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Assessing individual transit vulnerability to nuisance flooding in the Charleston, SC area

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by

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Dedication

For my family – sometimes I get lost in a distant future thinking about climate change and sea level rise, but whenever I think about all of you, I find my ground and remember why I have chosen to do this work. Thank you.

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Abstract

Minor coastal flooding, also known as nuisance flooding, is projected to be more frequent due to relative sea level rise. Nuisance flood events in Charleston have resulted in various social impacts caused by road closures, traffic disruptions, and economic losses. This thesis presents research conducted to understand the dimensions of individual transit vulnerability to nuisance flooding and how transit vulnerability will be affected by increased extents of nuisance flooding driven by rising sea levels and heavy rainfall. Mixed methods were used to conduct this research in Berkley, Charleston, and Dorchester Counties, South Carolina. An electronic, in-person survey was administered at public bus stops to collect data on normal transit behavior, route information, transit behavior during a nuisance flood event, and demographic characteristics. Changes in transportation vulnerability under different scenarios of nuisance flooding was evaluated by using a geographic information systems (GIS) model that calculated travel time for respondent route information. The survey results revealed that three sources mediate individual vulnerability: an individual's travel behavior and personal attributes, the vulnerability of the transit system, and the policies regarding late arrival and cancellations at the trip destination. Additionally, individual transit vulnerability varied depending on the type of transit disruption and transit network stressor. The GIS modeling results showed that the location and extent of road flooding play an important role in how transit vulnerability will vary under future scenarios of nuisance flooding.

The findings from this research highlight that adaptation strategies in the transportation sector to prepare for current and future levels of nuisance flooding will have to consider characteristics of transportation network users and their destinations in addition to vulnerability of the transportation network elements. Additionally, efforts to reduce individual transit vulnerability to nuisance flooding must consider how factors outside of the individual's control, such as which roads flood, disruptions to transit service, and destination absence or late policies, play an important role in determining the potential consequences an individual might experience.

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Chapter 1. Introduction

1.1 Research context

According to NOAA's State of the Coast (2013), over a third of the United States population lives in the 452 coastal shoreline counties. Although individuals living in coastal communities, such as Charleston, South Carolina, benefit from the wide range of opportunities that emerge from coastal and marine resources, they also must be prepared to accommodate or avoid potential losses and damages that can be caused by coastal hazards, such as hurricanes, flooding, and/or erosion (Moser et al. 2014; National Research Council 2014; NOAA and US Census Bureau 2013). In many places along the East and Gulf Coasts, the frequency of coastal flood events, particularly minor coastal flood events also known as nuisance flooding, has been increasing due to changes in mean sea level associated with relative sea level rise (Sweet et al. 2014). Factors influencing relative sea level rise include climate change-induced rises in global sea levels from glacial ice melt as well as geographically dependent features such as land subsidence, bathymetry, and ocean currents. Nuisance flooding causes immediate impacts to local communities, such as road closures and damages to property, and long-term, chronic degradation of infrastructure from increasing inundation of saltwater (Sweet et al. 2014). Additionally, following an extreme event resulting in a local disaster, a community might face challenges in recovery due to disruptions and minor damages caused by nuisance flooding. Thus, this increase in nuisance flood events requires a shift in how communities assess their coastal flood risk to consider repetitive, minor flood events in addition to quick-onset, major flood events, as they try to build their resilience to coastal hazards.

An analysis of tide exceedances above the minor coastal flood threshold measured by the Charleston Harbor tide gauge part of the National Oceanic and Atmospheric Administration (NOAA) National Water Level Observation Network (NWLON) from 1920 to 2013 indicates that nuisance flood days in Charleston, SC have been increasing since the 1980s (Sweet et al. 2014). Nuisance flood events in Charleston occur primarily during King Tide events, which are extreme high tides, and when localized precipitation and wind speed and direction increases the extent of flooding (NOAA Digital Coast 2015). During the 2015 tide year, Charleston experienced a historic record of 38 nuisance flood days (Sweet and Marra 2016). Social media and local news reports indicate that nuisance flooding repetitively disrupts local transportation by flooding roads, causing traffic, and altering normal public transit service (Peterson and Munday 2015; Peterson, Rindge, and Boughton 2015; Peterson 2015a), which in turn impacts individuals trying to accomplish essential daily activities, such as commuting to work or accessing medical care. These events in Charleston exemplify how changing relative sea levels impact transportation systems and their users by increasing salt water exposure, augmenting the extent of flooding, and increasing the frequency of nuisance floods (National Research Council 2008; Schwartz et al. 2014; Sweet and Marra 2016).

Adapting to the rising number of nuisance flood events and the resulting impacts requires assessing where vulnerabilities exist and increasing the capacity of existing systems to respond to impacts and mitigate damages. Vulnerability from a hazards perspective typically focuses on the characteristics of the entity that mediate its predisposition to adverse impacts and amount of resulting harm from these impacts (IPCC 2014). Conceptualizations of transportation vulnerability typically focus on the adverse impacts caused by a disruption to attributes of the transportation system rather than impacts to system users (Berdica 2002). Some vulnerability assessments of transportation systems may focus on infrastructural capacity to withstand exposure to flooding of different frequencies (National Research Council 2008; Rowan et al. 2014; Lu, Peng, and Zhang 2014). Other assessments consider the transportation network and its ability to remain functional either from the perspective of serviceability (Berdica 2002; Jenelius, Petersen, and Mattsson 2006) or accessibility (Suarez et al. 2005; Lu and Peng 2011a; Kim, Pant, and Yamashita 2013). The latter vulnerability assessments focusing on transportation network functionality provide a way to quantify how transportation vulnerability affects populations in terms of costs, such as travel time and distance.

However, many transportation network vulnerability assessments do not consider the differential impacts to populations that occur from travel disruptions unless planners have access and the ability to model individual travel patterns (Duthie, Cervenka, and Waller 2013; Kim, Pant, and Yamashita 2013) and focus predominantly on motor vehicle transportation rather than considering other modes, such as public transit. People depend on transportation systems for key aspects of their livelihoods including job security, childcare, and health services among many other activities (Jones and Lucas 2012), but not all individuals receive the same benefits from transportation systems or have access to or ability to use multiple modes of transit. Some subsets of the population have limited ability to utilize different components of the transportation system due to affordability or location of services that stem from systemic barriers resulting from economic, historical, and political factors (Böcker, Dijst, and Prillwitz 2013). Other individuals have reduced accessibility due to personal characteristics, such as age or physical disability. These individual and societal characteristics additionally influence the individual's transportation mode dependency, such as reliance on only on walking and/or public transit.

1.2 Purpose of research

Anecdotal evidence suggests that nuisance flooding impacts more than just the infrastructure and roads. Changes in road functionality not only disrupt regular public transit routes, but also the ability of individuals dependent on those services to conduct significant livelihood activities. Some transit users might have alternative options during these instances while others might be transit-dependent, which could result in transit-dependent individuals facing additional consequences during nuisance flood disruptions. The purpose of this thesis research is to understand relationship between nuisance flood events, public transit and road network functionality, and public transit users. The following research questions were proposed to guide the research:

1. How does individual transit vulnerability to nuisance-flood-induced transit disruptions vary along individual characteristics and travel behavior?
2. How does the potential vulnerability of public transit users change under different scenarios of nuisance flooding?

1.3 Structure of thesis

This thesis begins with a literature review on coastal flooding, hazards and transportation vulnerability, and transportation accessibility and mobility to summarize approaches used to study different elements of focus in this research. The literature review ends with key conclusions and sub-research questions used to answer the research questions proposed in this study. The following methods section describes the study area, research design, and data collection and analysis procedures. The discussion section evaluates findings from three analyses conducted to understand the relationship between nuisance flooding, public transit disruptions, and impacts experienced by public transit riders in the study area. Finally, the conclusion chapter of this thesis identifies contributions from this research to understanding factors that mediate individual vulnerability in the context of nuisance flooding and transportation and what this means as cities such as Charleston, SC plan for increases in nuisance flood days due to local sea level rise.

Chapter 2. Literature review

In order to address the research questions asked in this thesis, the literature review covers four bodies of literature to conceptualize key terms and evaluate methods. First, the drivers of coastal flooding are discussed to better understand why nuisance flooding has been increasing in coastal communities. The next three sections summarize approaches used to understand how coastal hazards and transportation systems affect individuals. A summary of the hazards literature highlights variations in risk and vulnerability assessments and the different dimensions and factors that influence individual vulnerability, such as adaptive capacity and sensitivity. A separate section covers how the transportation sector has conceptualized and measured the vulnerability of transportation systems to different disruptions, with an emphasis on climate and weather hazards. The final section of the literature review highlights findings from transportation accessibility and equity research in order to conceptualize the relationship between individuals and transportation systems. The chapter ends with a summary of the key points from each of the sections, refined research questions, and definitions of key terms that are used throughout the rest of this thesis.

2.1 Drivers of coastal flooding

Coastal flooding refers to inundation from the ocean caused by the movement of water on land as a result of high tides, wind patterns, erosion, and storm surge (NOAA 2015). The National Weather Service Weather Forecasting Offices set thresholds for minor, moderate, and major coastal flooding based on tidal datum elevations determined using mean sea level measurements taken by the National Oceanic and Atmospheric Administration's (NOAA) tide gauges part of the National Water Level Observation Network (NWLON) (Sweet et al. 2014). These inundation thresholds inform fixed elevations for coastal infrastructure design and when to issue public safety advisories in the event of potential flooding. For example, when tide levels reach above 7 ft. at the Charleston, SC tide gauge, which is referenced to local datum mean lower low water (MLLW), the National Weather Service issues a public safety advisory for minor coastal flooding (National Weather Service Charleston Weather Forecast Office 2015).

Physical drivers, such as geomorphological, hydrological, and climatological factors, influence the extent and likelihood of coastal flooding in an area (NOAA 2015). Geomorphological features of an area include elevation above sea level and shoreline processes and features can change the ability of the ocean to penetrate further inland and mitigate incoming water (National Research Council 2014; NOAA 2015). Meteorological and climate drivers influencing ocean temperature and currents and the formation of tropical systems, such as hurricanes, severe storms, and nor'easters, can cause storm surge and wind driven tides that add additional water on top of the existing tide and pushes water further inland than the normal tide at the time (NOAA 2015; National Research Council 2014). Localized precipitation influences the extent of coastal flooding by increasing runoff, placing additional pressures on stormwater systems that also might be inundated with tidewaters. Climate change also exacerbates drivers of coastal flooding by altering global circulation patterns that influence precipitation patterns and increasing global mean sea levels due to melting of glacial ice from increasing temperatures and thermal expansion of ocean waters (Moser et al. 2014).

Relative sea level rise, which is determined by global sea level rise and local factors including land subsidence, shoreline processes, and bathymetry worsens existing coastal flood patterns in many parts of the U.S. coast (National Research Council 2014; Wong et al. 2014; Parris et al. 2012; Sweet et al. 2014). According to Sweet et al. (2014), when local sea levels rise and change the mean sea level relative to fixed tidal datum elevations, there is a greater chance that the inundation levels will exceed the existing flood thresholds. Consequentially, relative sea level rise can worsen all flood types, resulting in spatial and temporal changes in flooding due to the potential increase in magnitude and frequency of coastal flood events, particularly minor flood events (Sweet et al. 2014). While Sweet et al. (2014) acknowledge that sea level rise will exacerbate extreme flood events by increasing the level of storm surge, their analysis of tide gauge records focuses on the increasing numbers of minor flood events observed across the country consistently over the past couple decades. They define the increase in floods above “the NWS ‘minor’ thresholds as a location’s nuisance flood level” (Sweet et al. 2014, 2), and many of these minor flood events are now known as “King Tides” which typically occur during astronomical high tides. After analyzing NWLON tide gauge water level exceedance data from records going back to at least 1920, Sweet et al. (2014) conclude that nuisance flood events have been increasing across the U.S. but at different rates. For example, tide gauge records along the U.S. and Gulf Coasts show accelerating increases in nuisance floods compared to those of gauges other regions. Although Sweet et al. (2014) note that nuisance floods occur primarily due to increases in relative sea levels, other drivers of coastal flooding can also exacerbate these minor floods, such as localized precipitation and seasonal climate variability influencing wind patterns and ocean forcing. For example, Sweet and Marra (2016) conclude that a strong El Niño Southern Oscillation during the 2015 tide year from May 2015 to April 2016 contributed to increased tidal flooding in the mid-Atlantic and California coasts.

While not a comprehensive discussion of all factors contributing to and types of coastal flooding, this overview highlights the variable nature of coastal flooding both spatially and temporally due to concurrently occurring physical and social processes that interact at various scales to create local coastal flooding conditions. Of the factors discussed above, storm surge and coastal erosion have and will continue to play a central role in the discussion around coastal flooding, especially since storm surge flooding has caused devastating damages throughout coastal areas in the United States (NOAA 2015). However, the increasing frequency of nuisance flooding caused by sea level rise also deserves attention due to the range of impacts that can result from repetitive nuisance flooding, including slow-onset impacts (e.g., infrastructure corrosion) and immediate impacts (e.g., business closures) (Sweet et al. 2014). Exceedances in the minor flood thresholds will have different impacts in communities depending on both the amount of water exceedance during nuisance flood events and how local infrastructure has been designed relative to fixed tidal datum, which not only determine current flood thresholds but also often inform building guidelines. Thus, communities will be better prepared for coastal flooding if they consider both the impacts of repetitive nuisance flooding and those caused by quick-onset storm surge.

2.2 Hazard risk and vulnerability

Impacts to society caused by hazards, such as nuisance floods, do not affect all entities equally due to variations in exposure, hazard likelihood, and vulnerability (IPCC 2014). Risk and/or vulnerability assessments provide a way to better understand the variations in impacts and identify options to allocate finite resources strategically to minimize consequences caused by the hazard (Füssel 2007). The conceptualization of risk and vulnerability differs depending on the discipline and sector of focus (Birkmann 2012; Adger 2006), which in turn results in numerous methods to assess risk and vulnerability varying along factors such as scale (e.g. temporal or spatial), entity (e.g. individual vs. household), and dimension (e.g. human, ecological, coupled socio-ecological) of interest. This first section provides an overview of the conceptualization of risk and vulnerability from the perspectives of the natural hazards and global environmental change literature followed by a section on transportation vulnerability.

Although a plethora of definitions and assessment methodologies exist in the hazard risk reduction and global environmental change literature, the majority of risk definitions identify two common components: 1) the likelihood of a hazard event or climate stressor occurring and 2) the potential adverse effects or consequences that may result (Pine 2014; IPCC 2012; National Research Council 2014; IPCC 2014). The first component of risk, the likelihood of a hazard event or climate stressor occurring, is often measured by looking at the probability of the hazard event occurring. For coastal flooding, future probabilities of flood events are determined by using historical tide gauge measurements and past occurrences of flooding (National Research Council 2014; Sweet et al. 2014), such as those used by FEMA to designate the 100-year and 500-year floodplain maps. The likelihood of future sea level rise has been depicted by projections adjusted to consider the impact of local conditions, such as land subsidence (Parris et al. 2012). However, calculating future probabilities becomes challenging since there is still much uncertainty regarding the expected magnitude and frequency of major and minor coastal flood events, which could vary dramatically depending on future rates of sea level rise and dynamic meteorological factors.

Rather than calculate the risk associated with impacts for a particular hazard event with uncertain probabilistic outcomes, Parris et al. (2012) recommend the use of scenarios to assist with planning for multiple futures with different amounts of sea level rise. The use of scenarios can be coupled with an assessment of potential consequences that may occur, which is typically considered a function of the entity's vulnerability and exposure to the hazard. The Intergovernmental Panel on Climate Change (2014) defines vulnerability as "the propensity or predisposition to be adversely affected" (5) and identifies key components to be "sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (5). Sensitivity is a measure how much the system of focus is impacted by the hazard while adaptive capacity is the ability to cope and mediate the number of changes that might occur during the hazard (Adger 2006; Birkmann 2012).

A vulnerability assessment differs from risk assessments in that it does not consider the probability of specific consequences, but instead focuses the hazard consequences a particular entity faces as a function of its sensitivity and adaptive capacity. Factors mediating sensitivity and adaptive capacity often are not hazard-dependent but rather existing characteristics of the entity (Adger 2006; Birkmann 2012). Attributes of an individual or population that influence adaptive capacity and sensitivity include income, education level, race and ethnicity, gender, and age. For example, a family with limited financial resources might be more sensitive to damages caused by a flood because they might not be able to afford flood insurance.

Beyond these core components of exposure, adaptive capacity, and sensitivity, Birkmann (2012) highlights that vulnerability also varies along spatial and temporal scales and dimensions, such as geographic, economic, social and biophysical. Assessing vulnerability along geographic dimensions focuses on characteristics embedded in geographic context, such as proximity to public transit stations or place of residence, that influence the entity's ability to cope with or sensitivity to different hazard impacts. Evaluating economic dimensions result in a focus on access to financial capital, income level, job stability, and other similar factors. At larger scales beyond the household or individual, evaluating economic dimensions help understand impacts to the economy by considering the number of jobs available after a disaster or changes in regional production and consumption. Social dimensions of vulnerability captures how personal characteristics, such as culture, demographics, access to information, and social networks, predispose individuals to adverse impacts (Susan L. Cutter, Boruff, and Shirley 2003). Additionally, economic and geographic factors, including income, occupation, and place of residence, influence social vulnerability. Biophysical dimensions of vulnerability emphasize how adverse impacts may result as a consequence of certain biological, ecological, or geological characteristics of the entity that influence exposure to the hazard. Evaluating how the entity functions normally because of factors in these different dimensions helps identify preconditions of vulnerability that exist independent of the hazard stressor. Thus, determining which factors result in hazard vulnerability requires evaluating how an entity with specific characteristics functions when exposed to a hazard. Factors making an entity vulnerable to a particular hazard are those that that increase the entity's sensitivity to the hazard and limit its ability to cope with any hazard impacts.

Vulnerability assessments and indicators help identify sources of vulnerability that stem from different dimensions, such as using a social vulnerability assessment to identify which population has a greater predisposition to be impacted by a specific hazard. These indicators and assessments can also be constructed to compare how vulnerability changes across temporal and spatial scales. For example, social vulnerability assessments and indicators can be developed for use at various geographic and population scales such as county or census unit (Susan L. Cutter, Boruff, and Shirley 2003), household, or individual. Sensitivity analyses of the Social Vulnerability Indicator (SOVI), which combines demographic and economic attributes of populations measured by the census to measure vulnerability, shows that vulnerability measured by SOVI changes across temporal and spatial scales (S. L. Cutter and Morath 2012). The variations in vulnerability that emerge across different scales and dimensions, or differential vulnerability, highlights that impacts caused by a hazard do not affect all entities equally. Differential vulnerability also highlights how certain groups may be disproportionately predisposed to more hazard impacts compared to others.

A limitation of many assessments arises from data availability on characteristics that make an entity vulnerable. Assessments like SOVI rely on readily available data for empirical analyses that can be compared across geographies and different time periods (S. L. Cutter and Morath 2012). However, while SOVI provides information available for various geographic units, this indicator does not provide information on how these attributes relate to sensitivity and adaptive capacity of populations to a specific hazard. To understand the dynamics between population characteristics and these other components of vulnerability, research at the individual scale would provide more detail but would require independent data collection since readily available data sets might not provide this information.

Hazards vulnerability assessments provide a framework to understand different components and dimensions that influence the vulnerability of an entity. By focusing on a particular dimension of vulnerability, researchers can better identify how social, economic, and geographic characteristics mediate and influence adaptive capacity and sensitivity, and ultimately the entity's vulnerability. However, in addition to focusing on a particular dimension, De León (2012) calls for a sectoral approach to vulnerability assessments that has policy applications beyond hazards mitigation and general planning. Based on De León's model, vulnerability differs based on the hazard, dimension, and sector of interest. Thus, the next section looks to the literature from the transportation sector to identify how they have characterized the transportation system vulnerability to hazards.

2.3 Transportation vulnerability

Vulnerability of transportation system functionality and performance has been conceptualized and measured in a variety of ways. Faturechi and Miller-Hooks (2014) review literature on transportation infrastructure performance and identify that the concepts risk, vulnerability, reliability, robustness, flexibility, survivability, and resilience have all been used to measure system performance. Similar to the hazards literature, most definitions of vulnerability consider the adverse impacts to the transportation system that result from an incident (Faturechi and Miller-Hooks 2014; Berdica 2002). Some authors explicitly differentiate vulnerability from risk in that vulnerability does not consider the likelihood of the incident (Berdica 2002) while others consider probability of incident and consequences as part of vulnerability (Jenelius, Petersen, and Mattsson 2006; Lu and Peng 2011b; Wang et al. 2014). Operationalization of vulnerability also varies depending on the transportation mode being assessed (Wang et al. 2014). The remainder of this section focuses on road network vulnerability since this is the primary transportation network used by the public in Charleston.

Typically, vulnerability of transportation networks has been assessed using spatial and quantitative models. Upon reviewing transportation literature on modeling vulnerability using network analysis, Wang et al. (2014) identify four common stages of vulnerability assessment research methodology employed by researchers (Figure 2.1). Vulnerability is quantified by assessing changes to network performance before and after a disruption scenario using a predefined vulnerability indicator. In vulnerability assessments of transportation to coastal flooding and/or sea level rise, variations among assessments emerge because of the type of coastal flood disruption scenarios and vulnerability indicator used to measure system performance during a flood event. Researchers use flood disruption scenarios based on different storm and flood intervals (e.g., 10-, 50-, 100-, and 500-year events) and/or sea level rise rates (Lu and Peng 2011b; Suarez et al. 2005; Kim, Pant, and Yamashita 2013; Lu, Peng, and Zhang 2014; Oswald and Treat 2013; Rowan et al. 2014) that have been created from hydrologic inundation modeling of flooding and storm surge. Some vulnerability models have been tested using various scenarios to assess the sensitivity of the road network under different amounts of coastal flooding and how vulnerability changes (Suarez et al. 2005).

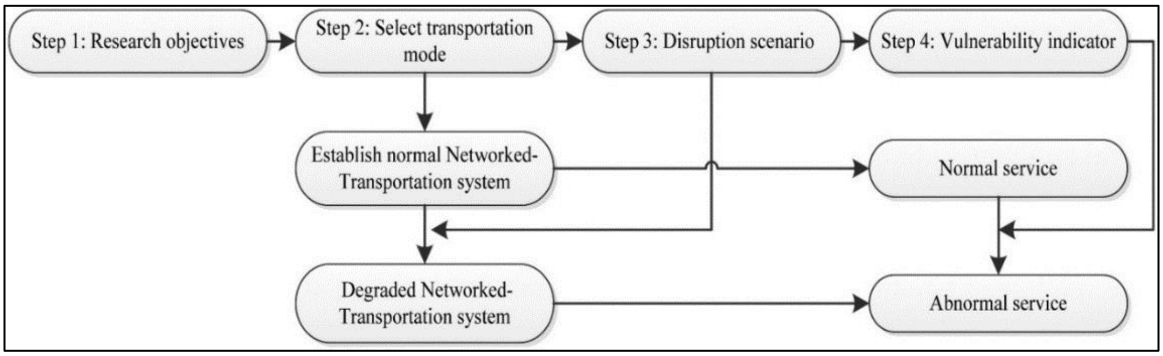

Figure 2.1. General research methodology in vulnerability of transportation networks from Wang et al. (2014, 4)

Vulnerability indicators vary depending on how researchers conceptualize and operationalize vulnerability. Berdica (2002) proposes that vulnerability in the road network should consider serviceability and mobility of the network, which shifts from other conceptualizations of vulnerability focusing on safety and infrastructure stability. Berdica defines serviceability of a road network as "the possibility to use that [road] network during a given time period" (118). She notes mobility considers both "the performance/effectiveness of the transport system in connecting spatially separated locations, and individual characteristics influencing the extent to which people are able to make use of the transport system" (Berdica 2002, 118). Berdica considers accessibility, another term commonly used to consider changes in road network vulnerability, as part of mobility. Serviceability, mobility, and accessibility are common measures of road network performance, but what distinguishes these system performance measures from general use to that of a vulnerability indicator occurs when they are used to measure changes in road network performance caused by a disturbance in the system. Thus, Berdica's proposed vulnerability framework defines vulnerability as "susceptibility to incidents that can result in considerable reductions in road network serviceability" (2002, 119).

Later research builds off of Berdica's conceptualization of vulnerability to also explicitly define consequences as a function of exposure to an incident as a component of vulnerability (Jenelius, Petersen, and Mattsson 2006). Others look at changes in accessibility and mobility as a function of travel time or vehicle miles traveled (Suarez et al. 2005; Kim, Pant, and Yamashita 2013) or by developing an accessibility index that incorporates weights for origin and destination attractiveness (Lu and Peng 2011b; Lu, Peng, and Zhang 2014). Some researchers developed vulnerability indicators using a hazards framework. For example, Rowan et al. (2014) developed a composite vulnerability indicator based on subcategories of sensitivity, adaptive capacity, and exposure and Kim et al. (2013) used the Threats Hazard Identification and Risk Assessment (THIRA) by the U.S. Department of Homeland Security in order to develop a transportation risk score.

Literature on transportation vulnerability highlights that most conceptualizations and assessments define vulnerability by looking at changes in transportation network functionality measured using proxies for travel cost, such as travel time and distance. These models provide useful insights on how to measure possible consequences to the transportation network caused by a hazard, but they do not provide a detailed understanding of the sensitivities of transportation users to a disturbance in the road network, which might be influenced by factors independent of the transportation network like individual socioeconomic or travel behavior characteristics (Böcker, Dijst, and Prillwitz 2013). Many models of transportation vulnerability focus on changes in vulnerability from the perspective of the network rather than the user and assume that individuals who use the disrupted transportation network experience similar impacts and have identical, unlimited capacities to afford the alternative least cost travel route. However, in reality, individuals will have different experiences depending on their transportation mode, with travel times often being longer and less flexible for public transit users than car riders. Similarly, if individuals have access to fewer financial resources or are transit dependent on a one transportation mode, they might face greater impacts during transportation system disruptions than someone else with greater flexibility in choosing their transportation mode.

2.4 Transportation accessibility and mobility

Impacts to the transportation system do not necessarily translate into burdens for all users. Depending on individual socioeconomic and geographic attributes, such as ability to afford a car or bus routes near residence, individuals might be impacted differently during a transportation disruption. Thus, measuring road network vulnerability as a function of accessibility and travel behavior provides an opportunity to better understand how transportation disruptions impact individuals dependent on the road network by focusing on travel characteristics dependent on individual traits and preferences (Böcker, Prillwitz, and Dijst 2013; Lu et al. 2014). Transportation accessibility captures the availability of transportation options and ability of riders to utilize these options to reach their desired destination while travel behavior looks at individual choices, such as start time and mode choice, over the course of a trip.

Although Berdica (2002) notes that traditional accessibility and system performance evaluation measures do not account for impacts of an incident on the system, research on broader transportation accessibility provides insights on general performance of the transportation network to meet user needs. In turn, an accessibility framework provides a way to understand how users (demand-side) are impacted by road network vulnerability to coastal flooding. Additionally, focusing on behavioral aspects provides a bridge to better understand how demand can adapt or fluctuate in response to road network disturbances.

Findings from past studies indicate that transportation accessibility, mobility, and travel behavior choices vary by demographic and socioeconomic characteristics (Hanson 2010; Alsnih and Hensher 2003), changes in weather (Böcker, Dijst, and Prillwitz 2013), and extreme events (Lu et al. 2014; Kim, Pant, and Yamashita 2013). Accessibility may vary by transportation mode (e.g. public transportation vs. car use), and changes in accessibility results in impacts to individual livelihoods, such as their journey to work and employment opportunities (Sanchez 1999; Hanson 2010; Niedzielski and Boschmann 2014). Weather and extreme events alter travel behavior depending on the meteorological or hazard event and the trip purpose, with more leisure trips being cancelled than work or other utilitarian trips (Böcker, Prillwitz, and Dijst 2013). However, many of these studies depend on detailed data on transportation behavior through time-intensive data collection methods, such as travel diaries, that may not be feasible to collect data for large study areas.

2.5 Conclusions from the literature and sub-research questions

In order to better understand impacts caused by coastal flooding in a community, coastal flood risk and vulnerability assessments should consider the impacts caused by increasing frequencies of nuisance flooding. Vulnerability assessments provide a way to understand how nuisance flooding affects the entity of interest. Conceptualizations of vulnerability from the hazards literature provides a way to evaluate which dimensions influence individual hazard vulnerability and how individual sensitivity to disruptions or adaptive capacity shape individual vulnerability. Selecting appropriate measures of vulnerability, however, also depend on the sector of interest. For this research, appropriate indicators of adverse impacts experienced by an individual during a public transit disruption requires understanding how the transportation sector determines vulnerability and measures social impact. Many methods of assessing transportation vulnerability to flooding focus on network performance measures that do not characterize how system performance may affect individuals. Thus, the research on transportation accessibility and travel behavior provides information on how changes in the transportation network affect individuals.

Based on the conclusions from the reviewed literature, additional questions were proposed to answer help the research questions identified in Section 1.2:

- How does individual adaptive capacity and sensitivity to transit disruptions vary among public transit riders?
- How does transit vulnerability assessments vary under different coastal flooding scenarios resulting from sea level rise?

- How does information from a hazard vulnerability assessment compare to results from a transportation vulnerability assessment of the same system of interest?

To emphasize the focus of this research on individual vulnerability to transit disruptions, the rest of this research refers to the following terms using the definitions below that have been selected based on the literature review and study area context:

- *Transit disruption* – an alteration in normal public transit service caused by a stressor in the system that has the potential to change transit riders' intended trips.
- *Travel behavior* – individual choices and characteristics, including transportation mode choice and accessibility to transit service, that influence how a person gets from one point to another
- *Nuisance flooding* - minor flooding that inundates roads partially or completely and is caused by high tides above the minor flood threshold, heavy rainfall events, or a combination of both (adapted from Sweet et al. 2014).
- *Vulnerability* – the potential for an individual to experience consequences from public transit disruptions (adapted from IPCC 2014)
- *Sensitivity* - severity of consequences that result from transit disruption
- *Adaptive capacity* – characteristics that allow an individual to cope with consequences caused by a transit disruption

This research focused on two types of transit disruptions: 1) trip delay (late to destination) and 2) trip cancellation. Transit disruptions were assessed in the context of two stressors—those caused by nuisance flooding and those that have the potential to occur on a regular basis, regardless of weather conditions (i.e., traffic, bus problems, railroad). Vulnerability was measured using adaptive capacity and sensitivity defined by travel behavior as well as using changes in travel time resulting from a transit disruption. Operationalization of these terms to address the research sub-questions is discussed in detail in the following section.

Chapter 3. Methodology

3.1 Research design

Mixed methods were used to conduct this research in the Greater Charleston Metro study area including Berkley, Charleston, and Dorchester Counties, South Carolina. Transit behavior characteristics were used to measure individual vulnerability to normal and nuisance flood-induced transit disruptions. An electronic survey administered in person at public bus stops was used to collect data on normal travel behavior, route information, travel behavior during a nuisance flood event, and demographic information. Variation of transportation vulnerability under different scenarios of coastal flooding was evaluated by using a geographic information systems (GIS) model that calculates transit travel time from respondent route using different flooding scenarios. The following sections discuss the rationale for the study area, the development of these methods, and data analysis procedures.

3.2 Study area

The study area was the Greater Charleston Metropolitan Area, which consists of Charleston County and parts of Berkley and Dorchester Counties (Figure 3.1). Although sampling only occurred at bus stops in Charleston County, this study area was selected to include individuals who live in the entire region for the following reasons: 1) the tri-county area has been designated as the metropolitan region for Charleston and using this area allows for participation of respondents who might not live in Charleston, SC but commute to and from the urban core; 2) regional public transit system and transportation planning include requirements to address impacts to vulnerable populations; and, 3) current and future levels of nuisance flooding disrupt roads and normal public transit service for riders who live outside of the flooded areas.

The Berkley-Charleston-Dorchester Council of Governments (BCDCOG) is the South Carolina regional planning organization for municipalities in Berkley, Charleston, and Dorchester Counties and also serves as the regional Metropolitan Planning Organization (MPO) in charge of regional transportation planning and distribution of state and federal funds for projects (BCDCOG 2012). To be eligible for Federal transportation funding, the BCDCOG must address how they will assess transportation equity and environmental justice impacts of transportation projects (BCDCOG 2015). Thus, transportation planners and managers with BCDCOG have an interest in vulnerable populations in the region, their transportation use, and their vulnerability to different transportation disruptions, such as those caused by nuisance flooding.

The Charleston Area Transportation Study (CHATS), which encompasses all long-range and short-term improvement projects and planning for the region, addresses all modes of transportation vital to regional economic and community growth including public transportation. Two public transit systems serve the BCD region: the Charleston Area Regional Transportation Authority (CARTA) (Appendix A, Figure A.1) and the TriCounty Link (Appendix A, Figure A.2). This research focused on CARTA routes, which run through Charleston County and are most likely to be affected by sea level rise and nuisance flooding since they run through areas in the tri-county region most exposed to future sea level rise (colored routes in Figure 3.1).

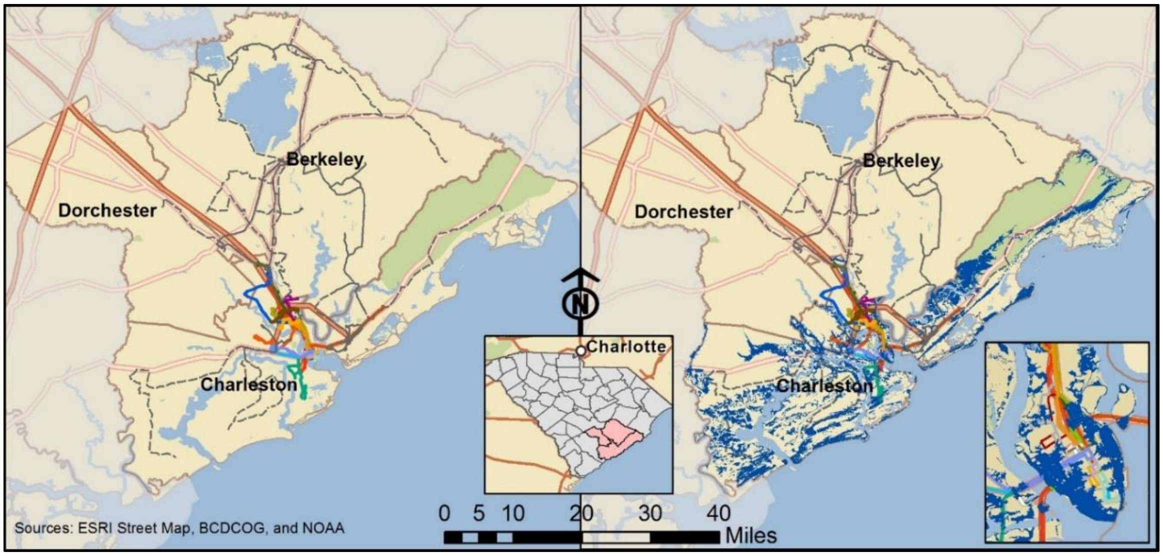

Figure 3.1 BCDCOG Region with no (left) and 6ft of SLR above MHHW (right). Colored lines represent CARTA Routes while dashed grey lines represent TriCounty Link.

As of April 2016, the CARTA transit system consisted of 16 fixed routes, 4 express commuter routes, and 3 downtown area shuttles servicing 1,371 bus stops in urban and suburban areas (CARTA 2015; BCDCOG and CARTA 2016). CARTA's routes include fixed, Tel-A-Ride with park and ride centers, flex/demand service, and express routes. In 2016, CARTA conducted a Comprehensive Operational Analysis (COA) to evaluate system strengths and weaknesses to determine short-, mid-, and long-range transit service goals and modifications that will improve CARTA service. They started implementing short-range plan recommendations to service routes in May 2016, which has resulted in new service routes and changes to existing bus routes.

In 2014, CARTA provided 5 million rides with weekday ridership averages of 15,694 riders (CARTA 2015). According to CARTA's Comprehensive Operational Analysis (COA) (2016), over half (51%) of all CARTA rides occur on one of four routes, and the majority (75%) of riders do not have access to a car for their trip. CARTA's ridership characteristics reveal that CARTA serves majority low-income (58% with annual income below $30,000) and minority (65% Black/African American) individuals. CARTA does serve non-transit dependent populations, such individuals who have access to a vehicle but use CARTA's Park and Ride locations and ride CARTA for convenience rather than necessity in order to avoid traffic and parking constraints in downtown Charleston. Many large employers, including College of Charleston and Medical University of South Carolina, also have partnerships with CARTA to encourage their employees to use these CARTA express routes. The diverse populations served by CARTA provides a unique opportunity to assess differential vulnerability among transit and non-transit dependent users who represent a range of socioeconomic backgrounds.

Currently, nuisance flooding in Charleston results in rerouting of public transit service provided by CARTA (Burns and Gilreath 2015). The National Weather Service in Charleston, SC issues a minor coastal flood warning when the tide level at the Charleston Harbor tide gauge reaches 7ft above MLLW. Sweet and Marra (2014) use the minor coastal flood threshold to define "nuisance flooding" in coastal areas. Minor coastal flood events typically occur during the astronomical high tides, also known as "King Tides." During these events in the past, many roads in Charleston County, primarily in the City of Charleston, have closed due to inundation from tidewaters (Peterson and Munday 2015). Although the timing of King Tides that cause nuisance flooding can vary, King Tides coinciding with morning or evening commutes can significantly impact individuals living throughout the tri-county area who travel to destinations that might be flooded. Additionally, even if individuals do not live or work in flooded areas, they might be impacted if any roads along the route they take from their origin to a destination has been flooded.

Sweet and Marra (2015) forecasted 26 days of nuisance flooding in Charleston, SC during the 2014 and the 2015 federal flood year, which runs from May 1 to April 30 of the following year. The forecast was exceeded in both years with a total of 33 days of nuisance flooding recorded in 2014 and a historic record of 38 nuisance flood days in 2015 (Sweet and Marra 2016). In some instances, these floods were exacerbated by heavy precipitation events, such as the October 2015 historic rainfall event in South Carolina that resulted in a shutdown of all CARTA operations over the weekend (Burns and Gilreath 2015). However, nuisance flooding has also occurred on days without precipitation, and have been called "blue-sky flooding" according to William Sweet, a NOAA Oceanographer in an interview with the Post and Courier (Peterson 2015b).

Factors contributing to nuisance flooding in Charleston, SC include relative sea rise as well as wind and precipitation patterns influenced by El Niño Southern Oscillation (Peterson 2015b; Sweet and Marra 2015; Sweet and Marra 2016). Mean sea level rise at the Charleston Harbor gauge has been increasing at a rate of 3.16 mm/year based on monthly sea level records dating back to 1921 (NOAA Center for Operational Oceanographic Products and Services 2013), and researchers project sea level rise to range from 0.6 to 1.8ft by 2050 in South Carolina (Strauss et al. 2014). Although estimates show a wide range due to uncertainty in global sea level rise rates, recent statements by public officials, such as former Mayor Joe Riley, and the establishment of groups like the Charleston Resilience Network indicate a local commitment to build resilience to sea level rise and a vested interest in preparing for a wide range of futures, regardless of the amount of sea level rise that occurs (Riley 2015). In 2015, the City of Charleston released its Sea Level Rise Strategy, further establishing a commitment to addressing sea level rise impacts.

3.3 Public transit and flooding survey

The survey instrument was designed and used to collect information about different dimensions of individual public transit user vulnerability: the type of impacts experienced by the transit user during transit disruptions, the sensitivity of the respondent to these disruptions, and whether the respondent had the ability to adapt or take alternative actions to prevent or reduce the impact from these disruptions.

3.3.1 Survey design and development

The survey instrument consisted of three sections with multiple-choice and short answer questions (Appendix B). The first part of the survey collected information on each respondent’s normal public transit use, including regularly used routes and stops, and established a baseline for individual sensitivity and adaptive capacity to two types of transit disruptions – late trips and cancelled trips under non-nuisance flood conditions. The second portion of the survey contained questions about the types of consequences and transit disruptions the respondent experienced during a nuisance flood event. The questions in this section were designed to collect information on CARTA service changes when nuisance flooding occurred and how this impacted the individual’s sensitivity (i.e. late, cancelled trip) and adaptations in response. The third section of the survey collected information on individual and household socioeconomic and demographic characters, transit dependency, and zip code.

Survey vulnerability indicator

Individual vulnerability was measured via the survey by assessing the individual's sensitivity to transit disruptions and adaptive capacity to handle any resulting consequences. Sensitivity is defined as the severity of the consequences and was measured by collecting data about the types of consequences the individual has or could experience during late and cancelled bus trips. Adaptive capacity is defined as any factor that enables the rider to cope with resulting impacts from the transit disruption or still complete the trip as originally intended. Adaptive capacity was measured in the survey by collecting information about how the respondent coped with or prepared for any experienced or future consequences. Table 3.1 shows the questions in the survey (Appendix B) that were used to measure adaptive capacity and sensitivity. The survey asked about consequences to transit disruptions resulting from general stressors and those that occur due to nuisance flooding (bolded questions in Table 3.1). This vulnerability indicator assumed the best possible situation is when the respondent's trip still occurred as planned – no change in trip route or the individual was still on time to his or her desired destination. Thus, types of consequences focused on what happened during two general outcomes of a transit disruption—late trip or cancelled trip—and in the case of nuisance flood-induced transit disruptions, two other outcomes were added as possibilities—rescheduled trip and unchanged trip. The latter two outcomes provided additional measures of adaptive capacity by providing information about how the individual still achieved his or her original trip despite experiencing a transit disruption and what options existed to mitigate the negative impact of missing the trip.

Table 3.1 Survey questions covering adaptive capacity and sensitivity dimensions of vulnerability

Question (Bold face questions were asked relative to nuisance flooding)	**Adaptive Capacity**	**Sensitivity**
Q6. How often can you be late to {{ Q5 }}?		■
Q7. What happens if you are late to {{ Q5 }}?	■	■
Q8. How often can you cancel your trip to {{ Q5 }}?		■
Q9. What happens if you cancel your trip to {{ Q5 }}?	■	■
Q21. If CARTA is unavailable, can you still get to {{ Q5 }}?	■	
Q22. How do you get to {{ Q5 }} if CARTA is unavailable?	■	
Q27. How did this affect when you got to {{ Q5 }}?		■
Q28. How were you able to still be on time to {{ Q5 }} when {{ Q25 }}?	■	
Q31. What happened when you cancelled going to {{ Q5 }} because of {{ Q24 }}?	■	■
Q32. Why did you cancel going to {{ Q5 }} when {{ Q25 }}?	■	■
Q33. What happened when you cancelled going to {{ Q5 }} because of {{ Q24 }}?	■	■
Q34. Why did you reschedule going to {{ Q5 }} when {{ Q25 }}?	■	■
Q35. What happened when you rescheduled going to {{ Q5 }} because of {{ Q24 }}?	■	■
Q36. Do you get information about CARTA route changes or delays?	■	

3.3.2 Survey pilot testing

The survey format and questions were developed and selected in conjunction with local stakeholders and were pre-tested in February 2016 (Appendix C). The purpose of pre-testing was to evaluate whether the survey questions elicited appropriate responses from individuals to answer the research question, how respondents reacted to the survey questions, which questions needed clarification, questionnaire logic, and the time the survey took to complete (Barribeau et al. 2012). Feedback from local stakeholders provided information about context and study population, which informed how to phrase questions and discuss sensitive topics. The first draft of survey questions was developed after meeting with the BCDCOG mobility manager and CARTA operations director in December 2015 to discuss how public transit operates during nuisance flooding and options available to transit users during a transit disruption (Burns and Gilreath 2015). The first draft of survey questions was then pre-tested with graduate students at University of South Carolina to assess clarity and flow of questions. The second round of pre-testing occurred with the BCDCOG mobility manager and CARTA operations director to provide input and suggestions on feasibility of administering the survey. The final round of pre-testing was conducted with a sample of the targeted study population and administered in-person at two CARTA transfer stops. Pre-testing the survey at the bus stops revealed bus riders associated the terminology "flooding" with extreme events, such as the severe flooding that occurred in October 2015 when CARTA suspended service completely. Thus, the wording in the survey was changed to ask respondents whether they experienced CARTA service changes during heavy rainfall or high tide events rather than saying minor flooding or nuisance flooding.

The final version of the survey and sampling protocol was submitted to the University of South Carolina Institutional Review Board (IRB) for review and approved as exempt research.

3.3.3 Survey administration and sampling logistics

The survey was administered in-person by trained interviewers using SurveyMonkey kiosk mode on an iPad mini. In-person survey administration was chosen to reduce barriers in participation due to low literacy or limited access to technology to take a mobile or web-version of the survey. Other advantages of having an interviewer administer the survey included the ability to get more short-answer responses, ask more detailed questions, and a higher response rate to questions (Barribeau et al. 2012). An electronic survey was chosen so that responses could be recorded directly into a database and to incorporate answer piping and question skip logic, which allowed for automatic skips of irrelevant questions based on the respondent's previous answer. All interviewers received IRB certification and completed survey training designed by the researcher prior to beginning data collection. During survey training, interviewers practiced administration of the survey, reviewed a standard protocol for probing open-ended questions, and were prepared on how to respond to different encounters that might occur at the study area (Appendix D).

Sampling occurred at four CARTA transit stops with larger volumes of riders in order to sample from a larger population of CARTA riders and to ensure that a wide range of transit users who take different routes were represented in the sample. In order to increase the chances of speaking with CARTA riders who have experienced transit disruptions caused by nuisance flooding, two of the sampling sites were also selected because of their location in downtown Charleston near streets that regularly experience nuisance flooding. The survey was administered at different times of the day and days of the week to capture variation in route service. However, since the survey asked respondents to discuss their most frequent route on CARTA, the sampling time did not seem to make a difference aside from having more declines during rush hour when buses ran very frequently (Table 3.2 for sampling logistics).

Survey respondents at each sampling site were recruited by interviewers asking individuals waiting for the bus to take the survey. Interviewers walked from one end of the bus stop to the other asking each person waiting for the bus if they would be interested in taking the survey. Each person waiting at the bus stop that was in the path of the interviewers was asked to take the survey in order to reduce sample recruitment bias. If the individual agreed to participate, the interviewer then read each question and answer choices aloud to the participant. The interviewer held the tablet so the respondent could follow along with the interviewer and mark answers directly on the tablet if desired. All survey questions were voluntary, and respondents were allowed to skip any questions they did not wish to answer. All declines to participate were marked on the tablet in order to keep track of the survey response rate (Table 3.2).

3.3.4 Survey data processing and analysis

Since survey responses were directly entered into a tablet using SurveyMonkey, the raw data spreadsheets were downloaded from SurveyMonkey. Each response was given a unique Respondent ID, and abbreviations that interviewers used during data entry were edited. Frequencies and descriptive statistics of survey answers were compiled using IBM SPSS 22.

Table 3.2 Sampling sites and survey response rate

Date	Day of the week	Time	Bus stop	Complete	Incomplete	Declines	Disqualified	Total	Response rate (%Complete/Total)
3/28/2016	Monday	3:56pm to 6::48pm	Mary Street Transfer	13	4	13	1	31	41.9
4/1/2016	Friday	8:37am to 11:21am	Mary Street Transfer	10	6	13	0	29	34.5
4/1/2016	Friday	1:31pm to 2:48pm	Mary Street Transfer	6	4	7	0	17	35.3
4/6/2016	Wednesday	10:52am-11:38am	Super Stop	4	1	3	0	8	50
4/6/2016	Wednesday	12:48pm-2:02PM	Super Stop	6	1	6	1	14	42.9
4/7/2016	Thursday	2:49pm-6:01pm	Super Stop	17	2	13	0	32	53.1
4/17/2016	Sunday	12:27pm-3:36pm	Mary Street Transfer	10	7	8	1	26	38.5
4/21/2016	Thursday	3:05pm-4:29pm	Super Stop	5	4	4	0	13	38.5
4/21/2016	Thursday	4:58pm-5:48pm	K-Mart on Rivers Ave	2	1	2	1	6	33.3
4/23/2016	Saturday	4:20pm-6:14pm	Super Stop	10	1	8	0	19	52.6
4/24/2016	Sunday	around 5pm-6:21pm	Mary Street Transfer	6	3	4	0	13	46.2
4/29/2016	Friday	4:19pm-6:01pm	Calhoun and Johnson	3	7	3	0	13	23.1
Totals				92	41	84	4	221	41.6

3.3.5 Study sample

For this research, the targeted population was CARTA bus riders who live in the study area. A total of 132 CARTA riders volunteered to take the survey, and of those respondents, 90 were complete responses. Table 3.3 shows a comparison of the study sample with CARTA rider demographics (BCDCOG and CARTA 2016).

Table 3.3. CARTA ridership and study sample characteristics

	CARTA (%)	Study sample (%)
Male	46	54
Female	54	46
Black/African American	65	68.5
Income below $30,000	58	51*
Under age 35	48	23

Source: CARTA Comprehensive Operational Analysis (BCDCOG and CARTA 2016)
*In the survey, this represents the sample with a household income below $25,000. CARTA does not provide information about whether the reported income below $30,000 is based on individuals or households.

The study sample has a slightly higher percentage of male respondents compared to female respondents and fewer respondents under the age of 35 compared to the available numbers on CARTA ridership. The lower number of respondents under the age of 35 might be due to the sampling time frames and the inability to get complete responses during rush hour when a younger working crowd or students might be at the bus stop. Overall, the majority of the sample had a household income of $25,000 or below and identified as Black or African American race/ethnicity.

Many respondents rode CARTA either every day or on weekdays (n=84, 63.4%) or at least a few times a week (n=26, 17.4%) and got to the bus stop by walking (n=85, 74.6%). The most frequent destination respondents traveled to using CARTA was work (n=82, 62.1%). Of the respondents who could find alternate transportation at least sometimes (n=91, 81.3%) if CARTA was unavailable, the most popular alternate mode of transportation was either getting a ride with someone they knew (n=36, 40%) or taking a taxi (n=31, 34.4%).

In addition to riding CARTA often, the majority of the survey sample was also transit-dependent, meaning that CARTA was their primary source of transportation for completing their most frequent trip described in the survey. The survey measured transit dependency using four indicators: alternate transportation if CARTA was unavailable (Appendix B, Q21 and Q22), household ownership of a car (Appendix B, Q48), access to a car (Appendix B, Q49), and ability to drive a car (Appendix B, Q50). Few respondents said they could drive a personal car if CARTA was unavailable (n=4, 4.4%). Additionally, majority of the study sample did not own a car (n=60, 64.5%). The other measures of transit dependency—access to a car and ability to drive—helped evaluate whether access to vehicles through the respondent's social network may reduce the individual's level of transit dependency. However, most respondents still indicated that they either never, rarely, or only sometimes (n=72, 79.1%) have access to a car if they need one. Over half the respondents can drive a car (n=67, 73.6%), which showed that transit dependency for most of the respondents stemmed from lack of access to a vehicle when they had to make their trip.

3.3.6 Sample biases and survey limitations

Many individuals volunteered to take the survey while they waited for the bus, with the total complete response rate being 43.6% (Table 3.2). The presence of interviewers might have increased interest and willingness to participate among respondents (Barribeau et al. 2012). However, a limitation of this sampling strategy was the high number of incomplete surveys due to respondents leaving in the middle of the survey when their bus arrived. Incomplete responses are used in the analysis of some research questions, which is why some survey questions have a smaller sample size than others. The higher frequency of buses during rush hour made it more difficult to sample during the morning and evening rush hour since many people declined to participate as they expected the arrival of their bus. Another possible bias stemming from this sampling strategy could be that the sample might consist of more individuals who arrived early to the bus stop. However, many individuals often gave information about trips different from the one they were taking during the interview, indicating that this bias might only be a relatively small issue. The sampling locations also influences the sample composition since the survey was administered only to individuals taking busses at those transit stops. To minimize this source of bias, two of the sampling sites selected were transfer stations, which increased the possibility of sampling riders from a diverse range of bus routes.

Another survey limitation came from the lack of detailed information about individual sensitivities and adaptive capacity to respond to various impacts that result from general and flood-induced transit disruptions. This research was designed as a first step to collect exploratory information about how transit disruptions affect CARTA riders regularly and during nuisance flood events. The survey tool was selected as the data collection method to determine how impacts varied among a larger sample size. Therefore, the short answers collected by the survey provide insight into general factors that influence the types of impacts the respondent described experiencing during transit disruptions but not necessarily detailed information about how these factors shaped the individual's sensitivity and adaptive capacity.

Finally, how individuals interpreted or perceived the questions could have influenced the results of the survey. Although the survey was pilot tested with CARTA riders and interviewers were trained to ask consistent survey probe questions, it is possible that some individuals still misunderstood the question and provided a response that reflected a different understanding of transit disruptions.

3.4 GIS model

GIS modeling was used to assess how individual vulnerability to transit disruptions varied under different coastal flooding and sea level rise scenarios by calculating and evaluating changes in transit travel time for survey respondents under different flood scenarios. The following sections describe the GIS model, assumptions, data inputs, and limitations.

3.4.1 Public transit vulnerability model

Public transit vulnerability to nuisance flooding was modeled using ESRI Network Analyst extension for ESRI ArcGIS 10.3.1. The following sections discuss the model used in this research, assumptions, and inputs. The model followed the general research methodology outlined by Wang et al. (2014, 4) in Figure 2.1 and focused on modeling the vulnerability indicator in Step 4. Figure 3.2 shows the data flow diagram for the model.

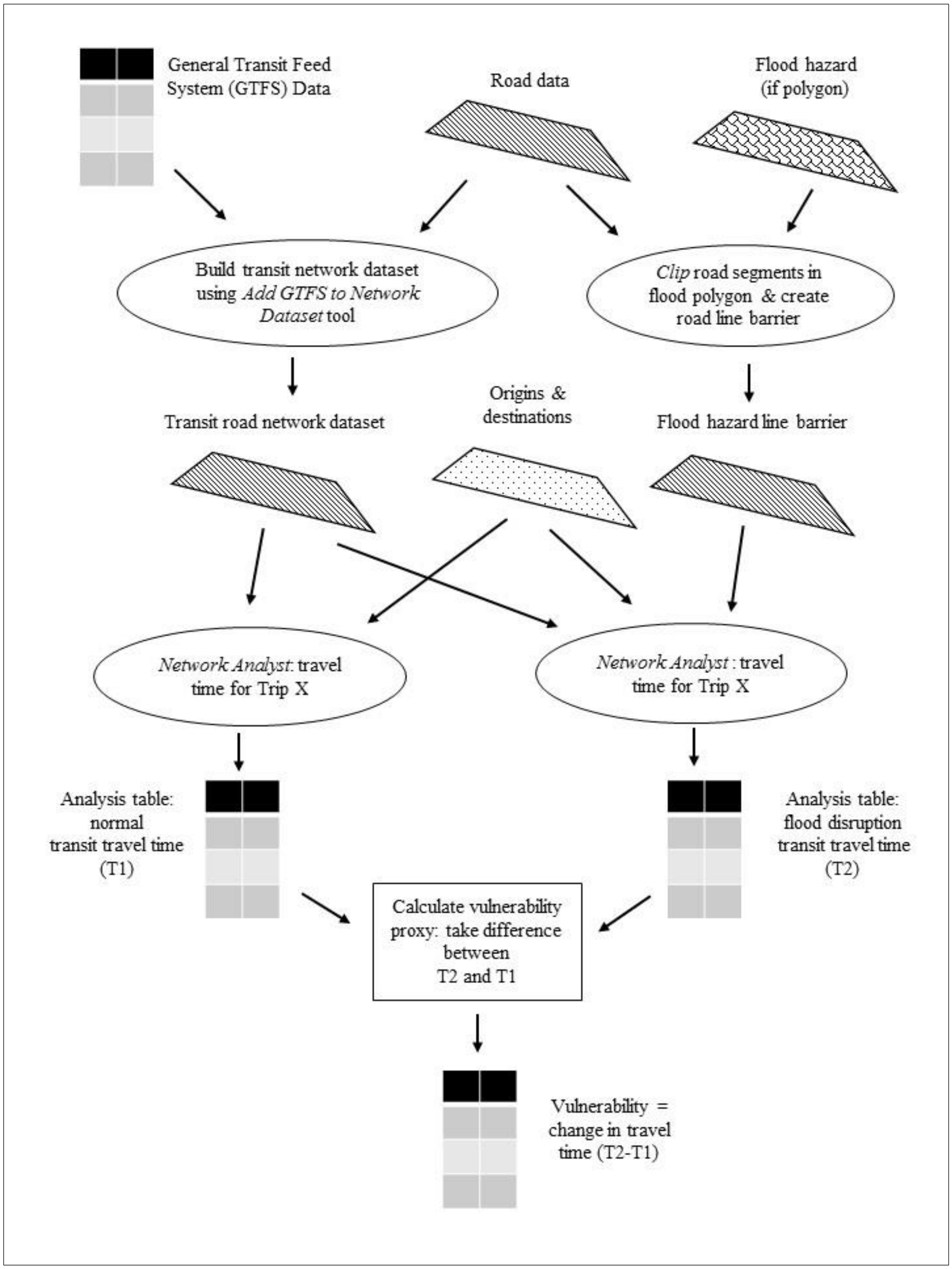

Figure 3.2. Model data flow diagram for vulnerability indicator

Vulnerability Indicator

Transit vulnerability was operationalized in this model as changes in travel time due to a stressor in the transportation network. In this research, the stressor was a nuisance flood event. Thus, changes in travel time served as a proxy for adverse impacts caused by the flood-induced transit disruption. Travel time was generated using the Network Analyst toolbox in ESRI ArcGIS 10.3.1 by calculating the time it takes to travel the distance from the origin to the final destination:

1. Travel time (T) as a function of distance from the origin to destination (x)

$$T\ (x)\ =\ \frac{x}{speed\ limit}$$

x = distance from origin to destination

2. Vulnerability as a function of changes in travel time for an origin-destination pair

$$Vulnerability\ =\ T2 - T1$$

T1 = travel time before stressor *T2 = travel time after stressor*

The travel time after a stressor (T2) was calculated by disrupting the transportation network using line barriers to block roads exposed to flooding and removing any bus routes intersecting flooded roads (see below for assumptions).

Measuring transit vulnerability using changes in travel time resulted in three possible outcomes. The first outcome was a “late trip” indicated by a positive difference between T2 and T1 since T2 was longer due to the flood-disrupted road network. The second outcome was a “cancelled trip”, which resulted when there was a negative difference between T2 and T1 due to T2 having a value of zero as a result of being cancelled by road flooding. Finally, a “same trip” resulted when the difference between

T2 and T1 was zero because both T1 and T2 had the same travel time, meaning the trip was not affected by road flooding in the model. The number of late, cancelled, and same trips and the magnitude of increase in travel time for late trips helped understand variations in transit vulnerability among different flood scenarios.

Transit road network dataset

This model used the Add GTFS to a Network Dataset tool developed by Morang and Stevens at ESRI (Morang 2016) to create a road network dataset that includes public transit route schedule information for CARTA and calculates travel time based on bus schedule info and walking times. The General Transit Feed Specification (GTFS) data format provides information on routes, stops, and schedules, and the Add GTFS tool incorporates this information into a road network data set that can be analyzed using the ArcGIS Network Analyst extension. Both the Add GTFS to Network Dataset tool and the GTFS data for CARTA are freely accessible. The GTFS feed data used for the model runs in this research were from February 2016. More recent GTFS feeds were not used in this model since they reflected new route and stop changes that CARTA implemented as of May 1st, 2016, after surveys were completed. Since origin-destination data was collected prior to these route changes, respondent route info would have differed from stops and routes in the newer GTFS data feed. The network dataset was also built with the parameter to exclude bus routes, which was used to remove any bus routes with flooded portions in each of the scenarios.

Flood hazard inputs

The model was designed to evaluate the impact of different nuisance flood exposures on the network dataset. In this research, each of the hazard data layers in Table

3.4 were used as a proxy for current or future amounts of nuisance flooding. A limitation of these flood hazard layers was that they might not capture the true extent of nuisance flooding due to variations among nuisance flood events from fluctuating wind patterns and other local factors influencing tides and relative sea levels. Additionally, inundation farther inland from the coast may vary depending on elevation, land cover, and storm water drainage. Despite these limitations, sea level rise projections and exposure layers from NOAA showing the extent of inundated land under 1 to 6 ft. of sea level rise above mean higher high water (MHHW) provided a way to estimate current and future changes in flood exposure that could occur when the highest of the high tides become even higher. Other commonly used flood hazard layers, such as FEMA floodplain maps and storm surge model outputs (e.g. SLOSH, ADCIRC) were not used in this analysis as these typically depict extreme flood events, during which emergency response operations, such as evacuation, have altered normal public transit service and road network service until the event passes.

The flood hazard layers were used in the model by converting them to line barriers if they were polygons, such as the sea level rise inundation layers from NOAA. Line barriers were chosen in order to block roads in the network route analysis and prevent them from being used by the model to calculate travel time. The 0ft MHHW sea level rise layer was used to correct the line barriers created from the other sea level rise layers based on the assumption that roads intersecting this layer, such as bridges, were designed to withstand the average highest tide in the area represented by 0ft MHHW. The road closure data from City of Charleston Emergency Management were already line barriers and did not have to be converted into new barriers. Additionally, the road closure data from City of Charleston Emergency Management were not corrected by the 0ft MHHW.

Table 3.4 Flood Hazard Data Layers

Flood scenario	Hazard data
Current nuisance flooding	• CHS3plus – Roads that have been temporarily closed three or more times since August 2015 by flooding from king tides and heavy rain. • SLR1 – 1 ft. above MHHW sea level rise inundation layers from NOAA; this layer represents the extent of tidal waters at approximately 9.53 ft. relative to the Charleston Harbor tide datum, which was used to create these layers (Datum for Charleston Harbor Tide Gauge – Appendix A, Figure A.3).
Future flooding	• SLR2 – 6 – 2-6 ft. above MHHW sea level rise inundation layers from NOAA

Origin and destination data

Origins were defined as the starting point of travel from which the model calculated travel time to the final destination. The model was tested using few sample origin-destinations from randomly selected respondents. Then it was run using all responses (n=88) with valid origin-destination information obtained from the respondent's reported route information (Figure 3.3). In the survey, respondents described stops on their trip by mentioning the nearby crossroads and a place marker, such as a restaurant. This information was used to select the CARTA transit stop by triangulating the respondent's answers with the bus route stops, Google Maps, and ArcGIS. Any trips where a stop could not be found were tossed out. All trips were modeled starting at 8am on a weekday schedule.

Of CARTA routes running during April 2016, 15 of the 16 fixed routes and 3 of the 4 express routes were represented in the sample (Figure 3.4). Model sample demographics are provided in Table 3.5.

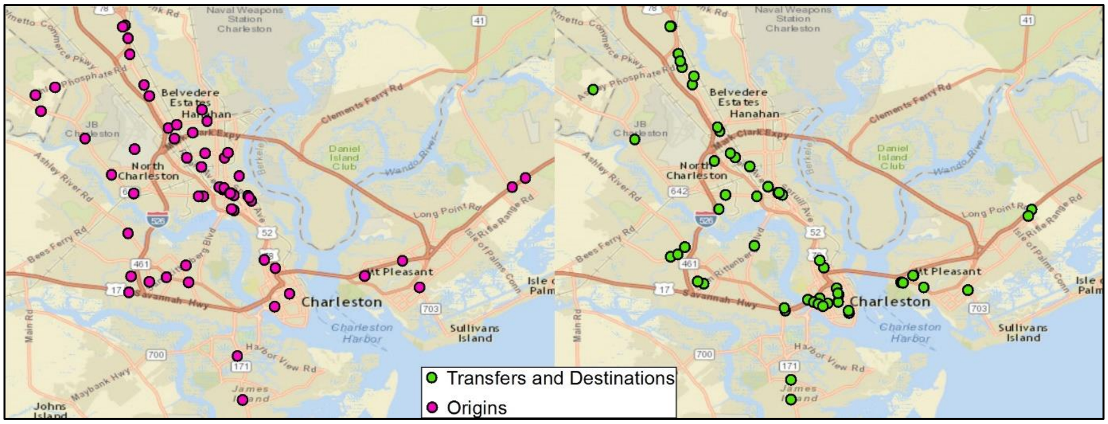

Figure 3.3 Location of Respondents Origins and Destinations

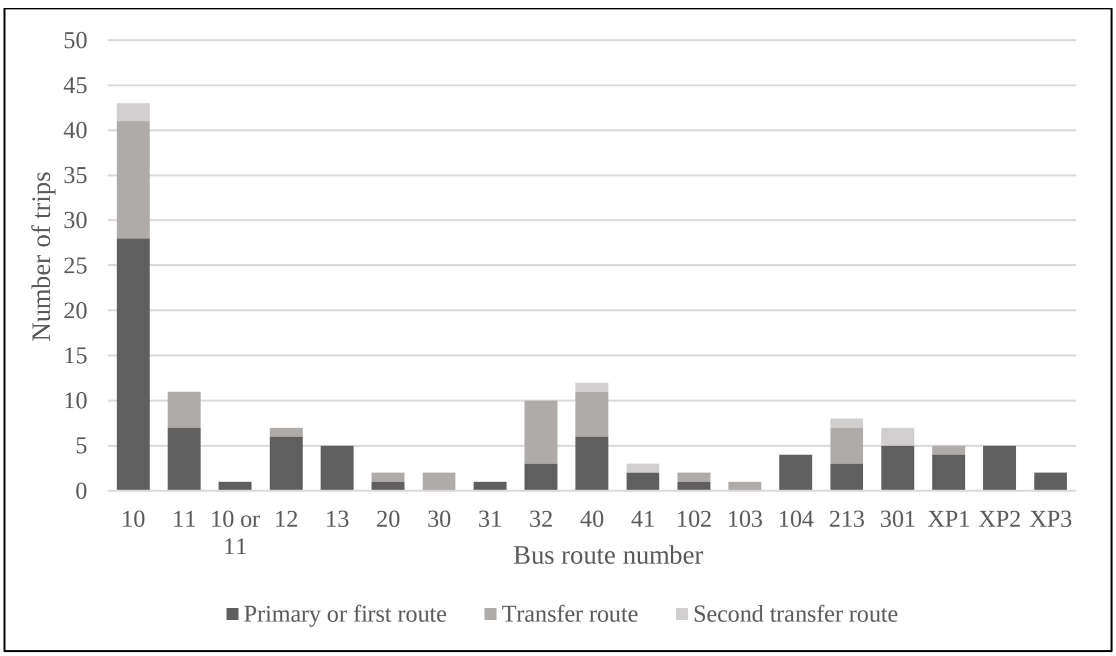

Figure 3.4 Bus routes represented in model

3.4.2 Model assumptions

In order to assess changes in road network functionality due to flooding, the following assumptions were made:

- Flooded roads can not be accessed by any transportation mode, such as walking or public transit (adapted from Suarez et al. 2005, 236). To capture this assumption in the model, portions of the road segment intersecting a flood polygon layer were clipped and turned a road barrier for the network analysis model to prevent walking along flooded routes. Additionally, any bus routes with flooded road segments were removed from that scenario model run because the model did not have the capability to reroute stops outside the stop order and time schedule specified in the GTFS data. Thus if one portion of the route was inaccessible, the entire route was removed from the analysis.
- Travel can not occur to and from a stop along a flooded road (adapted from Suarez et al. 2005, 236). As a result, any trip with an origin, transfer, or destination stop located along a flooded road in the model was cancelled.
- Road segments flooded at 0 ft. mean higher high water (MHHW) are passable to correct for bridges flooded at 0ft MHHW. The NOAA SLR layers are based on a bathtub modeling approach, and as a result, roads built above the land elevation, such as bridges, appear inundated even when they might be able to withstand certain tide inundation levels.

Since this model focused on the impacts of coastal flooding on the road network, a limitation of these assumptions is that some level of serviceability (e.g., very shallow flooding that might be passable) might exist on flooded roads in reality. Additionally, some of the assumptions represent extreme outcomes for a scenario, such as removing an entire bus route because one portion was flooded. In reality, buses might only be delayed or rerouted along streets not a part of the original bus route rather than being completely cancelled. However, the current model does not have the capacity to modify bus schedules and routes to capture these real-world adaptations of the transit system to flooding. The model results provide a snapshot of what happens if flooding occurred in the transit network at one moment in time while in reality road networks and flood extents are dynamic.

The model also calculated changes in travel times based on the following assumptions used to build the transit network dataset (from Morang 2016):

- The model calculated travel time based on walking times and bus travel and wait times.
- The model calculated travel time by selecting a combination of walking and transit routes and stops that resulted in the minimum travel time between trip stops based on the transit schedule at the specified time of day and road availability for walking.

3.4.3 Model limitations

While the GIS model provided a method to assess network vulnerability under current and future extents of nuisance flooding, there were several limitations to the model. First, the model results can only be as good as the data inputs. Since no true nuisance flood layer exists, partly because of the variability in the extent of nuisance flooding, the flood layers in the model were proxies and could have over- or underestimated the extent of flooding. While one flood layer was based on real-time road closures during three or more nuisance flood events, this layer only shows road closures in the City of Charleston and does not capture flooding in other parts of the study area. Additionally, the origin-destination information did not capture the exact start or stop location of the respondent because origins and destinations were determined using respondent-elicited information from the survey, which asked for respondent's bus stop locations rather than the exact origin or destination due to privacy concerns.

Other limitations of the model stemmed from the assumptions that simplified how transit and walking modes of transportation function when roads might be flooded. For example, the model assumes that any flooded road cannot be used, but in reality, roads with some flooding might still remain partly functional, such as the operation of one lane rather than two. Additionally, the model selects bus routes based on minimum transit time between the origin and destination, which might not always be the most convenient. A respondent might take one bus route from point A to point B without taking any transfers, but the model might use two bus routes to complete the same trip since transferring buses might be faster according to the fixed or a shorter travel distance. The model also assumes that individuals are willing to transfer any number of times or walk along any distance of unflooded roads in order to complete the trip, but in reality bus riders might not want to spend half their day switching bus routes or walking to reach their final destination.

3.5 Data analysis of individual transit vulnerability using the proposed indicators

This research developed two instruments to assess individual transit vulnerability—a public transit survey and a GIS network analysis model. Survey results were analyzed using descriptive frequencies of survey responses to multiple choice and short answer questions presented in Table 3.1. Short answer responses were also grouped and analyzed by frequencies of common terms and descriptions. The GIS results were analyzed using descriptive frequencies of same, late, and cancelled trips.

Finally, the survey and model-generated vulnerability measures were compared to evaluate how the model results corresponded to the respondent's experiences with nuisance flooding. Specific data used were the frequencies of the three types of transit disruptions captured by the GIS model vulnerability indicator and frequencies of responses from the bolded survey questions in Table 3.1.

Chapter 4. Findings

Dimensions of individual vulnerability to transit disruptions were assessed using public transit survey data and GIS modeling results. Section 4.1 presents survey results on respondents' experiences during normal and flood-induced transit disruptions and discusses how three sources of adaptive capacity and sensitivity mediate individual vulnerability. Section 4.2 evaluates what factors may influence individual vulnerability to nuisance flood disruptions in the future based on changes in travel time calculated by the GIS model. Finally, Section 4.3 compares the GIS model results with survey responses about nuisance flood experiences to identify strengths and weaknesses of the two approaches used to measure individual vulnerability to transit disruptions in this research.

4.1 Individual transit vulnerability as a function of adaptive capacity and sensitivity

To understand the broad range of factors influencing individual transit vulnerability, some of which may not be hazard-dependent, the public transit survey assessed respondents' travel behavior and experiences to both normal and flood-induced transit disruptions (see Section 3.3.1 for a summary of questions used to measure vulnerability). "Normal" transit disruptions refer to trips delayed or cancelled due to non-flood stressors, such as personal reasons, traffic, or the train. Nuisance flood-induced transit disruptions refer to trips altered because of heavy rain or high tide or a combination of both. The first and second portions of this analysis discuss the range of consequences and impacts respondents could experience due to normal transit disruptions followed by a comparison of respondent experiences during nuisance-flood disruptions. The final section identifies sources of adaptive capacity and sensitivity mediating individual transit vulnerability to nuisance flooding based on respondents' experiences during normal and flood-induced disruptions.

Since trip destination and purpose have been found to play an important role in the individual travel behavior under different weather conditions (Böcker, Dijst, and Prillwitz 2013), the discussion of the survey findings are framed using trip destination and transit disruption (late vs. cancelled) in addition to the trip type (time-dependent or time-independent) and stressor (normal vs. flood). The public transit survey collected information on the destination respondents travelled to most often using CARTA. Over half the survey respondents most frequently used CARTA to travel to work (n= 82, 62.1%). Respondents also said they used CARTA most often to go to the hospital (n=14, 10.6%), store (n=11, 8.3%), school (n=9, 6.8%), and other (n=16, 12.1%). The "other" category included destinations such as family member's home, volunteer site, church, and downtown. Trip type reflects trip purpose and importance by categorizing trips as either "time-dependent" if the trip must be completed by a specific time, such as going to the hospital for an appointment, or "time-independent" if the trip does do not have to be completed by a specified time. Respondents were not explicitly asked about their trip type in the survey, but the categories help evaluate the findings presented in this section.

4.1.1 Types of consequences from normal transit disruptions

Respondents reported a range of experienced or potential impacts when they were asked during the survey what would happen if they were late or had to cancel their CARTA trip that they made most frequently. The summary of responses in Table 4.1

shows sometimes these impacts resulted in consequences for the individual and varied in severity depending on destination and the type of transit disruption. While the questions in the survey asked respondents about general impacts rather than assuming a transit disruption caused a negative impact for the respondent, many respondents still explicitly or indirectly discussed consequences. Table 4.2 summarizes the frequency of how often individuals could be late or cancel their trip and provides additional insight about how respondents perceived the severity of impacts they described. Overall, impacts due to late or cancelled trips stemmed from destination related policies, with more consequences associated with transit disruptions during a time-dependent trip than a time-independent trip. Individual perceptions, travel behavior, and value attributed to the trip also appeared to influence whether transit disruptions resulted in consequential impacts.

Respondents travelling to work typically described impacts from being late or cancelling their trip in the context of work-related policies or financial repercussions. Frequently mentioned impacts for being late included receiving warnings or being written up, which some respondents also mentioned as occurring when they cancelled their trip. The severity of impacts varied by workplace because some had stricter policies that allowed individuals to be late or cancel their trip only once while others allowed up to three warnings or write-ups before individuals faced more severe consequences, such as suspension or being fired. Respondents described direct and indirect financial consequences, including losing pay or working extra hours to make up for lost time. These financial repercussions might have been dependent on whether the respondent worked an hourly pay or salaried job. However, additional research is needed to make a definitive conclusion about the relationship between job type and financial consequences since the survey did not collect this level of detail about the respondent's occupation.

Cancelled trips to work appear to result in more consequences than late trips based on the survey data. More respondents mentioned losing pay or being fired as a possible consequence if they cancelled their trip than if they were late, which suggests missing an entire day of work has greater negative impacts than being late by a few minutes or hours. Additionally, more individuals described no impacts or "nothing" happening when late compared to what happened for a cancelled trip, providing another example of how late trips might have fewer consequences than canceled trips. While many respondents described the ability to "call in" if they had to cancel their trip (n=24) versus if they were running late (n=9), some respondents further explained this option was only useful if they had a valid excuse, such as a doctor's note. Thus, the opportunity to mitigate the impacts of cancelled trips by calling in or taking a day off may depend on the reason for the trip cancellation and whether the workplace offers sick leave or paid time off.

Table 4.1 Summary of impacts described by respondents based on trip destination*

Destination	Late trip	Cancelled trip
Work (n=82)	• Warnings (n=9) • Call in (n=9) • Possible to get fired (n=7) • Suspended (n=2) • Lose pay (n=7) • Never (n=5) • Nothing (n=15) • Work late or make up hours (n=2) • Written up (n=17)	• No pay (n=13) • Fired/lose job (n=14) • Call in (n=24) • Need valid excuse (n=5) • Paid time off (n=3) • Sick day (n=7) • Warning (n=2) • Nothing (n=8) • Can't/never (n-4)
Hospital (n=14)	• Rescheduled appointment (n=7) • Miss appointment (n=1) • Does not matter/ go anytime (n=2) • Leave early (n=2) • Seen later (n=3)	• Reschedule appointment (n=10) • Nothing (n=2) • Charged fee (n=1) • Missed appointment (n=1)
Stores (n=11)	• No consequences/doesn't matter (n=11)	• Reschedule trip (n=3) • Nothing happens/doesn't matter (n=) • No food (n=1)
School (n=9)	• Nothing (n=3) • School or professor's policy on attendance(n=4) • Miss class (n=1)	• School or professor's policy on attendance (n=4) • Don't want to miss class (n=3) • Financial repercussions (n=2)
Other (n=16)	• No repercussions or nothing (n=6) • Reschedule or wait for new appointment (n=3) • Don't accomplish task intended to do (i.e. cannot donate plasma or fewer volunteer hours at the hospital)	• Nothing (n=7) • Reschedule trip (n=4) • Lose money

*Table 4.1 summarizes the number of respondents who mention the specific impact. Sometimes respondents mentioned multiple impacts, which is why the total n for each section will not represent the total n for the sub-groups under the column and row headings.

Table 4.2 Frequency that respondents could be late to or cancel the trip to their most common CARTA destination

Frequency	Work		Hospital		School		Store		Other	
	Late	Cancel	Late	Cancel	Late	Cancel	Late	Cancel	Late	Cancel
Never	33 (40%)	44 (54%)	6 (43%)	3 (21%)	3 (33%)	2 (22%)	0	4 (36%)	4 (27%)	2 (17%)
Once	8 (10%)	11 (14%)	0	2 (14%)	1 (11%)	1 (11%)	1 (9%)	0	0	0
A few times	25 (30%)	20 (25%)	6 (43%)	4 (29%)	4 (44%)	6 (67%)	1 (9%)	2 (18%)	3 (20%)	4 (33%)
Any number of times	15 (18%)	5 (6%)	2 (14%)	4 (29%)	1 (11%)	0	9 (82%)	4 (36%)	8 (53%)	6 (50%)
Other	1 (1%)	1 (1%)	0	1 (7%)	0	0	0	0	0	0

Percentages are based on the number of complete responses. Missing responses were excluded from the percentage.

The frequency of how often respondents said they could be late or cancel their trip to work also suggests late trips may have fewer severe impacts than cancelled trips (Table 4.2). The larger proportion of respondents who answered they could be late "A few times" or "Any number of times" to work suggests respondents could tolerate the amount of consequences from being late more often than if they missed work. For example, a respondent described being late a few times was okay because two write-ups were allowed but said s/he never cancelled going to work because what resulted was no pay for the day. Loss of pay might also explain why more respondents said they could "never" cancel their trip more often than "never" being late to work because missing an entire day of pay would have a greater impact on the individual's livelihood than missing a few hours of pay. Additionally, individuals might have more opportunities to make up a few hours of work than an entire day. Alternatively, the desire to never be late or cancel a trip to work might stem from individual perceptions of acceptable behavior shaped by workplace culture, which was alluded to by one respondent who described never being late because she worked for the military.

Similar to those travelling to work, respondents going to school experienced different impacts from transit disruptions depending on school attendance policies, which sometimes resulted in financial repercussions. Attendance policies described in the survey varied by class or school and resulted in different impacts depending on the threshold of acceptable number of absences or late arrivals. The types of consequences also varied when the absence or late thresholds were exceeded. For example, some respondents mentioned being late “affects participation,” while another respondent said he was being dropped from a class after being late too many times. Others described the potential consequence from six or more unexcused absences would be an F grade in the class. Conversely, one individual explained zero consequences occurred for missing class since there was no class attendance policy. Some respondents also described financial consequences resulting from attendance policies, such as having to pay back financial aid if late or absent too many times. Financial repercussions associated with being absent or late to class may depend on the individual’s perceptions of and ability to afford the cost of school, as suggested by a respondent who said “it is expensive to pay for school.” However, not all students might share the same view.

Cancelled trips to school appeared to impact respondents more severely than late trips, possibly due to absences having more severe consequences. Most respondents said they only cancelled trips to school a few times or were never absent. Some individuals explained being absent resulted in missing the entire class, which could have a greater impact if students cannot access material from another source or have the opportunity to make-up schoolwork. However, if the respondents were late to class, they still could participate even if they missed some of the material. Regardless, the severity of cancelled compared to late trips may vary for a different sample population depending on the attendance policies in place, which could make being late to class just as severe as an absence.

For trips to the hospital, most respondents described having to reschedule the appointment if the trip was delayed or cancelled. Similar to work and school destinations, rescheduling policies varied by the hospital or doctor's office and resulted in different experiences for respondents. For example, some individuals described being able to reschedule appointments any number of times without consequences while others had to pay a fee. A few respondents also mentioned another cost of rescheduling was having to wait longer, sometimes up to a month, for the next appointment.

Although both late and cancelled transit disruptions to the hospital resulted in rescheduling appointments, the respondents' descriptions about rescheduling late trips and how often they could be late to the hospital suggest being late to the hospital has greater consequences than cancelling the trip. The proportion of respondents who said they could never be late was greater than those who said they could never cancel their trip to the hospital (Table 4.2), which might be explained by the choice to reschedule as being the primary option for premediated trip cancellations, but not for unintentional late trips. For example, a few respondents mentioned that if they cancelled their trip early enough, they did not have to pay a fee. However, for late trips, some respondents described rescheduling as the last choice. Instead, their first choice was to still complete the trip to the hospital and wait to be seen later in the day even after missing their original appointment time. Since trips to the hospital are often planned in advance and occur less frequently than daily trips to work or school, unintentionally missing the appointment appears to result in more inconveniences than cancelling the trip ahead of time.

Finally, unlike respondents travelling to work, school, or the hospital, those travelling to the store described very few, if any, consequences caused by late or cancelled transit disruptions. All respondents said they could be late at least a few or any number of times, with the majority of them saying they could be late any number of times because it did not matter what time they got to the store (Table 4.2). Four respondents said they could never cancel their trip, but three of them further explained the trip was never cancelled because they rescheduled their trip to the store. Additionally, options to go to a different store than planned provided greater flexibility in changing the trip but still achieving the intended trip purpose. Only one respondent explained how a canceled trip to the grocery store would mean no food, highlighting that there are still consequences if the trip is never made despite the flexibility of being able to reschedule trips or be late to the store. Overall, respondents going to the store described fewer negative impacts from transit disruptions compared to those travelling to other destinations.

Based on the findings discussed in this section, impacts experienced by individuals due to normal transit disruptions depend on the trip type, destination, and disruption and individual characteristics. The influence of trip destination appears to depend on the trip type. Time-independent trips, such as those to the store, seem to have few negative impacts based on respondent answers because the trip could be completed another day or time if cancelled or delayed. However, for time-dependent trips, such as going to work, school, or the hospital, where respondents had to be at the destination by a specific time, transit disruptions seem to result in consequences. Additionally, survey responses suggest that the destination's influence on the type of impacts stem from destination-specific late or cancellation policies. For example, late trips seem to have fewer impacts than cancelled trips at school or work while the opposite was true for trips to the hospital where cancelled trips gave additional time to reschedule the appointment. Finally, individual characteristics, such as cultural background and socioeconomic status, might explain why individuals described consequences when others did not for a trip with the same destination and purpose. For example, individuals with an hourly-wage job might experience greater consequences from a cancelled trip compared to those with a salaried job. These associations could not be evaluated in depth in this research due to the small sub-group sample size for questions with multiple choices and limited detailed answers from respondents.

The findings in this section described consequences from a late or cancel transit disruption caused by everyday stressors, which could be due to personal reasons, such as being sick or missing the first bus, or an external source, such as traffic or train delay. The next section evaluates impacts experienced when the respondents had transit disruptions caused by nuisance flooding, an external stressor outside of their control.

4.1.2 Types of consequences from transit disruptions caused by nuisance flooding

Respondents described experiencing fewer negative impacts during flood-induced transit disruptions compared to impacts caused by normal transit disruptions discussed in section 4.1.1 although the impacts still varied by trip destination. To understand whether and how nuisance flooding has impacted their trip in the survey, respondents were first asked *"Has your CARTA trip to {most frequent destination} ever been different due to* *high tide or heavy rains?"* If they answered yes, respondents were asked additional questions about how their trip changed due to heavy rain or high tide. Although high tide and heavy rains do not always cause nuisance flooding, these two weather phenomenon were used as proxies for nuisance flooding since any CARTA trip alterations during these events typically occur due to minor road flooding on routes or increased traffic from road flooding in other locations (Burns and Gilreath 2015). Of the respondents who experienced a transit disruption caused by heavy rain or high tide, the majority of them were late to their final destination. A few respondents said they canceled or rescheduled their trip (Table 4.3). Additionally, some respondents reported not experiencing a transit disruption and still made it to their final destination on time despite saying their CARTA trip was different due to high tide or heavy rains.

Table 4.3 Types of transit disruptions resulting from nuisance flood events

Type of disruption	Number of respondents	Resulting impacts
Late	38	• They understood/more understanding because of rain/excused (n=12) • Nothing (n=11) • Time lost/make up time (n=4) • Rescheduled (n=1)
Cancelled trip*	7	• Cancelled trip because of rain (n=3) • October flood forced cancel (n=3) • Rescheduled, no fee (regularly there is a cancellation fee) (n=2)
No change/on-time	11	• Leave early in order to arrive on time (n=6) • Bus still on time/no change to CARTA trip (n=3) • Taxi instead (n=1)

*This sub-group includes respondents who answered that high tide or heavy rains caused them to reschedule their trip, which was also presented as an answer choice. Their responses were grouped with the respondents who answered that they cancelled their trip since those who rescheduled their trip only did so after deciding to cancel their trip either because of rain in the morning or the October 2015 flood event.

Most individuals who were late to their destination because of high tide or heavy rain described experiencing less severe impacts or that "nothing" happened. Respondents who were travelling to work said that their workplace "understood" why they were late when either heavy rains and/or high tide altered their CARTA trip. A possible explanation for this understanding might be that these proxies for nuisance flooding represent external stressors outside of the individual's control. Whereas in the previous section, it is possible the individual described impacts that occurred due to an internal stressor, or when he or she caused the late or cancelled transit disruption. Individuals going to other time-sensitive destinations, such as school and the hospital, also described fewer consequences or "nothing" happening during nuisance flood disruptions. However, detailed information about what the respondents meant by "nothing" is lacking and makes it difficult to distinguish whether nothing happened because policies determining consequences were waived because of the weather or something else.

A possibility for the lack of negative impacts mentioned might be that respondents forgot to mention consequences in light of some destination policies being changed to accommodate the transit disruptions caused by nuisance flooding. For example, respondents who were late to work did not explicitly mention any financial repercussions from being late during nuisance flooding. However, some respondents described having to still make up lost time. Thus, some workplaces might have been understanding and waived some portions of the late policies, such as warnings, but they still expected individuals to make up lost hours. Additionally, while one respondent did explicitly say there were "always consequences, time lost" for a late trip, many individuals might not have considered loss of time an explicit consequence. These types of impacts often cannot be measured or calculated by numeric metrics, made up for with forgiveness policies, and/or be recognized as costs by the individuals themselves.

Trips that were cancelled or rescheduled because of nuisance flooding resulted in different impacts depending on where the respondent was going and the source of flooding. Three respondents answered the questions about high tide and heavy rain disruptions by describing their experiences of having cancelled trips during the 2015 October flood event when all CARTA routes and many businesses were shutdown although this was not a nuisance flood event. These trips were cancelled without choice, but had slightly different consequences than a normal transit disruption. The two respondents who were travelling to work reported receiving no pay although other work consequences from absence or late policies seemed to have been relaxed. A respondent going to the hospital mentioned the rescheduling fee was waived since the cancellation was caused by flooding.

The other four respondents cancelled their trip because of rain or both rain and high tide, and all of them described choosing to cancel their trip because they did not like travelling in the rain or the bus would be running late. Half these trips were to the hospital while the rest were to places classified under "other" and included going to mom's house and downtown. For both these destinations, trip cancellations were either not consequential or less inconvenient than being late due to the option to reschedule. A previous review on the impact of weather on travel behavior that found people tended to cancel trips under adverse precipitation conditions if trip purpose was non-utilitarian (Böcker, Dijst, and Prillwitz 2013). In this case, hospital visits are still time-dependent and utilitarian, but the opportunity to reschedule appointments helps mitigate negative impacts from a trip cancellation.

A small subset of the respondents did not experience a cancelled or late transit disruption due to nuisance flooding although they said their CARTA trip has been altered by high tide or heavy rain in the past. Some respondents said they still reached their destination on time even if the bus took an alternate route or dropped them off at a different stop because of nuisance flooding. Other respondents avoided any transit disruptions because they left for their final destination anywhere from one to two hours earlier than usual. Respondents explained that they built in an extra time buffer for their travel to account for walking time and/or non-flood stressors, such as any delays caused by certain bus drivers, the train, an accident, or other stressors outside of their control.

In contrast to the impacts from normal transit disruptions discussed in Section 4.1.2, transit disruptions caused by nuisance flood stressors resulted in fewer severe impacts based on the survey responses. Similar factors discussed earlier, such as destination policies and individual travel behavior appear to still influence the impacts experienced by individuals. However, impacts may have been less severe due to a general understanding that nuisance flood conditions, such as heavy rain or high tide, are beyond an individual's control. While similar impacts might result for transit disruptions caused by other external stressors, such as late trips caused by a road accident, this research did not collect enough information about individual experiences during other transit stressors to conclude whether this is the case. Only a few respondents who mentioned that employers have been understanding in the past because they ride the bus alluded to this possible explanation. Additionally, while policies seem to allow respondents to be late or reschedule with fewer consequences, more detailed information is needed on whether individuals still lost pay or how long they had to wait until their next doctor's appointment and the consequences of that delay. The importance of individual travel behavior choices is highlighted by the few respondents who still made it to their destination on time regardless of experiencing an altered trip due to nuisance flood conditions. These individuals exhibited greater levels of preparedness for transit disruptions by making sure they always left early to get to their destination regardless of the weather conditions. Travel behavior choices might be influenced by other individual attributes, such as higher risk perception of transit disruptions, but there is not enough detail in the survey responses to make those conclusions.

The experiences and travel choices described respondents during their most frequent CARTA trip reveal how various factors determine whether or not they experienced consequences from normal and flood-induced transit disruptions. The next section discusses how these factors—individual travel behavior and attributes, transit system stressors, and destination policies—influence individual vulnerability by altering adaptive capacity and sensitivity to transit disruptions.

4.1.3 Sources of adaptive capacity and sensitivity

Individual vulnerability changes based on the sensitivity of the individual to disruptions and the individual's adaptive capacity to respond and cope with any potential hazard consequences (Adger 2006; Birkmann 2012). Survey respondents' experiences during normal and flood-induced transit disruptions revealed sources of individual adaptive capacity and sensitivity to transit disruptions stem from three primary sources: the individual, the transit system, and destination. Findings from Sections 4.1.1 and 4.1.2

showed how individuals might experience different impacts depending on the type of transit disruption (late vs. cancel), stressor of the transit disruption (normal vs. nuisance flood), and trip type (time-dependent and time-independent). These factors are organized in Table 4.4 to highlight which sources they originate from and whether or not they influence the individual's sensitivity and/or adaptive capacity. Many of these factors influence both the individuals' sensitivity and adaptive capacity to different transit disruptions, and the sources also influence one another, such as the individual being dependent on the transit system as well as the destination.

Individuals mediate their own vulnerability to transit disruptions by their travel behavior and trip characteristics. Based on the survey responses, these factors appear to increase sensitivity to transit disruptions by changing the potential loss individuals would experience if their trip were disrupted and their ability to avoid a transit disruption. While findings discussed in Sections 4.1.1 and 4.1.2 revealed that consequences varied by destination and whether the trip was time-dependent or independent, respondents still determined their trip destinations and how important the trip was to them. The value placed on the trip most likely depends on personal characteristics, as alluded to in the survey responses. For example, respondents going to work commonly described the loss of pay as a consequence from being late or missing work. However, the severity of income loss might have been greater for individuals in lower income brackets or hourly pay jobs than those in higher income brackets or with salaried jobs. Income level and other personal attributes may also determine individual transit dependency by influencing the individual's ability access to other modes of transportation during a transit disruption.

Table. 4.4 Sources of sensitivity and adaptive capacity that influence individual vulnerability to transit disruptions

Source	Sensitivity	Adaptive Capacity
Individual	• Personal characteristics - medical conditions, lower income bracket, hourly-wage job, transit dependency • Trip characteristics - high importance, time-dependent • Internal stressors for transit disruption • Limited flexibility in travel choices	• Personal characteristics - higher income bracket, salaried job, access to alternate modes of transportation, individual preparedness for external stressors • Trip characteristics - low importance, time-independent • Ability to adjust travel behavior - early departure time
Transit System	• Transit system vulnerability to external stressors - train, weather conditions, traffic, time of day • Bus stop shelters • Bus driver	• Bus rerouting • Picking up at different stops • Number of routes running • Redundancy of bus routes
Destination	• High impact consequences in absence and late policies • Rescheduling policies with fees • Limited of flexibility about external stressors, such as nuisance flooding	• Absence, late, and rescheduling policies with low impact or no consequences • Sick days, ability to call in or reschedule trip or make up lost work hours • Flexibility in policies due to understanding about external stressors, such as nuisance flooding

Despite personal attributes increasing the individual's sensitivity, these traits also enable transit riders to mitigate and adapt to any potential consequences due to transit disruptions. The individual's social network or income level are two factors that helped survey respondents access alternate modes of transportation. For example, while many survey respondents depended on CARTA for their primary mode of transportation, they said they would try to ask someone they know for a ride or take a taxi if CARTA were unavailable. However, a limitation of these sources of adaptive capacity is that they may not always be reliable, such as a limited number of taxis or members of the individual's social network do not have the capacity to offer transportation when needed. Another form of adaptive capacity exemplified by some respondents was their preparedness level for any type of transit disruption caused by external stressors they could not control. For example, some individuals described altering their arrival time by leaving anywhere from one to two hours earlier to complete their trip, especially if making a time-dependent trip to the hospital or work. Thus, even when the bus was running late because of nuisance flooding, they were still on time to their destination.

Outside of personal attributes and travel behavior determined by the individual, the transit system and their trip destination emerged from the survey results as external factors influencing the consequences from transit disruptions experienced by respondents. The transit system influences individual sensitivity and adaptive capacity depending on its ability to provide reliable and continued service. Overall, different factors influencing CARTA service can affect individual sensitivity negatively when they result in increased transit disruptions. One such factor described by respondents was the bus driver, with respondents knowing which driver would be late or on time. Survey responses also revealed how road conditions, such as traffic and trains, influenced the transit system and caused riders to be late regardless of the weather conditions. Other factors influencing whether the bus was on time or late included the time of day, with more busses running during rush hour and fewer running during off-peak hours, and the bus route since some of the popular bus routes had extra busses running to provide more frequent service. The severity of weather conditions also affected CARTA service. For example, during the 2015 October flooding event, all CARTA service was cancelled. However, during nuisance flood events, CARTA still continued to provide bus service even if delayed or original routes were altered. A few respondents also described a consequence of heavy rain occurred from getting wet at the bus stop because of limited or no sheltered areas to wait for the bus, which caused them to miss their bus, be late, or decide ahead of time to cancel their CARTA trip to avoid getting wet. Thus, the amount of sheltered space and quality of the station also altered the individual's actions.

The transit system also augments individual adaptive capacity by offering multiple bus routes and its ability to remain functioning despite stressors in the system. At the time of this research, CARTA provided 16 fixed transit routes and 4 express routes, and many of these routes have common transfer stops or take respondents to similar locations even if the route between the origin and destination varied. The redundancy in stops and routes, although not completely overlapping, provides individuals the opportunity to take an alternate route if one bus is not running. For example, a few respondents mentioned taking different routes or walking to another stop if the original route was running late or did not show up. The ability of CARTA to reroute busses and pick up individuals at different stops rather than discontinuing service during road flooding from high tide and/or heavy rains ensures service still continues even if the route changes. During these alterations, respondents described still completing their trips, whether on time or late.

Finally, the trip destination influences the type and the severity of the consequences experienced by the individual during transit disruptions. Respondents described experiencing different impacts resulting from a late or cancelled trip because some destinations allowed individuals multiple passes if late or absent before they faced any consequences while others were stricter and did not tolerate any transit disruptions. Conversely, individuals described almost no consequences when they travelled to destinations without any policies about being late or cancelling trips, such as grocery stores. The destination's ability to relax policies during nuisance flood events also seems to decrease individual sensitivity to transit disruptions. For example, respondents described experiencing fewer consequences during nuisance flood disruptions because workplaces were understanding about flooding and the bus being late.

Destination policies and characteristics also increase individual adaptive capacity by providing individuals with opportunities to make-up hours lost because of a transit disruption or reschedule trips proactively. Respondents described being able to make up hours after a transit disruption in order to not lose pay, which helped mediate consequences that could have resulted from being late or cancelling their trip. Individuals could also adapt to the impacts of transit disruptions depending on whether they could reschedule their trip to the destination. For example, when travelling to the hospital, respondents reported more flexibility in cancellations than being late because rescheduling the visit could be premeditated.

This analysis revealed how individual vulnerability is mediated by sources of sensitivity and adaptive capacity stemming from the individual, the transit system, and the trip destination. Some factors alter both sensitivity and the individual's adaptive capacity to transit disruptions. The type of stressor plays an important role, with external stressors such as flooding appearing to mediate individual transit vulnerability due to sources of adaptive capacity within the transit system as well as the trip destination. Additionally, the different sources of adaptive capacity and sensitivity suggest that individuals can only do so much to reduce their vulnerability to different transit disruptions because they do not have control over some factors shaping transit service or destination policies.

4.2 Individual transit vulnerability determined by GIS modeling

Individual transit vulnerability under different scenarios of nuisance flooding was evaluated by calculating changes in travel time using GIS modeling. This section begins by discussing what caused variation in the number and type of transit disruptions among the different scenarios. It concludes with a summary of how the model results inform potential changes in transit vulnerability under future nuisance flood scenarios.

Vulnerability was measured by comparing how trip travel time changed between a normal and flood scenario. Change in travel time was selected as a proxy to evaluate individual vulnerability because it translates how stressors affecting the transit system's functionality in turn impact the person using public transit. Travel time was calculated using the origin-destination information of 85 survey respondents, a transit road network dataset based on CARTA general transit feed systems data (GTFS), and ESRI ArcGIS Network Analyst. The model calculated travel time by completing trips using walking and transit modes of travel. For the normal scenario, the model calculated travel time using a transit road network without any barriers or removed routes. The normal travel times served as the baseline for how long trips take to complete without any stressors, such as traffic or flooding. For each flood scenario, the model calculated disrupted travel time using a transit road network with line barriers representing roads inundated by the flood extent of the particular scenario (flood scenarios summarized in Section 3.4.1). Additionally, if bus routes went through flooded areas, the route was removed from the scenario based on the assumption that if one segment of the route was flooded, then the entire route could not be completed (model assumptions summarized in Section 3.4.2).

Changes in travel time between the flood and normal scenarios calculated by the model revealed trips either stayed the same, became longer, or could not be completed when the road network was flooded. “Late trips” refer to the longer trips with an increase in travel time while “cancelled trips” represent the incomplete trips with a travel time of zero during the flood scenario (Table 4.5). The model results summarized in Table 4.5 and Figure 4.1 show late and cancelled trips occurred in every flood scenario. “Same trips” also occurred in every scenario and had the same travel time in both the normal and flood scenario. However, the single trip in SLR6 remained the same since the model determined the fastest route between the two stops in every scenario was completed by walking. These three types of trips represented in the results highlight what components of the transit system influence individual vulnerability.

Every flood scenario had cancelled trips that occurred between the origin and destination. The number of flooded roads was a major factor contributing to trip cancellations. As flood extent increased in the model, more trips were cancelled because the origin or destination was on a flooded road (Table 4.6). However, trips were also cancelled because the model could not find a route between the origin and destination that could be completed by bus or walking (Table 4.6). This was the case in scenarios with fewer flooded roads, such as CHS3plus and SLR1-2 (Table 4.7), where most cancelled trips occurred because the model could not find a route without any flooding between the origin and destination. The number of trips cancelled because no walking or bus route existed between the origin and destination highlights how flooding outside of the origin or destination location can impact accessibility of individuals taking public transit or walking.

Table 4.5 Variation in trip travel time among model runs for different flood scenarios

Scenario	Cancelled CARTA bus routes	Trips with same travel time as normal	Late trips	Cancelled trips	Mean travel time (minutes)	Mean travel time, without cancelled trips (minutes)	Mean difference between normal and late trips (minutes)	Min difference between normal and late trips (minutes)*	Max difference between normal and late trips (minutes)*
Normal	0	NA	0	0	63	NA	NA	NA	NA
CHS3plus	18	6	74	5	149	158	100	3	426
SLR1	12	41	35	9	406	454	852	8	2143
SLR2	19	28	39	18	480	609	939	1	2739
SLR3	20	5	59	21	581	772	769	1	3358
SLR4	20	4	51	30	438	678	664	1	3669
SLR5	22	3	31	51	53	133	84	5	161
SLR6	23	0	32	53	59	157	100	5	201

*Min and Max are based on the completed trips. Thus, cancelled trips are not included in these two columns.

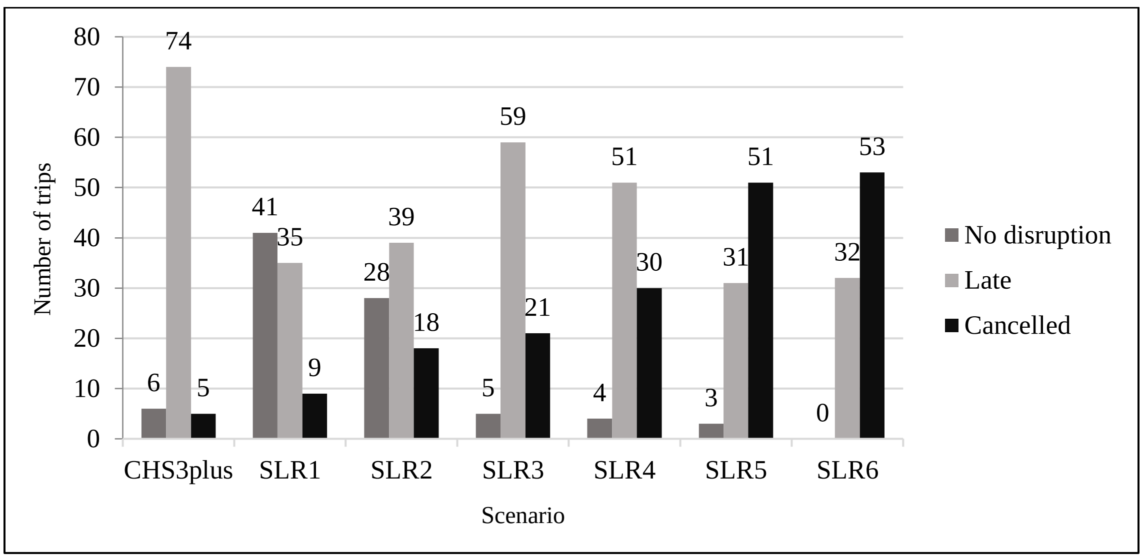

Figure 4.1 Transit Disruptions by Flood Scenario

Table 4.6 Cause of trip cancellation

Scenario	Total Cancelled Trips	Cancelled due to Inaccessible Stop	Cancelled due to No Route available
No flooding (Normal)	0	0	0
CHS3plus	5	0	5
SLR1	9	3	6
SLR2	18	4	14
SLR3	21	12	9
SLR4	30	17	13
SLR5	51	21	30
SLR6	53	25	28

Table 4.7 Number of flooded roads in study area

Scenario	Total length (Sum, km)	Percent of total study area roads inundated
No flooding (Normal)	15232.46	--
CHS3plus[a]	24.07	0.2%
SLR1	497.47	3%
SLR2	940.25	6%
SLR3	1561.65	10%
SLR4	2172.49	14%
SLR5	2757.84	18%
SLR6	3275.93	22%

[a] CHS3plus only includes roads within the City of Charleston.

Road flooding also played an important role in the number of late trips and how much longer they were compared to normal trips. The number of late trips did not simply increase or decrease with the percentage of roads flooded because as inundation increased, some trips either became late and previously late trips became cancelled. The scenario with the least amount of inundated roads, CHS3plus, had the most late trips (Tables 4.5 and 4.7). The high number of late trips might be due to the location of flooding in CHS3plus, which affected many bus routes, resulting in a higher number of cancelled routes in CHS3plus than either SLR1 or SLR2. However, despite having the most late trips, the mean difference between late and normal trips was smaller for CHS3plus than any other scenario except SLR 5 and 6 (Table 4.5). This might be because the model had more options to reroute trips with shorter walking distances since CHS3plus had the fewest number of flooded roads. For SLR 5 and 6, the average difference for late trips was smaller and might also be explained by the majority of completed trips only occurred in areas with less flooding while the rest of the trips were cancelled. Overall, late trips depend on the number of unflooded roads and location of flooding, which both influence the model's ability to reroute trips.

The number of trips with normal travel times in each scenario further emphasizes how location of flooded roads mattered in addition to the quantity. The difference in number of same trips and flood extent between scenarios CHS3plus, SLR1 and SLR2 reveals how flood location influenced the trip (Figure 4.2). CHS3plus had fewer same trips as the normal scenario than either SLR1 or SLR2, which is most likely explained by more inland flooding on roads serving more transit routes. The CHS3plus flooded roads represent areas documented by the City of Charleston that were closed at least three or more times due to tide and/or rain flooding. SLR1 and SLR2, however, have flooded roads influenced by coastal inundation. Thus, the roads in these scenarios flooded based only on the extent of coastal flooding indicated by a bathtub model.

Only two trips remained the same as normal until SLR6 when all bus routes were cancelled. This revealed which areas remained accessible with increased flood extent. These two trips were located in the upper portion of North Charleston where less road flooding occurred and one bus route, number 12, continued to provide service through scenario SLR5. While unflooded roads were critical to the completion of the trips, the location of the origins and destinations and availability of a route serving only that area were important factors for the completion of the trips. Other trips had origins or destinations in the unflooded region, but the trips either had increases in travel time or were cancelled because those trips occurred across a larger spatial extent. In SLR6, bus route 12 became flooded, but the model still identified one trip as keeping normal time the same as all the others due to unflooded roads, which allowed for walking. This trip represented a walking trip since the travel time was the same in every scenario, even SLR6 where all routes were cancelled and removed from the network dataset.

Overall, GIS modeling of transit travel time under current and future nuisance flood scenarios provided insight on how transit network vulnerability alters individual vulnerability and suggests transit network vulnerability depends on the spatial extent of nuisance flooding. The model results revealed transit disruptions varied among the different flood scenarios due predominately to changes in the amount and location of flooded roads servicing the transit network. Although the model rerouted trips by either switching routes or increasing the walking time, both of these options depended on availability of unflooded roads. Comparison of the scenarios representing current nuisance flooding (CHS3plus and SLR1) revealed that the location of road flooding also influenced transit disruptions, exemplified by CHS3plus having fewer flooded roads but more late trips than many of the other scenarios. However, many of the sea level rise scenarios had larger differences in travel time when compared to CHS3plus illustrating that the larger number of flooded roads increased the travel times by limiting the roads available for rerouting. While the location of origins and destinations mattered for trip completion, especially if they were located in flooded areas, the amount of flooded roads available for transit or walking between the two locations also determined whether the trip was completed or late.

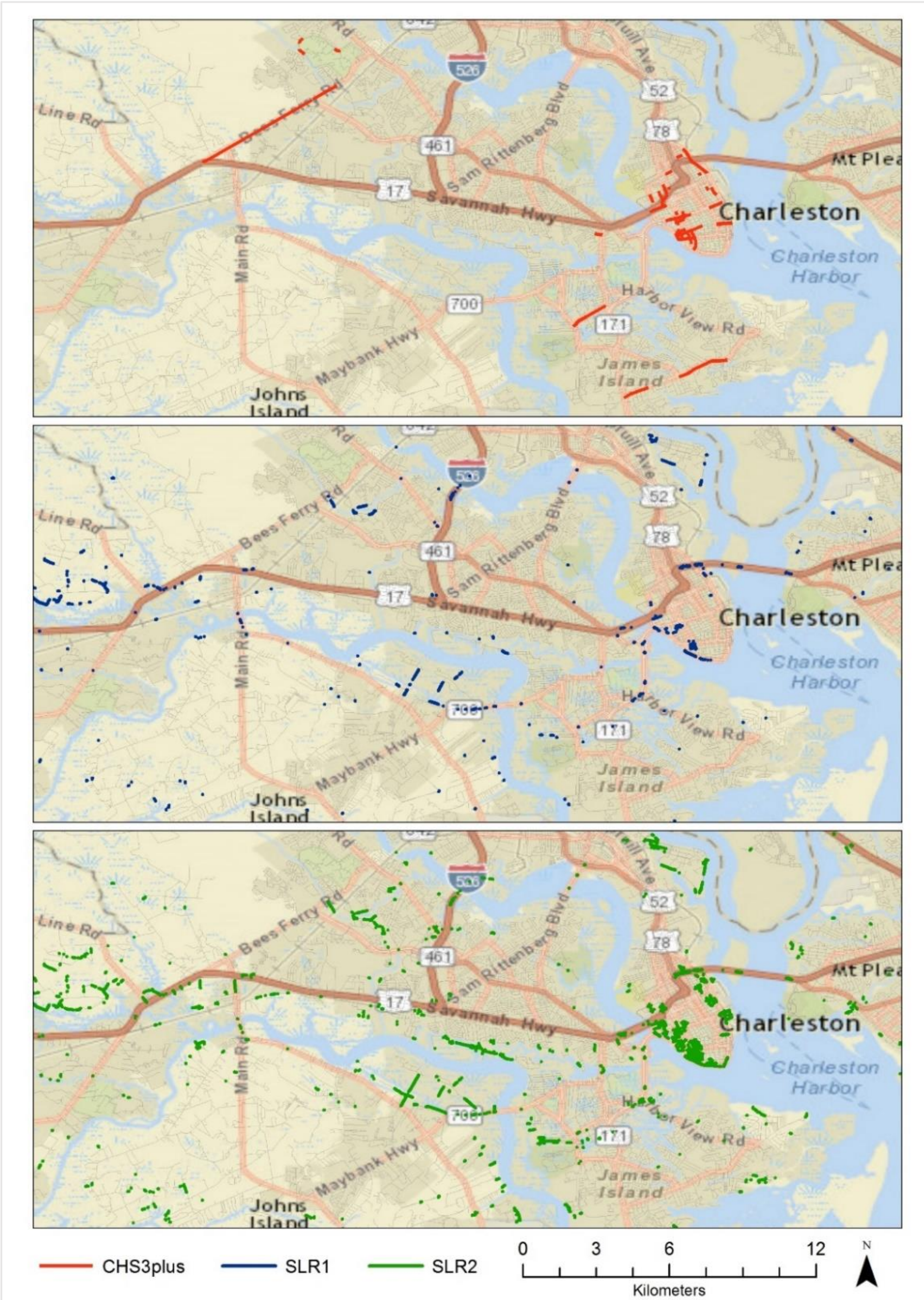

Figure 4.2 Flooded roads in scenarios CHS3plus, SLR1, and SLR2. Figure only shows roads in a portion of the study area.

4.3 Comparing individual vulnerability measured by the GIS model and survey responses

Survey responses and model results were compared by assessing how the travel time for a respondent's trip calculated by the model compared to the respondent's actual experience described in the survey. The section begins by focusing on how GIS model results compared to the answers of the respondents in the GIS sample who experienced an altered CARTA trip during nuisance flooding (n=52) and then to the responses of those who did not experience an altered CARTA trip (n=28).

The model's estimation of transit disruptions compared to answers of respondents who have experienced nuisance flooding during their CARTA trip differed depending on the flood scenario (Table 4.8). For the current flood scenarios, CHS3plus and SLR1, the model's estimation of whether a disruption would occur matched respondent's experiences more closely in CHS3plus than the SLR1 scenario. The differences between the two scenario results might be explained by the type of flood layers used in the model and the source of flooding described by the individuals. Many respondents described experiencing route disruptions from heavy rain or both high tide and heavy rain (n=38, 73%). The CHS3plus scenario used flooded roads based on data from City of Charleston road closures that occurred three or more times due to flooding from king tides and heavy rain, but the SLR1 scenario used flooded roads determined only by expected tide inundation resulting from sea level rise. Although the CHS3plus layer had fewer flooded roads, the location of the flooded roads caused more late trips and resulted in the model to rerouting trips differently than SLR1 because the number available bus routes were reduced but more roads were open for walking. Unlike the model, though, most respondents described the bus taking a different route or going slower instead of walking or switching bus routes. This highlights a limitation of the model's ability to incorporate incremental system adaptations, such as rerouting bus routes around flooded roads or moving a bus stop, that occur in real life.

Table 4.8 Number of trips late or cancelled according to GIS model by respondent's past experience with nuisance flooding during a CARTA trip

Respondent nuisance flood experience	Number of GIS trips altered by flooding (both cancelled and late)						
	CHS flood	SLR1	SLR2	SLR3	SLR4	SLR5	SLR6
Yes (n=52)	48	23	33	49	50	50	52
No (n=28)	26	18	21	26	26	27	28

For the future flood scenarios based on higher levels of sea level rise, the model also determined disrupted trips for most of the respondents who said they experienced a CARTA trip altered by nuisance flooding (Table 4.8). In these scenarios, the model predicted more cancelled trips and longer late trips than what respondents reported in the survey. Over half the respondents said they were late because of nuisance flooding (n=30, 58%), and only a few said they cancelled or rescheduled their trip (n=6, 12%). Additionally, average difference for late trips ranged 84 to 939 minutes for the model scenarios (Table 4.5) whereas respondents' estimates of how late their trips were ranged from 5 to 60 minutes. The model's assumptions might explain the differences between the model and survey results. The model assumed that if one bus route was disrupted, the alternate option would be to reroute by switching bus routes or walking. While respondents did describe the bus taking a different route during nuisance flooding, in the model, routes were altered based on the assumption that bus riders would be willing to take any number of transfers or walk any distance to complete the trip. However, in reality, individuals might not be willing or even know how to access these alternate options. Some survey responses mentioned that they were picked up or dropped off at a different bus stop, but none of the individuals described taking a different bus route to complete their trip. Only their existing trip was rerouted while the model did not have the ability to alter fixed bus routes. Finally, many respondents described being late because the bus was running slow or going slower, but this particular model did not have the capability to consider how changes in road congestion due to flooding might affect transit travel time. Despite limitations, these model assumptions might better reflect reality under future levels of sea level rise where more trips might be cancelled because of the nuisance flood extent increasing with sea level rise. However, future road flooding would be dependent on whether or not the city decides to implement other adaptation strategies to reduce road flooding from sea level rise, which cannot be captured by the sea level rise flood layers.

For respondents who said that they have not experienced nuisance flooding, the model estimated that many of them would have altered trips even during the current nuisance flood scenarios, SLR 1 and CHS3plus. In this case, differences between the model and the respondents might be explained by how respondents perceived a trip alteration during nuisance flooding. Some respondents might not have associated any changes in the bus routes with heavy rain or high tide events, especially since high tide flooding may occur on sunny days and might be less noticeable if the respondent has never seen the tide flooding firsthand. Additionally, since tide-driven nuisance flooding occurs during certain times of the month and year and only some heavy rain events result in nuisance flooding, respondent possibly never made the specific trip using CARTA during a date or time when nuisance flooding occurred. For future scenarios, SLR2-6, the model results showed altered trips for over two-thirds of the respondents who did not experience flooding. While the model might overestimate trip cancellations or length of late trips, the model results still provide valuable insight on possible increases nuisance flood disruptions for these individuals in the future even if they currently ride a route not impacted by nuisance flooding.

Overall, the survey results helped evaluate whether the model might be over- or underestimating transit disruptions caused by current and future nuisance flooding. Despite the model's limitations resulting from its parameters and data inputs, the model helped understand how future sea level rise might affect the number of nuisance-flood disruptions experienced by CARTA bus riders and possible sources of transit disruptions, such as which stops or roads will be flooded in the future. The survey responses provided insight into the causes of nuisance flooding and validation of different model assumptions. However, respondents not being aware of nuisance flood disruptions or not experiencing one due to when they make their trip might have limited the accuracy of some responses. Both methods in combination provided insight on portions of the road network CARTA will need to think about future adaptation strategies for if nuisance flooding continues to inundate roads.

Chapter 5. Conclusions

The increase in nuisance flood events in Charleston, SC and many other coastal areas in the United States due to relative sea level rise requires communities to consider how to prepare for the impacts of repetitive nuisance flooding (Sweet et al. 2014). A commonly documented impact of nuisance flooding in Charleston, SC has been road flooding, which has disrupted local traffic and altered normal public transit service (Peterson and Munday 2015; Peterson, Rindge, and Boughton 2015; Peterson 2015a; Burns and Gilreath 2015). This research investigated the impacts of nuisance road flooding on public transit riders in the Charleston, SC area by evaluating what factors influence individual vulnerability to transit disruptions and how vulnerability varies under different nuisance flooding and sea level rise scenarios. This research differed from previous studies on transit vulnerability by utilizing both surveys and GIS analysis of respondent route information to assess vulnerability in two different ways. By capturing individual experiences with the survey and transportation impacts as a function of travel time, this research highlights how nuisance flooding and sea level rise will affect public transit riders.

Key findings

The survey results captured individual experiences during normal and nuisance flood-induced transit disruptions and revealed three sources mediate individual transit vulnerability: an individual's travel behavior and personal attributes, the vulnerability of the transit system, and the policies regarding late arrivals and cancellations at the trip destination. All three sources influenced vulnerability by altering the individual's sensitivity to and adaptive capacity to respond to any potential consequences from transit disruptions. Individual travel behavior choices resulted in different consequences because some choices, such as trip purpose and travel mode, changed the importance and time sensitivity of the trip. Additionally, individual attributes, such as income and transit dependency, shaped the travel choices some people made by influencing the importance of some trips and their ability or inability to access other modes of transportation. Previous literature on travel behavior mainly focused on sample populations with access to alternate modes of transportation (Böcker, Dijst, and Prillwitz 2013; Lu et al. 2014). This research provided insights on how behavior changes when individuals cannot change transportation modes because they do not have access to other options. While alternate modes of transportation might be feasible occasionally, they will not provide a sustainable source of individual's adaptive capacity if nuisance flooding increases in the future.

Characteristics of the transit system and policies at the destination also shaped potential impacts caused by transit disruptions although these were often outside of the individual's control. The GIS model results showed that the transit system's own vulnerability to different external stressors translated into either late or cancelled trips for individuals depending on its ability to provide service according to schedule. Thus, factors influencing the reliability of bus service and the continuity of service, such as rerouting and picking up individuals at different stops, mattered in order for an individual to complete his or her trip.

Finally, since a transit disruption resulted in a late or cancelled trip to the destination, some of the potential consequences the individual experienced depended on the policies at the destination. At some destinations, strict absence and late policies increased the individual's sensitivity to transit disruptions. Some policies however offered room for the individual to mediate consequences, such as the option to reschedule trips or make up lost work hours. Additionally, the type and source of transit influenced how respondents experienced consequences at the destinations after a transit disruption. Respondents faced different impacts depending on whether they were running late or had to cancel their trips. For example, disruptions to time-sensitive trips, such as those made to work, were less consequential when there were delays rather than cancellations. However, for other destinations such as the hospital, cancelled trips were less consequential due to the opportunity for individuals to reschedule their trips in the event of anticipated or expected transit disruptions. The cause of the transit disruption, whether an external stressor such as nuisance flooding or an internal stressor such as individual actions, influenced the potential consequences depending on the destination's policies and understanding about different stressors and ability of the transit system to respond to these stressors. Many workplaces were more lenient when flooding caused delays.

While the survey revealed how individual vulnerability varied based on the respondent's experiences with general and flood-induced transit disruptions, the GIS modeling results showed that the location and extent of road flooding may influence how transit vulnerability will vary under future scenarios of nuisance flooding. The inundation extent possible from 2 to 6ft of sea level rise was used as a proxy for future sea level rise while 1ft of sea level rise and road closures from City of Charleston were used as current nuisance flood proxies. The number of cancelled trips in each scenario increased due to the number of flooded roads that resulted in cancelled bus routes and decreased availability of walking routes between two stops. Comparison of the two current nuisance flood layers revealed that the location of road flooding also resulted in different routes being cancelled. Finally, trips that had the same travel time in every scenario occurred in an area served by the only bus route that was not flooded, even at 5ft of sea level rise. The availability of bus routes specifically for this area showed how the transit system's vulnerability to flooding directly influences the availability of service to individuals. Thus, individual transit vulnerability may increase with future increases in nuisance flood extent due to sea level rise unless the transit system takes additional efforts to continue service despite road flooding. However, it is important to note that the model made several strict assumptions and was limited by data inputs, and future research should consider ways to incorporate real-time adaptions, such as rerouting to better capture the functioning of the transit system during nuisance flooding.

A comparison of both the survey and model findings revealed strengths and weaknesses of both methods. Individual vulnerability might be influenced by individual perceptions that color how respondents reported their experiences during nuisance flooding or the inability of the model to capture transit system adaptations that occur to reduce the impact of flooding on system functioning. However, comparing both measures of vulnerability also revealed strengths of both approaches. The survey provided a greater understanding of what happens when an individual has a late or cancelled trip and how they might adapt to different transit disruptions in the future. The model offered insight on how frequently different types of transit disruptions might occur in the future and which areas might be affected first or more resilient to the impacts of road flooding.

As communities prepare for increased amounts of nuisance flooding, especially due to rising sea levels, the findings from this research revealed the importance of considering all factors influencing the completion of a trip—the individual, the transit system, and the destination. These factors shape whether different transit disruptions, whether caused by flooding or not, may result in potential consequences for the individual.

Future research

This research provides a glimpse into what influences individual transit vulnerability to nuisance flooding. Future research should expand on the findings in this study by conducting additional research on the factors influencing individual vulnerability.

The survey results helped identify the three sources of adaptive capacity and sensitivity, but qualitative research would provide additional detail on the specific characteristics of each element's impact on vulnerability. Interviewing transit providers and destination policy makers would provide more information about their policies about transit disruptions and how they respond to them. The current research only provides insight on the external stressors to individual based on the respondents' perceptions and descriptions of their experiences. To better understand the influence of individual attributes, such as transit dependency and income, on adaptive capacity and sensitivity, a larger and more diverse sample should be collected representing different socioeconomic and demographic groups. The survey sample in this research represented individuals who were mainly low to middle income and relied on CARTA for their main form of transportation. Future research could adapt the survey to interview people who drive to work to better understand the impact of transit dependency on transportation vulnerability.

The modeling capabilities can also be expanded in future research. The model output depended heavily on the data inputs and assumptions. The model in this research used strict assumptions about how buses and stops were affected by flooding, which did not accurately represent actual service alterations made by CARTA during flood events. In reality, CARTA changes the location of a flooded stop to a nearby area not flooded or reroutes current bus routes to avoid flooded roads. Future model parameters can be designed based on information from the transit authority about their rules for rerouting stops and buses that better reflect reality. Another option would be to use transportation infrastructure vulnerability assessments that identify roads vulnerable to flooding to create road classifications capturing different levels of serviceability, with each category having a unique time cost evaluator based on its potential vulnerability to flooding.

The GIS estimation of individual transit vulnerability can also be expanded to assess whether there is temporal variation in transit disruptions since transit schedules change through the day. In this thesis, the model was run at 8am to evaluate how nuisance flooding would impact transit trips made during rush hour when more busses were running. However, the transit vulnerability might change depending on the bus schedules at different times of the day. For example, certain CARTA express routes only run during morning and evening rush hours, which might cause an increase in transit disruptions for during rush hour when more routes are operating.

Finally, more research is needed about individual perceptions about nuisance flooding and how heavy rainfall and sea level rise influence the extent of nuisance flooding. Both of these factors might have resulted in an underestimation of the impacts caused by nuisance flood-induced transit disruptions discussed in this thesis. The survey asked respondents about their experiences about when their trip was disrupted by high tide and/or heavy rain events. These two weather conditions served as a proxy for nuisance flooding since participants during pilot testing interpreted flooding to mean extreme flood events that completely shut down the transit system. Future research should be conducted to better understand individual perceptions about nuisance flooding and transit disruptions to understand whether individuals misperceive how their trip has been altered or not by nuisance flooding.

Additionally, the model's capability to measure vulnerability to nuisance flooding depended on the flood hazard layers. Currently, nuisance flooding is hard to capture in a static dataset because of its dynamic nature. For every tide event, the extent of nuisance flooding might change due to wind direction, current tide levels, and presence or absence of heavy rainfall. The differing model results for the CHS3plus scenario, which represented road closures resulting from nuisance flooding caused by rain and high tide, and the SLR1 scenario indicates that the change in nuisance flood extent due to storm water might matter in estimating transit disruptions resulting from nuisance flooding. While sea level rise layers can serve as a proxy for nuisance flooding driven by tides, this proxy underestimates future vulnerability to nuisance flooding without considering storm water inundation. Improvements in inundation modeling and flood data inputs will provide a better estimation of the location of flooded roads.

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Appendix A: Supplemental figures

Figure A.1 CARTA Transit Route Map

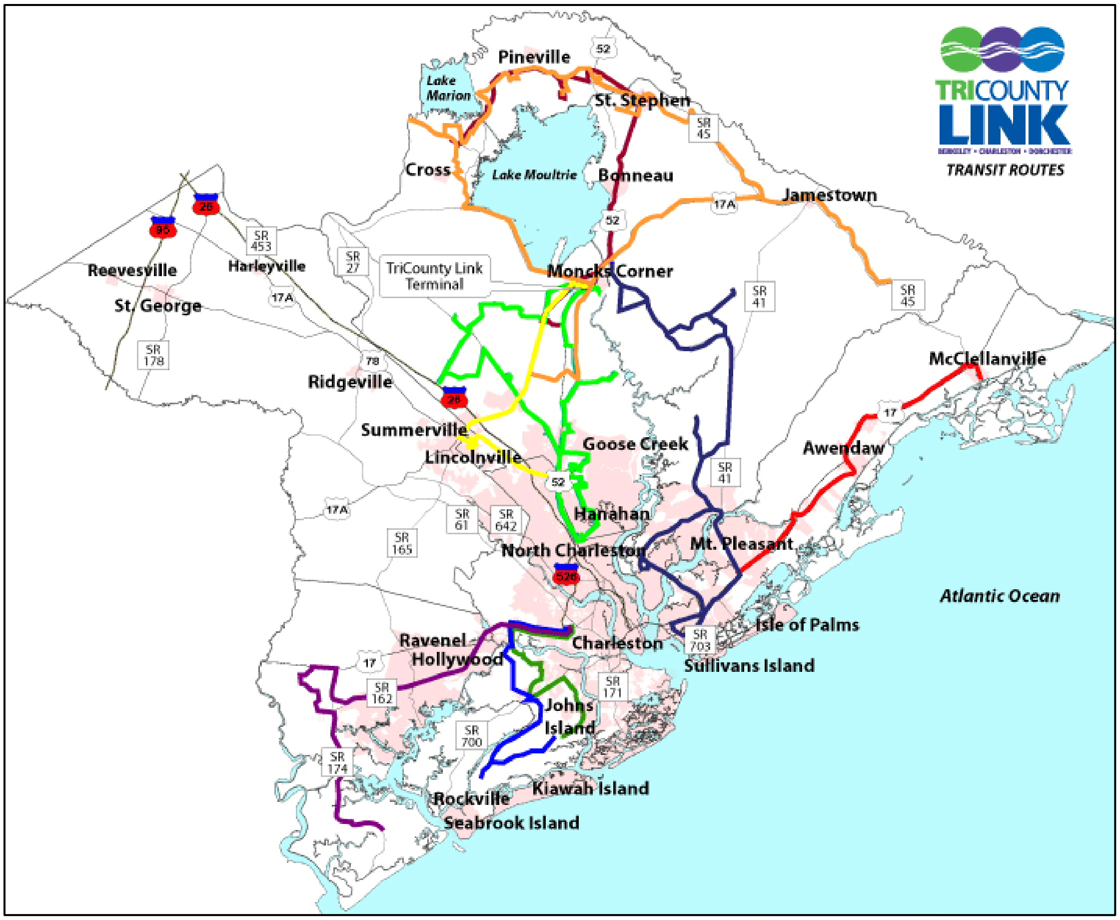


Figure A.2 TriCounty Link Transit Route Map

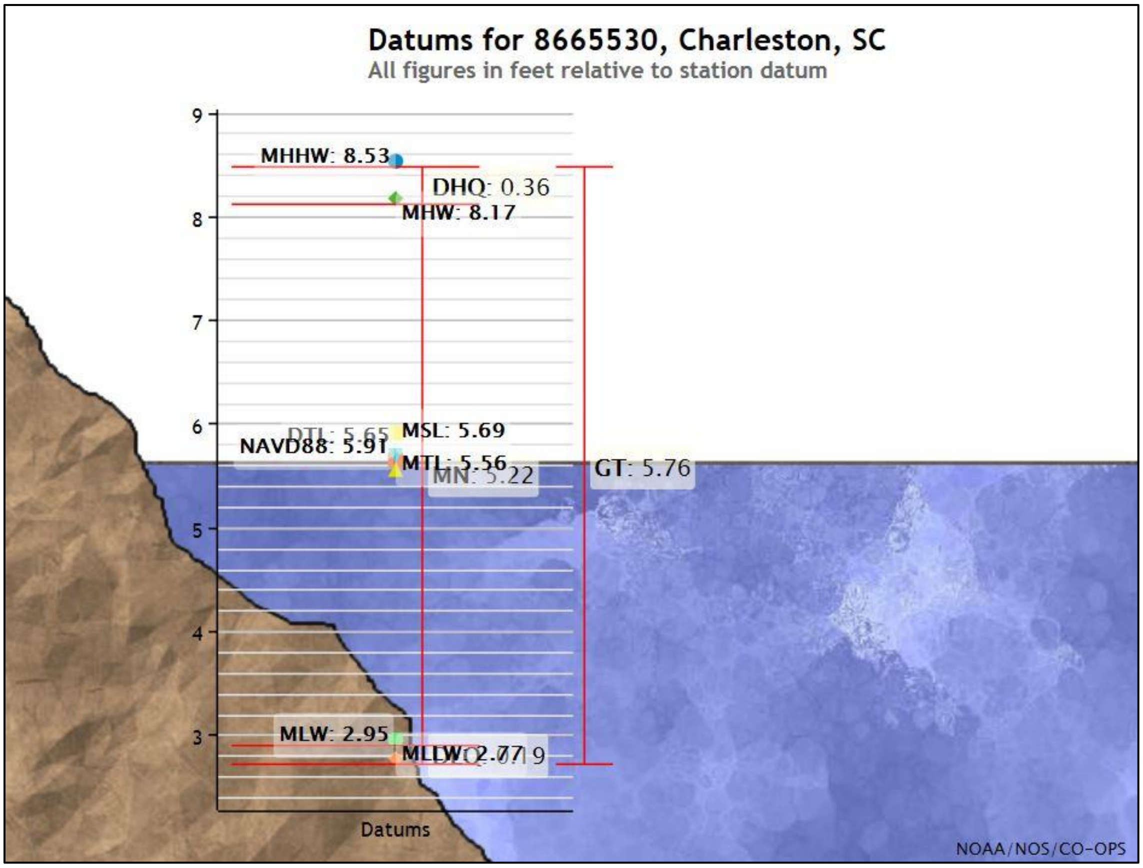


Figure A.3 NOAA NWLON Tidal Datum for Charleston, SC tide gauge

Appendix B. Final Survey

The public transit survey used to collect data for this research is found separately as an attachment. The survey was originally administered on electronic tablets using SurveyMonkey, and the printed version contains 14 pages with numbered questions for reference. .

Appendix C. Summary of pilot testing results

Overview

During the month of January and February 2016, I solicited feedback and pilot tested the public transit survey at two CARTA bus stops. I am proposing most revisions to my survey methods and timeline based on the feedback and my experiences during pilot testing.

I also have been working on establishing connections with other groups in Charleston. A conversation has been initiated with stakeholders from the Lowcountry Alliance for Model Communities (LAMC). Side conversations at the Charleston Resilience Network 2016 Flood symposium with someone from Charleston Housing Authority and City of North Charleston also revealed that major floods have been a big problem, but minor flooding might not be as noticeable since it only worsens existing traffic delays.

Pilot testing

I pilot tested the survey with three different groups. Prior to going to Charleston, I first pilot tested the survey with graduate students in the Department of Geography who do not have cars. This first round of pilot testing helped me edit question wording and flow of the survey. I also tested the usability of the tablet. I then went through the survey with the mobility manager at BCD COG and the operations director at CARTA. Both of them provided me feedback, and CARTA also gave approval to conduct the survey at their bus stops as long as I gave notification before going to the stops, the survey teams wore something that made them look unified, and I will prepare a final report for the executive directors. There is no need for board approval or internal IRB review at CARTA.

On February 18th, 2016, I pilot tested the survey at the Mary Street transfer stop and North Charleston Super Stop after getting approval from CARTA. I had a total of 6 responses and 7 declines. Two of the response were only partially complete since the bus came. Some key takeaways from pilot testing:

- The survey took about 6-10 minutes to complete.
- The first filter question at the stop should be whether or not the person is waiting for the bus. A lot of people were just hanging out at the bus stop because there are benches and shade.
- While two individuals did not complete the survey because the bus came, it seems that many individuals were waiting at the bus stop for at least 10 minutes. A lot of them knew when to expect the bus, so even if it is late regularly, they know this beforehand. Many of them actually said CARTA is on time, but they wait for the bus about 10 minutes. Some individuals get dropped off at the bus stop while others walked. This probably affects how long they wait at the stop.

- Many people also took a transfer bus. Using tablets did not pose a problem. People were patient with typing in answers. Some would look at the tablet, while others did not. The tablet was always pointed towards them while pilot testing so they could see the survey.
- The phrase “flooding” was associated with the October floods. Only the final response I got was with a respondent who initially said flooding was not a problem, and then later after probing said that the bus changes its route every time it rains. In the future, I will ask Jeff from CARTA which routes typically reroute during rain and king tides, and see how often people taking these routes mention noticing any changes.
- CARTA seems to be late because of traffic a lot of times. Since this is already an issue, people seem to already account for that in their travel time. So being late because of flooding might not be as big of a problem as not getting picked up at their bus stop or dropped off.
- Income question was difficult. Most people did not know the answer.

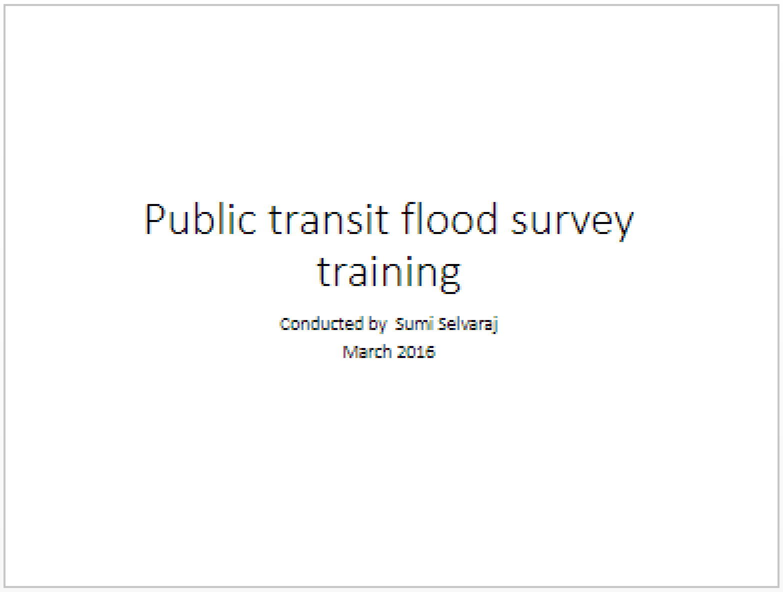
Based on pilot testing feedback, I am making the following revisions to my survey and sampling strategy:

- Changing the terminology from flooding to focus more on rain and tides.
    - Mentioning the word flooding shifts people’s attention to October floods. However, I will leave this as a choice if people say once and then mention the October floods.
- Changing income categories to be rounded numbers.
- Sampling
    - I think it will be possible to ask every other person.
    - I plan to stick to sampling in-person at the bus stops.
    - Surveying will always happen in pairs. I think having another person around while asking questions is good for personal safety as well as answering questions asked by other people at the stop. We also wore USC t-shirts, which helped.
    - Sites: Mary Street and Super Stop are the busiest stops according to the CARTA Comprehensive Operational Analysis. I will also select some other popular downtown stops in flood areas to sample and include some of the express route stops as sampling sites to sample some non-transit dependent riders. I will ask Jeff about shift times for big companies and hospitals to try and sample the shift workers as well.
- Filter questions – need to ask if they are waiting for the bus (instead of do you ride CARTA).

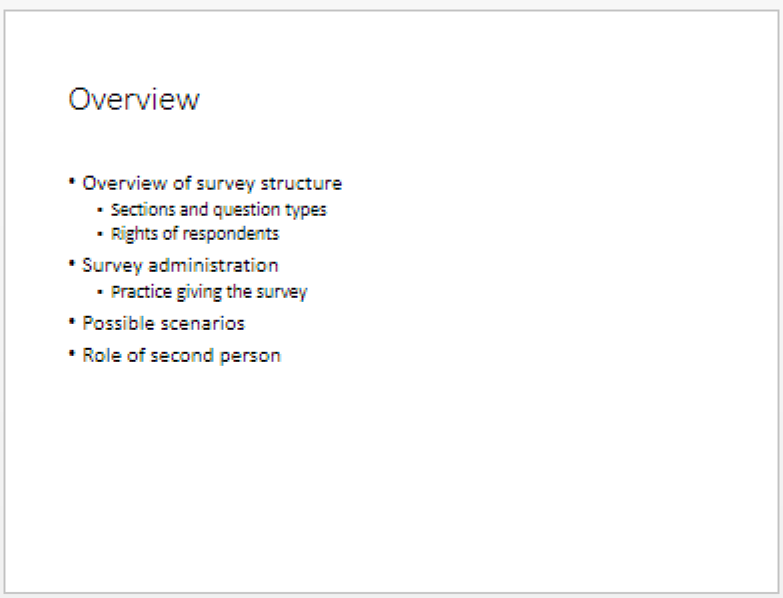
I will also make some updates to the GIS modeling methods, including some new assumptions about transit stops. The add-on from ESRI to include transit information is in development, so not a lot of options are available. Building the road network is taking longer than expected, but I hope to have a working one by mid-March.

Appendix D. Interviewer survey training materials

Survey training PowerPoint slides



1



2

Survey overview

- 3 sections
  1. General transit behavior
  2. Previous experience with rain or tide flooding
  3. Demographics
- Types of questions
  - Multiple choice and open-ended
  - Prompts for open-ended questions

3

Survey overview

- Rights of respondents
  - Opening section – privacy, confidentiality, voluntary participation
  - Important to stress these points
  - Respect a person's choice to not participate
  - Remind them to make sure their bus hasn't arrived

4

Survey administration

- Demo
- Practice on each other
- Possible scenarios – encounters
  - Drunk man
  - Person leaving to take the bus
  - Others?

5

Why survey in a team?

- Second person is there to…
  - Take note of body language of the respondent
  - Look out for the other person – safety
  - Engage other people while the other teammate is administering the survey
  - Cross-check respondent answers

6

Probes and answer protocol for public transit survey

Q7. What happens if you are late to _____?

- If response needs more detail
  - Probe: "What happens if you_[Response]_?"
  - Example:
    - Response: "written up"
    - You: "What happens if you get written up?"

Q9. What happens if you cancel your trip to ____?

- If response is "I can't, or don't happen" or a similar negative answer with little explanation
  - Probe: "Why not?"
  - Example:
    - Response: "don't cancel"
    - You: "Why not?"
- If response needs more detail
  - Probe: "What happens if you_[Response]_?"
  - Example:
    - Response: "written up"
    - You: "What happens if you get written up?"

Q14-16 Stop locations

- If they say the current stop (where we are surveying) is the stop they get on/transfer/off at, then just write "here" in the text box.
- If they are not sure about the stops, then ask if there is a store or other place marker.
- If they just give one street name, see if they know another road nearby or place marker.

Q. 17 – 19 Asks about the time they get on/off at different bus stops

- **Change after survey day 1: skip transfer stop time transfer (Question 18)**
- If they say "morning" or "evening" or not sure, use the following probe
  - Probe 1. Do you ride the bus around this time or in the morning or evening?
  - Probe 2. How long does your total trip to work take?
- If they misunderstand question 19, what time do you get off at last stop…

- Probe 1. Or what time do you get to Q5 when you leave at ?
  - Probe 2. Or how long does it take you to get to Q5?
- If they give multiple times that they ride the bus, choose one to focus on. Tell them that you will ask the questions about when they ride the bus in the __.
- **If they do not give you a time, ask them if it's in the morning, afternoon or evening. AM/PM is important information. Then ask them how long their trip takes**

Q24. What caused your trip to be different?

- October flooding answer should be selected if respondent refers to flooding when CARTA was shut down (all trips cancelled)

Q 47. What best describes your total household income in 2015?

- If they do not know, before marking "I don't know", use the following probes
  - Probe 1: Taxes are due soon, do you remember the household income from your taxes?
  - Probe 2: Do you know your monthly take-home pay?

Q53. What gender best describes you?

- We are just going to mark the answer and show them the tablet to make sure it's okay. This is mainly because some people might be offended if we ask them their gender. Then if the person does have a response, we can mark it in the box.

Other clarifications:

- Read the answers aloud to the participant so they know the choices.
- "What happened" questions – they're about consequences. The goal of probing is to get a little bit more information about the degree of the consequence.
- Many of the questions have "additional comments" boxes. If the person says something in addition to the answer they give, this is the space where you can make note of that additional information.
- If the person would like to have their response deleted. Just mark "delete this response" in the next blank and then exit the survey. I will go in and delete the response later.
- Stop names: http://www.ridecarta.com/riding-carta/routesmapsschedules/routes-schedules