A Novel Transportation Modeling Framework for Use in a Post-Disaster Landscape:

Incorporating Whole-Landscape Features

by

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ABSTRACT

Many coastal cities around the world are becoming increasingly vulnerable to natural disasters, particularly flooding driven by tropical storm and hurricane storm surge – typically the most destructive feature of these storms, generating significant economic damage and loss of life. This increase in vulnerability is driven by the interactions between a wide number of complex social and climatic factors, including population growth, irresponsible urban development, a decrease in essential service provision, sea level rise, and changing storm regimes. These issues are exacerbated by the short-term strategic planning that dominates political action and economic decision-making, resulting in many vulnerable coastal communities being particularly unprepared for large, infrequent storm surge events. This lack of preparedness manifests in several ways, but one of the most visible is the lack of comprehensive evacuation and rescue operation plans for use after major storm surge flooding occurs. Typical evacuation or rescue plans are built using a model of a region's intact road network. While useful for pre-disaster purposes, the immediate aftermath of large floods sees enormous swaths of a given region's road system flooded, rendering most of these plans largely useless. Post-storm evacuation and rescue requires large amounts of atypical travel through a region (i.e., across non-road surfaces). Traditional road network models (such as those that are used to generate evacuation routes) are unable to conceptualize this type of transportation, and so are of limited utility during post-disaster scenarios. To solve these problems, this dissertation introduces an alternative network conceptualization that preserves important on-network information but also accounts for the possibility of off-network travel during a disaster. Providing this *in situ* context is necessary to adequately model transportation through a post-storm landscape, one in which evacuees and rescuers are regularly departing from roads and one in which many roads are completely interdicted by flooding. This modeling approach is used to automatically generate routes through a flooded coastal urban area, as well as to identify potentially critical road segments in advance of an actual storm. These tools may help both emergency managers better prepare for large storms, and urban planners in their efforts to mitigate flood damage.

TABLE OF CONTENTS

Page

LIST OF TABLES vi

LIST OF FIGURES vii

CHAPTER

1 INTRODUCTION 1

1.1 Problem Statement 1

1.2 Aim and Justification 3

1.3 Dissertation Overview 5

2 STORM SURGE FLOODING AND COASTAL CITY VULNERABIILTY 7

2.1 Introduction 7

2.2 Vulnerability, Resilience, Reliability, and Continuity 10

2.3 Increasing Vulnerability: Social, Climatic, and Emergent Factors 12

2.3.1 Social Factors 15

2.3.2 Climatic Factors 18

2.3.3 Emergent Factors 20

2.4 Political and Economic Malfeasance 22

2.5 A Case Study in Miami, Florida 24

2.6 Conclusion 30

3 STORM SURGE, INFRASTRUCTURE DAMAGE, AND THE INADEQUACY OF TRADITIONAL ROAD NETWORK MODELS 32

3.1 Introduction 32

3.2 Background 35

3.2.1 Economic Vulnerability 36

3.2.2 Ecological Vulnerability 36

3.2.3 Social Vulnerability 37

3.2.4 Scale and Community Preparedness 38

3.3 Methods 40

3.3.1 Study Area and Data 40

3.3.2 Storm Surge Damage Metrics and Contingency Analysis 45

3.4 Results 52

3.5 Discussion 62

3.5.1 Limitations 65

3.6 Conclusion 65

4 USING VECTOR GRIDS TO IDENTIFY INFORMAL STREET NETWORK CONNECTIVITY 67

4.1 Introduction 67

4.2 Background 72

4.2.1 Real-world Systems as Networks 72

4.2.2 Road Systems and the Limits of Traditional Network Models 73

4.2.3 Road Networks during Storm Surges 77

4.3 Methods 79

4.3.1 Study Area and Data 79

4.3.2 Grid Generation 80

4.4 Results 85

4.5 Discussion 93

4.5.1 Limitations 96

4.6 Conclusion 97

CHAPTER Page

5 IDENTIFYING CRITICAL ROAD SEGMENTS USING OFF-NETWORK FEATURES 98

5.1 Introduction 98

5.2 Background 101

5.2.1 Roads as Networks 101

5.2.2 Critical Feature Identification 102

5.3 Methods 105

5.3.1 Vector Grid Generation 105

5.3.2 Road Criticality Measurements 107

5.4 Results 111

5.5 Discussion 120

5.5.1 Limitations 122

5.6 Conclusion 123

6 CONCLUSION 124

6.1 Dissertation Review 124

6.2 Urban Planning and Emergency Management 127

6.3 Future Work 130

REFERENCES 133

APPENDIX

A CO-AUTHOR PERMISSION FOR SUBMITTED AND PUBLISHED MANUSCRIPTS USED IN THIS DISSERTATION 157

LIST OF TABLES

Table Page

3.1 Storm Surge Damage to Volusia County by Hurricane Strength 51

3.2 Differences in Flood Damage Between Storm Surges of Different Strength 58

4.1 Land Cover Types and their Impedance Scores in a Flooded Area 83

5.1 Land Cover Types and their Impedance Scores in an Unflooded Area 106

LIST OF FIGURES

Figure Page

2.1 Conceptual Diagram Highlighting Drivers of Coastal Vulnerability 14

2.2 Map of Miami Metropolitan Area 26

2.3 Projected Sea Level Rise in Miami, Florida 29

3.1 Map of Volusia County, Florida with Hurricane Track 43

3.2 Map of Simulated Storm Surges in Volusia County 53

3.3 Road Degradation from Storm Surge Flooding in Volusia County 55

3.4 House and Business Inundation by Hurricane Strength 57

3.5 Number of Disconnected Blocks by Hurricane Strength 60

3.6 Flooded Evacuation Routes by Hurricane Strength 61

4.1 Example of Off-network Features Adding Street Network Connectivity 76

4.2 Example of Grid Impedances in Volusia County 84

4.3 Demonstration of Higher Connectivity than Reported by Traditional Models 86

4.4 Comparison of Grid-based and Traditional Routing in an Unflooded Area 90

4.5 Comparison of Grid-based and Traditional Routing near a Flooded Area 91

4.6 Comparison of Grid-based and Traditional Routing through a Flooded Area 92

5.1 Example of Edge Betweenness Centrality Calculation 108

5.2 Example of Grid-based Criticality Calculation 111

5.3 Comparison of Grid-based and Traditional Criticality Metrics along Clyde Morris Boulevard 114

5.4 Comparison of Grid-based and Traditional Criticality Metrics along Hernandez Avenue 117

5.5 Comparison of Grid-based and Traditional Criticality Metrics to the west of Tymber Creek Road 119

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

During the week of August 22, 2005, thousands of people began evacuating New Orleans, Louisiana ahead of Hurricane Katrina, which would make landfall on August 29, one week later (although a mandatory evacuation order was not issued until August 28). The majority of these people drove north, inland and away from the coast. The Office of Emergency Preparedness of the city of New Orleans made plans to bus the hundreds of thousands of residents that lacked the means or wherewithal to depart on their own approximately 80 miles north, just beyond I-12, to shelters the city had belatedly begun preparing. That plan began to fall apart the day before the storm hit. The roads heading north were so clogged with evacuee traffic that the city decided to instead bring residents to the Superdome to wait out the storm, intending to bring them north to the shelters as soon as the storm itself had passed.

Unfortunately, after the storm hit, not only were many of the planned evacuation routes flooded (particularly after the levees broke), but hundreds of city buses were also underwater, having been stored on roads that ended up being vulnerable to the storm surge. Thousands more refugees ended up at the Superdome, for days longer than anticipated, leading to at least six deaths. Post-storm rescue efforts were further hampered by the spread of lawlessness in the city (the entire New Orleans's police force was ordered to stop search-and-rescue missions and instead focus on controlling the looting within the city). The city of New Orleans was woefully unprepared for a storm of Katrina's magnitude, and the reasons for that are manifold. These reasons are explored in great detail in many post-mortems of the entire incident, and an enormous amount of work has gone into preparing for future storms so that their impacts are not as severe.

However, one consistent gap in this work is in the identification of evacuation routes and rescue paths during and immediately following a storm. In the immediate aftermath of Katrina, rescue efforts were poorly organized and poorly managed, in addition to being hampered by the lawlessness on the ground that was occupying some emergency personnel. New Orleans police reported being sent to the wrong districts of the city, being told to wait for orders that never came, or having the necessary rescue equipment but insufficient operating personnel. In part, these issues arose from the application of pre-storm evacuation plans to a post-storm landscape. Over the years, pre-storm evacuation plans have grown more useful, but they tend to be ineffective once a storm strikes a region – the storm's impacts themselves often change a landscape sufficiently to render the existing plans largely useless. In the case of Hurricane Katrina, this was evident when official evacuation routes and evacuation vehicles ended up underwater.

This was not an isolated incident. In just the last several years, Hurricane Harvey (Houston, 2017), Hurricane Florence (coastal North and South Carolina, 2018), and Hurricane Irma (southern Florida, 2018) all required extensive and complicated evacuation and rescue during and immediately after each storm. Preparation for these storms differed, but rescue efforts in the post-disaster landscape were consistently unorganized and presented enormous difficulties to emergency personnel. These difficulties arise for several reasons: 1) lack of an adequate command structure, 2) temporary lawlessness in the region, and 3) damaged infrastructure, particularly roads. As a region's road system is disrupted by a hurricane, response to and recovery from that disaster becomes more difficult. Large numbers of roads become flooded, potentially rendering some sub-regions isolated and cut off from inland areas. Entire swaths of a landscape may be flooded, meaning many households and businesses may be inaccessible via existing roads.

As a region's roads become flooded, traditional transportation models (that are often used to produce evacuation routes) become less and less useful. These models rely on intact road networks in order to automatically identify evacuation and rescue routes, and are typically unable to route through a flooded landscape. Combined with the difficulty inherent in producing accurate storm surge predictions, many emergency management officers serving urbanized coastal regions do not have comprehensive and detailed post-disaster evacuation and rescue plans. Instead, these agencies rely on *ad hoc* rescue efforts that are planned and executed in real time, often without the aid of useful transportation modeling tools. Thus, it is not surprising that this results in disorganization and at least some waste of rescue resources.

1.2 Aim and Justification

The primary goals of this dissertation are three-fold. First, the main methodological contribution of this work is to develop and introduce a novel transportation analysis technique that can be used to model travel through a post-disaster landscape. Second, this dissertation also aims to synthesize a wide variety of literature from the fields of urban planning, climate change, network geography, transportation geography, and natural hazards research to build an updated conceptual understanding of urban coastal vulnerability, reflecting the rapid changes that these areas are experiencing. And third, this dissertation uses its methodological and conceptual contributions to craft policy suggestions, modifications to emergency management operations, and additional tools for urban planners.

The novel transportation modeling technique introduced here produces higher-fidelity models that better reflect how evacuees and rescue personnel operate in and travel through these flooded landscapes. Specifically, during historical storms, both evacuees and rescue personnel were found to have traveled off-road as needed (when roads were flooded). However, traditional transportation models are typically limited to on-road travel only, limiting their utility in scenarios in which large numbers of roads are interdicted and thus impassable. This modeling framework uses urban development data, land cover data, and disaster-specific data to automatically generate an overall traversability measure for a landscape – including along non-road areas. In turn, this allows for the automatic generation of routes that could be used for evacuation and rescue in a post-disaster landscape, in which travel through these non-road features is required. Additionally, this model is then adapted to better identify a region's road segments that are particularly critical to the overall traversability of a landscape in a post-disaster scenario. Similar to the routing efforts, this work builds on traditional critical feature identification, but utilizes the existence and characteristics of non-road landscape features to better determine which sections of road may be especially vulnerable to storm surge flooding, with respect to evacuation and rescue.

These efforts build on a variety of existing literature. Previous studies have identified some of the limitations of applying traditional network analysis to urban road networks, but no suitable alternative has been developed or widely adopted. In most cases, these limitations do not hinder road network studies – but in certain scenarios, specifically those in which the road network is not operating as usual (for example, after storm surge flooding has knocked out large numbers of roads in a region), the limitations render traditional network modeling tools largely useless. In addition, the conceptual and technical framework introduced in this dissertation are timely. Coastal urban areas' vulnerability to large disasters is increasing. Urbanized coasts are growing in population while climate change drives sea level rise and increased storm intensity. Large, highly damaging storms are likely to continue striking coasts in the United States and elsewhere throughout the foreseeable future, highlighting the importance of effective, fast, and automated post-disaster routing.

Beyond aiding real-time evacuation and routing efforts, this work contributes to urban planning efforts designed to limit a city's exposure to flooding. Flood preparation is increasingly becoming a major concern for urban planners, even in non-coastal regions. Building tools that incorporate non-road feature characteristics into the identification of critical road segments gives urban planners additional tools to minimize potential flood damage. While drainage ditches, retention ponds, and raised roads all help mitigate flood damage, it turns out that the location and characteristics of a variety of other features not traditionally used for flood control also contribute to a region's vulnerability.

1.3 Dissertation Overview

The remainder of this dissertation is organized as follows. Chapter 2 consists of a comprehensive literature review that discusses the increasing vulnerability of the world's urbanized coasts to natural disasters, particularly storm surge flooding. This increase in vulnerability is driven by a host of complex factors, the most important of which are covered here. Chapter 3 introduces the suite of tools and associated methodologies that are used to generate storm surge predictions and explores how storm surges produced by hurricanes and tropical storms of a variety of strengths impacts a community's access to resources via their road infrastructure. The limitations of traditional road network analysis are introduced here, providing the justification and conceptual impetus for the methods developed in later chapters. These methods are demonstrated on Volusia County, Florida, the same study area used for the work in Chapters 4 and 5.

Chapter 4 serves as a direct response to many of the limitations identified in the previous chapter – specifically, this chapter introduces a novel network analysis method that produces higher-fidelity models of road systems under certain circumstances (such as when a large-scale disaster has impacted a large portion of a region's roads). Several applications of the new method are explored, including the automatic generation of evacuation routes. Chapter 5 identifies many of the limitations of traditional critical feature identification when applied to road systems. As an alternative, a novel critical feature method is introduced here, using the region-level traversability metric from the previous chapter. applies this new method to better identify critical segments of road in a potentially disaster-prone developed landscape. Finally, Chapter 6 summarizes the contributions of this research and discusses ongoing and future avenues of related research.

CHAPTER 2

STORM SURGE FLOODING AND COASTAL CITY VULNERABILITY

2.1 Introduction

There is a vulnerability crisis brewing along the world's urbanized coasts. Natural hazards are causing more damage than ever before, while exposure and associated impacts to these hazards are projected to increase. This crisis is fueled by a complex combination of political, economic, and climatic factors, with many local, state and federal responses typified by a combination of neglect and/or inertia for urban planning and emergency management. North Carolina's coastal population, for example, has grown by almost 50% in the previous two decades, along with the usual urban/suburban development that arrives with such population growth (Jurjonas and Seekamp 2018). Meanwhile, North Carolina's response to increased coastal development occurring in at-risk areas was to pass a law that banned state agencies from using up-to-date climate projections (Harish 2012). Over the next several years, the state defunded coastal protection efforts and gutted emergency planning agencies, exacerbating the damage caused by Hurricane Florence in 2018 (Schwartz and Fausset 2018). North Carolina is not alone. A massive amount of urban development has taken place in at-risk areas (McGranahan et al. 2007). Simultaneously, there is a serious lack of political will to solve these burgeoning (often long-term) problems (Burby 2006). Recent research suggests that climate change is likely to make future hazards more frequent, more powerful, or both (Knutson et al. 2010; Mann and Emanuel 2011). Taken together, these factors have increased the vulnerability of thousands of coastal cities in the U.S. and elsewhere to a variety of coastal hazards. This is only expected to increase, moving forward.

The fact that urbanized coastal regions are exposed to a variety of coast-specific hazards is not new – but hazard type and severity is contingent on the geographic profile of an area. Hazards range from the frequent and mundane (e.g., erosion, algal blooms), to the infrequent and catastrophic (hurricanes, tsunamis). Even mundane hazards can cause large amounts of damage, economic and otherwise, and are similarly made worse by political malfeasance. For example, the ongoing problems with red tides in Florida and Texas can be extremely destructive to the environment, marine life, and human health (Fleming et al. 2005; Kirkpatrick et al. 2004). Indeed, coastal Florida experienced a large tidal bloom event in 2018 that caused significant economic and ecological damage to the state's coast (Resnick 2018). Lax government pollution regulations contributed to the size and duration of that tidal event (Staletovich 2018), despite warnings and predictions issued by the scientific community.

In many instances, cities are better equipped to handle low-impact hazards that occur more frequently, such as the relatively routine flooding associated with Category I and II tropical storms. These hazards are better understood by the public and it can be easier to summon the political will to enact measures that mitigate damage. However, for hazards that occur less frequently, such as catastrophic (Category III +) hurricanes, there is less political will and economic traction to take steps that ensure community resilience (Moser and Ekstrom 2010). As a result, coastal areas that are subject to frequent, low-impact hazards continue to be developed, with many buildings and public spaces engineered to withstand these modest events, but unable to withstand the more extreme but less frequent storms. Interestingly, there are many coastal regions in the United States with little historical experience with extreme events. For example, although more than 100 hurricanes have impacted coastal New Jersey over the past century, none of the affected communities were prepared for Hurricane Sandy, which damaged nearly

350,000 homes and caused $30 billion in economic losses (Kunz et al. 2013). In short, these regions are particularly underequipped to withstand extreme coastal hazard events under new climate regimes.

This lack of resilience is compounded by significant demographic shifts in the United States that have contributed to massive increases in coastal populations in hazard-prone areas. Not only does this put more families in harm's way, but that rapid urban development has stretched city services (especially during an emergency) to the breaking point (Bhatta 2010). For example, in 2015, ten years after Hurricane Katrina, experts estimate that if another storm of a similar size were to strike New Orleans today, the economic impact of the storm would be 20% to 40% higher than caused by Katrina in 2005 (Fischetti 2015). In essence, too little work has been done to prepare for the unique threats posed by this complex combination of climate change, geography, and coastal settlement patterns. Research is understandably slow, given the enormity of the problem and the complexities involved. However, urban development is driven by *short-term* political and economic incentives that make accounting for large, long-term problems almost impossible (Abel et al. 2011). Further, emergency planning tends to be under-resourced, outdated, and often ineffective (Godschalk 2003; Alexander 2005).

The purpose of this review is to highlight the unique confluence of demographic, political, economic, and climatic factors that are helping to fuel urban vulnerability in coastal areas. Each coastal settlement is unique, in both site and situation, and this influences the overall exposure of a community to different hazard regimes. To that end, while the principles detailed in this chapter (and in later ones) are generalizable to most (but not all) hazards, the majority of this dissertation will focus on storm surge flooding for coastal cities along the southern and eastern seaboards of the United States. These areas routinely experience tropical storms and hurricanes and are home to a host of analogous geographic factors that allow for a detailed exploration of the principles behind coastal vulnerability to storm surge flooding. That said, it is important to acknowledge that coastal areas experience a range of additional hazards (e.g., coastal erosion, rainfall-induced flooding, eutrophication, etc.). However, due to the overall scope and space limitations of this dissertation, these hazards will not be covered in detail, except where they augment or interact with storm surge flooding. In sum, by synthesizing climate change science, settlement geography, storm surge modeling, and urban hazard vulnerability research, this work is structured to connect the most recent thinking on these complex problems to the real world – providing researchers and policymakers with a range of future pathways for scientific inquiry, as well as a variety of policy development options that may improve coastal resilience in the long run.

2.2 Vulnerability, Resilience, Reliability, and Continuity

The concepts of network vulnerability, reliability, continuity, and resilience serve as important foundations for this research. All of these terms are used frequently in the literature, but it is essential to clearly define them for the purposes of this dissertation. Here, these concepts are related to the operational characteristics of an infrastructure system. Specifically, *reliability* refers to the ability of a system to maintain its function and structure over time across a wide range of operating conditions (Little 2003). *Continuity* refers to the ability of an infrastructure to maintain operation and provide critical goods and services before, during, and after a major disruptive event (Grubesic et al. 2007). *Resilience* refers to the ability of an infrastructure system to “anticipate, absorb, adapt to and/or rapidly recover from a disruptive event” (NIAC 2009, 8). In practice, continuity precedes resilience. Finally, *vulnerability* refers to a system’s exposure to damage or capacity for loss and the susceptibility to injury or damage (Cutter 1996; Grubesic and Matisziw 2013; Proag 2014).[1] Hazard vulnerability in an urban setting can refer to both individual and discrete systems (such as the likelihood and type of damage to a power grid during storm surge flooding) (Kwasinksi et al. 2009) and social vulnerability (such as the potential for mortality and economic damage for a given group of people during storm surge flooding) (Frazier et al. 2010). Different systems for an urban region, while often treated independently for the sake of simplicity, are typically interconnected. For example, perturbations to a city's power grid can affect local telecommunications networks, while damage to environmental resources may depress tourism, creating lingering economic ramifications (Grubesic and Murray 2006; Little 2010).

It is also important to note that vulnerability and resilience are not monoliths for a particular hazard in a particular place. Instead, they vary over both space and time. The concept of *place vulnerability* refers to variations over space and is usually defined as the intersection of biophysical and social vulnerability for a particular location (Cutter et al. 2012). Specifically, biophysical vulnerability consists of the vulnerability imparted by the physical and biological features of an area. For example, a neighborhood of homes with an intact wetland serving as a coastal buffer will likely experience reduced vulnerability to flooding. However, an elevation change of just several feet can determine whether areas are inundated or not. In contrast, social vulnerability refers to the notion that different groups of people are differentially vulnerable to a given hazard, based on a variety of demographic factors – for example, households with young children or elderly

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[1] There are multiple conceptualizations of vulnerability within the literature, including 1) physical, 2) social, and 3) spatial (Wu et al. 2002). Physical vulnerability is concerned with the potential exposure to a physical hazard (e.g., hurricanes). Social vulnerability assumes some type of exposure to a disruptive event, and then details how social groups are differentially impacted. Finally, spatial vulnerability is a mashup, where both physical risk and social response for a specific location are considered (Cutter and Finch 2008).

residents tend to experience higher hazard vulnerability (Cutter 1996). A location's biophysical and social vulnerability profiles combine to make up its overall place vulnerability.

Temporal variation in vulnerability occurs at multiple time scales (Cutter and Finch 2008; Camarasa Belmonte et al. 2011; Grubesic and Matisziw 2013). As a result, the timing of hazards can play a large role in how much damage they cause. For example, the storm surge generated by a tropical storm at high tide will cause significantly more flooding than one that lands at low tide. There are also longer scale concerns. For instance, in a region that is economically reliant upon tourism, a hazard that strikes during tourist season may cause far greater economic damage than one that strikes during the off season. In a similar vein, many low-lying coastal areas in the developing world are focused on agricultural production. Hazards striking during harvest season, or when crops are newly planted, may negatively impact agricultural production, increasing regional food insecurity.

2.3 Increasing Vulnerability: Social, Climatic, and Emergent Factors

An enormous number of individual factors can be identified that are contributing to an increase in coastal vulnerability. Many of the primary drivers of this increase are identified here, but this will not be an exhaustive list. It is also important to note that the factors fueling vulnerability are comingled. Changes to one factor may affect others, which may in turn generate feedback to the original factor or spawn downstream changes to other systems. Due to the scale and scope of this problem, most of the existing literature on vulnerability isolates one or two factors for exploration, not unlike this dissertation (i.e., storm surge flooding). Many of these factors can be categorized as primarily social or climatic, with others that span both categories. In this instance, the category spanners, which represent elements of both social and climatic factors, are labeled as *emergent* (Figure 2.1).

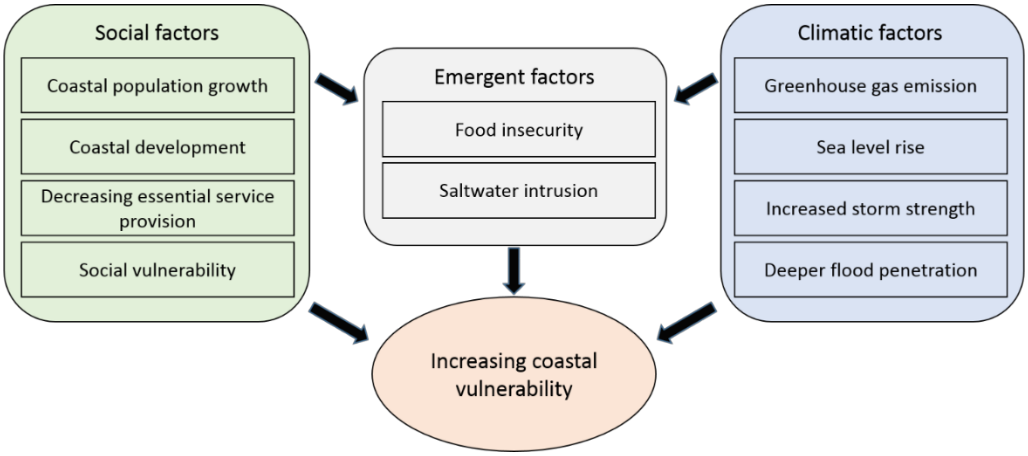

Figure 2.1. A conceptual diagram highlighting the primary drivers of increasing coastal vulnerability with respect to storm surge flooding. The overall effect on coastal vulnerability tends to be more than the sum of its parts, due to interactions between these factors that exacerbate them.

2.3.1 Social Factors

Today, 40% of the world's population (nearly three billion people) live within 100 kilometers of a coastline (UN-ESA 2017). Furthermore, that percentage is growing – people who live in inland areas, particularly in developing countries, are moving to the coasts at unprecedented rates (Neumann et al. 2015; Nicholls and Small 2011). Despite the concurrent explosion of global coastal development, many of these regions are unable to cope with a sustained influx of people, leading to strains on infrastructure and essential services (McGranahan et al. 2007). Ultimately, this combination of population growth, development, and strained urban services has radically increased the vulnerability of these coastal regions to natural disasters. Simply put, more people are living in potential disaster zones than ever before.

From a geographic perspective, much of this coastal growth is occurring in low elevation coastal zones (LECZ). LECZs are defined as contiguous coastal bands that are located fewer than ten meters above sea level (McGranahan et al. 2007). As defined, LECZs compose less than 2% of the world's surface, but are home to more than 10% of the world's population. Increases in LECZ population density is occurring throughout much of the developing world, with most new arrivals coming from subsistence farming operations. In general, these individuals are more socially vulnerable to hazards, especially when compared to the established residents of the cities to which they move (Black et al. 2011). New arrivals often find housing in poorly constructed, high-density apartment buildings located in particularly vulnerable areas (Brueckner and Lall 2015).

While this pattern is less pronounced in the United States, many U.S. coastal cities are growing quickly. Houston, Texas, for example, was the second fastest growing city in the United States in 2017 (the year Hurricane Harvey devastated the area). In the U.S., a constellation of economic (e.g., human capital and business environment) (Chen and Rosenthal 2008), cultural, and social factors drive migration (Flippen and Kim 2015). Coastal migrants in the United States are also encouraged by the existence of flood insurance. The National Flood Insurance Program (NFIP) is a federal government-backed insurance program that insures both public and private structures located in flood-prone areas (Kriesel and Landry 2004). In 2017, the NFIP had over five million active policies, and paid out over ten billion dollars in claims while earning just over a third of that in premiums (FEMA 2018). There is no doubt that the existence of the NFIP has saved the livelihoods of countless people living in flood-prone regions and made it economically feasible to sustain these communities despite their vulnerability. However, its ability to consistently operate at a loss due to government backing creates a dangerous moral hazard (Michel-Kerjan 2010; Browne and Hoyt 2000). This moral hazard arises because the NFIP is *de facto* subsidizing development in areas that are at significant flooding risk (Cutter and Emrich 2006). Unlike a profit-driven insurance company, the NFIP is able to keep its premiums artificially low and operate at a loss, with government funds making up any shortfalls. In essence, U.S. taxpayers are cross-subsidizing this program and indirectly promoting irresponsible development in flood-prone areas (Botzen and van den Bergh 2012).

In addition, the sheer number of new arrivals to many coastal cities stretches government services thin and renders them likely to fail during a large-scale hazardous event (Adelekan 2010; Douglas et al. 2008). The dominant urban development paradigm over the past several decades has been to provide infrastructure and service improvements reactively – as population grows, the city will construct additional capacity (Mayaud et al. 2019). Rapid population growth threatens this approach as cities are often too cash-strapped or too slow to make the required adjustments. This can then compound damage from extreme events. For example, consider the effects of Hurricane Sandy in New York City. The aging and under-capacitated sewer system backed up and spilled over 11 billion gallons of sewage into sensitive waterways (Kenward et al. 2016). When essential services are limited, the first groups to feel the effects are often those already most vulnerable (Zakour and Harrell 2002). Specifically, poorer households and neighborhoods wracked by concentrated poverty routinely have less access to emergency services during a disaster (Litman 2006). When combined with the fact that these households and neighborhoods not only may experience more severe effects from the disaster but are also less resilient, unable to absorb and recover from that damage, the outcomes for the most vulnerable residents of a city during a disaster are particularly poor (Squires and Hartman 2013). During Hurricane Katrina, for example, much of the flooding damage was concentrated in poorer neighborhoods while those same neighborhoods also received limited emergency services during and immediately after the flooding (Eisenman 2007; Squires and Hartman 2013).

In addition to stretched government services, population growth is driving irresponsible development. Many cities are experiencing uncontrolled development and sprawl – much of it in isolated, at-risk areas that are less accessible for essential service provision. Again, consider the damage caused by Hurricane Katrina. Impacts were amplified by the vast number of poorly-constructed dwellings in the poorer neighborhoods on the outskirts of New Orleans (van den Lindt et al. 2007). Many of these buildings were illegally constructed and did not meet engineering standards designed to mitigate even routine flooding, let alone the flooding that accompanied Katrina. These substandard dwellings permeate the coastal regions throughout the United States and beyond, where the lack of urban development regulations (or their lack of enforcement) puts countless communities at risk (Mirza 2001; Alcantara-Ayala

2002). When combined with the demographic factors detailed above, it is clear that the impacts of future climate change on these communities will be especially dire.

2.3.2 Climatic Factors

The emission of greenhouse gases (GHG) and attendant climate change is already having significant effects on global environmental systems. In addition to general warming, changing precipitation patterns, more frequent and severe drought, sea level rise, and new natural disaster regimes are emerging (IPCC 2014). These changes can directly or indirectly drive increases in vulnerability with respect to storm surge flooding and a host of other natural disasters. Again, a full accounting of these climatic effects is outside the scope of this dissertation, but the major factors of shifting tropical storm regimes and sea level rise (and the related flood penetration) are covered here.

Two mechanisms are responsible for sea level rise under climate change. The first is melting ice sheets and glaciers, most of which are found in Greenland and Antarctica (Overpeck et al. 2006). The second is due to ocean water expanding as it warms (thermal expansion) (Rahmstorf 2007). There is strong evidence that sea level rise is occurring at a rate of around nine millimeters per year, and that by 2100 the average global sea level will be several meters higher than it is today (IPCC 2014). As sea levels rise, more coastline is exposed to flooding caused by hurricanes and tropical storms. This includes many areas that have relatively limited experience with storm surge flooding in the past – rendering them particularly vulnerable (Hallegatte et al. 2010). For example, although Hurricane Sandy caused $12 billion in damage when it flooded New York City, approximately $2 billion of that was attributable to human-induced sea level rise (i.e., Sandy flooding areas that it otherwise would not have affected, had the sea level been lower) (Kulp et al. 2014). Moving forward, few (if any) coastal settlements will be immune to sea level rise, but low-lying countries (such as Bangladesh) will become especially vulnerable (Ali 1996).

Until recently, there was considerable uncertainty surrounding the likely effects of future global warming on hurricane and tropical storm intensity and frequency. Even now, due to the long timeframes and complexity of the systems involved, there is debate around the likelihood of future storm regime changes with respect to past patterns. However, as projection models have matured and atmospheric scientists have developed a better understanding of the circumstances surrounding tropical storm formation, a broad consensus is beginning to emerge – future tropical storms and cyclones in both the Atlantic and Pacific oceans are likely to increase in intensity (Knutson et al. 2010) while simultaneously decreasing in frequency (Knutson et al. 2008; Mann and Emanuel 2011). The likelihood of their making landfall is also projected to increase, due to the increased intensity and associated duration of the storms. Finally, the changing climatic conditions may also drive storms to make landfall on new areas of coastline, potentially impacting areas that rarely or never experience tropical storms and hurricanes in the present day (Goldenberg et al. 2001).

These stronger storms are also projected to feature more precipitation during landfall, with increases nearing 20% in and around the storms' centers. Combined with stronger storm surges, coastal flooding during storm landfall will also increase dramatically (Knutson and Tuleya 2004). Stronger winds and increased flooding will amplify the damage caused by these coastal storms, fueling a great loss of life and extreme economic damage (Pielke Jr. et al. 2008; Pielke Jr. et al. 2004). As discussed previously, the fact that storms may occur less frequently in the future may actually increase their potential for damage, as institutional memories (i.e., social, political and economic) can be relatively short. Furthermore, when evaluating the economic prospects of future developments, the nature of discounting future losses (and gains) makes it almost impossible to account for potential economic damages from storm events (Cavallo and Noy 2011). These problems are exacerbated in many developing countries where there is little regulation or oversight for urban development projects (O'Brien et al. 2006).

2.3.3 Emergent Factors

As detailed above, emergent factors often represent a *combination* of both social and climatic factors. In many instances, the merger of social and climatic factors creates a wholly new factor of concern that contributes to a general increase of coastal vulnerability, particularly in the context of storm surge flooding. The impacts of emergent factors are also difficult to predict, rarely operate in isolation, and often have significant downstream effects on unrelated systems. For example, consider the combination of two climatic factors, sea level rise and tropical storm intensity. Individually, both can spawn coastal flooding. However, when combined, their effects are multiplied (Karim and Mimura 2008). If one includes the interactions of climatic *and* social factors, including population growth along the coast, it is clear that more people are exposed to storm surge flooding and that individual vulnerability is likely increased due to the inadequate provision of essential and emergency services (Kubal et al. 2009). In short, developing an ability to more accurately predict the outcomes of extreme events and deepen our understanding of the ways in which coastal cities and their residents are vulnerable, social, climatic, and emergent factors cannot be evaluated in isolation.

Consider, for example, that many large cities are already facing challenges associated with high food and water consumption rates. The long drought impacting Cape Town, South Africa in the late 2010s had depleted groundwater reserves to the point where many existing wells could no longer draw water for the city or its occupants (Luker and Harris 2018). The city was able to avert the crisis due to intense water management efforts and the eventual lifting of the drought. However, the mere threat of running out of water caused a spike in the city's crime rates and significant civil unrest (many residents protested what they saw as racially-motivated government-mandated water management initiatives) (Sanchez and Rylance 2018). Cape Town is not alone; many large coastal cities and their immediate environs (e.g., Sydney, Singapore, Los Angeles, etc.) routinely suffer from freshwater shortages and drought (Purvis 2016). Miami-Dade County, Florida provides an instructive case study for coastal cities. Developments in this region were built with a particular estimate of groundwater availability, but supplies are much lower than anticipated due to accelerating saltwater intrusion (Czajkowski et al. 2018). Furthermore, as the groundwater becomes unusable, the water table is also rising, leading to additional flood risk in the county. These climatic-driven factors, combined with the population growth within the Miami area, means that freshwater supplies are shrinking, while the demand for water is increasing. Changing precipitation patterns may also negatively impact inland water sources used by coastal cities. This was certainly the case for California during the 2012-2014 drought (Griffin and Anchukaitis 2014).

Similar to water insecurity, food insecurity is also highly problematic for coastal settlements. Climate change is already impacting crop production in many regions, with warming temperatures associated with shrinking corn and wheat production around the world (Lobell et al. 2011). Furthermore, precipitation changes may lead to drought or flooding, limiting crop growth. Changes in temperature may also impact an area's growing season (Gregory et al. 2005). Incidentally, it is worth noting that the effects of climate change are not uniformly negative. In some regions, climate change may increase crop production, turning dry regions wetter, and cold regions warmer. However, the projected positive effects are relatively limited and there are sizable economic and geographic barriers to moving agricultural production on a large scale. In most developed countries, the projected near-future changes in crop production show signs of decrease, which will likely cause economic damage. Worse, the impacts in many developing countries will be more severe, with food shortages likely (Awuor et al. 2008). Meanwhile, sea level rise is limiting the ability for cities to import the food that they need. In part, this is fueled by coastal erosion and harbor inundation (Hallegatte et al. 2010). These flooded ports and harbors not only limit food imports, but cause large amounts of economic damage to the region that may further limit the abilities of impoverished households to buy food. Breakdowns in social order spurred by these and other changes could further disrupt food market operations (Douglas 2009). All of this is further exacerbated by accelerating population growth and its attendant effects.

2.4 Political and Economic Malfeasance

With rare exceptions, the political and economic incentive structures that drive local policy and development are unequipped to handle large, long-term, and potentially nebulous problems like climate change-related hazards. Consider the United States, which is relatively unique among developed countries for the high rate of climate change denialism in its population (McCright and Dunlap 2011) and its political representatives. From a political perspective, these representatives are simultaneously seeking to take advantage of the identity-protection politics of their constituents and are making themselves more business-friendly (Antonio and Brulle 2016). In addition, among individuals that are not climate change deniers, the overall public concern for climate change has declined significantly since 2008, due in large part to more immediately pressing economic and financial worries (Scruggs and Benegal 2012).

Alongside a disbelieving or uninterested public, many politicians and political institutions are beholden to pro-business special interests, with regulatory agencies experiencing some amount of capture (Helm 2008). The Environmental Protection Agency (EPA) under Scott Pruitt, for example, advanced business interests to an extraordinary degree, and by many metrics may have been almost entirely captured by the private sector (Dillon et al. 2018). This creates a situation in which proposed legislation is largely toothless or allows for significant rent-seeking on behalf of existing corporations, leading to high government costs and minimal effective change (Helm 2010). State and local policy is similar – most state legislation planning for climate change proposes voluntary actions and optional emissions reductions standards, which are rarely achieved (Wheeler 2008). Recall the previously mentioned example of the North Carolina state legislature mandating that state planning agencies *must* use inaccurate and outdated climate models (Harish 2012).

Successful adaptation to climate change will require a long-term sociopolitical transition involving changes in personal behavior, industry (particularly energy), and regulation. This type of long-term transition is an enormous undertaking, and is likely to be difficult, messy, and inefficient (Meadowcroft 2009). Part of the reason that existing political systems fail so dramatically at solving these types of problems is that they are largely unable to effect change over a long enough time horizon. Political actions are inherently linked to political cycles, which tend to be connected primarily to term limits (Garri 2009). This political short-termism naturally weeds out nearly all politicians that wish to provide a public good whose benefits are only realized in the future while their costs are borne in the present. In addition, political short-termism is driven by politicians' uncertainty avoidance, the natural tendency to avoid spending limited political capital on uncertain problems when certain problems exist. These patterns manifest in a variety of ways when it comes to local governments acting on climate change. Policies tend to favor short-term economic growth over long-term sustainable solutions, with the most attention and political-will focused on short-term hazards (specifically, those that have a recurrence interval similar to or less than the given politician's term limit) (Slawinski et al. 2015; Ford et al. 2011).

Economic incentives tend to be similar. Economy projections use various temporal discounting methods when it comes to accounting for future economic change (both positive and negative) in the present. Combined with uncertainty about future projections, this naturally leads to discounting the welfare of future generations of people and discounting the likely economic damage of climate change (Nordhaus 2007). In coastal regions, this leads to urban expansion and development in areas that are or soon will be at risk for flooding (Muis et al. 2015). In addition, temporal discounting discourages strict regulation on behaviors that contribute to climate change, such as pollution generation (Hendrickx and Nicolaij 2004).

2.5 A Case Study in Miami, Florida

While many cities along the southern and eastern coasts of the United States are experiencing increased vulnerabilities to climate change, Miami, Florida is an excellent location to study these effects in practice. Due to its geographic and geologic profile, Miami is several years ahead of its coastal city peers – that is to say, it is today experiencing social and climatic factors that other, similar cities are projected to experience in the next decade. This makes Miami an ideal case study to examine how these factors are likely to play out in the near future, with particular respect to their unique interactions. Furthermore, this is unlikely to change in the future, meaning that many cities should look to Miami to determine how their own vulnerability profiles are likely to shift, and to see which mitigation and adaptation strategies work (and which ones do not).

Miami's is the seventh largest metropolitan area in the United States, with a total population of 5.5 million people. In addition, it is growing fast, and that growth rate is likely accelerating. Miami's population increased by 8% between 2000 and 2010, but by 14% from 2010 to 2016 (Census 2018). Miami is located on a long, narrow strip of land located on the southeastern coast of Florida, with the Atlantic Ocean to the East and the Florida Everglades to the West (Figure 2.2). It is low-lying, and the majority of the underlying ground is composed of porous limestone (its porosity means that levees and seawalls are of limited utility because water is able to rise through the underlying bedrock). Its climatic profile is such that it experiences regular hurricanes and tropical storms, more so than any other urban area in Florida (Davidson and Lambert 2001). It is also facing sea level rise of around nine millimeters per year (Wdowinski et al. 2016).

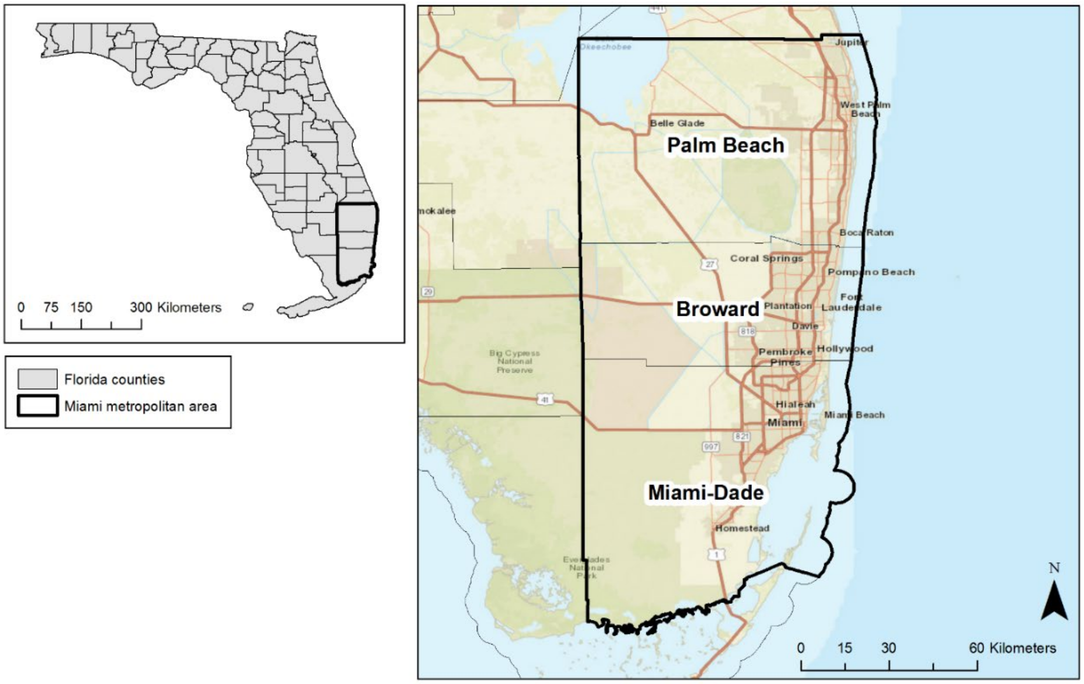

Figure 2.2. The Miami metropolitan area is located on the Atlantic coast, in southern Florida. While the Miami metropolitan area extends west, into the Florida Everglades, its urbanized area is a relatively narrow strip of land that stretches along the coast.

Miami's demographic and climatic profiles are such that it is already dealing with the dangerous confluence of factors that are serving to increase its vulnerability to storm surge flooding. It is a large, highly-developed urban area, and its growth is accelerating. That population growth is driving urban development, much of which is explicitly built with no eye towards future sea level rise (Wdowinski et al. 2016). In a classic example of climate denialism, political short-termism, and short-term economic gain, local government had repealed a variety of regulations designed to require developers to account for sea level rise (among other things). As a result, many areas throughout Miami are now experiencing regular tidal flooding, absent any extreme weather, and are being forced to raise roads and other infrastructure at great expense (Loria 2018).

Unsurprisingly, many of Miami's poorest residents are most negatively affected by these changes. The majority of cheap development occurred in poorer neighborhoods, which are then the last in line to receive the required retrofitting (Chakraborty et al. 2014). There are other, subtler social vulnerability issues at play in Miami as well. Inland flooding disproportionately affects lower-income, minority households, while coastal flooding does the opposite. However, the majority of engineering solutions and structural adaptations are developed and installed to mitigate coastal flooding, often doing little to nothing to ameliorate inland flooding (Chakraborty et al. 2014). This problem is not unique to Miami – many cities focus their adaptation efforts on protecting areas with high median household incomes while ignoring poorer neighborhoods. Furthermore, many poorer or otherwise disenfranchised residents are less able to recover from damage that does occur.[2]

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[2] Many residents of traditionally poor neighborhoods are also being priced out – historical pressure dictated that many of these neighborhoods were located inland, away from the desirable real estate on the coast. As sea level rise occurred, developers began buying property located on high ground, breaking apart and gentrifying many inland neighborhoods (Curtis and Schneider 2011).

In addition to the routine flooding caused by sea level rise, hurricanes in the region are likely to get stronger. In 2017, Hurricane Irma struck Miami, causing enormous amounts of damage. Irma was the strongest hurricane to strike the continental United States since Katrina, and the first Category IV storm to hit Florida since 2004. Storm surge and heavy precipitation flooded large portions of Miami, while strong winds uprooted trees, signs, cell towers, and electrical poles. Millions of Floridians were left without power for up to a week after the storm, resulting in several elderly deaths. Furthermore, the time spent without power (i.e., time before power restoration) was found to be positively correlated with socioeconomic vulnerability – in other words, Florida Power & Light was clearing debris and restoring power first to richer, whiter neighborhoods (Mitsova et al. 2018).

Miami will necessarily undergo major changes over the next several decades. As it stands now, there are no feasible and cost-effective engineering solutions that will protect Miami from sea level rise – while levees, seawalls, and raised structures do mitigate some damage, the area's overall geologic profile is such that preventing flooding entirely is not realistic. Even a relatively modest 20 inch sea level rise (expected at least by the end of the 21st century; Wdowinski et al. 2016) will flood enormous urban areas (see Figure 2.3). Storm surge flooding in particular will likely grow worse in the future. Sea level rise will continue and hurricanes will get stronger, meaning that the surge will be taller and will penetrate inland to a larger degree. Meanwhile, the city's growth continues, resulting in more people being affected by surge when it does occur, with a disproportionate amount of that damage occurring to the area's poorest and least capable residents. Certainly, Miami's specific profile is unique to the city – but many of these same patterns are beginning to play out in other developed coastal cities around the world.

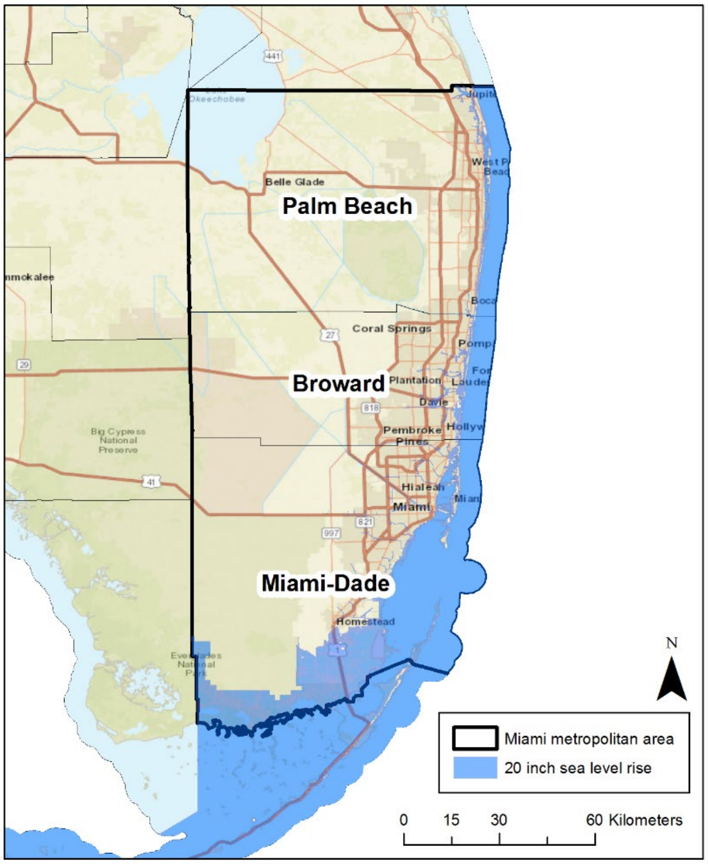

Figure 2.3. Sea level rise of at least 20 inches will almost certainly occur during the 21st century, possibly as early as the year 2050. Substantial portions of the Miami metropolitan area will experience increased flooding as sea level rises.

2.6 Conclusion

The problems facing coastal urban cities in the future are enormous. They are experiencing a range of serious social and climatic factors that are contributing to a significant increase in their vulnerability to natural disasters. Furthermore, barring major engineering efforts and/or shifts in political practices, mitigating these vulnerabilities remains a challenge. Moreover, demographic and climatic projections suggest that many of the driving forces behind the increasing vulnerability will continue long into the future.

Given this constellation of problems for coastal urban areas, it is tempting to advance a handful of policy recommendations that seek, at least in some way, to ameliorate known problems. Unfortunately, there is no single policy recommendation or "silver bullet" solution that cities can adopt, *en masse*, to slow this increasing vulnerability. The exceedingly complex systems behind this increase are only just beginning to be understood, and many of the projected social and climatic shifts are inevitable, at least in the near-future. The vast majority of coastal cities, including those along the southern and eastern coasts of the United States will experience more intense and potentially more frequent flooding in the future. Meanwhile, as these cities continue to grow, their development patterns will continue to reflect of mix of the responsible and irresponsible.

Despite the similarities of these trends for coastal settlements in the U.S. and beyond, most regions have distinct geographic, geologic, political, cultural and economic profiles. This means that proposed solutions will need to be tailored, at least to some degree, to fit each city. For example, although seawalls make sense for New York City, these types of structures are less useful for Miami. Meanwhile, places like Atlantic City, New Jersey may be more sensitive to the long-term decline of the casino business and associated tourism revenues, when compared to Charleston, South Carolina’s growing business and professional services sector. As such, it is imperative that mitigation and adaptation efforts begin locally – individual cities may be able to do little about melting ice sheets in Greenland, but they have the ability to encourage responsible building, develop appropriate emergency management measures, and ensure that they have sufficient resources for an effective recovery should a climate-related disaster strike. Naturally, these are not easy goals to achieve, but some cities have begun making progress. New York City, for example, has begun the process of constructing a series of artificial islands and an enormous seawall to help mitigate the damage from future floods (Garfield 2018). These sorts of solutions are expensive, but their costs are a fraction of the estimated damage from future floods. Similarly, there are an enormous number of future research avenues that may contribute to solving this problem. These include geoengineering (the development of new mitigation/adaptation technologies), climate science (to better predict future storm regimes), urban planning (responsible urban development), regional science (effective solutions will require intimate knowledge of the city in question), and others. The remainder of this dissertation will deal with improving evacuation and rescue plans that can be used in landscapes that have just been flooded by large storm surges, with the aim of helping emergency managers and urban planners.

CHAPTER 3

STORM SURGE, INFRASTRUCTURE DAMAGE, AND THE INADEQUACY OF TRADITIONAL ROAD NETWORK MODELS

3.1 Introduction

A cubic yard of salt water weighs approximately 1,728 pounds, or nearly 789 kilograms. During hurricanes or other large cyclonic storms, trillions of kilograms of sea water are pushed toward the shore by powerful winds. The underlying physics of storm surge are complex, as are the many geophysical and atmospheric features that can impact surge severity. Regardless, as detailed by Balica et al. (2012), storm surge is the number one factor associated with loss of life and infrastructure damage during storm events. In particular, developed, low-lying coastal areas are the most vulnerable, along with inland bays or rivers near the coast where storm surges can move along connected bodies of water. One of the largest storm surges ever recorded in the United States was over 25 feet, caused by Hurricane Katrina in August, 2005 (Fritz et al. 2007). Economic damage from Katrina was estimated at $156 billion (Burton and Hicks 2005). Storm surges flood basements, buildings' ground floors, and underground infrastructure such as subways. In many developed areas, the surge also picks up and spreads wastewater, creating a health hazard that may outlast the actual storm surge event (Crabill et al. 1999). Larger surges knock out electrical infrastructure and wash out roads, stranding people who may be left for days without fresh water, food, or electricity (Kleinosky et al. 2007). As detailed previously, storm surges fueled by hurricanes or tropical storms are exacerbated by tidal phase when the surges make landfall. As a result, surge events vary significantly in both size and scope. Global climate change also contributes to the projected frequency and severity of future hurricanes and tropical storms. More storms, combined with rising sea levels will further exacerbate the damage caused by storm surges (Balica et al. 2012; Kleinosky et al. 2006; Scavia et al. 2002). Even now, areas that are affected by hurricanes or tropical storms are likely unprepared for the severity and potential damage of future storms (Pielke Jr. et al. 2008, Michener et al. 1997).

Despite the growing concerns regarding coastal resiliency and the likely future increases in storm frequency and severity, many municipalities fail to develop adequate coastal hazard mitigation plans (Shepard et al. 2012). Specifically, most plans drastically underestimate damage extent, loss of life, economic damage and infrastructure-related complications. As a result, most (if not all) coastal communities suffer from inadequate stores of emergency supplies, incomplete evacuation routes, and undertrained emergency personnel (Shepard et al. 2012; Warner and Tissot 2012). Equally problematic is that mega-storms, at least for now, occur infrequently enough that many people living in high-risk areas have grown complacent – often ignoring storm warnings and evacuation orders (Lamond et al. 2009).

Although the exact size, strength, and timing of storm surges are difficult to predict, the overall damage cause by storm surges is not random. As alluded to previously, storm surges are directional, in that coastal and low-lying areas near rivers or bays flood preferentially. This often generates disproportionate impacts to low income groups within a community, many of which gravitate to lower rent neighborhoods in these coastal or riverine areas (Cutter et al. 2006; Rygel et al. 2006; Frazier et al. 2010). Thus, not only are the economically challenged groups within a community more vulnerable to the actual property damage and loss of life caused by the storm surge, but they often have limited access to public services during the recovery process (Cutter et al. 2006; Laska and Morrow 2006). As detailed by Cutter et al. (2003), although a wide variety of inequalities related to gender, race, ethnicity, age or health can lead to social vulnerability during hazard events, the most influential facet tends to be socioeconomic status. Place-based inequalities, including regional economic vitality, level of urbanization and access to public services also contribute to vulnerability but are often correlated with social inequalities (Cutter et al. 2003).

The purpose of this chapter is to explore elements of the vulnerability and the resilience of coastal communities during major storm surge events using Volusia County, Florida as a case study. In addition, the inadequacies of utilizing traditional road network models for use in flooded landscapes will be detailed. This chapter and future chapters use Volusia County as a representative location because of its site, situation, and demographic and socioeconomic compositions – contributing to the generalizability of the framework presented in this dissertation to other coastal communities along the Atlantic seaboard and Gulf of Mexico. This chapter will present a combination of computerized numerical models, a geographic information system (GIS), and network, spatial and statistical analyses to simulate the impacts of five different hurricanes of varying strength (Categories I – V) and their associated storm surges on local infrastructure systems, populations, and access to resources. This type of analysis is important for several reasons. First, the ability to simulate storm impacts, even if the simulations exhibit imperfections, provides local agencies and emergency management planners with foresight and an ability to evaluate and improve existing hazard response plans under a range of extreme event scenarios. These storm surge simulations will also be used throughout this dissertation. Second, the simulations can be used to create benchmarks, which provide empirical reference points for evaluating storm severity and its potential social, economic, and infrastructural implications for a community. In turn, these benchmarks can be used to prioritize mitigation efforts and optimally allocate limited recovery resources (Matisziw et al. 2009; Marcelin et al. 2016; Nowell et al. 2014). Third and finally, understanding spatial vulnerability can facilitate important planning and policy dialogues that may help prepare high-risk groups for catastrophic storms, reducing vulnerability and associated storm impacts.

3.2 Background

As detailed by Trenberth (2005), the majority of hurricane activity occurs in oceans where the sea surface temperature (SST) exceeds 26°C. SSTs in the Atlantic Basin, as well as the Gulf of Mexico routinely exceed this threshold during the summer months, helping to generate tropical cyclone activity that has the potential to impact North America. The eastern coast of Florida, with its more than 5 million urban residents, is a high-risk location for storm damage. Large storm surges have caused tens of billions of dollars' worth of damage to this coastal region (Genovese and Green 2015). Hurricane Andrew (1992), for example, caused $25.3 billion in damage alone and bankrupted 11 insurance companies (NOAA 1998; TB Times 2012).

As discussed in Chapter 2, climate change and a variety of social drivers are also adding additional layers of complexity to hurricane research and our understanding of vulnerability throughout the Atlantic Basin. In this chapter, building on the general principles introduced in Chapter 2, four key domains are delineated where these changes are manifesting: 1) economic vulnerability, 2) ecological vulnerability, 3) social vulnerability, and 4) scale and community preparedness.

3.2.1 Economic Vulnerability

The economic implications of this increase in hurricane activity are important to acknowledge. For instance, Estrada et al. (2015) found that between 1900 and 2005 there has been a significant increase in the number and intensities of storms in the North Atlantic basin, as well as in the total economic losses caused by these storms each year. In 2005, around eight billion dollars (7% of the total annual normalized losses that year) of tropical cyclone damage in the United States could be attributed to climate change. Estrada et al. (2015) further finds that many existing management strategies are not keeping up with projected changes in hurricane and storm intensity and frequency driven by climate change, and will likely be inadequate in dealing with these future storm regimes. In general, a large storm such as Hurricane Katrina will slow annual economic growth in the United States by about 1% (Cashell and Labonte 2005). Obviously, these effects are more pronounced in the local economies of the areas hit directly by the storm. Hurricane Sandy, for example, cost about $72 billion, primarily in property damage (Blake et al. 2012). This includes both private losses (i.e., households and businesses) and public losses, such as infrastructure.

3.2.2 Ecological Vulnerability

The ecological implications of climate change, especially in coastal areas, are important to consider. For example, sea level rise and variation in storm frequency and timing can hinder ecosystem services provided by coastal wetlands. In the Florida Everglades, flooding risk is higher than one might expect solely based on sea level rise due to the wetland's inability to handle even routine flooding after climate change (Koch et al. 2015; Michener et al. 1997). Climate change has increased storm severity in the Everglades, increased drought frequency, and changed species assemblages. All of this, combined with increased development near and in the Everglades, has diminished their capacity to mitigate flooding (Koch et al. 2015). In addition, sea level rise is gradually weakening the Gulf Stream, causing further coastal disruptions, such as an increased frequency of toxic algal blooms (Gilbert et al. 2014).

3.2.3 Social Vulnerability

Damage caused by storm events is not distributed evenly in geographic space. Depending on the path and intensity of a storm, areas are differentially impacted. This is true for the local population as well, but the implications of a storm's impact are also contingent upon a myriad of other factors. The concept of social vulnerability – that not all groups of people exposed to a hazard are similarly at risk – emerged in the 1990s (Alwang et al. 2001). Individual vulnerability depended both on one's ability to handle the impacts of a hazard (resistance) and the ability to recover from whatever damage a hazard inflicted (resilience) (Rygel et al. 2006, Wu et al. 2002). Cutter et al. (2003) developed a comprehensive vulnerability index that captures many of the social indicators and their complex interactions that inform exposure to environmental disasters in developed areas. Cutter et al. (2006) also described the social conditions that specifically influenced vulnerability in the United States to Hurricane Katrina.

Not surprisingly, climate change exacerbates the differential social vulnerability experienced by populations on developed coastlines. As detailed above, increased flooding frequency and intensity, more storm events, and less effective ecosystem services all magnify a coastal area's exposure to damaging natural disasters, but these also disproportionately affect more vulnerable segments of the population (Arkema et al. 2013; Ruckelshaus et al. 2013; Kim and Marcouiller 2015). More vulnerable groups experience more loss during storms (Cutter et al. 2003), are less able to recover from those losses (Kim and Marcouiller 2015), and are less aided by mitigation and recovery plans (Cutter and Emrich 2006). Too often, disaster management agencies adopt a 'one-size-fits-all' approach to emergency management and recovery, and these plans routinely fail to account for the specific situations experienced by the more vulnerable segments of a population.

3.2.4 Scale and Community Preparedness

In the past, hurricane and storm surge evacuation plans were the sole responsibility of emergency management agencies, at least where such agencies existed. In regions without emergency management agencies, law enforcement officials are generally charged with these planning efforts (Urbina and Wolshon 2003). Sadly, once the emergency plans are developed, little effort is expended to update these plans to reflect the changing threat environment. For example, many emergency plans have failed to evolve in coastal communities where the population has exploded in recent years (Urbina and Wolshon 2003). In addition, as hurricanes become more frequent and stronger, many evacuation and preparedness plans are not updated to reflect these changes (Urbina and Wolshon 2003).

The federal government requires all states to produce and maintain an emergency management plan, covering hazards ranging from natural to manmade; however, the specifics of these plans vary by state, and are usually limited to a discussion of hazards historically endemic to the region. Furthermore, many states delegate emergency planning efforts to individual (i.e., local) jurisdictions. Although this allows plans to be finely tailored for local conditions, it often results in a wide range of emergency plan quality and comprehensiveness – with most failing to provide any strategic direction for agency coordination between localities after a catastrophic event (Boin and McConnell 2007). Florida, due to its statewide vulnerability to hurricanes, has adopted a stronger top-down approach for hurricane emergency planning (Kapucu 2008). In spite of this additional oversight, an analysis of hurricane evacuations throughout the 1990s shows that they were largely inadequate. The plans were often under-detailed, did not accommodate regional-scale disasters, failed to include newly developed areas, and included flood-vulnerable segments of road (Urbina and Wolshon 2003).

It is also important to note that most emergency planning efforts are based on historical experience and do a fairly good job of outlining strategies for easily anticipated disasters. Work from Needham et al. (2015) involved cataloging more than 700 storm surge events, dating back to 1880. They found that the U.S. Gulf and Atlantic coasts experience a very high frequency of low intensity storm surges relative to other hurricane-exposed coasts on the planet. Developed communities in these areas tend to be well-prepared for these weaker surges because they have significant and regular experience in dealing with disasters of this scale. However, when larger storm surges hit developed coastlines (e.g., Andrew and Katrina), few communities have plans in place to deal with disasters of such scale and magnitude. As mentioned previously, the city of New Orleans lacked any sort of effective post-storm evacuation and rescue plans in the aftermath of Katrina.

Lastly, development efforts and emergency management plans are slow to adapt to climate change, and so are often ineffective at disaster mitigation and adaptation post-climate change (Moser et al. 2012). Many emergency management plans also ignore spatially variable vulnerability (Cutter et al. 2013; Yoon 2012). Ignoring place and social vulnerability further exacerbates the vicious cycle in which the most vulnerable populations experience the most loss from a given disaster and then receive the least benefit in recovering.

3.3 Methods

Given the multifaceted nature of vulnerability for coastal communities, particularly within the context of global climate change and sea level rise, it is more important than ever to address the potential implications of storm impacts. In addition to providing local agencies and emergency management planners an ability to explore the contingencies associated with (potentially) catastrophic storm events, simulations can be used to create benchmarks and empirical reference points for evaluating storm severity and community impacts (e.g., social, economic, and infrastructural). Furthermore, these benchmarks can then be used to prioritize mitigation efforts and develop more nuanced and effective strategic plans to enhance infrastructure, protect important assets, and increase community resilience. Finally, understanding spatial vulnerability can facilitate important planning and policy dialogues that may help prepare high-risk areas for catastrophic storms, reducing vulnerability to the associated storm impacts.

3.3.1 Study Area and Data

Volusia County, Florida was chosen as the study area for this and later chapters for several reasons. First, its location along the Atlantic Coast places Volusia County at risk for tropical storm or hurricane landfall each year, making its site and situation generalizable to many other high-risk coastal locations in/around the Gulf of Mexico and the Eastern seaboard (see Figure 3.1). Second, the county is already experiencing the effects of climate change through increased flooding and storm intensity (Daytona Beach NJ 2014). Third, it has a large area of highly developed (residential and commercial) coastline, meaning that significant social, economic and community assets are at risk for flooding and storm surges during tropical storm events. Fourth, it has a demographic and socioeconomic profile that is similar to many other U.S. communities at risk for tropical storms and hurricanes making the results relevant and generalizable to other areas. Finally, Volusia County makes all of its storm evacuation routes and associated infrastructure data publically available.

In spite of Volusia County's fairly low hurricane recurrence interval (21 years for all hurricanes) (Keim et al. 2007), it remains an appropriate location for a general case study for several reasons. To begin with, it is already experiencing exacerbated flooding from routine sources, due to the continued development of its coastline and the general sea level rise that has occurred to date. Both development in the area and sea level rise are projected to continue increasing, and so even baseline flooding is likely to get worse for the area. Additionally, its low hurricane recurrence interval is a characteristic shared by many other developed locations on the coast – and this low frequency of strong storms influences the political and economic pressure involved in responsibly developing the coastline and preparing for emergencies. This complacency is not uncommon in locations like this, and is precisely why Volusia County serves as an appropriate case study for this methodological framework. However, this complacency may be especially dangerous in the near future – Mann and Emanuel (2006) have found that Atlantic SST is rising, and that rise is associated with a projected increase in the frequency of strong storms in the future (Holland & Bruyere 2014). Finally, there is some evidence as well that traditional flooding regimes may be changing for areas on the Atlantic coast, due primarily to increased development and a warming ocean. Lin et al. (2012) found that 100-year and 500-year floods may be occurring every 3-20 years and 25-240 years, respectively.

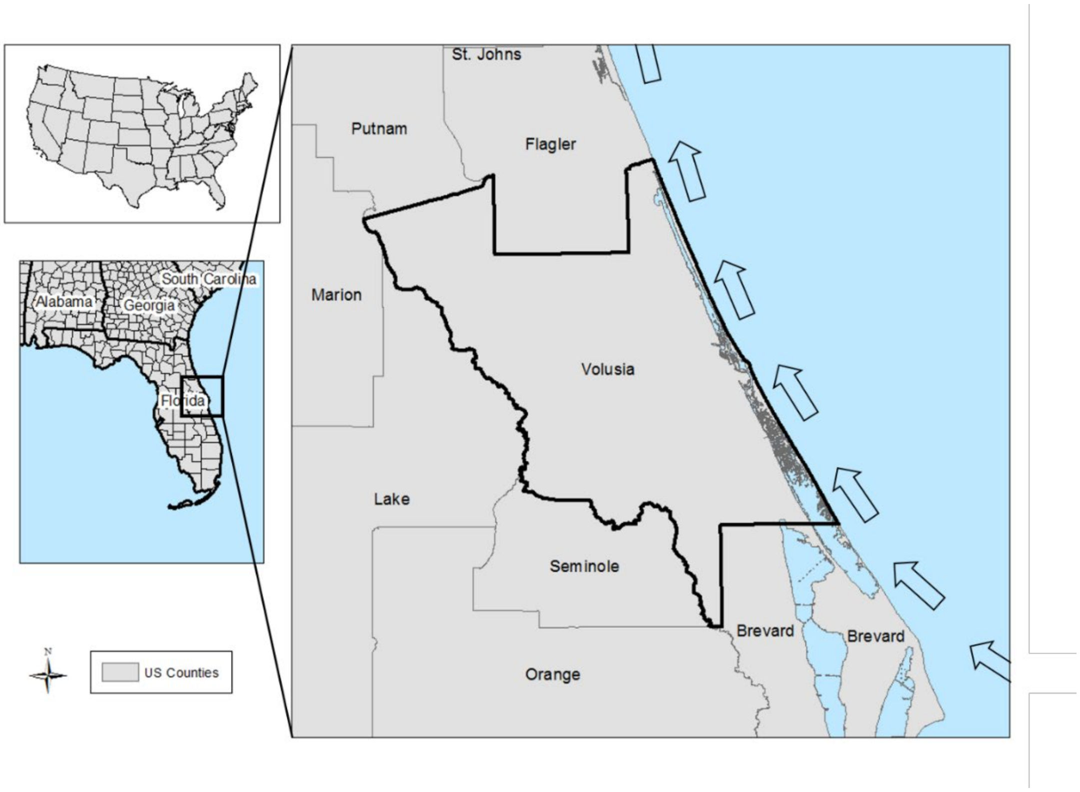

Figure 3.1: Volusia County, on the Atlantic Coast in the center of Florida. The arrows represent the simulated storm track.

A variety of Volusia County data sets are used in this and later chapters to evaluate and benchmark storm severity and its potential impact(s) to Volusia County. First, the Volusia County Geographic Information Services branch (Geographic Information Services 2016) provided the census block and street shapefiles used for analysis, as well as the official and proposed evacuation route shapefiles. The street and evacuation route shapefiles, which will be used to develop one metric of storm surge damage, are not only geographically comprehensive (in that they cover all of the developed areas of the county) but are an important infrastructure feature leading up to, during, and immediately following storm surge events. Importantly, these shapefiles are the same ones used by the Volusia County emergency management office in the development of their official evacuation routes.

The Florida Geographic Data Library (FGDL Explorer 2016) (administered by the University of Florida GeoPlan Center) provided the hospital and medical center shapefiles. Hospitals and medical centers were used to demarcate important destinations to access during storm surge flooding. These, combined with the road shapefiles, will be used to develop a metric of storm surge damage in the county. Hospital access during or after a storm is a derived measure that is more sensitive to individual characteristics of a given location, especially when compared to more general measures such as overall network connectivity for a region – this approach will also serve to highlight many of the limitations of traditional network routing in a flooded landscape.

The demographic data used for each block point came from ESRI Business Analyst Desktop (ESRI 2016) and included both the total number of households and businesses for each block. These aggregate counts allowed for a more nuanced snapshot of storm surge damage, and were used to calculate the number of households and businesses flooded during catastrophic events. In an effort to minimize the influence of outliers, blocks with fewer than ten households were excluded from the analysis (n = 1,124 out of 10,555 total).

3.3.2 Storm Surge Damage Metrics and Contingency Analysis

The Sea, Lake, and Overland Surges from Hurricane (SLOSH) model, developed and maintained by the National Weather Service, is commonly used to model storm surges resulting from hurricanes of different strength in the United States (Forbes et al. 2014). Previous work finds that the storm surges predicted by SLOSH are on par with actual observations analyzed by the Hurricane Research Division of the National Oceanic and Atmospheric Administration, except for a slight tendency to occasionally underestimate the extent of surges for large hurricanes (Houston et al. 1999). The SLOSH model is used by the National Hurricane Center to predict storm surge when a hurricane is developing in real time. The model can be applied to one or more demarcated coastal areas and/or basins along the Atlantic and Gulf coasts. The Federal Emergency Management Administration and state and local planning agencies use it to develop simulations used for hazard analysis (Glahn et al. 2009).

While there are a variety of other hurricane and storm surge modeling tools, SLOSH was the best fit for this dissertation. One commonly used alternative is the Federal Emergency Management Agency's Hazus program. While Hazus can model earthquakes, hurricanes, and floods, it is primarily focused on economic and social impacts, and is often used in conjunction with the physical flooding simulation from SLOSH (Shepard et al. 2012). Another alternative that is frequently used to hindcast historical storm surge is the Advanced Circulation (ADCIRC) model – which is composed of a bundle of algorithms that model hydrodynamic flow at a high resolution (Westerink et al. 2008). However, the accuracy of this model depends strongly on the accuracy of the forecast parameters – this is not a problem when it comes to hindcasting well-known storms, but it limits its applications when it comes to simulating possible future storms (Dietrich et al. 2011). SLOSH model results generated with hindcast information have also been compared against the actual storm observations made by NOAA's Hurricane Research Division and have been shown to be quite similar, typically within about 6% of the actual data (Houston et al. 1999).

The SLOSH model uses a variety of atmospheric data (e.g., atmospheric pressure, wind speed, and likely hurricane track direction) and physical data (e.g., bay and river configuration, shoreline shape, and bathymetric data) along with some user-input directives to produce potential storm surges. SLOSH allows for three different methods to estimate storm surges: 1) deterministic, 2) probabilistic, and 3) composite. The deterministic approach includes a single simulation developed from a forecast which is assumed to be perfect. As a result, the generated results are highly dependent on the correct forecasting inputs. The probabilistic approach leverages past hurricane data to generate several simulations with an explicit error envelope. Finally, the composite models run thousands of SLOSH simulations under different storm conditions to generate an envelope of results. It is this last approach that best incorporates forecasting and/or meteorological uncertainty. The composite approach generates Maximum Envelopes of Water (MEOW) using the same hurricane category, speed, and wind direction but slightly different landfall locations. The maximum height of water in a given cell across all the simulations is saved as the MEOW value for that particular cell. Next, the maximum of MEOWs (MOMs) are calculated by overlaying MEOWs of different simulated hurricanes (slightly varying the atmospheric conditions in each case) and determining the maximum possible surge for a given area for that category. These MEOWs and MOMs are used to generate the simulated storm surge output for particular hurricane conditions. For this and later chapters, the composite approach was used to generate predicted storms in the Jacksonville operational basin. This composite approach is frequently used for emergency management and storm prediction, and due to its ability to account for weather condition forecast uncertainty, is considered the best approach for analyzing surge vulnerability. The storms were generated at high tide, with a mean storm speed of 15 mph, while traveling parallel to the coast. This matches conditions under which most historical storms impact Volusia County. These conditions were kept identical between simulations, with only the strength of the hurricane itself changing. Specifically, five storm surge outputs were generated, one for each category of the Saffir-Simpson scale.

The goal for quantifying impacts from storm surge was to develop several metrics that are applicable at all levels of storm severity and are generalizable to other areas with a similar development profile. The most obvious measurement of storm surge damage is flooding – eight inches of water on a road, household, or business plot was considered inundated. Naturally, stronger storms flood a larger area, inundating more total households and businesses. To ensure an unbiased comparison of storm severity, these effects are controlled for through the use of a damage density metric. Specifically, the total number of flooded households and businesses were normalized by the total land area of Volusia County that was flooded. The resulting metric, albeit simple, indicates the location and extent of predicted flooding for each block – across a range of scenarios.

Both road access and network accessibility are important factors when considering the impacts of storm surge flooding. Geurs and Van Wee (2004) define access as the opportunity (and level of effort) associated with entering a transportation system.

Conversely, accessibility consists of the “extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)”. It is well established that flooded roads increase direct and indirect storm mortality (Ruin et al. 2008; Drobot et al. 2007; Jonkman and Kelman 2005), as well as inhibiting post-storm recovery efforts, emergency resource access, and evacuation ability (Shen et al. 2016; Jonkman et al. 2009). Two unique metrics were used to measure the effects of storm surge flooding on access and accessibility for Volusia County.

The first includes a basic exploration of the impacts of storm surge flooding on county-wide storm evacuation routes. These evacuation routes are the official evacuation routes generated and maintained by the Volusia County emergency management office. This office produces a variety of evacuation plans that dictate when residents should evacuate from their homes – the plans account for household location, household type (e.g., mobile homes are encouraged to evacuate regardless of hurricane strength as they are especially vulnerable to strong winds), and hurricane strength. These plans dictate specific routes that should be taken by residents to move to generally safer areas – they are not storm-specific, but rather account for the most likely surge flooding from the most likely storm to hit the area (these are the same conditions that were used to generate the storm surges within SLOSH, above). The flooded-status of these routes, in turn, was tabulated using the results derived from the simulated storm surges and evacuation routes were considered to be interdicted (i.e., impassable) where the projected water depth was greater than eight inches. Both the numbers of flooded evacuation roads and the total miles of flooded roads were calculated under the different storm surge scenarios.

The second metric provides a more thorough snapshot of accessibility to important emergency services and facilities during storm surge flooding events. Specifically, accessibility to local hospitals was measured. During major storm events, hospital accessibility helps decrease storm morbidity and mortality by making medical treatment available. Hospitals also serve as official (or unofficial) centers of emergency management in the aftermath of a large disaster (Platz et al. 2007; Sauer et al. 2013). To that end, six storm scenarios were generated for examining the accessibility of every Census block in Volusia County to area hospitals. The first scenario is structured to examine the base road network, with no storm surge flooding. The remaining five scenarios include one simulation for each hurricane category (I-V). Again, for each scenario, roads were considered to be interdicted where the projected water depth was greater than eight inches. The actual accessibility metric was constructed by generating five origin-destination (OD) cost matrices for Volusia County streets. For each matrix, the centroid of each block served as an origin and each of the hospitals in Volusia County served as destinations. Each block point was allowed to search a maximum of 50 feet to connect with the larger network in the base scenario (no storm surge). If a connection could not be made, the block was excluded from the analysis (<2% of block points). Descriptive statistics for block points, the road networks, and medical facilities can be found in Table 3.1. Specifically, Table 3.1 contains the number of accessible Census block points (i.e., centroids of the Census block polygons), the number of accessible medical facilities, the total number of roads, and the total network length of roads that are not flooded in each scenario. These were then the available block points and medical facilities for which the OD cost matrices were generated.

Notably, for both the evacuation route analysis and medical facility analysis, *only* the road network was used for transportation – off-network travel was assumed to be impossible. Although off-network travel typically *does* occur in a post-storm landscape by both rescuers and evacuees, this analysis used solely traditional network analysis methods, which do not model that type of behavior. This is a lower-fidelity approach than is otherwise possible, and serves to highlight the limitations of traditional network analysis techniques and traditional OD routing in a post-disaster landscape. These limitations serve as the conceptual impetus for the methodological framework introduced in the next chapter.

Table 3.1. Total number of Census blocks, medical facilities, individual roads, and total road length remaining for each storm surge scenario. In each case, the 'lost' block points, roads, and medical facilities are due to flooding.

	Base network	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
Block pts	10,555	10,125	9,892	9,253	7,635	6,886
Med. Facilities	9	9	8	8	8	8
Road count	15,978	14,749	14,405	13,623	11,738	11,071
Network len. (km)	9,151	7,902	7,427	7,076	6,236	5,992

3.4 Results

The SLOSH model produced storm surges with a maximum depth on land of 3.5 feet (Category I) to 17.1 feet (Category V). By way of example, Figure 3.2 displays the areas of Volusia County at risk for flooding during a simulated Category II and Category IV hurricane storm surge. The storm surges were primarily located on the Atlantic Coast (east side of Volusia County) and secondarily in the northwest corner of the county, which is low-lying, marshy ground that is adjacent to two large bodies of water (Lake George and Crescent Lake) that also experience storm surge due to their direct connections to the ocean.

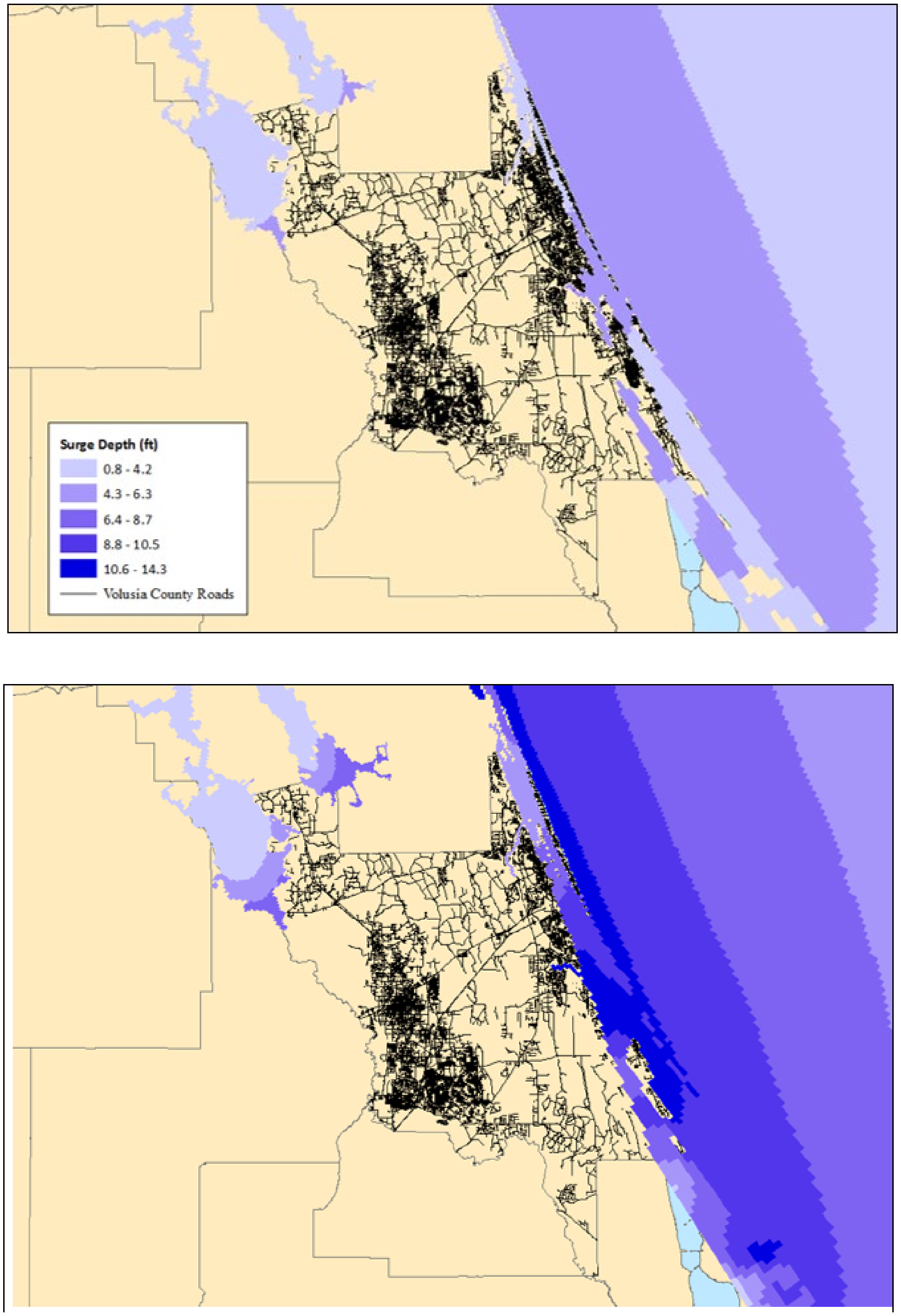

Figure 3.2. Simulated storm surges in Volusia County for Category II (a) and IV (b) hurricanes.

Figure 3.3 displays the degradation of the Volusia County road network during the flooding resulting from a simulated Category II and Category IV hurricane. For example, storm surge flooding from a Category II hurricane affects the low-lying, marshy ground in the northwest corner of the county (Figure 3.3a) and near Bethune Beach along the Atlantic Coast. Where the former is concerned, although there are no major urban areas located in northwest Volusia County, there are many townships along the east bank of the St. Johns River that are at-risk for flooding in almost any major storm event. The major urban areas on the coast, including Daytona Beach and New Smyrna Beach are hit especially hard in Category IV storms and beyond (Figure 3.3b). These are areas frequented by tourists and consist of shopping districts, restaurants and bars, and some high-end residential development. Flooding, therefore, not only causes immediate economic damage through the destruction of property, but negatively impacts the local economies associated with tourism.

Figure 3.3. Road network degradation in Volusia County for Category II (a) and IV (b) hurricane storm surges. Light blue roads are those that are washed out. Black roads are still intact.

The infrastructure damage density results are displayed in Figure 3.4. These are the total number of households and businesses flooded by at least eight inches of water standardized by the total flooded area in each storm surge scenario. The household density damage ranges from just over 18 flooded households per square kilometer in a Category I storm surge, to over 90 households per square kilometer of flooded area in a Category V storm; while the business density ranges from 2 flooded businesses per square kilometer to 8. Table 3.2 displays the pairwise derivatives for those density results, showing the increase in damage between each consecutive storm surge. These derivatives simply represent the change in damage density between two consecutive hurricanes' storm surges, demonstrating where a change in storm surge strength is linked to a major change in damage. The largest increase for both occurs between storm surges of Category III and IV hurricanes.

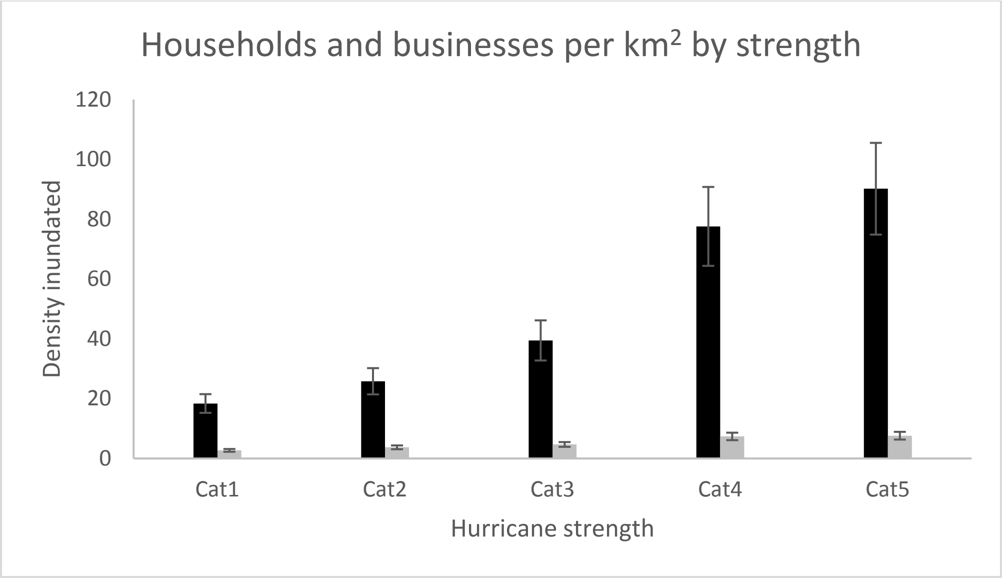

Figure 3.4. The numbers of households and businesses flooded per flooded square kilometer in each of the five simulated storm surges.

Table 3.2. The increase in flooded household (HH) and business (bus) density between simulated storm surges of increasing hurricane strength. The bolded numbers show the largest increase in damage for both.

	Flooded HH/km2	Flooded bus/km2
From cat 1 to 2	7.4	1.0
From cat 2 to 3	13.6	1.0
From cat 3 to 4	**38.1**	**2.7**
From cat 4 to 5	12.6	0.2

Finally, Figures 3.5 and 3.6 detail the results from the street network analysis. Figure 3.5 shows the total number of block points that become unable to reach all hospitals during storm surge floods of varying strengths. Interestingly, the number of disconnected block points more than double from a Category III storm surge flood to a Category IV storm surge flood, representing the largest between-category increase in the analysis. Figure 3.6 includes the numbers and total length of official evacuation roads that are washed out by storm surges of differing strength. Relatively few roads are washed out at lower scale flooding, but a similarly-sized increase occurs during Category IV storm surges (again, about a two-fold increase, from 650 roads washed out during a Category III storm surge compared to 1100 during a Category IV surge).

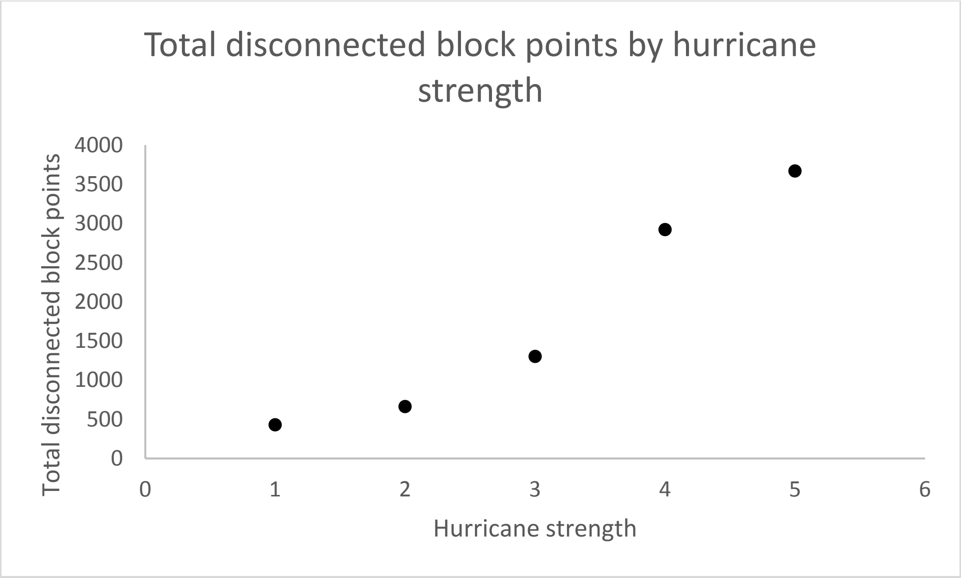

Figure 3.5. Total number of block points that are unable to access any hospital via road during different storm surge scenarios.

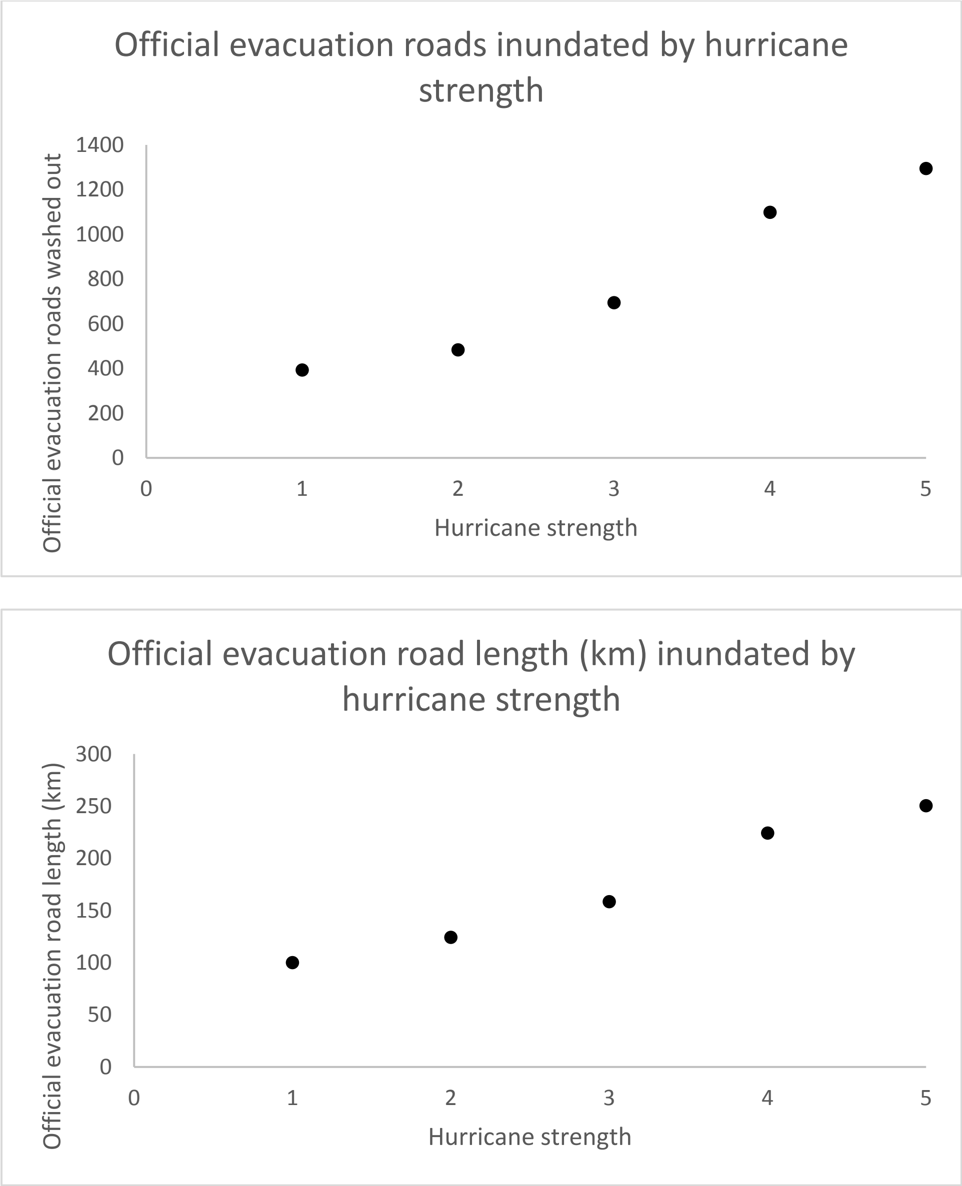

Figure 3.6. The number of official evacuation roads that are washed out in each storm surge scenario (a) and the total length of those washed out roads (b).

3.5 Discussion

Given the evidence detailed above, the results suggest that there may be a 'tipping point' of storm surge intensity which significantly increases and/or amplifies the likely damage to a coastal community. Figure 3.4, for example, shows that for storm surges at Category III and below, the damage to households and businesses is relatively minor, and the increase in damage between storm surges is fairly small. However, for a Category IV storm surge, the inundated households and businesses per square kilometer increase drastically (both metrics approximately double between a Category III and Category IV storm). The same increase is seen in Figure 3.5, where the total number of block points disconnected from the road network increases dramatically between Category III and IV storm surges (28% disconnected in a Category IV storm up from 12% in a Category II storm). The tipping point, in this case, represents a threshold of storm surge damage above which Volusia County is especially vulnerable. This threshold is likely caused by a wide variety of factors, including political and economic pressure, resident mindsets, the typical storm surge flooding regime of the area, and climate change (Sweet and Park 2014).

In short, these results suggest that Volusia County may be well positioned and prepared for low-intensity storm surges that occur somewhat frequently, but poorly prepared for larger or catastrophic storm events. Specifically, relatively few households and businesses are built at such a low elevation that minor flooding inundates them, and the road network has enough redundancy to handle small-scale floods as well. However, when storm surges become sufficiently large, during a Category IV hurricane for example, the overall damage increases precipitously. Flooding during surges of this size are able to reach elevations where development density is much higher. Additionally, much of the road network redundancy fails with floods of this magnitude, leaving large areas of Volusia County disconnected from the network at large and unable to reach important emergency medical facilities such as community hospitals via roads.

It is widely known that residents living along coastal areas in the United States have a tendency to consistently underestimate the danger posed by hurricanes and their associated storm surges, particularly when those storm events will be more severe than usual (Morss and Hayden 2010). Humans have a natural tendency to categorize unknown future risks in terms of recently experienced similar examples. In practice, this results in people assuming that forecast storms will be largely the same as previous storms they have endured, even in the face of predictions to the contrary (Slovic and Weber 2013; Slovic and Peters 2006). For example, despite numerous warnings from the National Weather Service (NWS), including a "certain death" statement issued by the organization, many residents in Galveston, Texas did not evacuate ahead of Hurricane Ike in 2008 (Morss and Hayden 2010). Most instead chose to ignore the warning, seriously underestimating the potential damage of the hurricane. Ultimately, over 110 deaths have been attributed to Ike, along with damages in excess of $29 billion (NOAA 2014).

In addition to a general lack of appropriate risk perception among residents, coastal areas tend to be developed aggressively (Kleinosky et al. 2007). Long periods of benign weather (the time between major hurricane storm surges, for example) erode the political will preventing overdevelopment of areas that are at risk for more severe but less frequent flooding. Not only are these areas over-developed (given their vulnerability), but they are often developed under the assumption of minimal or even no flood risk at all (Wu et al. 2002). Furthermore, climate change and its associated sea level rise exacerbate these problems. More areas in coastal communities are at risk for flooding due to sea level rise, including areas that have never been at risk before, many of which have not been developed appropriately to accommodate storm surge floods (McGranahan et al. 2007).

Volusia County, FL is no exception to these patterns. The bulk of its low-lying areas or those directly adjacent to the coast experience regular, minor flooding and are built with appropriate infrastructure. Residents in these areas understand the risks that flooding poses, and are familiar with evacuation routes. These are the areas that are flooded during Category I, II, and III hurricane storm surge simulations. While some roads are washed out and some properties are flooded, the damage is comparatively minor. However, during Category IV storm surge simulations, far more damage is done. Enough roads are washed out that the entire network loses a significant measure of redundancy and large swatches of densely developed areas are inundated. These are precisely the conditions that require evacuees and rescuers to travel off of the road network. Instead, they may be walking or driving through parking lots, constructions sites, or parks. This type of off-network travel is necessary during these large storm surge floods, but is inherently difficult to model using traditional network analysis, as seen in this chapter. During a Category IV+ storm surge, enormous numbers of businesses and households are disconnected from the road network – so the traditional network approach fails to find any appropriate routes for individuals in these locations to seek a medical facility (evacuate). Many emergency management offices face the same limitations, which is often the cause for inadequate evacuation and rescue planning. This same pattern is visible when examining the official evacuation routes – Volusia County provides these to its residents, but they consist only of the major roads that lead away from populated coastal areas. As these roads themselves become inundated during large storm surges, the established evacuation routes are of limited utility.

3.5.1 Limitations

There are known difficulties in attempting to accurately quantify storm surge damage using simulation models. First, for the purposes of this study, flooded households, businesses, and roads provide one indirect measure, but may fail to appropriately capture potential morbidity, mortality, and economic damage. To be sure, not all properties are flooded equally. In addition, by not incorporating personal attitudes or responses to storms, individual variation in response to storm warnings or actual flooding outcomes is ignored. Second, and inherent to traditional network analysis, the use of a derived metric of road network access to hospitals and allied evaluation of road system damage for Volusia County is somewhat limited. A more direct measure, one that incorporates the impacts of non-road landscape features on travel through Volusia County, might give a more holistic picture of the damage to the region’s traversability.

3.6 Conclusion

Similar to many locations along the Atlantic Coast and Gulf of Mexico, Volusia County and its communities are fairly well-prepared for low-intensity storm surges, such as those resulting from Category I, II, and III hurricanes. This is evident through the relative robustness of their official evacuation routes and underlying redundancy of the county road network. However, storm surge flooding caused by a Category IV hurricane reaches a tipping point that massively increases the scale of damage to the county. Far more households and businesses become flooded, more roads are washed out, and many of the official evacuation roads become unusable.

In many ways, this identified tipping point concretely represents the level at which Volusia County officials and development agencies planned for storm surge events: low elevation development is limited, but only to a certain extent. Severe (but relatively rare) storm surges were not accounted for during the development process. This means that many homes and businesses are vulnerable to flooding during catastrophic (>= Category IV) storm events. The same can be said for residential streets and other major arterials throughout the county, including formal hurricane evacuation routes. The problem for Volusia County, and many of its peers, is that community resilience benchmarks are changing. Given the likely future increase in storm surge intensity and frequency, it is important that coastal communities begin to prepare for more severe flooding, particularly in places that have long been immune to the effects of major storms. Part of this preparation includes the development of more effective and comprehensive evacuation routes provided to residents, and rescue plans provided to emergency personnel. Limiting these plans to solely on-road network travel is of limited utility, particularly during large floods that require effective plans all the more. The remainder of this dissertation concerns itself with solving this problem.

CHAPTER 4

USING VECTOR GRIDS TO IDENTIFY INFORMAL STREET NETWORK CONNECTIVITY

4.1 Introduction

The road network, and its interconnected system of major highways, commercial corridors, and residential streets is considered critical infrastructure and is essential to the day-to-day functioning of a region. Generally, roads are conceptually organized into a hierarchy (Yerra and Levinson 2005), consisting of four distinct road types that balance the opposing demands of through-traffic speed/volume and access (both to other roads and to road-adjacent property). At the top of the hierarchy are expressways – these offer high-volume, high-speed travel, with limited, controlled access to other roads and typically no direct property access. Next are arterial roads offering more property and road access at the cost of traffic speed and volume. Third are collectors, designed to funnel traffic to arterials, and at the bottom of the hierarchy are local roads. Local roads have the lowest speed, are low volume (often consisting of only one lane) and frequently have traffic calming features that discourage extended travel (Levinson and Zhu 2012). While the specific criteria for categorizing roads may differ from place to place, the complete road network of a given area will comprise these types of roads (Levinson and Yerra 2006).

Access to the road network is important for commerce and economic efficiency, personal and public transport between school, work, and recreation, as well as the provision of critical and emergency services to a community. Unforeseen disruptions, stemming from natural or technological disasters (e.g., flooding or bridge collapse) or more mundane problems such as congestion, can create significant negative consequences for communities that rely on this infrastructure (Jenelius, Petersen, and Mattsson 2006). For example, business impacts may include delayed supply delivery and increased shipping costs (Cavalli and Grigolato 2010). For individuals, longer commutes to work and/or school and an inability to run needed errands can disrupt both professional and personal activities. For public servants, road network disruptions may result in slower police or fire response, as well as delays in providing emergency medical care (Jotshi, Gong, and Batta 2009; Jones and Bentham 1995). Thus, given the large array of potential negative consequences associated with road network disruptions, it is increasingly important to better understand how extreme events impact terrestrial transportation systems and to better predict the likely locations of potential disruptions, their frequencies, and their associated impacts for a community.

As alluded to previously, there are countless types of road network disruptions, all of which have varying impacts. These range from simple on-network disruptions such as debris and accidents, to full road closures from auto/truck fires or traffic fatalities. Conversely, off-network disruptions such as natural disasters (e.g., flooding, earthquakes, etc.) are largely exogenous to the system. Nevertheless, these off-network disruptions can generate both primary and secondary impacts by disrupting travel corridors, fueling congestion, contributing to the collapse of key network elements (e.g., bridges), and balkanizing neighborhoods from the rest of the system (Haghighi et al. 2018).[3] It is anticipated that global climate change will only exacerbate the frequency and severity (Yang et al. 2013; Tao et al. 2013) of secondary disruptions, as very few

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[3] For the purposes of this chapter, primary effects are recognized as slowing or stopped traffic, as well as increased traffic loads and/or congestion on alternative routes. Secondary effects include the collapse of key network elements, fractured network connectivity, and being forced to bear additional fuel costs, lost productivity, and increased carbon emissions because of an extreme event.

regions are making proactive efforts to improve the resilience of their infrastructure (Huq et al. 2007).

In this context, road network vulnerability and network resilience are consistently two of the most important features in determining how a region responds to and recovers from a natural disaster (Jenelius and Mattsson 2015; Lida 1999; Hsieh and Feng 2014). During extreme events, network frailties not only inhibit the evacuation of residents (Berdica 2002), they limit emergency service response and post-disaster recovery efforts (Sohn 2006; Ozdamar et al. 2014). Despite the importance attributed to identifying vulnerable road segments, it remains difficult to determine precisely where and how road network reliability may be negatively impacted during a disaster (Jenelius and Mattsson 2012; Jenelius et al. 2006).

Interestingly, these uncertainties concerning network performance under duress are not because of a lack of interest or scant empirical work. There is a robust and growing corpus of research concerning the impacts of large-scale and sudden disruptions to a road network (Chen et al. 2002; Lida 2010; Haghighi et al. 2018; Khademi et al. 2015; Lo and Tung 2003; Matisziw et al. 2009; Pregnolato et al. 2016; Scott et al. 2006; Shi et al. 2015; Starita et al. 2017). However, one glaring gap in this body of work is a close examination of how proximal, off-network areas have the potential to interact with network space, potentially helping to mitigate both primary and secondary effects of network disruptions. Recall the hierarchy of roads detailed previously. While this hierarchy will consist of virtually every road in a region, including unpaved or very minor network segments, it does not fully capture a network's *de facto* connectivity, particularly during an emergency. For example, there are a wide variety of informal networked spaces which are intertwined with the road network such as parking lots, parks, construction sites, alleys, and driveways that are navigable for many vehicles.

These informal network spaces are rarely captured in traditional network abstractions and representations (Hu et al. 2007).[4] However, these off-network features can function as network links (in certain situations), depending on *in situ* context and the geophysical composition of an area. This is especially true during emergencies, when the normal rules of the road and associated societal restrictions preventing the use of these alternative pathways are relaxed (Shieh et al. 2014). For example, on a typical day, driving through a construction site or across a park would not only be illegal, it would rarely be more efficient than using the existing street network. However, these off-network features, which do informally connect to the road network, can be used by residents and emergency personnel both during and/or immediately after a disaster. In short, these informal connections provide alternative pathways to reconnect and temporarily heal the street network when disruptions occur during an extreme event. From a modeling perspective, these informal connections are difficult to account for in traditional street network/graph abstractions. Thus, new approaches are required to include these informal paths when evaluating network continuity and local emergency response strategies.

The purpose of this chapter is to demonstrate a new conceptualization by which a region's transportation network can be modeled using both on-network and off-network space, primarily for emergency evacuation, rescue, and response. This approach disambiguates on- and off-network features into a flexible matrix of grid cells, which adopt the characteristics of the underlying terrain's geographic features and allow for an alternative, higher fidelity snapshot of local network context, while providing an improved characterization of network continuity during a disaster. Specifically, the grid-

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[4] Abstracted representations of the road system almost exclusively consist of roads and intersections (Hu et al. 2007).

based approach allows for the consideration of off-network (i.e., non-road) travel. Again, drawing conclusions about regional resilience, network continuity, access, and mobility in a given area by solely examining on-network features fails to account for *in situ* context and the many pieces of a developed landscape that abut roads – potentially providing alternative pathways to the disrupted network. Continuing from the previous chapter, the newly developed conceptualization is explored on portions of the road network of Volusia County, Florida during a simulated hurricane storm surge event.

This work is important for several reasons. First, this type of alternative approach could lead to more effective emergency planning efforts. In fact, it is during emergencies when evacuees and first responders are using off-network space to move through an urban landscape. For example, the evacuation routes of some flood-vulnerable communities are, in fact, more vulnerable to flooding than an area's overall road network. The ability to identify alternative, off-network paths to reconnect and temporarily heal the local road system during an extreme event would be immensely valuable to emergency response. Second, planners in coastal communities are rightfully concerned with minimizing community vulnerability to floods (Lamond and Proverbs 2009; Zevenbergen et al. 2008). Thus, developing a more holistic understanding of transportation network vulnerability is key to the development, design, and placement of proximal, off-network features that can improve network continuity during extreme flooding events. Finally, the methods developed in this chapter are a good first step for improving the representation of complex, real-world transportation systems. While abstracting roads and intersections into a series of edges and nodes is useful for many types of analyses, this process ignores every interaction that occurs with off-network features. Real-world systems are not completely discrete, nor are they divorced from interactions with their surroundings. The incorporation of local, *in situ* context will be critical for developing higher fidelity tools for modeling interactions between infrastructure systems and their local environments.

4.2 Background

4.2.1 Real-world Systems as Networks

Network modeling is strongly rooted in graph theory, where a network is defined as a graph G = (V, E) comprising a set of V vertices/nodes and a set of E edges/arcs. The nodes and edges are often assigned feature-specific attributes, including name, location, capacity, and the like. The power of network abstractions and associated graphs is their ability to represent (and subsequently facilitate the modeling and analysis of) a wide range of natural and technological systems, including: trophic networks (Thebault and Fontain 2010), molecular networks (Tanay et al. 2004), pollinator systems (Olesen and Jordano 2002), telecommunication systems (Matisziw et al. 2012), social networks (Eagle et al. 2009), transportation systems (Murray, Matisziw, and Grubesic 2007; Jenelius, Petersen, and Mattsson 2006), and many others.

Interestingly, most of these systems possess a real-world physical design and/or layout that is easily abstracted to a graph. For example, representing the nodes (e.g., routers) and links (e.g., fiber optic cables) of a telecommunication system is relatively trivial with a graph (Grubesic and Murray 2006). Similarly, in rail networks, train stations act as nodes with rail lines functioning as edges (Wang et al. 2011). Some systems may have infrastructure elements for a subset of network features, but not for all. For example, air transport networks use airports as nodes, but there is no “built” infrastructure that serves as the edges (i.e., routes) between airports in this system

(Bagler 2008; Coldren et al. 2003). In other instances, networks may be completely devoid of built infrastructure. For example, network models can be used to describe how people walk through open space. In such instances, the edges and nodes do not represent built features, but there is still quantifiable flow along a particular path between places in continuous space (Sugiyama and Thompson 2008).

4.2.2 Road Systems and the Limitations of Traditional Network Models

When traditional network models are used to disambiguate real-world systems, oversimplification occurs. The abstraction process reduces these systems into a graph and its constituent components, G = (V, E). Lost in this process is any relationship between the features of the network (V, E) and their ambient operating area or *in situ* space. This is not always a problem, because some systems have very little interaction with their off-network space (e.g., broadband telecommunications infrastructure tends to be insulated from its surroundings). That said, even when there are off-network perturbations that affect broadband infrastructure (e.g., construction inadvertently severing a cable line), the disturbances tend to lead to binary impacts, in which segments of the network are either unaffected or completely interdicted – there are virtually no situations in which off-network features function as ad-hoc edges or nodes (Grubesic and Murray 2006; Grubesic and Mack 2015).

However, this is not the case for street networks. The off-network space that surrounds roads and intersections can have a much larger and more variable effect on the operational continuity of these systems. Specifically, due to the relatively exposed operating environment for the street network, and the fact that much (but not all) of the space surrounding roads is built to be accessible by vehicle, the boundaries between on-and off-network space are blurred. For example, vehicles traveling along roads frequently leave the network by entering parcels adjacent to the road (e.g., stores, parks, etc.), and may rejoin the network in a different place, at a later time. These off-network locations influence a wide variety of network characteristics (such as structure, connectivity, and flow patterns) without ever being represented by traditional network models. In practice, of course, these effects are usually minimal. During normal operating conditions, the vast majority of network flow is occurring on-network, traveling along roads and passing through intersections. However, when considering other forms of transportation (such as biking, which requires different network connectivity rules than driving; Winters et al. 2010), or situations in which normal rules are not in effect (such as during an emergency, when roads are closed or damaged; Sakakibara, Kajitani, and Okada 2004), the effects of these off-network areas can be outsized.

Consider Figure 4.1, which illustrates a relatively major intersection in Phoenix, Arizona (Northern Ave. and 12th St.). Again, while the bulk of the traffic flow occurs on-network, there are many opportunities for interacting with off-network space (represented with red arrows). Most of these off-network spaces consist of parking lots, alleys, and corner retail spaces (e.g., gas station), but the sheer number of these opportunities is notable. For these reasons, road systems provide an excellent case study for examining the limitations of traditional network models, especially since they are an indispensable feature of modern urban life, their flow patterns are temporally variable, and their network connectivity rules vary by mode. The situation of interest for this chapter concerns the conditions of a road network during, and immediately following, a large storm surge flood event that leaves significant portions of the system impassable. In particular, it is important to determine how on- and off-network spaces might interact when used by evacuees, rescuers, and other emergency personnel. Recall the limitations of exclusively using traditional network analysis on these post-storm landscapes from the previous chapter.

Figure 4.1. An illustration of how off-network features (such as parking lots, alleys, and driveways) provide *de facto* street network connectivity.

4.2.3 Road Networks during Storm Surges

As mentioned previously, storm surges of sufficient strength can flood roadways and render them impassable for several hours to multiple days or weeks (Karim and Mimura 2008; Kleinosky et al. 2006). The roads are not only interdicted by standing water, they are blocked by deposited debris, or may actually be destroyed by the force of the storm surge via hydrostatic uplift (Kelman and Spence 2004). Aside from directly impacting the overall connectivity of the network, in the worst cases, local and regional damage to the streets may accelerate the balkanization process, where large portions of the road network are disconnected from the system at large, creating distinct sub-networks.

Interestingly, it is during these types of disasters that the normal operating rules of the road least apply. Moreover, this also means that the *in situ* context of the street network and its off-network space is a critical consideration for community response. For example, emergency evacuations of urban areas often require entirely different road enforcement rules for maximum efficiency. During emergencies, both vehicles and pedestrians utilize road networks differently. Pedestrians may prefer to move along on-network spaces (i.e., follow a road) but are able to easily move between on- and off-network space when required to do so (Zhang and Chang 2014).

It is important to acknowledge that these changes to how the road network functions during emergencies occur for several reasons. First, after any formal evacuation, people tend to shelter in place, so there is almost no flow on the street network when compared to normal operating conditions. This means that first responders can reach those in need without any concerns for traffic or traditional rules of the road. Second, there may be late evacuees in vehicles, or on foot, as well as emergency responders attempting to rescue trapped individuals or distribute survival goods. In either case, individuals can traverse off-network space, as needed, to reach their destinations. For these reasons, the *de facto* network structure changes during disasters, but as mentioned previously, these changes are not captured in traditional network models.

From a pragmatic perspective, the formal evacuation routes for disasters in a given region may not realistically reflect how people are interacting with the local street network. Again, many evacuees travel on foot, wading along flooded roads, parking lots, or parks, but this blended on-network/off-network travel is not captured by models that limit themselves to the analysis of formal network footprints. In addition, real-time rescue efforts during a disaster may be multi-modal, where first responders move from an emergency dispatch location to a flooded area, transfer to a boat, and then navigate via boat through a flooded urban landscape. Not only are these unique ways of travel ignored when it comes to determining emergency operation hubs, dispatch locations, and rescue routes, but the multi-modal nature of this travel is unique.

Issues associated with strategic planning for urban flood management are also salient here. Although the most vulnerable regions would certainly benefit from a coordinated plan, many municipalities plan in isolation, lacking important feedback from neighboring communities and their associated planning agencies. The politics of flood management plans and the influence of developers as well as a dependence on centralized infrastructure are also concerns (Zevenbergen et al. 2008). Regardless of the challenge, introducing a new, higher fidelity network conceptualization for evaluating urban connectivity, routing, and emergency response during extreme events will provide stakeholders with a foundation for minimizing flood vulnerability during development efforts (Price and Vojinovic 2008).

4.3 Methods

4.3.1 Study Area and Data

Hundreds of municipalities are vulnerable to hurricane storm surge flooding, including virtually all the Atlantic and Gulf coasts in the United States. The method developed in this chapter explores residential and light commercial areas of Daytona Beach, Florida in Volusia County (Figure 3.1). While this approach is demonstrated on a relatively small piece of developed coastline, it is important to note that the methods detailed here can be applied to any developed urban area, of any size, at risk for flooding. As mentioned in the previous chapter, Volusia County is an ideal location to study these effects.

In addition to the Volusia County road database and SLOSH-generated simulated storm surges (for details, see Chapter 3), building footprint shapefiles were supplied by Oak Ridge National Laboratory (Florida Building Footprints 2017), land cover data was obtained from the Florida Department of Environmental Protection (Statewide Land Use 2017), and impervious surface data was obtained from the Multi-Resolution Land Characteristics Consortium National Land Cover Database (MRLC NLCD) (Xian et al. 2011).

A Euclidean-based distance buffer was assigned to each road segment, commensurate with the physical size of the type of road being represented. Specifically, U.S. highways, interstate highways, and state highways were given a buffer of 22 meters across. 22 meters was chosen as that it is the average width of a four lane highway (two lanes in each direction). Naturally, highway width is not strictly consistent across an entire county, but this figure serves as an appropriate estimate for the highways present in Volusia County (Staff 2001). County roads were given a buffer of 14 meters and surface streets a buffer of 10 meters (Urban Street Design Guide 2013). Given the fine scale at which the vector grid (detailed below) are produced for this analysis, this is a higher-fidelity alternative to treating a road as a two-dimensional line.

4.3.2 Grid Generation

A generated surface of vector grid cells (400 meters squared, 20 meters to a side) was overlaid on the study area containing the road, storm surge, land cover, impervious surface, and building footprint shapefiles. This grid cell size was used for several reasons. First, and most importantly, 400 square meters represents an appropriate cell size to reconcile the different resolutions and scales at which the other datasets are operating. While a smaller cell size would appear to increase the resolution of our approach, this would be somewhat misleading since some of the datasets (specifically the simulated flood, road footprint, and land cover data) are generated at a coarser scale. Second, many of the actual phenomena represented by these datasets are operating at a scale similar to the cell size. It is uncommon, for example, for land cover or land use to change dramatically or multiple times within a 400 square meter cell. Finally, this approach becomes prohibitively computationally intensive when using very small cell sizes. It is worth noting that even with a cell size of 400 square meters, the generation of these grid cells requires some computational heft. The methods outlined here were performed in Python 2.7 primarily using the packages GDAL, PySAL, and Shapely on a Windows 8 machine. For a study area the size of Volusia County, Florida, nearly 10,000,000 cells were generated, taking approximately 20 hours.

Each grid cell was assigned an impedance score based on the estimated difficulty of passing through it during a storm surge flood. As detailed by Upchurch et al. (2004), traveling along a road is preferable to traveling on non-road surfaces (e.g., through a parking lot, a park, or a yard). However, both rescue personnel and evacuees will depart from a road as needed to reach safety. To that end, impedance scores were assigned based on a set of rules governing likely travel preferences and capabilities through a flooded landscape. First, travel through an unflooded landscape is always preferable to traveling through a flooded area. Second, traveling along roads is superior to traveling off of them. When forced to travel off of roads, impervious surfaces (such as parking lots) are preferable to parks or lightly wooded areas, while lightly wooded areas are preferable to heavily wooded space. Finally, buildings and water features are impassable, in both an unflooded and a flooded landscape.

These rules create a hierarchy of travel preference when navigating a flooded landscape. To quantify the ‘cost’ of moving through different cells, impedance scores are used, with each cell receiving a score based on the mixture of landscape features and flood status that make up that cell. These scores are somewhat arbitrary, as a variety of combinations of scores could fulfill the travel preference rules, and it is important to note that they can (and should) change for different regions, different disasters, or with different landscape data. The approach outlined here is easily adapted to other regions and datasets. In each case, impedance scores should be determined based on specific *in situ* characteristics. For this study, the impedance scores were determined by sensitivity analysis, with this particular combination of scores deemed feasible.

The first step of this alternative conceptualization assigns cells that are located inside buildings or water features an impedance score of 999, with the assumption that these cells are entirely impassable. Next, off-network and flooded cells are given scores based on the dominant land cover of the cell – heavily forested cells receive a score of 100, lightly forested cells receive a score of 80, cells with a non-road impervious surface receive a score of 60, while flooded cells along a road receive an impedance score of 50. Unflooded cells that are off-network receive the following scores – heavily forested, 10; lightly forested, 8, and non-road impervious surface, 6. Finally, unflooded cells located on-network (along roads) receive an impedance score of 1, representing the strongest preference for travel. See Table 4.1 for details and Figure 4.2 for an example. These impedance scores are functionally categorical variables – however, the assignment of a specific value allows for more nuanced routing methods to be applied and for comparisons between the relative impassibility of different combinations of conditions. Shortest-distance routing through the gridded landscape is accomplished by globally minimizing impedance scores, instead of being constrained to network space as in traditional network models.

Table 4.1. Land cover types and their associated impedance scores.

Impedance score	Land cover	Flooded?
1	Road	No
6	Impervious	No
8	Light forest	No
10	Heavy forest	No
50	Road	Yes
60	Impervious	Yes
80	Light forest	Yes
100	Heavy forest	Yes
999	Buildings/water	N/A

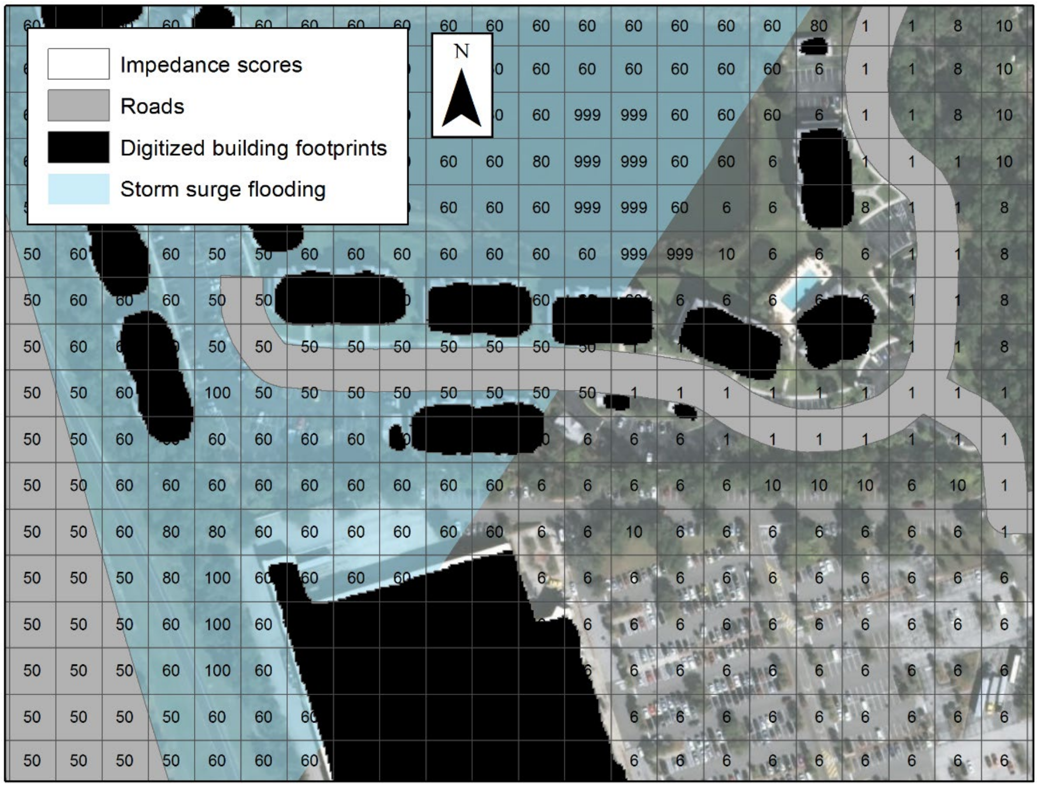

Figure 4.2. Example of grid impedances with roads, digitized building footprints, and storm surge flooding layers.

4.4 Results

Ultimately, this grid-based approach allows for a more nuanced model of network systems that better reflects how systems function in the real world. Figure 4.3 provides a more detailed example using a suburban area, north of Daytona Beach. There is a large subdivision located on relatively higher ground between low-lying marshy areas (to the west) and the beach (to the east). During a simulated Category IV hurricane storm surge, this entire swath of businesses and residences remains unflooded, but they are cut-off and isolated from the surrounding community. Residents in this area may try to evacuate during or immediately after the storm surge, potentially requiring rescue services. In this context, and as detailed in Figure 4.3, a traditional network model built on this road system would categorize the area as being entirely interdicted, forming a disconnected subnetwork.

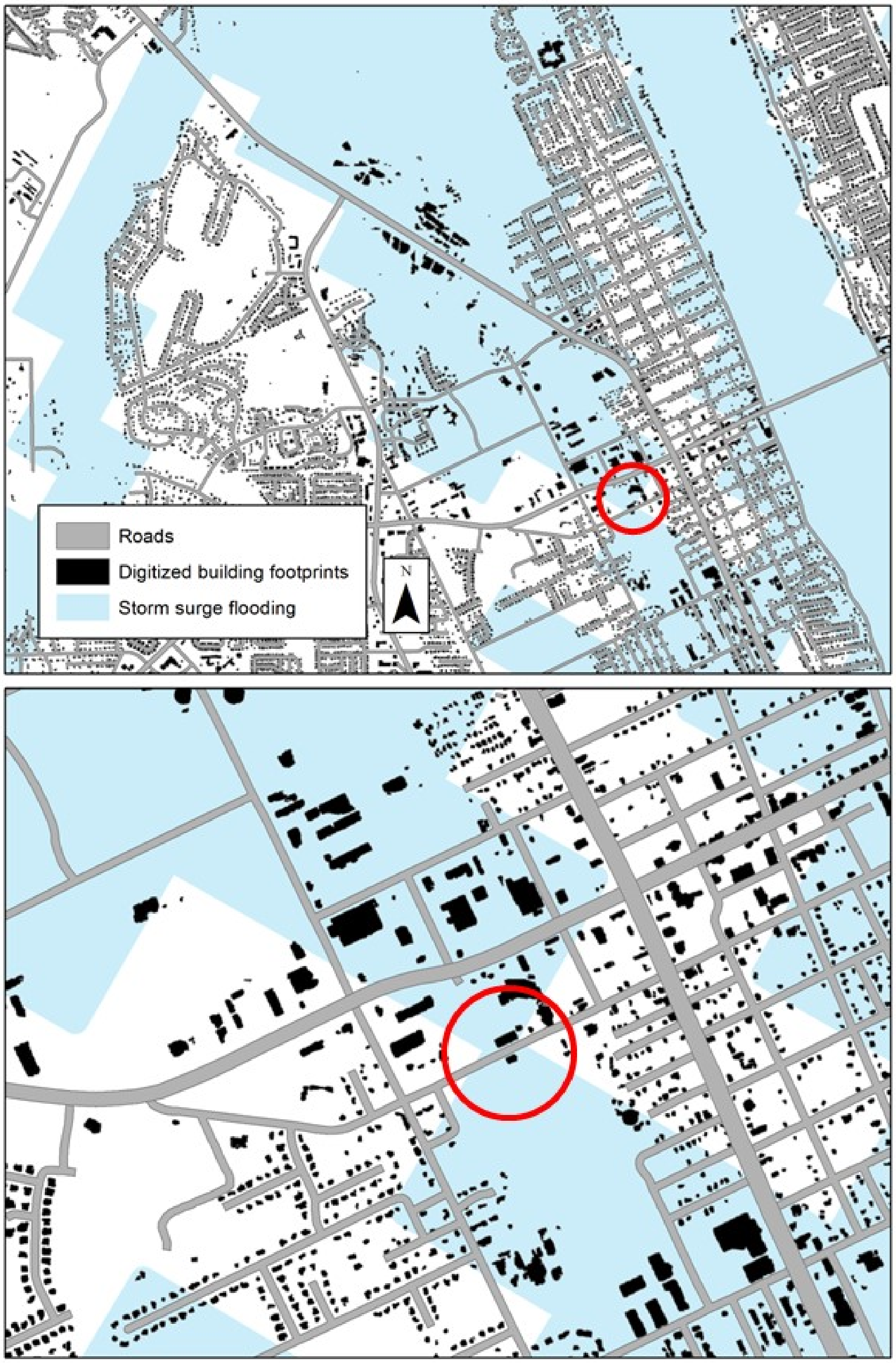

Figure 4.3. Portion of the study area likely experiencing higher *de facto* connectivity than reported by traditional network models. A red circle highlights the flooding across Tomoka Avenue that creates the separate and disconnected sub-network to the east.

Of interest is the area highlighted by the red circle in Figure 4.3. Because of storm surge flooding, a traditional network model would show Tomoka Avenue as completely interdicted. Functionally, there would be no difference between Tomoka Avenue and any of the more flooded roads to the north – all would be tagged as impassable. Again, this highlights the limitations of a more traditional network modeling approach, and is exactly what led to the large number of households and businesses disconnected from the network in Chapter 3. Standard representations of network disruptions provide no insight on how to access isolated sub-networks, particularly if there are real-time emergency management decisions to be made. As a result, routing would require a manual examination of a map like Figure 4.3, or the addition of criteria that assign situation-specific attributes to network features. To be clear, these may be in place and understood by local emergency management teams. However, the grid-based approach detailed here can provide a fast and relatively accurate snapshot of how network degradation manifests for any region with no manual input.

Consider Figures 4.4, 4.5, and 4.6, which highlight the differences between traditional network routing and grid-based routing in several different scenarios. Figure 4.4 compares the routing methods when navigating between two points in an unflooded landscape. Both methods find the same route between the two points, since the shortest network distance route is the same route that minimizes impedance scores in the grid-based approach. Assuming the existence of a comprehensive and complete road network dataset, the grid-based approach provides no benefit here (although there is also no drawback). However, when navigating a fractured landscape with interdicted road segments, the grid-based routing is superior. Figure 4.5 demonstrates the difficulties associated with traditional routing through a flooded landscape. As detailed previously, traditional network models are unable to find a route between these points. The grid-based approach, however, is able to utilize the adjacent parking lot to recommend a route that is not only shorter than using the road network, but requires no travel through flooded areas. Finally, Figure 4.6 highlights how each method performs when travel through a flooded area is necessary (travel through flooded terrain may be necessary when navigating landscapes like that shown in Figure 4.3, in which flooding has completely isolated pieces of the landscape from each other). The traditional network method usually fails to solve – road interdiction in that model is binary, and a flooded road is considered impassable (Figure 4.6a). By explicitly ignoring the flooding, the traditional routing method solves, but cannot distinguish between unflooded and flooded roads, and so suggests a route that requires passing through more flooded terrain than is necessary (Figure 4.6b). Finally, the grid-based approach prioritizes unflooded travel more than minimizing distance traveled (Figure 4.6c).

For emergency rescue personnel, many of their destinations will be located in (or through) flooded territory. Traditional network methods either fail to find any route connecting the rescue personnel and their destinations or are completely blind to the presence of flooding. The grid-based approach attempts to minimize impedance scores while routing, enabling it to prioritize unflooded areas, roads, and other traversable surfaces as much as possible, while also maintaining the possibility of travel through a flooded area if needed. When visually examining the terrain in Figures 4.4, 4.5, and 4.6, the proposed routes are obvious – but these scenarios, involving micro-modules in the network, occur dynamically throughout a flooded urban region, and the grid-based approach's strength is in its ability to automatically generate these sorts of routes between O/D pairs.

This information can be quantified and used for strategic planning efforts to ensure that alternative, off-network pathways and their connectivity are better understood. Of course, during an actual disaster, not all road segments are flooded equally. Thus, using impedance scores that reflect a variety of underlying geographic data allows for a higher fidelity model that better reflects on-the-ground conditions. In addition, since the grid-based approach rasterizes an entire landscape, routing efforts are not limited to network space.

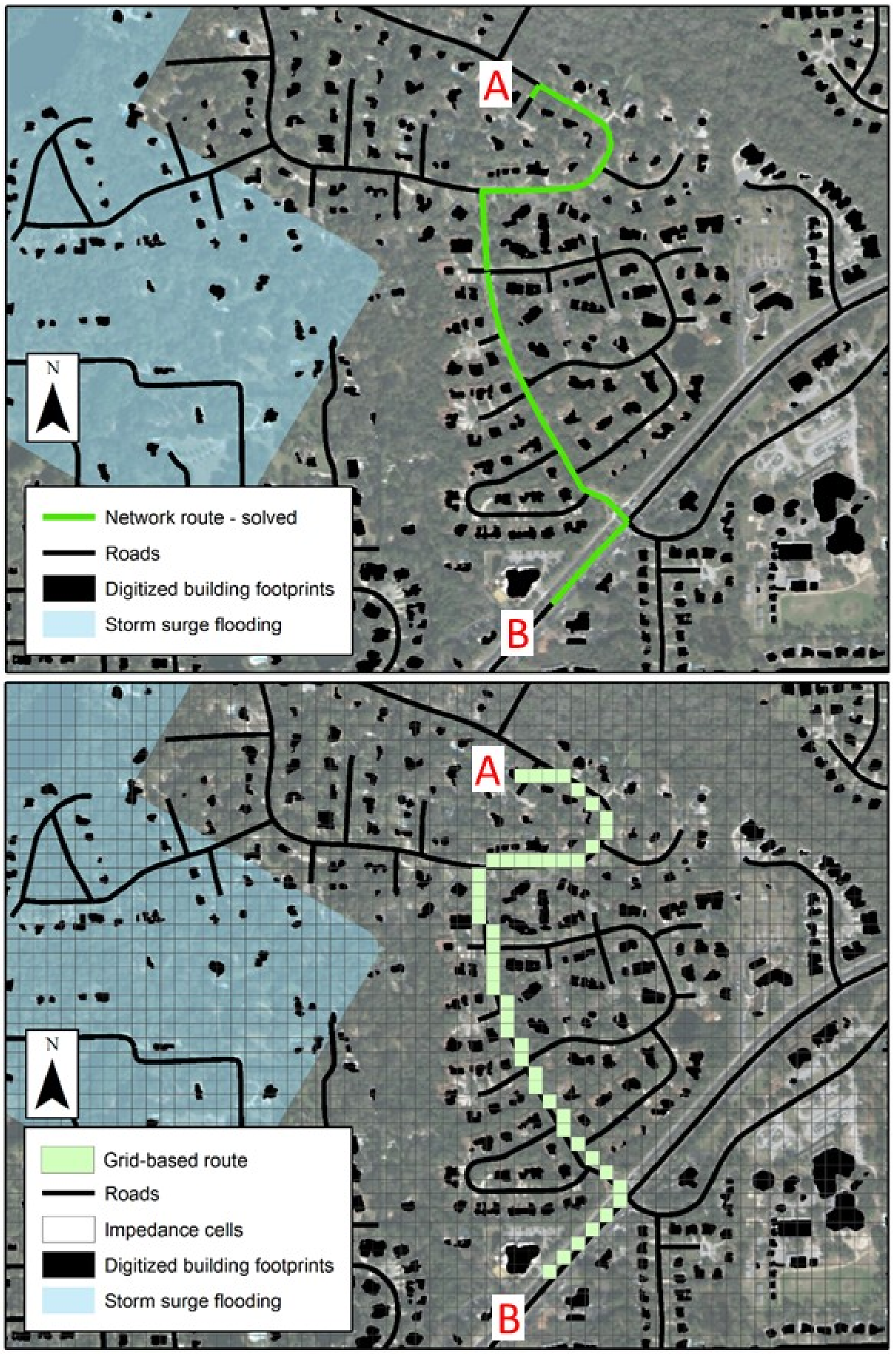

Figure 4.4. Both the traditional network and grid-based network routing methods are able to find a route between points A and B. When routing through unflooded landscape, the two methods will typically find the same route. This is due to the traditional network's requirement that routes can only follow unimpeded roads and the fact that the grid-based approach incentivizes road travel via its low impedance score.

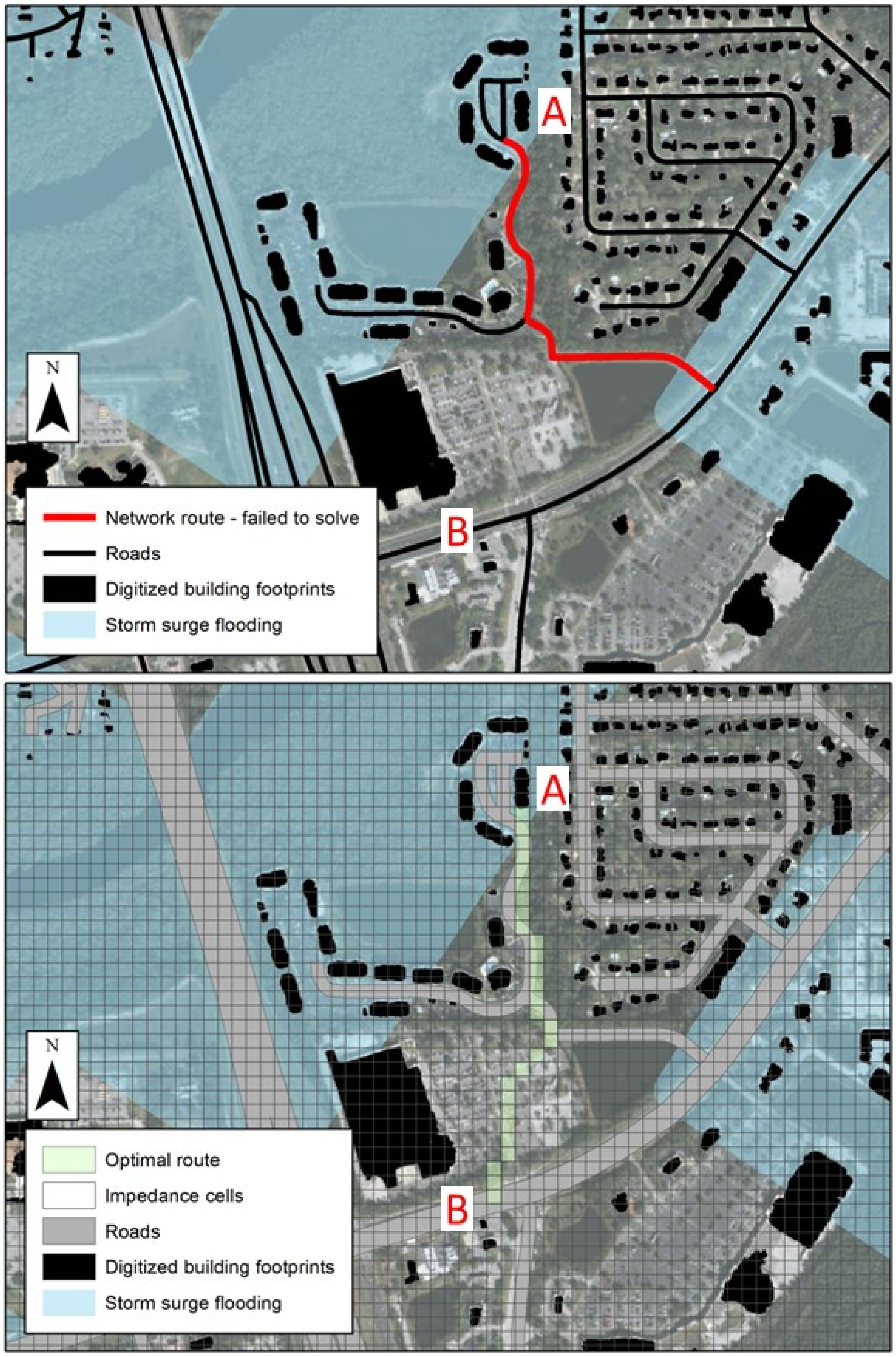

Figure 4.5. When attempting to find a route between points A and B, a shortest-distance approach in a traditional network model fails to solve (4.5a), due to the interdicted road segments. However, generating a route that minimizes the impedance scores between the same points finds a route through a parking lot (4.5b), which may be of interest to rescue personnel or evacuees. Note the preference for roads but also the ability to route through adjacent, non-road features.

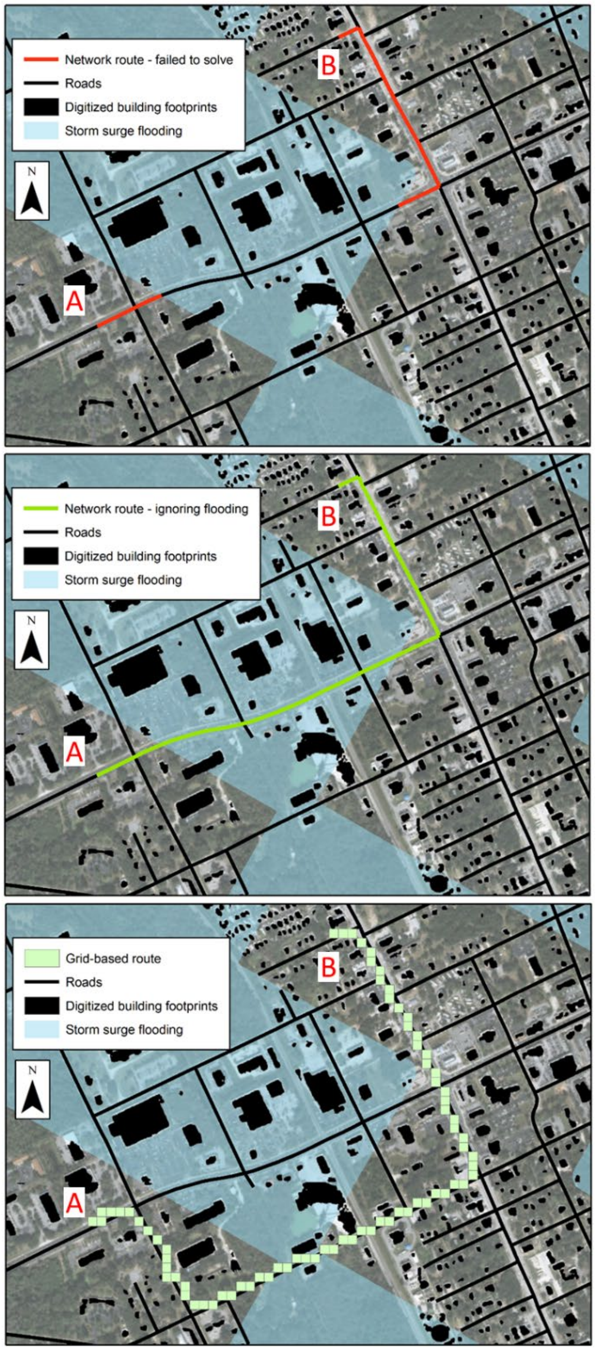

Figure 4.6. Traditional network routing methods are typically unable to find a route between points A and B due to road interdiction (4.6a). They can be modified to ignore flooding, in which case they simply try to find the shortest distance between the two points, even if that route requires extensive travel through flooded areas. (4.6b). The grid-based routing approach is able to find a route that minimizes travel through flooded landscape while prioritizing keeping the route on a road (4.6c).

4.5 Discussion

The grid-based approach outlined in this chapter provides a different framework for conceptualizing and modeling networked systems in the real-world. While traditional network models offer powerful techniques to quantify and understand network structure and function, they require a large degree of abstraction. This results in systems being analyzed as networks in a vacuum, with no dynamic influence from their surroundings. In many cases, this is ok, where the loss of fidelity is not necessarily detrimental to understanding the networked system (e.g., telecommunication or social networks). However, some systems are 'messier' and are not operating in isolation. Street networks are a prime example of this. It is important to acknowledge that all network flow has an origin and a destination off-network. For example, cars are moving from a house (off network, but connected by a driveway) to a school (off network, but connected by a parking lot). The characteristics of these off-network features matter. They can provide additional connectivity, they can change network structure, and they can influence network flow.

In most cases, the flow processed by a large parking lot near a major street intersection can be ignored. The impacts are small and likely trivial considering the overall volume of flow occurring across the primary network. However, there are some unique situations in which these spaces can matter a great deal – this chapter highlights how during an emergency, the normal operating rules of the road may not apply, the total volume of network flow is dramatically decreased, and the specific nature of the off-network features immediately adjacent to roads may be important in determining the overall connectivity of a region. During a large-scale flood, many residents of an area evacuate along flooded roads, parks, and parking lots, while rescue efforts or supply delivery are occurring along the same routes. These routes are dynamic and dependent on a variety of local conditions. Determining how best to travel through a flooded region (either in real-time or for the strategic planning of evacuation routes) requires a more nuanced understanding of how people will travel through a post-disaster landscape. This is information that is difficult to account for in traditional network models.

An example route in a simulated flooded landscape is shown above, in Figure 4.5. Note that the route preferentially selects travel through the unflooded parking lot while avoiding flooded roads and more heavily wooded areas. These are precisely the types of routes that evacuees and rescuers would prefer to use during an emergency and finding them for strategic planning purposes or in real-time during the immediate aftermath of a disaster is incredibly important. The route in Figure 4.5 could not be generated by traditional network analysis; such approaches fail to account for off-network features. In addition, by preferring certain types of off-network terrain over others, the grid-based method more reliably simulates the thought processes (and actions) of evacuees or rescue personnel making decisions on the ground.

Besides routing efforts, the grid-based method provides for a more realistic picture of the overall street network's characteristics during a disaster. When it comes to network connectivity, for example, while flooding may interdict a road, the overall network's connectivity may be buoyed by adjacent, drivable features, such as parking lots. Again, this more nuanced conception of a region's overall connectivity cannot be produced by graph-based representations of a network. In addition, network modularity as determined by a grid-based approach, is more realistic. Consider the example from Figure 4.3. While the flooding results in a large portion of the road network being Balkanized and disconnected from the remaining network, that disconnection is visibly less severe than one in which a portion of the network was surrounded by more flooded terrain. By rating the traversability of off-network features with impedance scores, the grid-based approach allows for the generation of higher fidelity network characteristics when it comes to road networks – benefiting emergency responders and other stakeholders involved in strategic planning efforts for a community.

Flood damage mitigation is critical to any comprehensive urban planning framework, and the grid-based approach highlighted here provides an additional tool for evaluating how non-road features will factor into a region’s overall connectivity during a disaster. With the addition of supplementary geographic data, planners could use this approach to make more informed decisions on where to locate parks, parking lots, or other types of “connective network tissue” to improve regional resilience. The grid-based approach is highly scalable, which means that urban planners may easily adapt the general modeling framework for their particular location and existing geographic datasets.

Finally, the use of this more holistic model will allow for a more comprehensive quantified understanding of a region’s transportation network. Existing road network studies that examine network structure, connectivity, or critical features ignore off-network areas (Chen et al. 2002; Jenelius 2009). New measurements that seek to determine the overall transportation capability of a region under a certain set of circumstances will provide higher fidelity tools for quantifying phenomena in the real world. Existing network routing and network connectivity tools on a partially flooded network are largely unable to capture how people may actually be moving through the landscape, and thus are of limited help to emergency personnel.

4.5.1 Limitations and Future Work

The grid-based approach demonstrated here is a compromise between the tensions of high spatial resolution and model utility. Every cell in the grid is 400 square meters in size, meaning that any underlying geographic phenomena that manifest at a smaller size are overlooked. However, shrinking the cells increases the computational load significantly – ideally, the grid dimensions will vary between study areas and their circumstances, as needed. In addition, the impedance scores in this chapter were determined arbitrarily, but these scores are highly site-reliant. Determining appropriate impedance values for a given disaster in a given location will require familiarity with the area itself as well as an understanding of what those scores will be used for. There are a wide variety of additional datasets that could inform impedance scores for a region. These could include the presence of elevated roads, the existence of flood prevention technologies (such as levees), the presence and capacity of natural features to mitigate flooding (such as wetlands), and more detailed land-use data. Incorporating any of these would allow for a more nuanced and higher fidelity set of impedance scores. The potential impacts of these datasets are highly site-specific. Future work should explore which assortment of data accurately allows for impedance calculation, as well as consider alternative methods to assign the impedance scores. Instead of assigned static scores, land-use categories could be given score ranges, from which a cell draws its individual impedance score stochastically. There are also a variety of different routing methods that could be adapted to function on a rasterized landscape. Emergency response and evacuation data from historical disasters could also be used to fine-tune the production of the impedances and to help identify potential real-world uses of the model.

4.6 Conclusion

This chapter demonstrates a novel approach to modeling networked systems that better reflect how those systems interact with their surroundings in the real-world. This grid-based method was used to produce a higher fidelity road network model during a simulated hurricane storm surge flood. While traditional network models are useful for describing both global and local network characteristics, they necessarily divorce the network from its surroundings. In many cases, this is irrelevant, but some systems that are best understood as networks (roads, for example) have frequent and non-trivial interactions with the off-network features that immediately surround them. These off-network features can impact network structure and connectivity, particularly when the typical rules of network function are dynamic, such as during a disaster. For roads in particular, the grid-based approach trades resolution for the ability to capture the influences of the surrounding off-network areas on the roads themselves. This type of model can positively influence emergency management, emergency preparedness, and urban planning. Fortunately, the grid-based model is not limited in utility to solely post-disaster landscapes – it can be modified so that it can be used to identify potentially critical road segments absent any specific disaster scenario. This method is detailed in the following chapter.

CHAPTER 5

IDENTIFYING CRITICAL ROAD SEGMENTS USING OFF-NETWORK FEATURES

5.1 Introduction

A variety of infrastructure systems make modern society possible – everything from sewerage and wastewater systems, to the power grid and urban street networks. There are high costs, both economic and otherwise, to a region when these systems are disrupted. Internet or power outages of short durations cost businesses billions each year (Plattner et al. 2004), while temporary road disruptions have similar impacts (Connelly and Supangan 2006). As discussed previously, day-to-day social functions also become impossible absent this infrastructure. Road disruptions prevent personal and public transportation to/from work, school, or shopping, and can also drastically increase shipping costs or slow first-responders and emergency services from reaching areas where lives and/or property may be in danger (Cavalli and Gigolato 2010; Jenelius et al. 2006).

Research pertaining to the vulnerability of road systems takes several forms. For example, a significant body of research focuses on predicting disruption types, durations and locations (Bil et al. 2015; Bono and Gutierrez 2011), as well as the development of strategies for mitigation and adaptation (Sakakibara et al. 2004; Lida 2010; Sumalee and Kurauchi 2006). Other work in this domain explores the reliability and underlying structure of the damaged network (Horner and Widener 2011; Grubesic and Murray 2006; Tatano and Tsuchiya 2008), often with a focus on identifying specific features that are critical to the performance of the system (Grubesic and Matisziw 2013; Jenelius and

Mattsson 2015; Sullivan et al. 2010). A more detailed review of this literature can be found in the following section.

This chapter is primarily concerned with the last approach – the identification of critical features in a road network. In this context, critical features are defined as those that are particularly integral to the structure, continuity, and function of the network, as a whole (Taylor and Susilawati 2012). In many road networks, these features are often a bridge, highway, or interstate exchange that connects two heavily used (but sparsely connected) sub-systems.[5] The identification of critical features is important for many reasons, including the development of strategies for hardening and/or defending the infrastructure from attack (Brown et al. 2006), increasing infrastructure reliability and efficiency (Amin 2008), and responding to and recovering from natural disasters (Kitigawa et al. 2017), among others.

For most of the studies detailed above, road systems are modeled as networks; sets of nodes (network intersections) and edges (network links/streets). Representing networks in this way means that a variety of graph theoretical approaches can be used to both summarize and evaluate the system. As mentioned in the previous chapter, this type of generalization and abstraction is necessary to provide a common framework and set of tools that can be used to investigate these phenomena (Grubesic et al. 2008). As previously identified, these abstractions are not appropriate for certain real-world systems in certain scenarios. In these cases, network models are not high-fidelity representations of real-world systems. In disambiguating a real-world system into sets of nodes and edges, graph theoretical approaches require that the system be considered in

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[5] The Interstate 5 bridge that spans the Columbia River between the U.S. states of Oregon and Washington is a good example. It is one of the few crossing points on the river for connecting the state highway systems of Oregon and Washington. Any disruption to this bridge would force traffic six miles east to the Glen L. Jackson Memorial Bridge (Interstate 205) or 40 miles north to the Lewis and Clark Bridge on Washington State Route 433.

isolation, with no interactions between the network and its physically-adjacent surroundings. In practice, this is not a realistic assumption for some of these systems, especially road networks.

The previous chapter established that during extreme events, evacuees and rescue personnel do not limit themselves to road travel (Aksu and Ozdamar 2014; Li et al. 2009). Instead, they readily use non-road features that help to increase the traversability of a region. This includes travel through parks, parking lots, construction sites, malls, and private yards – anything that works to facilitate efficient movement through a post-disaster landscape. Most of the spaces that can accommodate individual (or perhaps vehicle) travel in these scenarios are not captured by traditional, abstract network modeling approaches – which are unable to account for non-network features, even when those features are in fact influencing network connectivity. As a result, traditional network models tend to provide poor representations of landscape traversibility and human mobility, post-disaster, drastically limiting their utility for emergency planning and management.

The purpose of this chapter is to expand the methodological framework established in Chapter 4 in order to identify road segments that may be particularly critical during evacuation or rescue efforts during (and immediately after) an extreme event. The development of a criticality measure that includes the impacts of whole-landscape features is better suited for identifying elements of regional street networks that may be important in facilitating mobility and traversability when a disaster requires evacuees and rescue personnel to travel off-network (as they often must). Furthermore, the developed criticality metric operates at such a high resolution that it can identify critical subsections of a single road segment. This offers a vast improvement to traditional network approaches that assign monolithic criticality scores to entire road segments, regardless of their actual size or length.

5.2 Background

5.2.1 Roads as Networks

Traditional critical feature identification has the same graph theoretical roots as established previously – for planar systems such as the street network, network models use road intersections as nodes and the roads that connect them as edges (Lin et al. 2011). Recent work includes efforts to categorize distinct sub-networks to better understand urban development and predict urban sprawl (Unsalan and Sirmacek 2012; Expert et al. 2011). Traffic is also a common subject of investigation, with studies examining general traffic flow (Wu et al. 2008), the formation and impacts of traffic congestion (de Martino et al. 2009), and the relationship between traffic and road safety (Lord and Persaud 2004). Other studies examine how to maximize evacuation efficiency for disasters using local street networks (Jiang et al. 2010; Cova and Johnson 2003).

Regardless of the substantive foci for the studies detailed above (and others like them), each disambiguates the road network in a similar way – treating the streets as if they exist in a vacuum, eliminating any possibility for interaction with their ambient environment. If non-network features are incorporated into the model, they are typically added as sources of additional network flow (traffic). For many applications, this is a perfectly valid assumption. For example, when studying traffic congestion, the impacts of non-network features are minimal. While parking lots, alleyways, and driveways adjacent to roads will have some impact on traffic congestion (adding flow), the magnitude of these impacts are small, particularly when compared to the amount of traffic already flowing across the network. Similarly, there are scenarios where pre-disaster evacuations on a street network can safely ignore non-network features. These include hazards that have not disrupted the network (yet), such as efforts to evacuate prior to a hurricane, wildfire, or flood. In these cases, the road networks are intact and evacuees are traveling distances large enough that vehicles are required. For these scenarios, any relevant non-network features (most commonly origins and destinations) can safely be modeled as flow sources and flow sinks.

5.2.2 Critical Feature Identification

One outstanding challenge in network evaluation, both from a methodological and pragmatic perspective, is the identification of critical network elements. For example, at the most basic level, degree centrality can be used to evaluate the overall importance of individual nodes in a network (Borgatti 2004). Specifically, scores are based on the number of edges that intersect a given node. Nodes can then be ranked in order of importance, based on the centrality score (Borgatti 2004; Crucitti et al. 2006). Other measures of criticality are more nuanced and complex. For example, betweenness centrality is used to calculate the number of times a given node appears in shortest paths between all other node pairs (Freeman 1977). Centrality analysis is common in infrastructure studies. Air transport network analysis frequently uses centrality-based approaches to quantify the importance of individual airports (Guimera and Amaral 2004; Wang et al. 2011), while studies focused on the electrical grid use centrality analysis to identify highly connected power hubs (Hines and Blumsack 2008).

For road networks, node centrality tends to be less important than edge centrality (conceptually identical, only concerned with the identification of critical edges instead of nodes) since intersections, as nodes, have such a narrow possible range of degree centrality (typically just three or four, occasionally higher) (Crucitti et al. 2006; Leung et al. 2004). Edge betweenness centrality is a common method to quantify the importance of individual roads within a large road network – this measurement calculates the number of times a given edge appears in all shortest paths between all paired nodes in the network (Bono et al. 2010). Road network studies have used these centrality measurements to identify critical segments of road for the purposes of reducing social inequity in transportation networks (Taylor and Susilawati 2012), preparing for potential terrorist attacks aimed at knocking out major roads (Bell et al. 2008), identifying traffic congestion bottlenecks (Li et al. 2014), and mitigating natural hazard damage (Croope and McNeil 2011).

Although these applications of centrality measurements can be insightful, there are limitations, especially when applied to street networks. By excising the road systems from their ambient environment, standard graph-theoretical evaluations of network criticality (e.g., centrality measures) fail to capture any impacts that non-network features might have on the criticality of the road infrastructure. Furthermore, even when non-network information is used to evaluate the criticality of a street network, it is typically introduced solely as feature attribute data (e.g., local household counts). While informative, this does not provide any context on network connectivity. Edge centrality measurements (including edge betweenness centrality) are also limited in several important ways. First, edge centrality metrics tend to overvalue the criticality of longer edges (Scellato et al. 2006). All else being equal, longer edges have more options for connectivity in a given network, and naturally account for more of the total network distance. Second, edge centrality measurements fail to account for any nuance when looking for shortest routes between nodes. As a result, selected routes may be fractionally shorter than the alternatives, leading to an overvaluation of their importance in the network's overall structure (Morris and Barthelemy 2012). It is important to note that these are features, not bugs, of these centrality metrics. They are working as intended, but they lack the sensitivity to adequately describe the contextual nature of real-world networks, most of which are strongly interconnected with other systems and not isolated from their ambient environment. Finally, it is important to note that when natural borders for a network are absent, edge centrality measurements tend to produce anomalous results on the periphery of a study area (Gil 2016).

Ultimately, these drawbacks limit the ability of urban planners and emergency managers to adequately prepare for large-scale hazards that disrupt a region's road network. Of these hazards, the most common and generally most disastrous is flooding (Price and Vojinovic 2008). Floods can quickly interdict large portions of a region's road network, causing death, illness, and enormous amounts of economic damage (Gupta 2007). Urban planners, particularly those practicing in coastal regions, are keenly aware of this, and seek to minimize a region's exposure and vulnerability to these floods. This includes the development of hydro infrastructure (e.g., dams or levees), redundant road construction, flood forecasting, and efforts to increase public awareness (Tingsanchali 2012). Hardening the infrastructure for a region is both expensive and time consuming. In addition, there are no guarantees that such efforts will provide a return on investment, especially if these efforts are based on imperfect information concerning the vulnerability, robustness, and criticality of local street networks. In fact, previous studies have identified many of the limitations of using traditional road network models to assess a region's flood readiness (Balijepalli and Oppong 2014). By including the impacts of non-network features in determining the criticality of a region's road system, urban planners will be one step closer to developing more efficient and effective strategies for ensuring community resilience during large-scale disasters, including floods.

5.3 Methods

5.3.1 Vector Grid Generation

The analysis of this chapter used the same study area as the previous – portions of Volusia County, Florida, in and around Daytona Beach. The datasets used were the same, and the impedance grid generation followed largely the same methods as in Chapter 4. There were two differences – the first is simple, buildings and water features (i.e., impassable land cover) received an impedance score of 200 instead of 999, and the second is that no storm surge datasets were used, since the goal here is to analyze the landscape in the absence of any specific disaster scenario. See Table 5.1 for a reminder of the impedance scores used for this chapter.

Table 5.1. Impedance scores assigned to cells based on their predominant underlying land cover type.

Impedance score	Land cover
1	Road
6	Impervious
8	Light forest
10	Heavy forest
200	Buildings/water

5.3.2 Road Criticality Measurements

Two road criticality measurements are compared here. First, to establish a baseline, edge betweenness centrality is calculated for each road segment in the study area. Specifically, for any given edge, its betweenness centrality score is the number of times that it appears in a shortest path between origin and destination nodes in the network. For this analysis, individual road intersections function as nodes, while the individual roads correspond to edges. Therefore, all unique pairs of intersections in the network have a shortest path calculated between them (using network distance). Again, each time a given road appears in one of those paths, its betweenness centrality score increases by one:

$$g(e) = \sum_{s \neq t} \frac{\sigma_{st}(e)}{\sigma_{st}} \qquad (1)$$

Where σ_{st} is the total number of shortest paths between nodes s and t and $\sigma_{st}(e)$ is the total number of shortest paths between nodes s and t that travel along edge e, for all unique node pairs st. Figure 5.1 provides a basic example of how this measure functions for a small network. Ultimately, this results in a centrality score for each edge in a network, which represents the importance of each edge to the overall network.

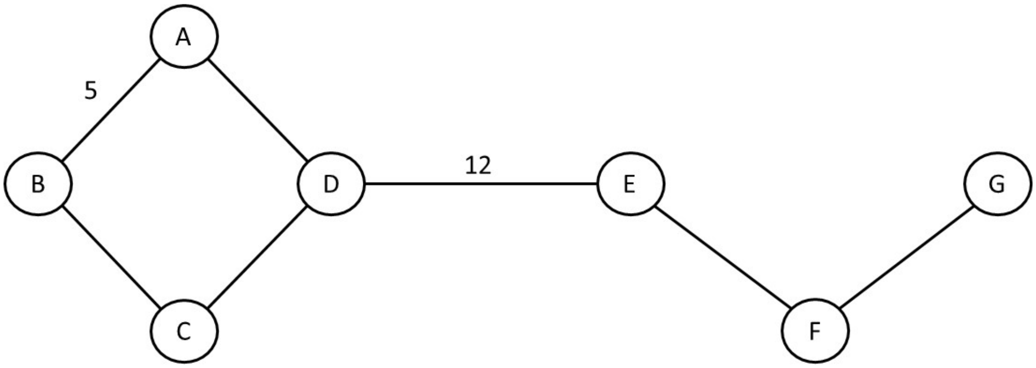

Figure 5.1. Example network calculating edge betweenness centrality for two edges. To derive these scores, a shortest route is determined for all unique pairs of nodes in the network. Each time a given edge appears in one of those shortest routes, its centrality score increases by one. Edge AB appears in five shortest routes across the network – those routes include node pairs AB, BD, BE, BF, and BG. Edge DE appears in 12.

For many networks, edge betweenness centrality is an appropriate metric for measuring edge criticality. However, its limitations become apparent when applied to certain real-world systems, especially for infrastructure that interacts heavily with its immediate physical surroundings. To allow for criticality measurements that operate at a higher resolution and that incorporate characteristics from the landscape surrounding roads, a moving window is utilized (structured from the underlying impedance grid) to give individual grid cells that fall along a road their own criticality score. This is important because unlike traditional network measures which treat each road segment as a unified, aggregate element, the moving window/grid approach allows for different sections of the same road segment to receive unique criticality scores. This provides significant flexibility in the evaluation process because it recognizes that geographically proximal road segments may have similar levels of connectivity in the overall network. More importantly, it incorporates the impassability of the terrain immediately surrounding the road. For example, the grid-based approach can represent that a bridge on the street network may be surrounded by water, and no alternative "off-network" routes exist. As a result, this segment may be more critical than a road surrounded by parking lots – which are features that can provide *de facto* network connectivity, particularly during an emergency.

For every cell that falls predominantly on top of a road (i.e., has an impedance score of 1), its criticality is evaluated by using a grid-based window centered on that cell, but incorporating the impedance scores from the immediately surrounding landscape (Figure 5.2). Guidance for the moving window size is provided by a historical examination of road network disruptions and associated evacuation efforts (Opper et al. 2010), as well as sensitivity analysis. For the purposes of this chapter, a moving window of 15x15 cells (300m x 300m) was used. Again, this window is centered on a given road cell and that cell's criticality score represents the inversely weighted sum of all impedance scores in the window. This results in criticality scores that are isolating individual sections of a given road segment that may be more (or less) vulnerable than the aggregate road segment. More importantly, the ability to account for local features of the surrounding landscape provide more fidelity for this process – a marked improvement over standard methods that treat road segments as completely independent from their local environment and assign an entire road the same centrality score:

$$C(k) = \sum_{i \neq k} v_i / d_{i,k} \tag{2}$$

Where $C(k)$ is the criticality score of the central cell, v_i is the impedance value of cell i, and d is the distance between cells i and k, for all non-k cells i within the moving window. For the sample cell k in Figure 4, the resulting criticality score is 26.623.

As in the previous chapter, these analyses were performed in Python 2.7 with the addition of the NetworkX package, on a Windows 8 computer. The calculation of each road cell's criticality score took fewer than ten minutes for the entire study area, but determining each road's edge betweenness centrality required approximately four hours of computation.

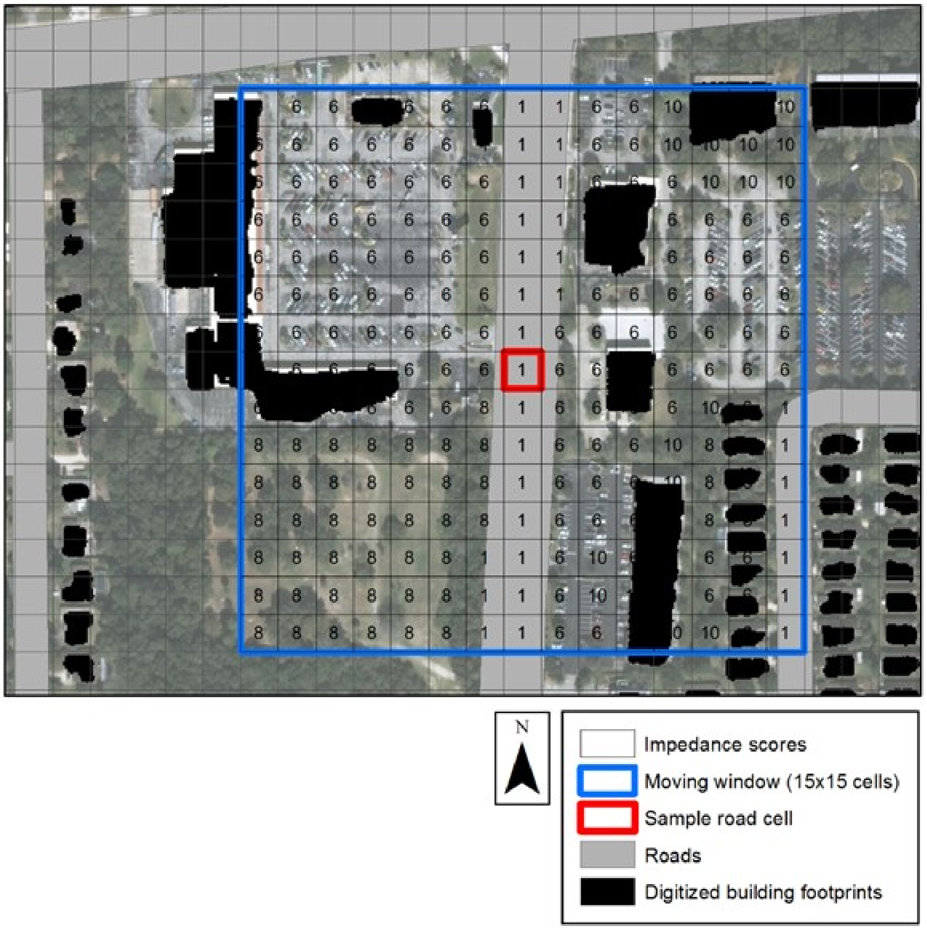

Figure 5.2. Example of how the criticality score is calculated for each road cell. Above, a sample road cell is highlighted in red. It is at the center of a 15x15 cell window, within which the impedance scores are visible. These scores are summed using an inverse distance weighting scheme to arrive at the sample cell's criticality score. For this sample cell, the resulting criticality score is 26.623. This is repeated for each cell that falls along a road (i.e., has an impedance score of 1).

5.4 Results

Quantified comparisons between a traditional edge betweenness centrality score and the modified grid-based centrality are challenging, since they are operating at different scales and on different data types (i.e., a raster of impedances instead of a graph). Additionally, the aim of this modified approach is not to entirely supplant the traditional, graph-based centrality measures, but to instead highlight specific real-world scenarios in which the grid-based technique provides additional information that can be used alongside more typical centrality metrics. To this end, a selection of areas within Volusia County are examined in which the grid-based criticality score produces higher-fidelity models of the landscape and identifies potentially critical road segments more accurately. In each of these areas, results from both methods are compared.

Figure 5.3a displays the edge betweenness centrality results for a central portion of the study area. The long north-south corridor to the northwest of downtown Daytona Beach is Clyde Morris Boulevard, and its edge betweenness centrality is quite high. That is exactly what one would expect; the road is a major thoroughfare running through an area of low road density, and it connects two higher density neighborhoods. However, the limitations of this traditional approach necessitate that the entire road be given a single edge betweenness score. Edge betweenness considers only connectivity information, and cannot account for any of the landscape context that surrounds a road *in situ*. While this likely *is* an important road in maintaining network structure (there are few other redundant roads in the area), identifying critical features solely using edge betweenness lacks the subtly required for many urban planning and emergency management applications. Instead, certain sections of the road may be more or less critical in maintaining the connectivity of the region, particularly during an emergency.

Figure 5.3b shows the same area, but using the modified, grid-based criticality score. Here, Clyde Morris Boulevard's criticality score varies across its entire length. Certain segments of the road, especially those that are located in areas with high road density, or near other impervious surfaces, are less critical, representing the fact that redundant paths (potentially including portions of non-road travel) may exist. Other segments receive notably higher scores. These are more isolated, or located near a body of water, indicating that there may be no alternative feasible paths through the surrounding landscape. The strength of this modified approach is apparent when considering situations that may require off-network travel, along non-road portions of the landscape. These may arise during emergency evacuations or rescues, and it is in these situations that the higher resolution snapshot provided by the modified approach is especially helpful. The added resolution allows for more nuanced evacuation and rescue route development and the identification of potential 'problem areas' of a landscape when preparing for a hypothetical storm.

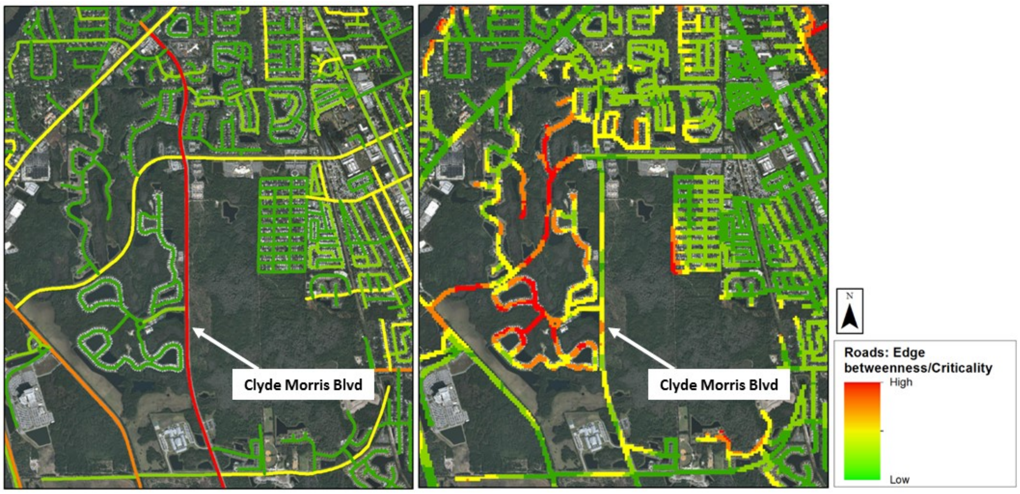

Figure 5.3. Traditional edge betweenness centrality scores (5.3a) and the grid-based criticality measurements (5.3b). Note the differences along Clyde Morris Boulevard, the lengthy north-south thoroughfare running through the figure.

In Figure 5.4a, another limitation of the traditional betweenness approach is on display. In a relatively dense suburban neighborhood with high network connectivity, there is one anomalous edge betweenness score given to Hernandez Avenue, in Ormond Beach. Is this road, in fact, an order of magnitude more important to the overall network structure than any of its neighbors? Likely not. Upon investigation, it turns out this result is due to a small connectivity error in the network dataset being used to generate the edge betweenness scores.[6] Several of the neighboring roads to Hernandez Ave were missing a crucial node that connected them to the nearby major road. These missing connections meant that many of the nodes in this area had a shortest route that traveled through Hernandez Ave, giving it an edge centrality score much higher than it should be. Ideally, of course, road network datasets would be free from errors like this. In practice, however, this is rarely the case. And while this error, and others like them, are relatively simple to fix, their identification can be difficult. This underscores the value of a method, like the one introduced here, that inherently provides more fail safes for evaluating road criticality.

Figure 5.4b displays the same area as in 5.4a, but with the modified grid-based criticality scores. The results here are far more logical. Hernandez Avenue receives a much lower criticality score, reflecting the fact that it is in a developed area with high road density, indicating that the landscape contains many potentially redundant routes. Notably, the grid-based approach produces identical results using both the corrected and uncorrected datasets, potentially mitigating some sources of careless error. This is because the missing node was an artifact of a slightly mismatched road shapefile – but

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[6] Upon discovery of this error, the dataset of the entire study area was more closely examined for these errors and in each instance they were corrected manually. The corrected dataset was used for all other analysis in this dissertation.

that mismatch is well under the cell size (20 meters) that is used to disambiguate the landscape.

Figure 5.4. Traditional (5.4a) and modified (5.4b) criticality measurements for a portion of the study area. Note the anomalously high edge betweenness criticality for the relatively short Hernandez Avenue. This is due to missing connectivity data in the underlying road shapefile. The modified grid-based approach corrects for this error.

Finally, consider the residential areas to the west of Tymber Creek Road, near the edges of Ormond Beach (Figure 5.5). In Figure 5.5a, traditional centrality measurements would likely not classify any of the neighborhood roads as critical. This makes sense – these roads do not serve to connect disparate parts of the network and are not impacting the overall network structure very much. More importantly, when navigating between different parts of the overall network in Volusia County, very few shortest paths will route through these neighborhoods. The only exceptions are some of the collector roads that connect these neighborhoods to major urban arterials. Routes that have one node inside of the neighborhood and one outside are likely all routing along these collectors.

The results from the modified grid-based criticality score can be seen for the same area in Figure 5.5b. The difference this time is that the modified approach identifies many more of these roads as potentially critical. Elevated criticality for these road segments says nothing about the overall network structure, but instead indicates that these road segments may be surrounded by less-easily traversed terrain. These neighborhoods are located in an area of relatively low road-density, few non-road impervious surfaces, and many small bodies of water. As a result, the mobility of residents in these areas is limited, especially if local roads are interdicted by flooding. For additional context, recall that neighborhoods structured just like these were common and difficult targets for rescue efforts in Louisiana during Hurricane Katrina (Curtis et al. 2013).

Figure 5.5. Traditional (5.5a) and modified (5.5b) criticality measurements for residential areas in western Ormond Beach, Florida. Traditional edge betweenness metrics identify these roads as non-critical, but due to the relative impassability of the surrounding terrain, they receive elevated criticality scores from the modified grid-based approach.

5.5 Discussion

The ability to identify critical features in a network, those that are particularly important to structure and function, is a primary strength of traditional graph theoretical methods. From air transport to power grids, the ability to identify critical nodes and links is both important and insightful and graph-theoretical methods help analysts do this. However, applying traditional network analysis techniques to real-world infrastructure systems imposes certain limitations. These primarily arise from the fact that traditional modes of analysis disambiguate infrastructure into sets of nodes and edges, divorced from the infrastructure's physical surroundings. For most analyses, this assumption of isolation does not pose a problem because networks are modeled as closed systems. This works for some infrastructure, where the components of the network and their non-network surroundings exhibit limited (or no) interaction. Broadband telecommunication infrastructure is a good example of this – absent unforeseen disruptions (e.g., a backhoe severing an underground cable). In short, most off-network interactions can simply be construed as flow sources or sinks.

But not all infrastructure systems are so isolated from their surroundings. Roads are a perfect example of this. Roads are surrounded by landscape features that affect network structure and connectivity, such as parking lots and driveways. Consider the fact that a typical road network abstraction treats intersections as nodes and individual roads as edges – but virtually all network flow (i.e., traffic) leaves and enters the network at points adjacent to the roads themselves. There is typically no reconciliation of this fact with the most common network modeling approaches. However, these are usually minor issues. Typical road network studies that seek to identify critical features do so for defense preparation (Brown et al. 2006), to evaluate the overall efficiency of transportation (Scott et al. 2006), or to identify locations at which infrastructure investment is maximally effective (Taylor and D'Este 2007). For these purposes, the abstraction of the road network from its surroundings may be appropriate.

For some research goals, however, that is not the case. When it comes to identifying critical roads with respect to large-scale hazard resilience, these assumptions of isolation are less appropriate (Croope and McNeil 2011). Consider the fact that in many flooded landscapes, evacuees and rescuers must frequently travel through or along non-road features (Ragi et al. 2013; Versini 2012). When considering situations like these, critical feature identification must include the impacts and influences of the landscape features that surround a given road in order to effectively determine which road segments may prove especially difficult to move through. Most emergency management offices currently lack the ability to do this automatically for their communities, contributing to the ineffectiveness of many official evacuation and rescue plans once a disaster actual strikes an area.

The geocomputational approach introduced in this chapter provides an alternative method for identifying critical segments of a road network. It does this by incorporating a traversability score of the immediately proximal landscape for a given road segment. In turn, this process helps to identify areas that may be especially difficult to reach during emergency operations. To be clear, this method is not meant to replace more traditional network-based critical feature identification methods. Rather, it offers a high-fidelity alternative that improves the geospatial intelligence portfolio for urban planners and emergency managers in communities that are vulnerable to extreme events (Godschalk 2003). Consider the neighborhoods visible in Figure 5.5. These roads are definitely not critical to the overall network structure – they are not main thoroughfares, and they likely receive little traffic during day-to-day operation. As such, their edge centrality score is, as one would expect, low. But during an emergency, such as one in which large portions of the county are flooded after a storm, it is easy to imagine residents in these areas needing rescue, or attempting evacuation. In these specific cases, individuals may be forced to travel off the road network – through backyards, parks, parking lots, or construction areas – to reach safety. The lack of easily-traversable non-network surfaces in the neighborhoods (in this case, the fact that most of the surrounding landscape is marshy and undeveloped) indicates that these areas may be especially at-risk in a post-storm landscape.

These are precisely the types of risk the grid-based model introduced here is attempting to capture. In turn, this allows emergency managers to develop more robust and effective evacuation and rescue plans specifically tailored for a post-disaster landscape, one in which roads may be temporarily interdicted. Additionally, urban planners, armed with this knowledge, may be able to situate certain non-road features (such as a new park) with the aim of mitigating flood risk for this area. The notion that the landscape surrounding roads impacts evacuation efforts is not new (Henry et al. 2017; Wood and Schmidtlein 2012) but until recently there have been few efforts to automate the identification of these problem areas, at scale, in a landscape.

5.5.1 Limitations

The primary limitation of this study centers on the generation of the landscape traversability grid. It is site-specific. However, the overall conceptual framework highlighted in this chapter is generalizable to *any* urbanized area that is vulnerable to large-scale disasters. Because the landscape features in each location inform the traversability of off-network space, there may be difficulties in comparing locales. This is particularly true when developing impedance scores for a landscape – the specific impedance scores may depend on a suite of local factors. A second limitation to the framework presented in this chapter is the missing element of demography. Not all subpopulations of an area require emergency assistance (or rescue) at the same rate. The incorporation of household characteristics and population would greatly enhance the identification of critical areas.

5.6 Conclusion

A novel geocomputational approach for identifying critical road segments that incorporates the impacts of off-network landscape features was presented in this chapter. Imminently useful in disaster-prone areas (e.g., urbanized coastal regions that face semi-regular flooding), this methodological framework helps identify areas that may be particularly difficult to reach when a disaster negatively impacts a region's road network. The road segments identified in this approach are those that are surrounded by landscape features that are particularly difficult to travel through, in the event that non-road travel is necessary (as it often is in a post-disaster landscape). This tool may aid emergency management offices develop effective and comprehensive evacuation and rescue plans for a given region.

CHAPTER 6

CONCLUSION

6.1 Dissertation Review

Coastal cities are being squeezed from both sides when it comes to large-scale disaster vulnerability, particularly storm surge flooding. From a demographic perspective, cities are growing, often at unsustainable rates, which is in turn contributing to stretched or inadequate public service provision. This is further exacerbated by political mismanagement and irresponsible urban development, particularly in risk-prone areas. From the geophysical side, climate change is causing sea level rise, higher tropical storm and hurricane intensity, and more precipitation. Taken together, these engender food and water insecurity, and can cause disparate social vulnerability. To put it mildly, these are enormous problems, whose solutions are not obvious nor easily implemented. But these issues set the stage for this dissertation, which was motivated both by the growing number of hurricanes and tropical storms that make landfall in or around urban coastal regions, and by the increasing amount of damage each of these storm events inflicts.

Specifically, the central problem that this dissertation sought to address was that many evacuation and rescue efforts in the immediate aftermath of a large storm are ineffective, slow, and marked by disorganization. Even this relatively smaller problem has several causes, including many that are location-specific, making generalized solutions difficult. However, one consistent issue, identified by existing literature, emergency manager interviews, post-storm biopsies, and original research presented in this dissertation, was that of a large disconnect between the transportation models that are used to build the evacuation and rescue routes, and the realities of movements through a flooded landscape. Typically, this stems from the fact that most transportation models are network-based, built using a region's road system. However, many evacuees and rescuers are forced to move through non-road portions of a flooded landscape. In order to solve this, transportation models need to be able to conceptualize non-network space – the parts of a landscape that *are not* roads. Graph theoretical approaches to road network modeling are fundamentally incompatible with this requirement, and so a novel framework was needed.

To that end, this dissertation presented methodological tools by which the traversability of an entire landscape could be quantified, incorporating land-cover and built feature data, enabling seamless routing both along roads, and through non-road features as needed. There are a variety of situations in which this approach builds higher-fidelity models as compared to a traditional network-based solution. These occur primarily when a large portion of a region's roads are inundated or for some reason interdicted. When enough roads become impassable, traditional network analysis breaks down, since too much of the network is disconnected, and too much landscape area is no longer near intact network space. A grid-based modeling approach, as introduced here, allows for the production of evacuation and rescue routes in a dynamically disrupted landscape, in real time.

In Chapter 2, this dissertation established the breadth of problems facing coastal urban areas, particularly in the United States. Climate change (sea level rise, storm intensity) and demographic shifts (increasing LECZ population, stretched public service provision) are combining to create even more drivers of vulnerability such as food and water insecurity. These, in turn, are exacerbated by political short-termism, and economic incentives that drive irresponsible development and inadequate emergency preparation. These drivers are increasing urban vulnerability to a large number of potential disruptions, but in order to limit the scope of the research presented here, a focus on hurricane and tropical storm surge flooding was established. A case study of Miami, Florida demonstrated how these issues interact in a real city, and some of the potential solutions that Miami is using to mitigate their exposure to storm surge flooding.

This increasing vulnerability set the stage for Chapter 3, which examined the impacts of a potential storm surge flood on Volusia County's road system. This county, located in central Florida on the Atlantic coast, is an ideal location to study the impacts of storm surge flooding. This region contains a mixture of urban, suburban, and rural development, notably with an extensively developed coastline. There are low-lying inland regions, and several surface bodies of water with connections to the ocean. With a hurricane interval of 21 years, the region experiences tropical storms/hurricanes frequently enough that residents have a sense of the damage potential of storm surges, and the county itself has an official emergency management department. However, the research presented in Chapter 3 indicates that a 21 year interval is infrequent enough that larger and less frequent storms are likely to cause a disproportionate amount of damage – out of line with their simple increase in strength. Storm surge flood simulations were produced here, using SLOSH, and the contingency analysis began to highlight some of the limitations of using traditional network analysis on a flooded landscape.

In order to address these limitations, Chapter 4 introduced the grid-based methodological framework that serves as the primary contribution of this dissertation. This grid-based approach rasterized the study area's landscape using road data, natural land-cover data, impervious surface data, building footprint data, and surface feature data to construct an overall impedance score for moving through any particular area. Additionally, with the aid of prior evacuation literature, a hierarchy of travel preference is established for movement through a flooded landscape. This hierarchy reflects the fact that individuals prefer to travel through unflooded areas, and will stick to roads or other impervious surfaces whenever possible. These impedance scores represent the overall traversability of a landscape, and allow for automatic route generation, similar to traditional OD routing on a network. These routes are useful when navigating adjacent to or directly through flooded roads, and perform identically when navigating entirely unflooded regions.

Finally, Chapter 5 modified the grid-based approach presented in the prior chapter to build a novel critical feature identification tool. Critical feature identification is a common field of study for many infrastructure systems. For roads specifically, previous studies have been concerned with hardening road infrastructure in order to defend it from attack, minimizing traffic congestion, or mitigating natural disaster exposure. With the same rationale as established in the previous two chapters – that evacuees and rescue personnel will move through non-road portions of a landscape as needed – this chapter demonstrated a method by which these requirements can be incorporated in determining high-risk roads in the event of a disruption.

6.2 Urban Planning and Emergency Management

This dissertation was informed and inspired by the real-world problem of inadequate post-storm evacuation and rescue plans. As such, the proposed solution to this problem was designed with the goal of building something that could aid urban planners and emergency managers, in real situations. To be clear, the specific details of this type of rollout are beyond the scope of this dissertation, which concerned itself with the conceptual justification for the novel approach, and its basic implementation. However, there are several avenues by which the work presented here could be used to solve real problems with which urban planners and emergency managers are concerned.

Many emergency management offices are tasked with producing, maintaining, and disseminating evacuation plans for a variety of disruptions, including flooding. These evacuation plans are made available to residents, often with an outreach component for households or businesses located in high-risk areas (e.g., low-lying coastal property). In general, there are two types of evacuation plans that these offices may produce. Short-term evacuation plans concern themselves with high-risk property, and provide instructions for immediate use, in the event of an imminent storm. These tend to simply be directions to nearby high-ground or inland areas that are out of the direct path of the anticipated storm surge. The areas to which residents are directed may not have any type of permanent or temporary shelter, but are simply designed to be relatively safe staging areas from which broader evacuation efforts can take place. These broader evacuation efforts are the focus of the second type of plan that many emergency management offices produce. These plans are designed to move large numbers of people a relatively longer distance – these were the routes utilized by New Orleans in the days leading up to Hurricane Katrina, and were also the type of routes analyzed in Chapter 3. These routes tend to identify large thoroughfares or arterials, and contain provisions for creating unidirectional travel on roads.

These latter routes, unfortunately, are those that suffer the most from their reliance on intact roads – creating precisely the problem that New Orleans faced immediately after Katrina, when evacuation vehicles, located on evacuation routes, were inundated. These evacuation routes work well before a storm actually disrupts a region. The vast majority of evacuees are traveling by vehicle, and are generally heading in the same direction, and so routing this traffic onto appropriate roads increases evacuation efficiency. However, an alternative set of routes, built using an alternative set of criteria, are needed for post-storm evacuation. This is where the grid-based approach presented in this manuscript may aid emergency management offices. It is conceivable that these offices could produce post-storm evacuation plans, based on the specific, dynamic characteristics of the storm surge as it develops.

Perhaps more compellingly, this same tool could be used to build rescue plans and routes, in a flooded landscape. During previous major storms, many rescuers have operated with incomplete information, no central plan, and overworked/understaffed central control offices. In these cases, rescue efforts are frequently inefficient or ineffective, increasing the overall human cost of major storms. In order to navigate a flooded landscape, rescuers may be forced to make logistic decisions on the ground, based on their observations, expertise, or local knowledge. The alternative, that routes could be generated dynamically using a repository of landscape datasets and real-time flood data, would help make rescue efforts smoother and more effective. In these cases, rescuers could quickly identify ways to bring stranded individuals to shelters with available space, with an efficient distribution of resources.

The benefits to urban planners are similar – urban planners in coastal cities around the world are increasingly concerned with mitigating their cities' flood exposures. Not only does flooding cause morbidity, occasional mortality, and enormous economic damage, but large-flood frequency is increasing in many areas. These concerns already direct urban planners to take a variety of actions that work to minimize flood damage, such as building raised roads, constructing parks and other natural areas to double as flood control basins, and installing levees or seawalls as needed. Beyond attempting to limit the physical extent of floods, urban planners are also concerned with maximizing their communities' abilities to recover from a flood, both in the short and long term.

With the ability to identify potential problem areas when it comes to post-storm evacuation (as covered in Chapter 5), urban planners can make decisions about where to site a variety of urban development projects in an effort to increase a particular area's non-road traversability, particularly if that area is located in a high-risk flood zone. Consider the construction of redundant roads – road redundancy is typically determined only by the presence and characteristics of nearby roads, and how those impact the overall network structure and connectivity. However, by also including the impacts of non-network features (i.e., the traversability of the non-road landscape), planners gain a more holistic picture of the impacts of new roads in an area, particularly with respect to post-flood evacuation and rescue. Naturally, these are second order concerns – planners have to consider a large suite of factors when greenlighting development projects, but both the concepts and methods behind including the impacts of non-road features on a region's traversability may provide planners with an additional tool.

6.3 Future Work

There are four primary avenues of immediately-available future work that should follow what was presented here. They are the adaptation of additional network metrics to the grid-based approach, historical storm model truthing, confirmation of model generalizability, and emergency management functionality rollout. These cover purely methodological improvements and developments, confirmatory analysis, and a focus on implementing the potential solutions presented here in a real-world agency. This is not to say that these are the only areas of potentially fruitful future research, but these four themes are the most immediately pressing, while offering concrete benefits.

The first, the conversion and development of additional network metrics, seeks to build upon the routing efforts from Chapter 4 (built from traditional OD routing) and the alternative critical feature identification from Chapter 5. With the effective rasterization of a given landscape, and the conversion of that raster into a landscape's overall traversability, there are numerous traditional transportation modeling tools that could provide additional insight when converted to utilize a grid of traversability. These might include an alternative conceptualization of network structure, connectivity, or perhaps most promising in light of this work's focus on natural disasters, modularity. As the suite of tools that rely on this grid-based approach is developed, it becomes ever more useful, and begins to allow for a type of landscape traversability quantification similar to that provided by graph theoretical network modeling approaches, only with a higher-fidelity underlying framework.

The first of the two confirmatory analyses that would benefit this work would be that of using historical storm data to verify some of the assumptions used in the development of the grid-based modeling approach. With historical datasets, notably including extensive rescue data, for a particular storm, the routing approach introduced in Chapter 4 could be verified. This may be a quantified comparison – examining the actual rescue routes that occurred as compared to those generated by this model – or it could be a qualified comparison, using a panel of emergency management personnel who were in charge of a particular storm's rescue operations. This would confirm that the routing method presented here, as well as the overall impedance grid generation, are potentially effective tools during a large-scale storm surge flood.

The second type of confirmatory analysis is to establish the generalizability of both the study area and the modeling approach. This should be done by replicating the efforts presented here in another urban coastal area that also faces storm surge flooding. A new location may require a slightly different set of underlying datasets to generate the impedance grid, and the impedance scores themselves could also be tested to ensure that the travel hierarchy remains intact in different regions. An expansion of the work performed in Chapter 3 could also confirm whether other emergency management offices are producing ineffective evacuation plans with respect to a post-storm landscape.

Finally, while the solutions presented here were developed with the real-world problem of ineffective post-storm evacuation plans in mind, rolling these solutions out to actual emergency management offices was outside the scope of this dissertation. To that end, perhaps the most immediately-useful future work would be to develop a prototype user-facing application that used the grid-based traversability model and test it with actual emergency personnel. This would require extensive model refinement and focus testing, but could both inform future versions of this model and also ensure that any further development was focused on improving the user experience and producing an effective real-world solution.

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APPENDIX A

CO-AUTHOR PERMISSION FOR SUBMITTED AND PUBLISHED MANUSCRIPTS USED IN THIS DISSERTATION

Several previously submitted and published papers are used directly and indirectly in this dissertation. Each of these was co-authored by Tony H. Grubesic, and this appendix is confirmation of his permission to use these works here. These works include:

Helderop, E. and Grubesic, T.H. (2019a). Hurricane storm surge in Volusia County, Florida: Evidence of a tipping point for infrastructure damage. Disasters 43(1), 157-180.

Helderop, E. and Grubesic, T.H. (2019b). Streets, storm surge, and the frailty of urban transport systems: A grid-based approach for identifying informal street network connections to facilitate mobility. Transportation Research Part D: Transport and Environment (in press).

Helderop, E. and Grubesic, T.H. (2019c). Why coastal cities are particularly vulnerable to storm surge flooding: A review and synthesis. Ocean and Coastal Management (under review).

Helderop, E. and Grubesic, T.H. (2019d). Flood evacuation and rescue: the identification of critical road segments using whole-landscape features. Transportation Research Interdisciplinary Perspectives (under review).