroads, and ship transport. There are also numerous manufacturing facilities located in this area because the close proximity to shipping reduces costs. Consequently, the portion of industrial land affected by inundation is much greater than the other zoning categories. According to all three models, the area of industrial land inundated is greater than the total area of the other zoning categories combined.

Figure 8 Potential areas of inundation by the end of the 21st century

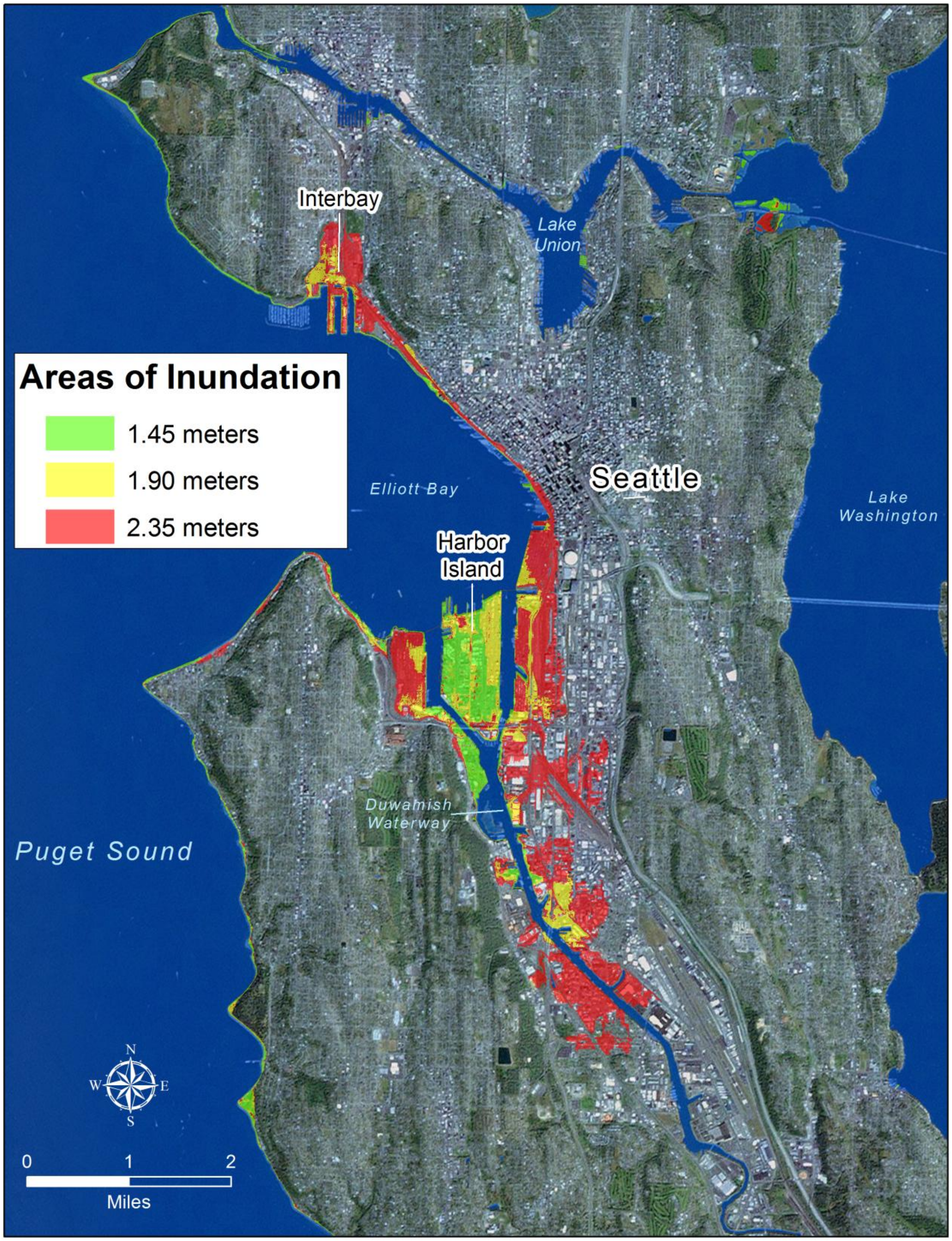
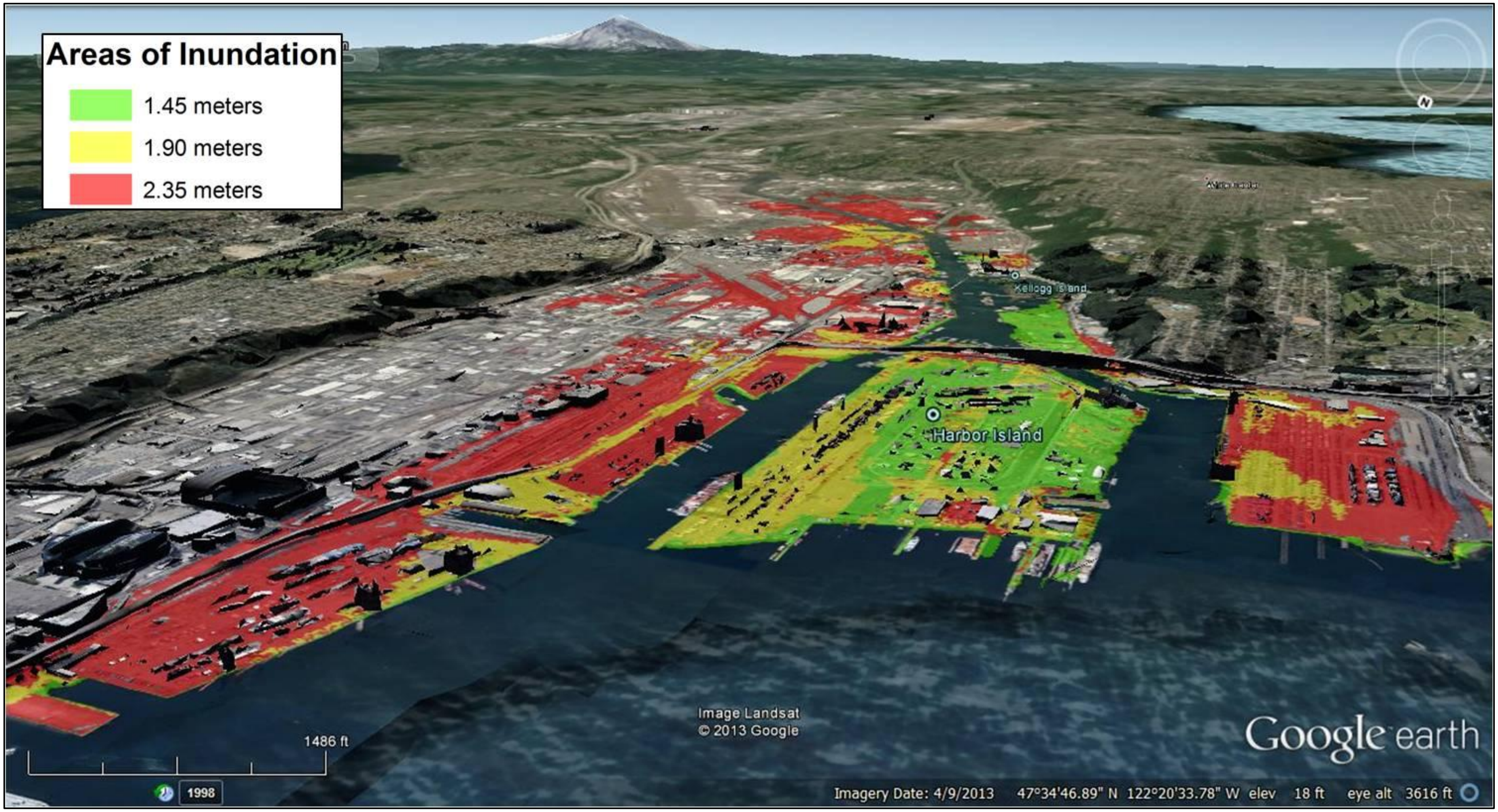


Figure 9 Visualizing sea level rise models in Google Earth



Note. This Google Earth image was generated by converting the ArcGIS models into KML files which were then exported to Google Earth. Using the navigation toggles, the point of view was recast at a southeasterly direction from Elliott Bay looking towards the Duwamish Waterway. The sunlight function was used to create a shade effect to highlight the terrain relief. The green, yellow, and red colors correspond to the map in Figure 8.

Figure 10 Maps showing SLR inundation by zoning class description

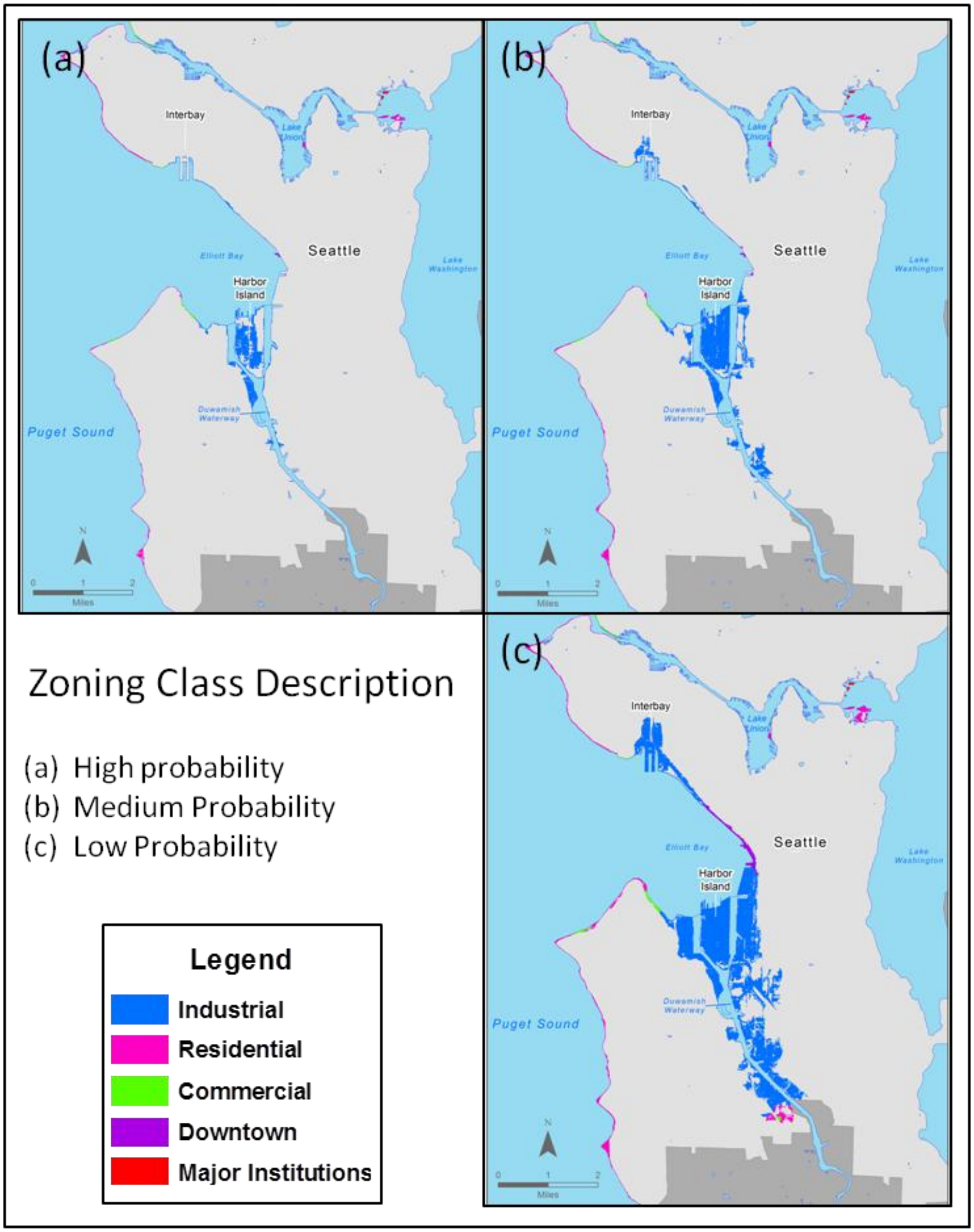
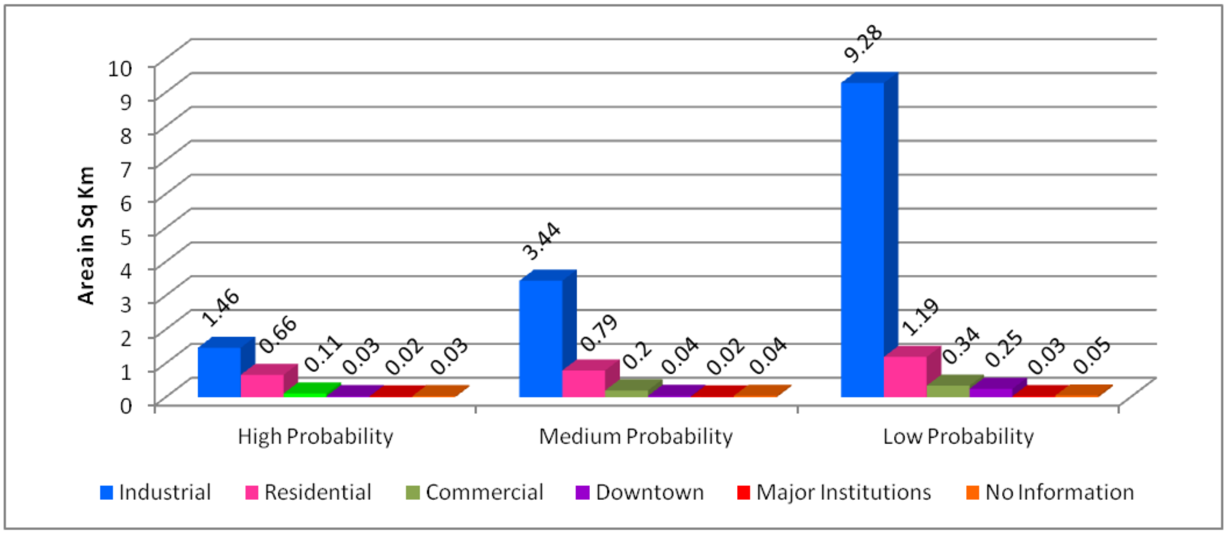


Figure 11 Zoning categories inundated by SLR by the end of the 21st century



Note. Colors correspond to zoning in the maps in Figure 10

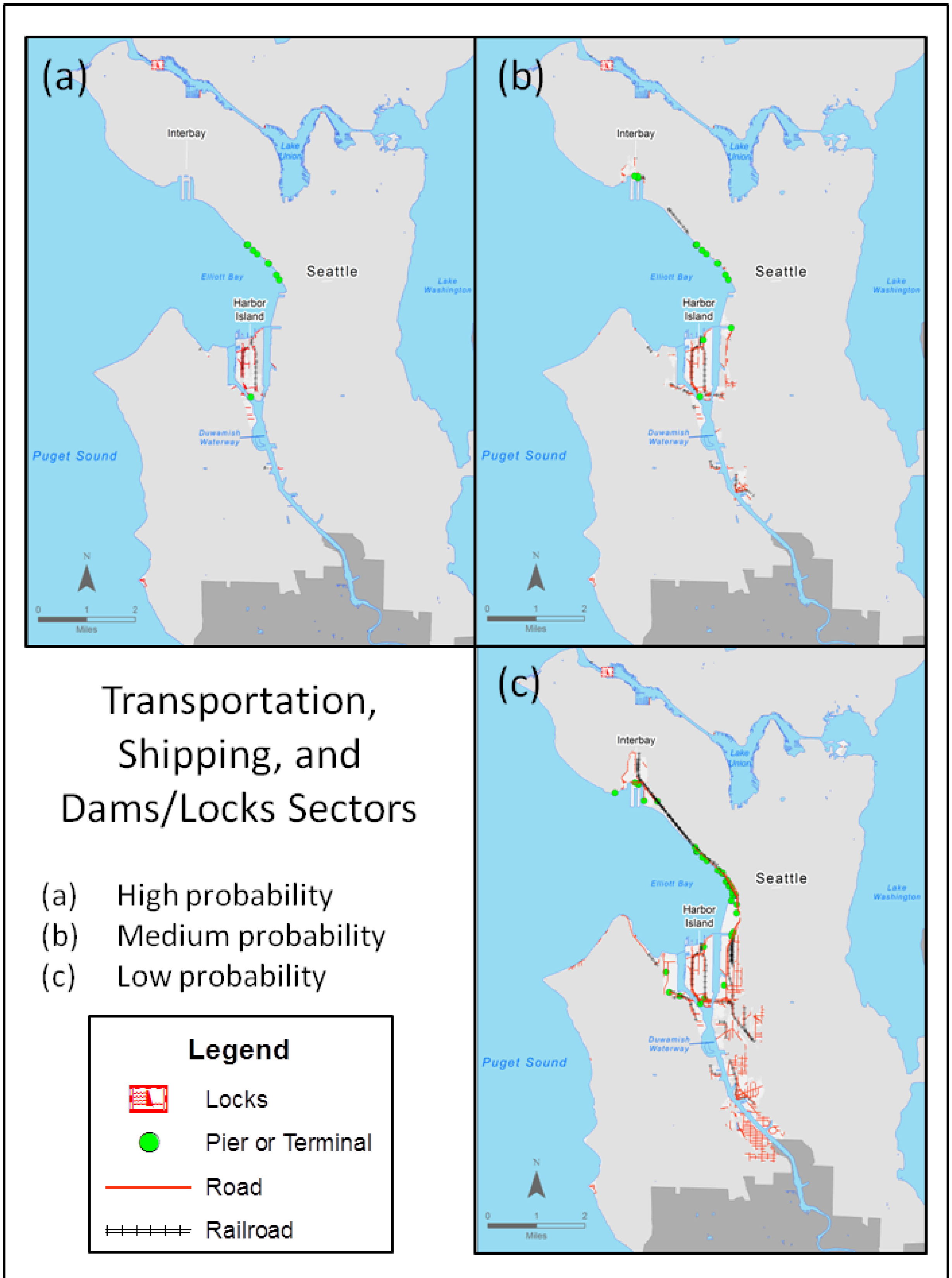
According to the three SLR models, numerous aspects of critical infrastructure were shown to be inundated including transportation networks, communications facilities, military installations, water, and energy facilities. The key resources that were affected include several public safety institutions (i.e., police and fire/EMS), schools, and common points of interest consisting of food facilities, major employment centers, parks, banks, and others. The results of the CIKR analysis are shown in Table 6.

Due to the extent and density of CIKR elements in Seattle, it is impractical to create a single map showing the comprehensive results of the GIS analysis. Indeed, designing maps to communicate information requires achieving visual harmony and equilibrium; this is known as balance (Slocum, McMaster, Kessler, & Howard, 2009). Map elements should achieve balance by complementing one another rather than competing for space and creating a visual discord. Thus, to show an example of the results of the GIS analysis, a series of maps in Figure 12 isolate the inundated elements of the transportation, shipping, and dams/locks sectors for each of the three SLR models. Each of the CIKR elements in Table 6 were isolated and quantified in the three SLR models using the same methodology that was employed for the transportation, shipping, and dams/locks sectors.

Table 6 Sectors of CIKR inundated by each SLR model

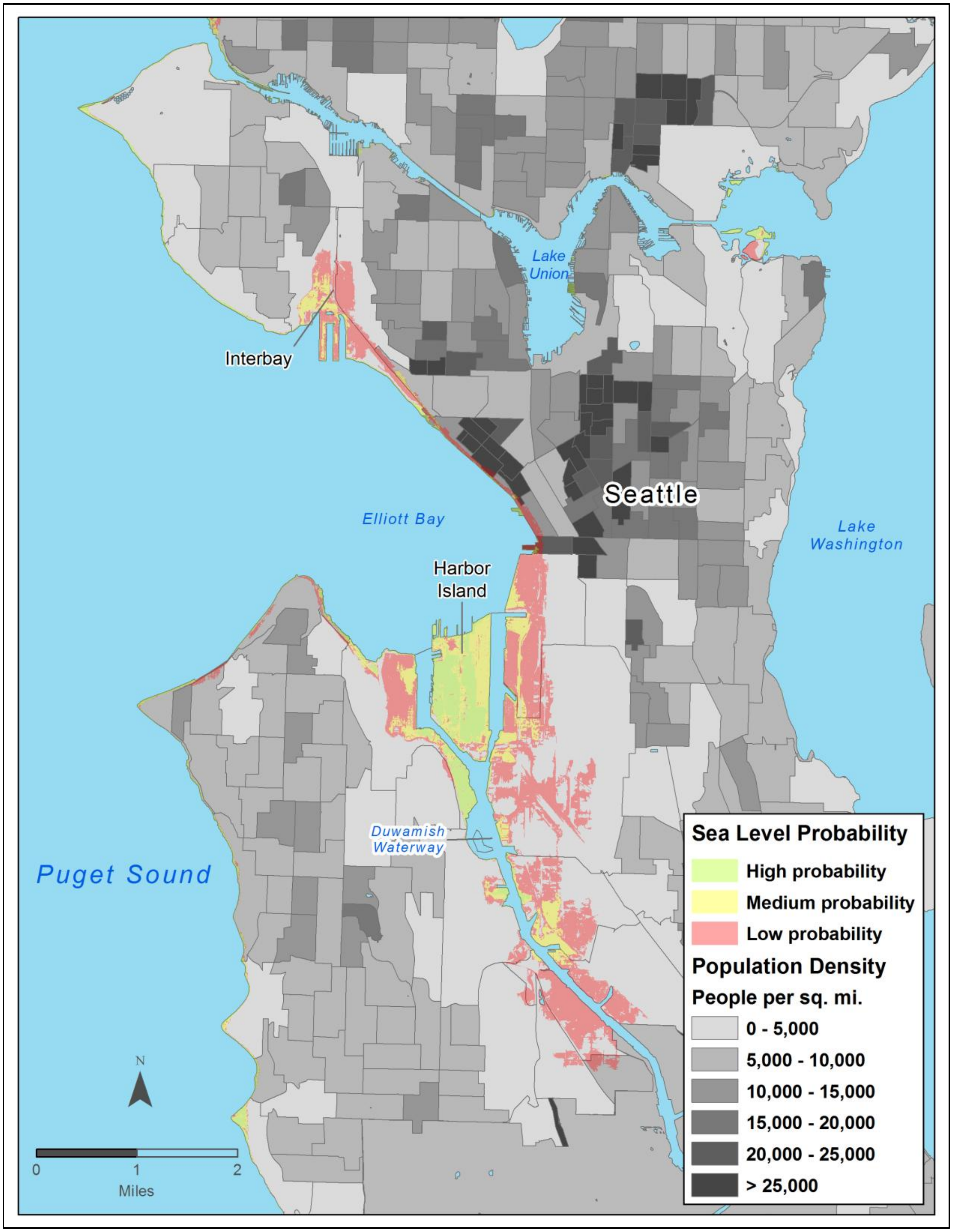
Critical Infrastructure and Key Resources Sector	High Probability	Medium Probability	Low Probability
Transportation			
Roads	9.30 km	27.46 km	102.58 km
Rail Lines	4.96 km	11.96 km	35.44 km
Shipping			
Piers or Terminals	11 structures	16 structures	38 structures
Dams			
Dams/Locks	1 structure	1 structure	1 structure
Water			
Sewer Lines	7.56 km	13.20 km	34.34 km
Chemical			
Hazardous Materials Sites	0 facilities	3 facilities	10 facilities
Energy			
Oil Pipeline	1.17 km	1.59 km	2.67 km
Oil Facilities	1 structure	1 structure	1 structure
Communications			
FCC Licensed Stations	38 stations	60 stations	114 stations
Defense			
Military Installations	0 facilities	0 facilities	2 facilities
Emergency Services			
Police Stations	1 facility	1 facility	1 facility
Fire Stations	2 facilities	2 facilities	3 facilities
Schools	0 facilities	0 facilities	1 facility
Uncategorized CIKR			
Common Interest Points	82 locations	97 locations	201 locations

Figure 12 Visualization of inundated transportation, shipping, and dams/locks sectors for each SLR scenario



Although residential land was the second largest area inundated in the models, the percentage of Seattle's residential population that was affected was relatively low. The analysis, based on 2010 Census Bureau data, showed residential population affected at the HP scenario was 2,072 people, or 0.34 percent of Seattle's inhabitants. The MP scenario led to 3,470 people, or 0.57 percent affected. Lastly, the LP scenario revealed that 8,704 people, or 1.43 percent of Seattle's inhabitants were affected. The majority of the inundated residential areas were located along the Puget Sound rather than the Elliott Bay area. Furthermore, the populations of the census blocks groups along the Puget Sound are less dense than other areas of inland Seattle. A map in Figure 13 shows the population density of Seattle using data from 2010 Census block groups. The reader should note that inundation extent colors (green, yellow, and red) are highly transparent, and therefore somewhat faded in appearance, in order to show the underlying block group density.

Figure 13 Population density of Seattle and projected inundation



Note. Population density is shown by 2010 Census block group.

6 Discussion and Conclusions

According to Collier and Lakoff (2008), there are three historic conceptions of security: (a) sovereign state (territory) security, (b) population security, and (c) vital systems (i.e., critical infrastructure) security. Any climate change phenomenon that directly impacts any or all of these security frameworks should be viewed as a threat (Gilman, Randall, & Schwartz, 2011). In each of the three scenarios modeled in my GIS analysis, the combined effects of SLR and storm surge resulted in damage and disruption to several aspects of CIKR, a loss of land, and displacement of population. Simply put, the models indicate impacts to the sovereign state, the population, and vital systems. Therefore, based on the assumption that SLR is a proxy for climate change (Parker, 1992), my analysis has shown that future climate change poses a potential threat to the homeland security of the United States.

6.1 Loss of Land and Sovereign Territory

According to Barnett (2003), the loss of sovereign territory caused by SLR is a direct threat to security. The loss of land resources may challenge state capacity and the welfare of the population at a scale large enough to reduce national stability (Dabelko, 2009). Although the worst case scenario for Seattle revealed an inundation extent of 11.14 km^2, equal to 5.12 percent of Seattle's land, similar results to coastal cities across the United States would lead to a substantial loss of land. For example, a recent study using a LiDAR DEM for Kahului, Maui in Hawaii estimated that a 1.9 m SLR plus MHHW would yield a loss of 2.98 km^2 and over $369 million in land value (Cooper et al., 2013). Because of local variation in SLR, other regions in the United States may experience even greater loss of land. For instance, Zhang (2011) used high resolution LiDAR DEM to model high, medium, and low probability SLR in southeast Florida and found that in three counties alone, a 1.5 m SLR would inundate 3,205 km^2 affecting over 500,000 people.

Local SLR variation has also made it difficult to determine an estimate of land loss for the entire United States. Currently, there is no coordinated interagency effort within the United States to determine agreed upon estimates of SLR projections for coastal planning, policy, and management (Parris, et al., 2012). This lacuna has led to numerous SLR studies at the regional (Yin, Schlesinger, & Stouffer, 2009), state (Heberger, Cooley, Herrera, Gleick, & Moore, 2009), and local (Cooper et al., 2013) levels by various stakeholders including governments, academic institutions, and non-governmental organizations such as environmental advocacy groups.

Therefore, no estimate of land loss exists for purposes of quantifying a reduction in sovereign territory for the entire U.S. by the end of the 21st century.

6.2 Loss of Industrial Land

Like many other large, port cities, much of Seattle's industrial land is located on the coast and along waterways with access to the coast. As a result, the industrial land in Seattle sustained the largest extent of inundation in all three models. According to the Seattle Planning Commission (2007), Seattle's industrial land is a key economic component to the city. Industrial businesses in Seattle constitute about 25 percent of the city's total employment, provide high paying wages, and foster an agglomeration economy which draws in businesses from all over the world (Seattle Planning Commission, 2007). The Seattle Planning Commission (p. 12) also made three critical observations for the future of industrial lands in the city:

- There appears to be no excess capacity in the region to accommodate future land use demand for industrial businesses.
- Industrial land that is converted to other uses is rarely returned to industrial use.
- Seattle is at the center of a land-constrained region in which industrial land is in short supply as compared to other uses.

The Seattle Planning Commission report did not take into consideration the potential land loss from SLR. Thus a reduction in land, primarily industrial land, as a result of SLR could have catastrophic consequences for the industrial economy of Seattle. The encroachment of sea levels could force businesses to relocate or shut down. Moreover, the loss of industrial land would likely deter new industrial businesses from locating in Seattle. As a result, many residents could lose employment due to a reduction in industrial land.

6.3 Population Impacts

Although the results of the GIS analysis indicate a relatively low percentage of the population would be impacted, it is still a consideration for security. The population impacts in Seattle are twofold. First, the displacement of population by encroaching SLR could potentially lead to a shortage of labor for local industries. It is well known that labor is required for all forms of economic production and is considered a fundamental determinant for business location (Stutz & Warf, 2012). Therefore, a shortage in labor caused by displaced persons could lead to business shutdowns and discourage other businesses from relocating to Seattle.

The second population impact is a byproduct of the loss of industrial and commercial land. As previously mentioned, the loss of industrial land in Seattle could lead to business relocation or shutdown. As a result, many jobs could potentially be lost and the rate of unemployment could rise. Gilman et al. (2011) noted that reduced economic productivity as a result of impacts on individual economic wellbeing can diminish overall national security.

The estimates in this study were calculated using 2010 population figures, however by the end of the 21st century it is likely that Seattle's population will increase (City of Seattle, 2013). A team of researchers attempted to account for future population projections in four sample areas in the U.S. and found that by using 2000 population data, SLR could impact 12.5 million people as compared to 2030 estimates of 19.3 million people (Curtis & Schneider, 2011). However, Curtis and Schneider did not account for local variation in SLR. Thus, unlike estimating land area, population estimation for SLR is a much more difficult, and often contentious, variable to model and predict – and there is no standard methodology (Gemenne, 2011).

At the national level, land loss resulting in tens of millions of internally displaced persons, as Curtis and Schneider (2011) estimate, can lead to conflict through competition of resources such as land, housing, water, employment, and basic social services (Scheffran & Battaglinin, 2011). Internationally, environmental migrants and climate refugees relocating to the United States could create ethnic tension and social fault lines (Raleigh, Jordan, & Salehyan, 2008).

6.4 Impact on Critical Infrastructure and Key Resources

Because much of the built environment, including CIKR, is located on land, it is reasonable to assume that a loss of land will often lead to a disruption of CIKR. As previously stated, much of the nation's critical infrastructure is located in coastal areas and is therefore vulnerable to SLR. My analysis of Seattle's CIKR showed that even low SLR projections would lead to disruptions and incapacitation of infrastructure, especially transportation. The analysis further revealed that thirteen of the eighteen CIKR sectors were affected to some extent (when including common interest points). It should be noted that this analysis was accomplished using free, publicly available data, and it is plausible that more CIKR sectors may have been impacted if additional government and private sector data were made available.

Quantifying the direct impacts to CIKR – that is to say, the structures and resources that are directly damaged or incapacitated – is easier to calculate than indirect impacts. Indirect costs are difficult to calculate (Hallegatte, et al., 2011). The proximity of infrastructure in a dense urban environment can have numerous cascading effects (Zimmerman & Restrepo, 2009). For example, damage to one infrastructural element such as a water main can lead to damage in surrounding components such as electric, telecommunications, and gas mains (O'Rourke, 2007). System interdependencies can have effects that extend past the local area and are unpredictable. In the aftermath of Hurricane Katrina, the supply of crude oil and refined petroleum was disrupted because of lost electrical power, which in turn led to a reduced gasoline and diesel supply to Southern, Eastern, and Midwestern states (O'Rourke, 2007). In Seattle, the seaport is a critical shipping hub for the country and the world in both volume of goods and dollars of goods shipped (Port of Seattle, 2011) and, similar to Katrina's effects, a disruption to the Seattle seaport could have far reaching regional and national impacts.

Leavitt and Kiefer (2006) classified infrastructure interdependencies as tight coupling or loose coupling. Tight coupling systems are largely dependent on one another and often there is no buffer between them. Loose coupling systems may not necessarily affect one another depending on the type of connection or proximity. Interdependencies increase the magnitude of negative impacts that natural hazards have on infrastructure (Zimmerman & Restrepo, 2009). An example of tight coupling in Seattle is the aging, combined stormwater and sewage systems. Heavy rains and storm surges, coupled with higher sea levels, can lead to overflows causing the release of toxins and pathogens into local waters (Kessler, 2011). According to the U.S. EPA (2013) between 2007 and 2010 approximately 200 million gallons of raw sewage was dumped into Seattle waters annually, including the Duwamish Waterway and the Puget Sound. Rising sea levels could cause greater backflows of sewage into the water systems, which in turn could lead to public health issues. Public health is, indeed, a concern for homeland security and is included in the designated CIKR sectors in Table 2.

6.5 Local Implications for Homeland Security

Although there has been much agreement in the scientific community on the seriousness of climate change, two decades of international governmental negotiations have yet to deliver a substantial global initiative (Bulkeley, 2013). Terms such as "global climate change" and "global warming" often dominate the scientific, political, and social discourse. However, Bulkeley

(2013) argued that cities are fundamental to our understanding of vulnerabilities and risks as well as management and responses to climate change. Similarly, Agrawal (2010, p.173) posited that climate change adaptation is "highly local, and its effectiveness depends on local and extralocal institutions." Likewise, state and local institutions are paramount in securing the homeland from disasters (Chertoff as cited in Kaplan, 2007).

Though few in number, most studies of SLR and CIKR have been done at the state and local level. For example, Heberger et al. (2009) quantified several elements of CIKR, including schools, police and fire stations, EPA regulated hazardous material sites, transportation networks, and many others that may be inundated by SLR on the California coast. Similarly, researchers at the University of Florida used GIS to quantify the impacts of 2 ft of SLR on critical infrastructure in the Tampa Bay area (Adaptive Tampa, n.d.). These studies were conducted to provide information for a wide range of stakeholders, including public officials, the private sector, and the general public. Until my GIS analysis of Seattle, there has not been a comprehensive SLR study of this city providing a quantifiable impact to CIKR, land resources, or population (City of Seattle, 2013). Although this study does not put forth policy recommendations, it does offer semi-empirical information and insights to support stakeholders' decisions.

The City of Seattle (2011) currently has a draft document titled *City of Seattle Sea Level Rise Planning Guidance for Capital Projects* calling for the incorporation of SLR projections into city planning. However, the SLR projections are based on outdated projections and the document contains no locational information for potential inundation areas. Therefore it is the implied responsibility of the stakeholder to know whether or not a given project lies within a potential inundation zone. In January 2013, the City of Seattle published a draft *Sea Level Rise* map for the year 2050 which was based on SLR projection estimates from 2008. The primary shortcoming in each of these city draft publications is the underestimated contribution of melting ice in the cryosphere from Alaska, Antarctica, and Greenland, which more recent research has highlighted (NAS, 2012). Consequently, the City of Seattle may be underestimating the potential impacts of SLR.

Although Seattle has policy and guidance relating to climate change, research has shown there is often a gap between local government commitments toward climate change and the actions taken (Bulkeley, 2011) Furthermore, the current Seattle climate change strategies do not anticipate potential long term direct and indirect impacts to the security of the city. Modern society is dependent on CIKR to provide public services, improve quality of life, and bolster economic growth (Boin & McConnell, 2007). Therefore, protecting critical infrastructure will ensure the "functioning, continuity, and survival" of societies (Aradau, 2010, p. 500). For this reason, the DHS NIPP (2008, p. 21) assigned responsibility to state and local government for "implementing the homeland security mission, protecting public safety and welfare, and ensuring the provision of essential services to communities and industries within their jurisdictions." This notion led Gilman et al. (2011, p. 251) to remark "the question is no longer whether or not to securitize the climate change debate, but how to do so properly." This present study has shown that SLR does indeed have the potential to threaten the security of Seattle residents and therefore has made a case for the "securitization" of climate change at the local level. Therefore Seattle is faced with the question of how it will properly securitize the threat of climate change to protect its citizens.

6.6 Limitations of the Study

There were three primary limitations of this study design. First, the SLR models represent potential inundation areas by the end of the 21st century, yet the data available reflects current conditions (i.e., CIKR, land use, and population). Although this type of modeling may be useful as a communication tool for public officials, coastal communities, and conservationists, it is not fitting for national government policy development (Mcleod, Poulter, Hinkel, Reyes, & Salm, 2010). Primarily, this study's modeling does not account for the impacts of future population shifts, adjusted land use strategies, and local adaptation strategies. However, what it does do is project the effects of SLR if no adaptive actions are taken. In the case of SLR, the impact is likely to develop at a slow pace, allowing time for adaptation. However, the presence of storm surges, and even tsunamis, which are often experienced in rapid, intense bouts, could necessitate quicker adaptation and mitigation strategies.

A second limitation was the use of hydrographic modeling with LiDAR data. The ArcGIS functions used to model sea level rise and storm surge did not account for flow pathways. For instance, the presence of a culvert under a road could potentially alter the inundation results. When the initial models were created, the inundation area included the King County Regional Airport located along the Duwamish Waterway. However, a close visual inspection of the hillshade image revealed a narrow, protruding ridge between the Duwamish

Waterway and the airport. To account for these sinks in disconnected areas, the Fill tool was used. As a result of the fill, the airport was no longer inundated in the corrected models. Yet, in reality it is difficult to conclude with a high level of confidence whether or not the airport would be inundated. Similar sinks were identified near Safeco Field and CenturyLink Field downtown. Additional hydrodynamic and geomorphic factors such as groundwater levels, presence of precipitation, and soil erosion could lead to drastically different results.

The DEM, with vertical accuracy of 1 ft and horizontal accuracy of 6 ft, creates a smoothed (or average) surface from the raw elevation data. For this reason, digital elevation models are approximations of reality and are subject to errors such as misplaced elevation values, data gaps, or missing values (Gonga-Saholiariliva, Gunnell, Petit, & Mering, 2011). Consequently, it is unlikely that the DEM depicts small breaks in terrain, such as a curb for example, within the six foot horizontal grid. These small breaks in reality, could also yield altered hydrodynamic flows.

The third limitation was the availability of data. Because this research was unfunded, the analysis relied on the availability of free data. Care was taken to ensure credible sources were used, and when possible data was obtained from local institutions. Using local sources such as the King County and Seattle GIS departments ensured the data was trustworthy. In essence, the county and city planners rely on this data to conduct projects throughout the area; therefore it is regularly updated for accuracy. Nevertheless, certain data, particularly for CIKR were not available. For example, GIS data for the electrical grid, a significant infrastructural component, was not publicly available.

6.7 Future Research

This study offers considerable potential for further investigations into the effects of climate change on homeland security. Future research could be conducted at both the local and national scales. For example, understanding the direct economic impacts of SLR on CIKR and land resources would benefit local and national stakeholders vastly. There are software packages available, such as FEMA's Hazus (hazard mapping software), that use national databases to estimate damage costs. However, there are limitations to these types of software, including the use of national data on replacement costs which often do not reflect local conditions.

Additionally, future studies could attempt to propose and explore local mitigation strategies based on the extent of SLR and storm surge inundation presented in my analysis. For instance, researchers may consider possible land use strategies for dealing with the loss of highly productive industrial zoned land, or population relocation plans.

Lastly, because this study is perhaps the first of its kind to securitize the local impacts of climate change, it has created opportunities for others to investigate additional climate change phenomena at the local security level. The prospect of SLR is just one of many potential climate change scenarios that may have devastating large scale impacts. The increase in both frequency and intensity of wildfires, drought, and flooding are just a few examples of climate change scenarios that possess enough destructive potential to disrupt the security environment from the local to the national scale. If local institutions begin to explore the security implications of climate change in order to bolster resiliency, the results are likely to lead to a more secure homeland.

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