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Developing a Flexible Disaster Relief Supply Chain Model

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Abstract

The goal of much of the research in disaster logistic models is to position facilities to meet a specific demand. These types of models locate distribution facilities based on relative weights of locations determined by demand. These types of models are similar in nature to classical location theory models such as p – median and or coverage type models. The ultimate goal of these types of models is to cover or service as much of the anticipated demand as possible. However, there is a growing consensus that the population or number of households within a specific geographical area is not necessarily the only weighting factor in determining need and/or demand for disaster relief.

In an era after disaster events, such as Hurricanes Katrina and Sandy, there is an understanding that recovery efforts require large amounts of time and some populations, because of their vulnerabilities, may require more assistance than other populations. This requires that traditional disaster logistic models require additional weighting factors to help influence locating distribution facilities. This research proposes a simple multi-criteria approach that uses a geographical area's relative measurement of social vulnerability to influence a model's ability to locate distribution facilities. Using the research's foundational model's locations, as a basis, the solution network is transformed into a hub network

Developing a Flexible Disaster Relief Supply Chain Model

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Doctor of Philosophy Dissertation

Developing a Flexible Disaster Relief Supply Chain Model

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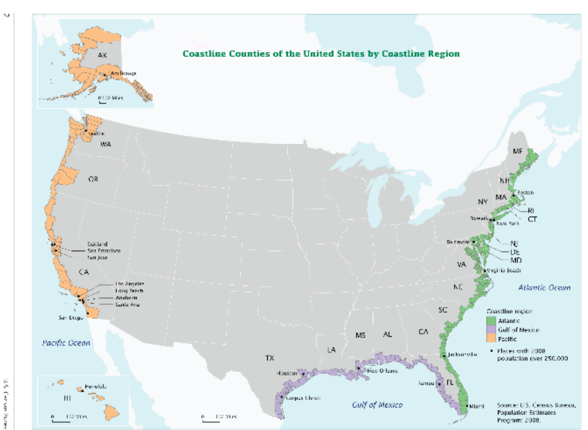
Chapter One

Introduction

1.1 Introduction

As the United States entered into the 21st century people became aware that a quicker response to a disaster would lead to a better recovery for affected areas and populations (“National Response Framework” 2008; “National Disaster Response Framework” 2011). Over the last decade, there has been an understanding that the United States is facing increasing numbers of devastating events to communities because of three broad factors. The first factor is that populations are moving towards areas of high risk. The second factor is a two-pronged problem – the belief that there is a greater occurrence of events and that those events are costing more. The third factor is an aging infrastructure.

The United States has become an increasingly coastal country. From 1960 to 2008 there has been an 85% increase in the population living in saltwater coastal counties (Wilson and Fischetti 2010). This trend is outlined in Figure 1.1.In addition to more people living along the coast, increasing numbers have moved into other potentially hazardous natural areas. These areas could be prone to events such as forest fire, river flooding, or an earthquake. Table 1.1 summarizes some findings about wildland urban interface (WUI), which is associated with damage to homes because of a wild fire. More people moving into these areas have put these populations at greater risk and they are made more vulnerable (Stein et al. 2013; White 1945; Burton, Kates, and White 1993). Similar trends are seen as populations move closer to existing industrial areas or as those industrial areas expand out towards existing populated areas (Santos and Kraus 2013; “West Virginia Oil Train Derailment Threatens Water Supply” 2015; Zelinsky and Kosinski 1991).



Population Change in Coastline and Noncoastline Counties: 1960 to 2008

Area	Period					Change, 1960 to 2008
	1960–1970	1970–1980	1980–1990	1990–2000	2000–2008	
NUMBER (in milions)						
United States	**23.9**	**23.3**	**22.2**	**32.7**	**22.6**	**124.7**
Coastline counties	**9.3**	**6.9**	**9.5**	**9.1**	**5.3**	**40.0**
Atlantic	3.8	1.5	3.3	4.0	2.4	14.9
Gulf of Mexico	1.4	2.2	1.6	1.8	1.4	8.4
Pacific	4.1	3.2	4.6	3.3	1.6	16.7
Noncoastline counties	**14.6**	**16.5**	**12.7**	**23.6**	**17.3**	**84.8**
PERCENT						
United States	**13.3**	**11.5**	**9.8**	**13.2**	**8.0**	**69.6**
Coastline counties	**19.5**	**12.1**	**14.9**	**12.4**	**6.5**	**84.3**
Atlantic	14.2	4.9	10.3	11.3	6.0	56.0
Gulf of Mexico	24.7	31.9	17.2	17.1	10.9	150.2
Pacific	27.0	16.4	20.4	12.0	5.2	109.7
Noncoastline counties	**11.1**	**11.2**	**7.8**	**13.5**	**8.7**	**64.3**

Note: Data for 1960 to 2000 are as of April 1 of each year; data for 2008 are as of July 1.
Source: U.S. Census Bureau, Decennial Census of Population and Housing: 1960 to 2000; Population Estimates Program: 2008.

Figure 1.1 Coastal counties as defined by the US Census Bureau and population growth trends (Wilson and Fischetti 2010)

Table 1.1 WUI Quick Facts

• Almost 1/3 of US homes (37 million) were located in the WUI in 2000
• 3.8 million homes in California are in WUI – the most of any state in the US
• Over 2/3 of all the land in Connecticut is identified as WUI
• More than 1 million homes were added to the WUI in CA, OR, and WA between 1990 and 2000
• The greater the natural amenities in an area the more prevalent the WUI – such as places like northern Great Lakes, Missouri Ozarks, and northern Georgia
• Almost every urban area in the Rocky Mountains or Southwest has a large ring of WUI because of population growth and the buildup of medium and low—density housing in low-elevation forested areas.

(Stein et al. 2013)

Within the discussion of climate change, there is an ongoing debate as to whether or not such changes are creating more events. In this debate, there is an acknowledgment that one of the impacts of climate change will be changes in climate variability and weather extremes. In the 21st century, projections are that the number of hot and very hot days will increase and the opposite will occur for cold and very cold days. There will be more intense precipitation events and increased summer drying over mid-latitude areas, which could lead to more drought periods. Tropical cyclone and Asian summer monsoons precipitation is predicted to increase in intensity, frequency, and unpredictability (van Aalst 2006).

The worldwide views is that disasters triggered by natural hazards are harming more people and costing more to recover (O'Brien et al. 2006). There is economic evidence and analysis that disasters will cost more in the future. For the City of New York**,** Swiss Re estimates that the annual losses due to weather will increase by over 250% from 1.7 billion dollars to 4.4 billion by 2055. Figure 1.2 shows the results of Swiss RE's loss models for the City of New York through the mid—21st century ("Swiss Re Provides Expert Input for New York City Study" 2013). The United States' National Oceanic and Atmospheric Administration (NOAA) reported that from 1980 through 2013 there were nearly 200 one billion dollar weather related disasters in the United States, and that those events are increasing at a rate close to 5% per year. The billion

dollar events are summarized in Figure 1.3. (“NOAA: Billion-Dollar Weather/Climate Disasters” 2013; A. B. Smith and Katz 2013). In addition to the increase in events, there is an ever-increasing reliance on higher levels of governments to help local governments finance the recovery from such disasters. This trend can be seen in the increase of United States federal government disaster declarations over the last several decades (“Disaster Declarations by Year” 2013).

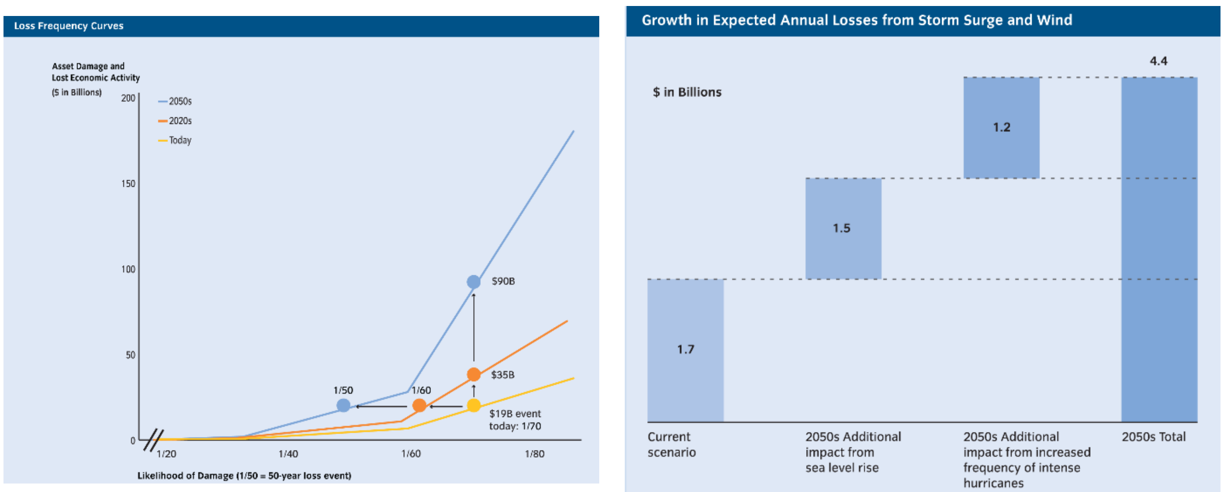


Figure 1.2 Loss Frequency curve and growth in losses from storm surge created by Swiss RE model for New York City (“A Stronger, More Resilient New York” 2013)

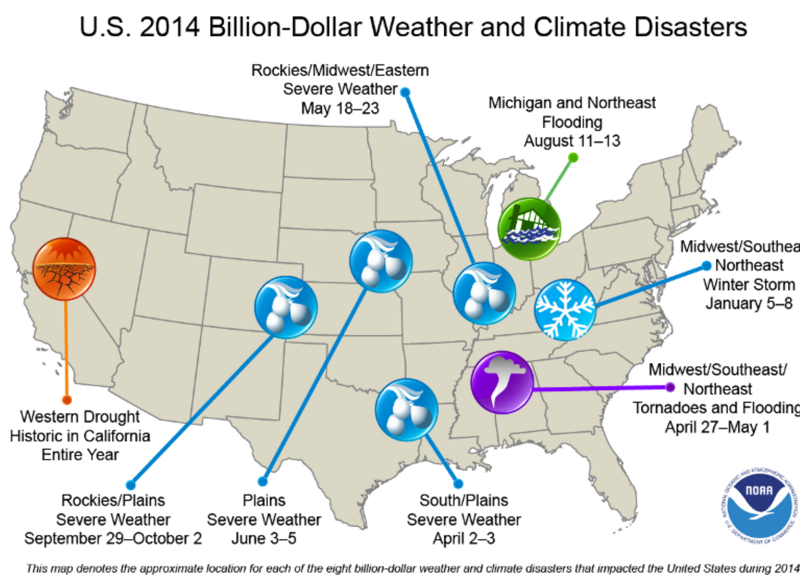


Figure 1.3 Weather and climate billion dollar disasters for year 2014(“Billion Dollar Natural Disasters 2014” 2015)

The third critical factor, within the United States, is an aging infrastructure. The problems with United States' infrastructure can be seen as twofold. The first problem is that the lack of resiliency within these systems can magnify the consequences of harmful events. Research on the causes and magnitude of Hurricane Katrina focused on how the weakened and aged flood control systems contributed to the severity of the event. Mileti views a city as a complex system which is continuously exposed to risks and threats from physical, engineered and socioeconomic subsystems (Mileti 1999). The systems that were in place did not perform as they were expected to or outright failed, and those failures led to greater damage to the City of New Orleans as a result of Hurricane Katrina (Comfort 2006). Interconnections between different infrastructure systems and how those systems co-exist, in the same space, are critical to managing a harmful event (O'Rourke 2007). Infrastructure can suffer greater damage if aged or **if it** has not been made resilient as required (Lieberman 2014). The aging infrastructure can be the cause of the disaster. Over the last decade, several major interstate highway bridges have collapsed. This has led to economic hardships and stresses on the affected communities (ASCE 2015). Table 1.2 outlines the "report card" for United States infrastructure as compiled by the American Society of Civil Engineers for 2013. Further increased use of aging infrastructure, such as the increases in oil railcar traffic, can lead to hazardous conditions or disasters ("West Virginia Oil Train Derailment Threatens Water Supply" 2015).

Table 1.2 2013 Infrastructure Report Card for the U.S.

System	Grade
Dams	D
Drinking Water	D
Hazardous Waste	D
Levees	D-
Solid Waste	B-
Waste Water	D
Aviation	D
Bridges	C+
Inland Waterways	D-
Ports	C
Rail	C+
Roads	D
Transit	D
Energy	D+

(ASCE 2015)

1.2 Research Statement

This research will address the issue of being able to account for a location's vulnerability into a model to develop a disaster relief supply chain. The research will attempt to incorporate a location's vulnerability information into location-allocation model to establish a disaster relief supply chain. A multiobjective approach is used to integrate information about risks and

population vulnerabilities of a place to make the required location-allocation models more accurate.

The research will have two overreaching questions:

1. How can information gathered from existing techniques, to measure social vulnerability and risks of a place, be integrated into location-allocation models to better optimize a disaster relief supply chain?

2. In examining the current conditions of the state of Connecticut can the developed or proposed model be used with actual available data for the state, and can that model and data be used within the simulation of disaster event?

1.3 Summary and Dissertation Outline

The literature offers a robust examination and debate as to what is a disaster. There has been considerable research on the optimization of disaster relief supply chains. Furthermore, there have been discussions on how to measure risk and vulnerability to hazards. However, there has been little research on how to integrate information about population risks and vulnerabilities into developing disaster relief supply chains. This research will attempt to present a straightforward method to integrate such information into the decision making process. Additionally, this research will offer insights of how the model would respond to an actual disaster event.

This project will use a combination of census data, locational data, statistical analysis and geospatial analysis to help identify vulnerable populations in order to create input values for

location-allocation modeling techniques that will be used to develop disaster relief supply chains. A disaster relief supply chain is similar to a conventional supply chain. It is a network or system of facilities and distribution options for a bundle of goods or services. The supply chain can consist of all the stages required to fulfill a consumer's request. For the case of a disaster relief supply chain, the consumers can be considered those populations affected by the event. The network contains the transporters, warehouses, facilities, suppliers and consumers of the required goods. This research will emphasize the development of the foundational supply network without regard to specific goods or services required by people affected by a disaster. The research will develop a stepwise analysis of the development of a multiobjective approach to developing a disaster relief supply chain. A foundational model will be developed in which information about a geographical area's vulnerability could be utilized to influence the performance or options proposed by the model. The research proposed will add to the broader understanding of disaster relief location-allocation models by developing techniques to better pinpoint and prioritize potentially affected populations.

Chapter Two will review the current body of literature to define the idea of disaster for this research. The chapter will present and develop the concept of a disaster event from a geographic perspective. Examined within the chapter will be the relationships among disaster, risk, hazards and vulnerability. A discussion of techniques to measure risk and vulnerability will be presented. Further, examined will the development and use of location-allocation models to locate public facilities.

In Chapter Three, a model will be developed and tested within a randomly generated universe for the distribution of disaster relief supplies. The model will incorporate measures of social vulnerability to better pinpoint neighborhoods that may require more aid. This will differ

from other research in which population or household values were used as the only measure of demand. A stepwise approach will be presented to develop a multiobjective location allocation model.

The study area will be examined in Chapter Four. The chapter will discuss the development and collection of information for the State of Connecticut. Since the State of Connecticut does not have an intermediate governmental organization, i.e. county government, an argument for a regional cooperative area is presented, and the regional cooperative area is defined. The chapter will put forth the required information and data required by the model, developed in Chapter Three, to build disaster relief supply chain.

Chapter 5 will build on the region of study developed in Chapter 4. In the chapter, the proposed model will be tested for a developed region in the State of Connecticut. The performance of the model will be examined. The model will then be tested for a simulated event. To conclude, a summary and ideas for future research will be presented in Chapter 6.

Chapter Two

Literature Review

2.1 Introduction

Over the last sixty years, there has been a large body of literature where geographers have studied disasters. Geographers have primarily focused on a single aspect of what defines a disaster. They tended to examine disasters from the perspective of the natural hazards associated with such events. The concept of a disaster is much more complex than a single factor. Other social scientists have examined disasters in terms of the social and psychological effects on a group or community. Coupling those concepts and understandings with those of geography's understanding of the interactions between people and place allows for a more comprehensive definition of a disaster.

As disasters become more complex and grow in scale there is a need for longer recovery times. Longer recovery times may require establishing recovery systems for extended periods,

and those systems are required to be more stable over longer timeframes. Location-allocation models allow planners to simultaneously locate facilities and allocate the associated demand for those facilities. These models allow planners to place public facilities in locations to achieve the greatest social utility. The models also allow planners to account for the size and makeup of the required demand. These characteristics make the models extremely useful in planning for disaster recovery supply chains.

2.2 Defining the Concept of a Disaster

The sociologist Carr is considered the first to study and develop an understanding of what a disaster is and how such an event progresses. Carr discussed the scope, character and phases of a disaster. At a foundational level, he classified disasters based on their consequences. He built upon the foundation to clarify that disasters differ in complexity. A single disaster can have many different physical forces operating at any time during the event. These differing forces could result in differing "violence" or degrees of cultural destruction. Carr believed that different disasters could be distinguished in two ways: (1) the character or type of event and (2) the scope or extent of "cultural collapse." Carr defined four types of disasters. The first type was an instantaneous-diffused type. This type of event occurs rapidly, and is short lived. The impact or extent is seen throughout an entire community. The opposite of that type is an instantaneous-focalized type. This event happens rapidly and is short lived, but the impact of the event is confined to a smaller area. The next two types are similar in extent, but occur over longer periods. A progressive-diffused event occurs over hours, days, or weeks and affects a large area, where a progressive-focalized event effects a smaller geographical area. (Carr 1932).

Carr discussed disasters in the context of social/cultural change. In such change, he believed that there were “sequence-patterns.” This “sequence-pattern” to change had three phases. The first phase was the preliminary or prodromal period. During this phase, the forces that are going to cause the change, damage or collapse are getting under way. The second phase is the actual onset of the catastrophic forces. This phase is highlighted by the collapse of “cultural protections,” and was called the dislocation or disorganization phase. The third phase was the readjustment and reorganization. Carr points out that the time from the catastrophe until the emergency plans begin to operate is the “confusion-delay.” The length of “confusion-delay” helps to distinguish between diffused (covering wider areas) and focalized (smaller area) disasters. At the time of his research, Carr points out that no communities had, in his time, any plan or pre-arranged organization to deal with the disorganization of community services caused by a disaster (Carr 1932).

Almost ten years prior to Carr’s examination and defining of disasters the discipline of geography was at one of its historical crossroads. Harlan Barrows, in his speech to the Association of American Geographers in 1923, examined the crossroad facing geography and the paths that lie ahead. He developed his concept of geography as being the study of human ecology. He pointed out that many other sciences had begun to study many aspects of the earth’s environment in more detail than had been studied by geography. Barrows believed that geography’s strength would be in its ability, as a scientific discipline, to study human interaction within a particular “environmental complex,” and within this complex would be various elements such as landforms, vegetation, soils, climate, and animals. Geography’s job would not be to determine the origin or foundation of those elements, but to examine how humans react to the elements or how humans interact with those elements in the complex (Barrows 1923). A

simpler understanding of this concept is that geography's strength was in studying, describing and understanding the interaction between people and place, and how the characteristics of place form those interactions. Barrows belief in the study of human – "environmental complex" interactions would be fundamental in the study of natural hazards.

In 1942, Gilbert White wrote his seminal work regarding how people in the United States had dealt with and adjusted to the flood hazard. His study covered about 24 years of the early Twentieth century. White studied the problem of flooding at the national level, and presented a "geographical approach" to the nation's flood problem. His "geographical approach" to the flood problem examined issues within the flood plains over a wide geographical area. He examined the issues and alternative solutions to flood abatement in terms of how they affected the United States not just the particular flood plain. He attempted to find solutions to flooding issues that would yield maximum returns for the United States with minimal costs to the country. He focused not only on the type of physical adjustments and adaptions taken on by people in response to flooding, but also the historical policy changes taken by the United States federal government. His research found a system of hodgepodge laws, policies and spending bills to help alleviate the suffering caused by flooding (White 1945).

Two significant historical contexts help understand White's work. The first being the date White wrote it – June 1942. In June of 1942, the United States was six to seven months into a worldwide war that would last for another three years. Within disaster research, events of World War II and the subsequent Cold War period, between the United States and the former Soviet Union, would add to the definition of disaster. The second is that during the Depression Era (1929-1940) the United States embarked on a campaign that attempted to tame the environment. The federal government through work projects and other programs would spend tens of millions

of dollars draining swamps, changing and controlling river courses, damming rivers for both flood control and electricity production, and developing techniques to keep winds from stripping vast areas of soil. The forces of nature had not tested many of those projects and ideas at the time of White's study. White had the insight to examine both the physical adjustments people made to flooding and the policy adjustments taken by the US federal government (White 1945). His main conclusion about such policies was that some of those policies may have actually caused more harm than good (Hewitt 1997). White felt that many policies might have encouraged people to stay or rebuild in risky areas.

White's work was in step with Barrows human ecology model for geography. White examined the flooding problem in the United States from what he called a "geographic approach." This approach examined the interaction between people and place, in addition to how these interactions contributed to, adjusted to or prevented the flooding of an area. The "Natural Hazard Paradigm" would emerge from White's work

The "Natural Hazard Paradigm" would be foundational to the growing body of disaster/hazards research in geography over the next several decades. Burton, Kates, and White make the observation and connection between the state of hazards research and Barrows' human ecology concept (Burton, Kates, and White 1968). Additionally, they succinctly presented the Natural Hazard Paradigm in five points:

> 1. Assess the size and extent of the population within the hazard zone.
> 2. Identify the full range of possible adjustments the population has made because of the hazard.
> 3. Observe or study how people perceive and estimate the occurrence of the hazard.
> 5. Develop the optimal set of adjustments to the hazard and their social consequences *(Burton, Kates, and White 1968)*

The Natural Hazard Paradigm is still used as a practical basis in research today. Even though the paradigm is foundational to the study of disasters, the definition of disasters would develop into a more complex concept.

As the idea of what defines a disaster has been discussed and researched, there has been some criticism of the full acceptance of the natural hazard paradigm. The paradigm is not seen as the definitive description of a disaster. Hewitt believes that following the paradigm leads to thoughts or beliefs that communities are passive victims of natural and technological hazards. He believed in the need for a more comprehensive definition of what makes up a disaster, because such a definition makes it seem those communities need only technical knowledge and advice to control hazards. He concludes that a disaster is a much more complex thing that involves technical knowledge, uncertainty, and social and political vulnerabilities of a community (Hewitt 1995).

Erikson examined the complex nature of the relationship among people, place, and disaster in his analysis of the 1972 Buffalo Creek, West Virginia flood. In February 1972, over 100 million gallons of water broke its way through an old earthen mining company dam. The water flowed through the narrow hollow of Buffalo Creek and it devastated the community. Erikson pointed out that though the people of Buffalo Creek were victims of the terrible flood they might not have been passive to the events. The community's strong interaction with the place, through their employment by the mining-company and their strong engagement in the mining operations, would make them fully aware of the dangers. Erikson did point out the community was most likely powerless to prompt the mining company to better maintain the dam, but they were well aware of the risks in living in the area and other risks associated with the mining of coal (Erikson 1976).

As the United States exited World War II and entered the Cold War era, with the former Soviet Union, disaster research became a more formalized field of research in terms of studying the various components of a disaster. The concept of a disaster would also take on a more ominous tone and approach in study. The ideas of massive evacuations and panic would be studied (Bernert and Iklé 1952; E. Quarantelli 1954). Those types of studies got much of their data, insights and emphasis on situations from World War II Europe. Additionally massive aerial bombings were also studied (Hewitt 1983). Fritz would echo the tone of the era regarding disaster studies. Fritz believed there were two practical needs for such studies:

> "…first, to secure more adequate protection of the nation from destructive and disruptive consequences of potential atomic, biological, and chemical attack, and second to produce the maximal amount of disruption to the enemy in the event of war." (Fritz 1961)

Claude Gilbert would present that one of the three approaches to disaster research was "Patterns of War Approach." He believed that the United States undertook disaster research to understand the reactions of populations during wartime circumstances. Natural hazards were used as wartime analogs, and the "market" directed the topics focused on by disaster research. The "market" was organizations, such as U.S. Dept. of Defense, involved in the planning for any potential war and the defense of the United States from an enemy (Gilbert 1995).

Fritz believed that disasters could have varying degrees of scale. He said that disasters could occur to individuals, a family or small group, a community, a region, a nation, or the entire world. A disaster causes disruption of the social context or is a departure from what is normally expected. These events are concentrated in time and space. He does clarify that events that do not disturb the vital functions of a society are considered a crisis or an emergency, but not a disaster. According to Fritz, disasters differ in six main ways:

1. Degree of predictability, probability, and controllability.
2. Nature of the damaging agent (i.e., flood, fire, explosion, or hurricane).
3. The origin of the event (man-made or natural).
4. Speed of onset (instantaneous or progressive).
5. Scope or extent (focalized or diffused).
6. Destructive effects of people and physical objects.

(Fritz 1961)

Zelinsky and Kosinski reached some of the same conclusions as Fritz's definition. They described disasters as events that were concentrated within a defined space and time. The event caused damage to property or loss of life. A disaster disrupts all or some functions of routine life. They observed that a disaster that does not take place or is deferred long past the anticipated or expected date could still be considered a true disaster if such anticipation caused disruptions to the normal or expected routine of life. In other words the threat of a potential disaster could lead to disruptions that in themselves are a disaster (Zelinsky and Kosinski 1991). Kreps would further emphasize the time and space boundaries and impacts on social units within his definition of disaster (Kreps 1984). Hewitt examined techniques to determine the probability and predictability of natural events that may lead to disasters (Hewitt 1970).

In the wake of the Three Mile Island Nuclear Power Plant accident (Dauphin County, PA), in 1979, Perrow examined the incident as a "normal" accident. He believed that "normal" accidents are products of their systems. He emphasized that a "normal" accident will occur at some facility, the particular event accident will probably occur again, and most likely even occur at the best of facilities. He saw a "normal" accident as a sequence of connected events that moved along because of the events relationship within the system. He outlined four characteristics of a "normal" accident: (1) the signs of the impending problem are only recognizable after the accident, (2) the accident encompasses multiple design and equipment failures, (3) operator error – which like the signs of the problem are not seen as errors until the

final analysis, and (4) the three other characteristics have a cascading effect that compounds or intensifies the problem much greater than the sum of each single design, equipment, or operator error (Perrow 1981). This type of analysis makes it clear how a natural event coupled with technological and socioeconomic subsystems of a place can lead to the amplification of the event into a disaster (Comfort 2006).

In examining the "Natural Hazard Paradigm" and the debate of what are the components of a disaster allows a definition of a disaster to emerge. The event is confined within specified time and space boundaries. An outside agent causes the event, which may be man-made or natural. This outside agent causes damage to physical structures, injuries to people, and/or major disruption to the normal expected flow of everyday life or society. Disasters have a spatial organization. The extent of the damage caused by a disaster is the spatial definition. This damage could be in terms of physical infrastructure or location of human casualties. Wallace examined a tornado in Worcester, MA, and as part of his analysis, he produced a diagram to describe the spatial organization of disaster relief effort. This diagram is shown in Figure 2.1. In his diagram, he represented the disaster area as a series of concentric circles. In the center, ring/circle is the "Total Impact" area. In this area, the most powerful of the outside forces are concentrated, and within this area, the most damage and injuries occur. The next ring is the "Fringe Impact" area. This ring includes less damage and casualties. The two rings Total and Fringe make up the "Impact Area." The third ring is the "Filter Area." This is the area where people are traveling through to move away from the "Impact Area" and responders are traveling through to enter the "Impact Area". The next rings show how the aid to the "Impact Area" is spatially organized (Wallace 1956). Zelinsky and Kosinski presented a similar type of spatial organization. Their "doughnut "shaped model was used to describe the spatial organization of an evacuation

following a disaster. In their model, people avoided the “doughnut hole.” Their “doughnut” portion could be seen as Wallace’s “Filter Area” and their “doughnut hole” was the same as Wallace’s “Impact Area.” The “doughnut hole” was the area where the most damage had occurred. The greatest collection of people avoiding the event would be found outside of the “doughnut.” Zelinsky and Kosinski emphasized that people will flee away from danger. ((E. Quarantelli 1954; Zelinsky and Kosinski 1991). Cutter points out that the spatial boundaries or extent of a disaster sometimes cannot be determined until after the actual event occurs (Cutter 2001).

Figure 2.1 Wallace's description of the spatial organization of relief efforts for the 1953 tornado in Worcester, MA (Wallace 1956).

Included in the definition of a disaster are the classifications of different disaster types. The specific agent or cause of damage or disruption is used to classify disasters. The broad categories of the causes of disasters are natural, technological, and social. Types of natural disasters include things like flood, hurricane, and earthquake. Technological disasters are things like accidental explosions, unintentional chemical releases, and transportation accidents. Social disasters are caused by human-to-human interactions. A disaster can be caused by a compound

hazard, which can be a combination of a natural and a technological hazard that combine to cause the disruption. Disasters can also be considered complex. This type of disaster is similar to a compound hazard – however, there is generally some aspect of a social hazard in combination with other factors. An example of a complex disaster is a widespread famine which is caused by natural hazard (flood or drought) and this condition is amplified by an oppressive government (Hewitt 1997). Figure 2.2 describes the types of disasters as outlined by Hewitt.

Hazard	Type	Examples
Natural	Atmospheric	Hail, snow, tornados, hurricanes, blizzards
	Hydrological	Floods, drought, sea-ice, glacier advances
	Geological	Landslides, earthquakes, volcanic eruption
	Biological	Epidemic, blights, insect plagues
Technological	Hazardous Materials	Physical (asbestos fibers), chemical, flammable, biotech Structural failure, explosion, fire, radiation
	Destructive processes	Explosive, aircraft, oil tankers
	Devices or machines Installations	Power plants, dams, LNG terminals, pipelines
	Sector or organizations	Petrochemicals, airlines, road transportation, mining
Social	Weapons	Conventional (gun, bombs), unconventional (nuclear, chemical, biological)
	Release of dangerous natural forces	Arson, triggering landslide or flood, weather modification
	Release of dangerous technological forces	Terroristic acts against fuel storage, nuclear plants, chemical plants, and dams
	Armed forces and weapon systems	Massive air bombing, guerilla warfare
	Strategies and tactics	Economic blockade, sieges, ethnic cleansing

Figure 2.2 Disaster Classification (Hewitt 1997)

2.3 Hazard, Risks and Vulnerability

As disaster research began to enter, the latter part of the Twentieth Century there was an understanding that populations were not simply at the whim of natural or man-made forces. From this understanding developed the idea that some elements of a disaster may be based on socially or politically constructed parts of a societal unit. These socially or politically constructed elements may work in concert with the outside agent to form a disaster. The term vulnerability began to appear within disaster research. When the term first appeared, the idea of vulnerability was vague and not clearly defined (Wisner 1993).

Early research would link vulnerability with the income and poverty levels of differing segments of a population. Wisner argued for a larger pool of factors to be used to determine the vulnerability of a population to particular hazards. He believed that a community's overall structure for the production of goods and housing was not a direct indication of the vulnerability for the basic community units (households, for example). He pointed the households, of a community, access to resources in the time of crisis as a more accurate indication of vulnerability. In his opinion, this measurement of vulnerability was much more complex than the simple formula of wealth or income of a region (Wisner 1993).

Working along the path forged by White, geographers looked within the Natural Hazard Paradigm to establish vulnerabilities. As previously discussed, the paradigm examines how a population makes, chooses, and executes adjustments made because of the hazard. Population evacuation is an adjustment to a hazard. Baker studied who would leave and who would stay during an evacuation period prior to a hurricane. His work developed a description, for planners and emergency managers, of those who would be vulnerable (not leave) and those who would not be vulnerable (would evacuate) to a hurricane hazard. This analysis would form a crude

measure of vulnerability to the hurricane hazard. Additional factors beyond wealth and income of household began to emerge a factors relating to vulnerability. Baker examined things like age, mobility, transportation options, location of the household, and perception of warnings. His initial research looked at who evacuated and who did not, but later he would examine the "preparedness" of a household, offering an early predictor of the factors that may make a household vulnerable (Baker 1979; Baker 2011). Similar studies were done for technological hazards. The response of population during the Three Mile Island accident were studied (Zeigler, Brunn, and Johnson Jr 1981). Hypothetical scenarios were studied to develop an understanding as to who would and would not evacuate, when given instructions to do so, during a potential nuclear power plant accident (Zeigler and Johnson 1984; Mileti and Peek 2000).

Disasters are the result of the relationship among hazards, risk, and vulnerability. A hazard is a potentially damaging event or phenomenon. Vulnerability is the susceptibility to harm from exposure to a hazard (Adger 2006). Vulnerability can take several forms and locus. The forms which vulnerability can take are among exposure to a hazard, structural weakness, lack of response capabilities, and powerlessness. The locus can be at any of the following levels: individual, domestic (or household), gender (or race), geographic space (Hewitt 1997). Of importance, to this research, will be vulnerability in the form of exposure to a hazard and with a locus of defined geographic space. Risk is the probability that a hazard will result in damage or disruption to a community. Risk can be measured in terms of the number of potential casualties or cost of economic loss or physical infrastructure damage. Quarantelli observed that there was complexity in the concepts and defining elements of a disaster, and he proposed that the research move towards a more holistic approach while moving away from the particular hazard case-based approach (E. L. Quarantelli 1987). The "hazards paradigm" was not static, but dynamic.

The research had moved from the study of specific hazards towards concepts that encompassed both complexity of an event and social causation. The past research was further criticized for neglecting the social and economic constraints that could lead to limited choices of affected people and governments (Burton, Kates, and White 1993).

Gilbert broadened the analysis of hazard, risk and vulnerability. Two of his three models of a disaster involved vulnerability and uncertainty. One model was an understanding that the social and economic makeup of a group or community may present vulnerabilities that result in hazards becoming disasters. His second model represented that uncertainty played a role in a disaster. His uncertainty had a basis in the communication about, understanding of and acceptance of particular events. If there was poor communication about particular events or hazards within a community this would lead to an uncertainty or lack of understanding of the dangers of a those hazards. It was the lack of understanding that would lead to disasters (Gilbert 1995). Vulnerability and hazard are interwoven in the concept of “hazard of place.” The “hazard of place” describes the relationship between hazard and vulnerability from a geographical perspective. The “hazard of place” is defined as the geographical space a vulnerable population is located with respect to hazards and/or events that could occur at that place (Cutter 1996). Hewitt and Burton had discussed the “hazardousness of a place.” Their underlying theme was much different – they cataloged the hazards of London, Ontario to show that any place could be a dangerous place at any time (Hewitt and Burton 1971).

This relationship among hazard, risk and vulnerability can be expressed as a pseudo-mathematical expression: Disaster Risk = Hazards + Vulnerabilities. Where the magnitude of the risk of disaster can be related to the hazards of a place and the vulnerabilities of a population (Cova 1999). The relationship has been expanded and vulnerabilities was expanded to include

mitigation. The vulnerabilities factor was transformed to be defined as the inverse of resiliency of a population or community (Wisner, Gaillard, and Kelman 2012). Once the observation was made that disasters not only occur because of the risks caused by a hazard, but also by vulnerabilities of a community, the idea to identify those vulnerable populations was developed. Morrow proposed a system or model to map the vulnerabilities of communities using geographic information systems (Morrow 1999). The abilities to identify and map vulnerabilities led to the development of social vulnerability indices (Cutter, Boruff, and Shirley 2003). However, with decades of analysis and techniques to develop these types of indices there has been no attempt to integrate that information into the planning of disaster relief supply chains. Much of the modeling done has used gross percentages of populations to develop the locations and demands required.

In recent years, the United States government has taken a more comprehensive approach to disaster response and recovery. This approach is called the “all hazards” approach. The government takes a more encompassing approach in planning for disaster events. In this approach, the government weighs the potential for differing types of events and the associated risks of each event. Plans are then developed to include a wide range of hazards. These plans are more comprehensive and flexible. This allows communities to have one or two master type plans as oppose to numerous hazard specific plan for each individual hazard. The allows for a quick, scalable, adaptable response that will allow for a quicker recovery (“National Response Framework” 2008; “National Disaster Response Framework” 2011)

2.4 Equality vs Equity

At the heart of public facilities, location analysis or model is the attempt for equality and/or equity in the distribution of public services. Planners attempt to balance the needs of a community, as a whole, versus the population that might need or utilize the desired facility. Drezner clearly describes the dilemma and concept:

> "Why should a few users have a very short distance to a public facility,
> Whereas many users have longer distances to travel (or vice versa)?"
> (Drezner 2004)

Drezner believes that facility location models in the public sector have an equity objective, and the aforementioned quote is a statement of the conflicts the concept of equity. However, the concepts of equity and equality tend to be co-mingled as a single concept or objective. Drezner examined these concepts in building models for casualty collection points for Los Angeles, and argues that location models that were attempts at equity models tended to have equality objectives (Drezner 2004).

In 1969, McGuire and Garn examined the ability or the requirement to include equity considerations in the analysis of federally funded projects. In their analysis of the state of the situation, in 1969, they could not find a single unambiguous measure or meaning of poverty or community need, and without this type of measure or definition, they argued that many local planners had to interpret how programs fit the needs of their communities. Generally, local officials were confronted with programs that may have been designed as "a one size fits all," or "a shotgun approach." McGuire and Garn believed that there was a need to measure a community's "need" on some universal scale and such a scale or metric could help determine the distribution of such federal programs (McGuire and Garn 1969).

Savas examined three metrics to measure the ability to deliver public services. He believed that the delivery of such services could be measured by efficiency, effectiveness, and equity. He described equity as fairness, impartiality, and equality of services. He introduced the concept of equality in his belief of how public services should be distributed. He argued that the distribution of public services could be done by following one or more of four formulas. The first formula was the use of equal payments, where the payments could be equal payments for equal amounts of services or equal payments for the equal ability to pay for such services. The second formula was equal output. Programs are distributed in such a manner that all communities have equal results. The third formula focuses on the equality of inputs. Communities all receive the same level of inputs, and the input is measured against some scale such as per capita, per district, or per some areal unit. His fourth formula was not as straightforward as his other three formulas. He described it as the equal satisfaction of demand, and it could be described as "being the squeaky wheel." The fourth formula is equal satisfaction of demand and could be implemented as equal inputs per unit of demand. An example of this would be assigning one police car for every 1,000 calls per year. Savas further develops the fourth formula such that it could be measured as equal inputs per complaint or equal inputs per politically weighted complaints – "the squeaky wheel" (Savas 1978).

Schilling and Marsh argue that the earliest and most frequently used measure of equity is an attempt to maximize the effect over a group or location. They define equity as when each group receives a fair share of services provided by the location of public facility. They discuss twenty approaches to the measure of equity, but they believe that there is little agreement on which ones are the most effective measurements. They note that this measure of equity is used as an objective for the p-center model. The p-center model has the objective to locate p facilities

that minimize the maximum distance from a demand node. They observe that the p-center is more equitable than the p-median model, which attempts to minimize travel distance (Marsh and Schilling 1994). Building on Marsh and Schilling's work, Ogryczak examined the ability to build the ideas of inequality measures and equity into location models. He focused on bicriteria models and examined the use of several inequality measures such as maximum deviation, mean deviation, and mean difference. These measure were used to incorporate equity factors into facility location models (Ogryczak 2000).

According to Morrill and Symons the comparison between efficiency and the idea of distributional equity, concerning, a location is not so clear. They argue that the idea of equity was absent from classical location theory. They believe that the idea of measuring equity only arises when a community believes that some population or location is not receiving fair or adequate services. However, they cannot pinpoint whether the observed inequity is the result of some economic inefficiency or an inefficiency of the goals (Morrill and Symons 1977). Leventhal believes that equity theory uses a unidimensional rather than a multidimensional approach, and considers only the final distribution, or reward, of goods and services. He comments that equity theory exaggerates the importance of fairness (Leventhal 1980).

2.5 Location-Allocation Models

Planners are confronted with the problem of accessibility of services. In the public sector, these types of services can be things like schools, emergency services of various types, courts or motor vehicle licensing centers. Similarly, locations of things like warehouses, service or repair centers or branch offices can be types of locations in the private sector in which accessibility is important. The factor of accessibility is measured by some metric such as travel distance or travel time, or in the case of a commercial setting travel or transportation costs. Accessibility

becomes important because if the facility is located such that it is too demanding for the public or the customer to reach it, the facility will not be useful.

In the simplest form, this type of problem is a Weber problem. Weber was able to demonstrate that a factory will locate itself in a manner as to minimize the transportation costs for raw materials and to the final customer (D. M. Smith 1981). However, when there are multiple facilities to locate the system becomes much more complex. The system will have to provide a particular service using multiple facilities. These facilities have to be located in a way as to meet the demands of the public or customer. Those demands must also be met within a set of constraints established by the planners. These types of systems are location-allocation models. Further complexity arises because facilities in an optimal multi-facility network or pattern have to be selected simultaneously rather than choosing one location at a time. Church and Murray calls this their Third Law of Location Science (Church and Murray 2009).

The process of allocation also reinforces the differences between a single facility system and a multi-facility system. Allocation is the process of determining who is served by a facility. Allocation splits up the demand between the different facilities. Thus, in a location-allocation model not only do the set of facilities have to be selected simultaneously, but also the allocation of the demand to each facility in the system. In other words as a facility is located it is given its associated demand for that particular location.

In 1958, Baumol and Wolfe proposed a solution to the warehouse-location problem. Their innovative approach broke the problem down into two transportation problems: (1) from the factory to warehouse and (2) from the warehouse to the customer location. Additionally, the confronted both the assumption of linearity and the possibility of nonlinearity within their development of a solution. They also presented another simplification of aggregating locations

within a city, i.e. all the warehouses located within New York City were considered to be located in a single location (Baumol and Wolfe 1958). Following in 1963, Leon Cooper developed a framework for a solution for the location-allocation problem. He stated the general form of the problem. He said that the problem began with three givens: (1) location of each destination (customer); (2) the requirements (demand) of each destination (customer); and (3) shipping costs for the region. Cooper's method would then solve for: the number of sources (facilities); the location of each source; and capacity (supply) of each source (Cooper 1963). About the same time as Cooper Kuehn and Hamburger developed a heuristic program that located or selected potential warehouse sites. Their work differed from Baumol and Wolfe in that their program was able to consider many more potential warehouse locations (Kuehn and Hamburger 1963). Haley also offered a unique approach. He described the warehouse siting problem as a mechanical or physics analogue. He described demand as weight in the system and that the optimal solution was when the system came to rest. According to Haley the system had the minimum amount of potential energy (Haley 1963). Hakimi attached the sources and destinations to a network system. Hakimi was optimizing the location of telephone switching centers on a communication network, but he saw his solution analogous to locating police or fire stations on a road network. He used the two examples, the telephone switching and police stations, to differentiate between centers and medians of a graph. Hakimi's police station example would introduce a class of location-allocation problems known as p-median problems (Hakimi 1964). Goldman would examine Hakimi's work from a different perspective. Where Hakimi believed that one only needed to consider vertices as location for centers, Goldman was able to minimize transportation costs over a set of origin-destination pairs, and not necessarily all centers located at a vertex. Goldman's work would form the basis for hub-and-spoke models (Goldman 1969).

In a p-median problem, each demand is allocated once. The demand is restricted to locations that have been determined to be facilities. Additionally, the entire demand from a location will be assigned to the closest facility. ReVelle and Swain presented a mathematical formulation of the p-median problem. Their formulation allowed for linear programming techniques to be used to solve the location-allocation problems for what they called “central facilities” (ReVelle and Swain 1970).

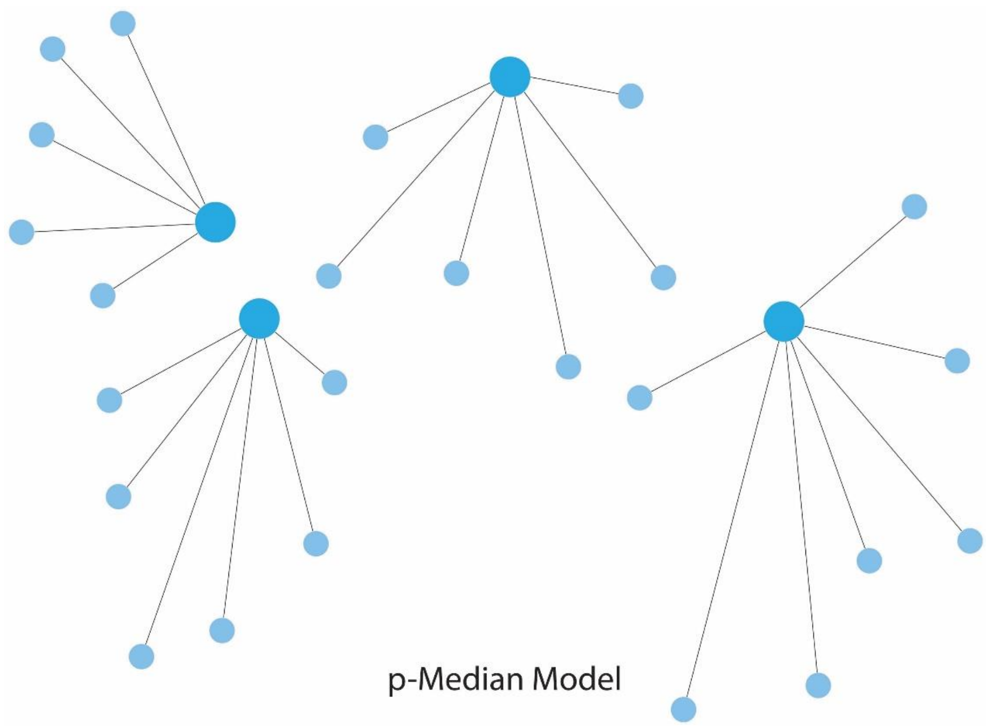


Figure2.3 Spider diagram of p-Median model.

Some of the earliest uses for the location models were for the siting of emergency services (Revelle, Marks, and Liebman 1970). Location analysis and location-allocation models were used in the private sector or in commercial settings and the constraints between public and private models are slightly different. One such difference is the subtly between “best” and “optimal” parameters – this difference can lead to looking for surrogates to measure or quantify social utility (Toregas and ReVelle 1972). There have been models developed for public

facilities that are similar to private facilities in that both construction costs and transportation costs have been included in the objective function (Wagner and Falkson 1975). Location-allocation models have been examined as dynamic systems. This type of modeling accounts for changes (or relocations of facilities) over time (Wesolowsky and Truscott 1975). Church and ReVelle examined the connections between set covering and p-median problems. Figure 2.3 shows a p-median model, where p = 4. They observed that there exists computational and theoretical links between the two classes of models, and the p-median problem is general enough to solve most types of location models. The flexibility in the p-median problem can be achieved by changes in how the input data is formatted (Church and ReVelle 1976).

As disaster relief and recovery requirements become more complex the need for flexible relief supply choices becomes important. Haghani and Oh examined the problem of logistics from a network flow perspective. Their examination was with the belief that the transportation network framework was already in place – choices within their system were based on time and transportation types (Haghani and Oh 1996). During most disaster events the relief and supply centers have to be located (Dekle et al. 2005). Location-allocation models allow for the simultaneous location of centers and assignment of demand. Top-down and p-median type solutions have been offered to the relief supply chain problem (Horner and Downs 2007; Horner and Downs 2010; Widener and Horner 2011).

Goldman's work would set the foundation for the development of the analysis of hub-and-spoke models. Working separately, Campbell and O'Kelly examined the hub-and-spoke location-allocation model (O'Kelly 1986b; O'Kelly 1986a; O'Kelly 1987; O'Kelly 1992; O'Kelly 1998; Campbell 1994; Campbell 1996). In this model, a hub can be considered a trans-shipment location, and Figure 2.4 shows a schematic of a hub and spoke system. An advantage

of this system is a large number of direct connections can be replaced with fewer indirect connections (O'Kelly and Miller 1994). The hubs have the ability to interact with each other (O'Kelly 1986b). The interactions between the hubs could possibly allow supplies to enter the network at any point (hub) in the system. The network could also be designed such that hubs could accommodate routing algorithms from the hubs. These routing algorithms are extremely complex and computer resource intensive to solve. (Liu, Li, and Chan 2003).

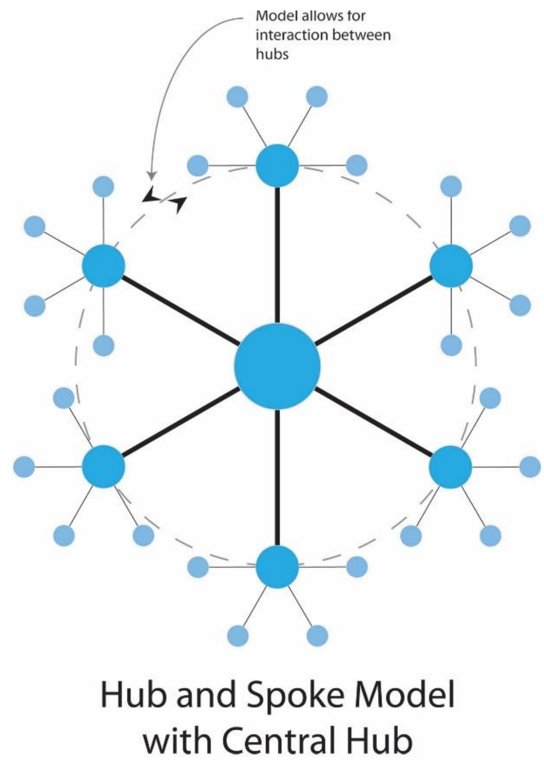


Figure 2.4 Hub and spoke arrangement.

Hub networks allow for the modeling of two-way traffic along the network – a first step to multicommodity flow. The classic analogy, for a hub system, is airline passenger or freight travel. There are disadvantages to the use of hub systems. The first is that the formulation of a hub network requires a shift in thinking. The classical models discussed are demand focused. These models try to attempt to cover a demand location or meet the demand represented by a location in space. A hub network is concerned about the flow between an origin—destination

pair. In a hub network these pairs are linked as a unit – passengers wanting to go from point A to point B want only those beginning and ending points. Whereas in a classical p – median model the demand a point A does not care from where the demand is met. The second disadvantage is that attempting to formulate hub networks is a complex modeling task. Campbell and O'Kelly use differing methods. Campbell presents an integer linear programming method, and O'Kelly a quadratic method. The differences between the two are beyond the scope of this research, but each method appears to work equally as well. Each method results in complex computational methods where the number of decision variables can quickly expand beyond available computer hardware and software performance and memory. This limitation generally requires that the sets of origin—destination pairs be small, in the order of less than 50, and a small number of eventual hub locations(Daskin 2013).

2.6 Use of Optimization in Disaster Management

Four foundational articles about the use of optimization and location allocation models for in disaster management help outline the research. Altay and Green offer an overview of the state of disaster management research in the field of operations research. They discuss many articles within several areas of emergency/disaster management. They do not offer many examples of past study in disaster relief optimization, but they do argue that existing location allocation models can be improved for emergency services and adapted for disaster situations (Altay and Green 2006).

Kovacs and Spens conducted a review of disaster logistics for the same period as Altay and Green. They believed, as Altay and Green, that the field was relatively new, and had many areas in which it could grow (Kovács and Spens 2007). Covering a later period is Caunhy, et al. Their work covered the use of optimization of logistic models for emergency situations. They

explained that optimization models were initially used to develop locations for oil spill and similar maritime disaster response teams in the 1970's, and that in the 1980's these models were expanded to such things as hurricanes, floods, and earthquakes. They reviewed models that were similar to this research. They found that the facility location researched generally formulated models that were of the maximal covering type, and the models had either quantity of coverage or quality of coverage requirements. Models could either have deterministic or stochastic parameters. The stochastic parameters were either probabilistic or scenario based. Their research found single level and bi-level models. A bi-level model is described as having a leader and a follower in the decision making process, and these types of models can introduce differing levels of information at different stages of the decision making process. They found that when simple facility location models were expanded the resulting expansion included things like relief distribution and/or stock pre-positioning into the models. They also found models that dealt with unmet demands, facility expansion, different types or levels of facilities, and other factors such as ordering costs, holding costs, and facility operation costs (Caunhye, Nie, and Pokharel 2012).

A model similar to this research by Horner and Downs (Horner and Downs 2010) was classified by Caunhye, et al as a single objective, deterministic, single level facility location model. They also acknowledge that the Horner and Downs model locates different types of facilities. Caunhye, et al found two multiobjective models (Caunhye, Nie, and Pokharel 2012). The first being a partial covering solution to locating oil spill response teams (Belardo et al. 1984). The second model optimized the location of pre-positioned medical supplies and the distribution of such. This model is an example of a bi-level model – the second objective the distribution of the supplies builds on the first objective – the location of warehouse/stockpiles. The model has stochastic parameters developed from a scenario of a Seattle, WA earthquake

(Mete and Zabinsky 2010). Ransikarbum and Mason explain the use of FEMA's HAZUS software to develop a scenario to test their Goal programming method (Ransikarbum and Mason 2016).

In a more recent article, Gutjahr and Nolz examined the use of multicriteria optimization. They found a growing use of multicriteria optimization techniques in developing disaster relief logistics. They believed that this increase in the use of multicriteria optimizations was because the management of disasters requires the balancing of many objectives. They discussed the use of models that examined various factors that could be used as either objectives or constraints. These factors included costs, travel distance, coverage, reliability, security, and distress. They found various techniques were being used to develop such models. They could not find much discussion about equity measures, or the examination of tradeoffs. They believed that future research is required in the examination in differing demand needs based on measures of equity and equality (Gutjahr and Nolz 2016).

2.7 Summary

A disaster is complex event that may combine many natural, technological and social factors to cause damage or disruption to a community. Disasters do occur within definable time and space boundaries. The complicated and unpredictable nature, of disasters, calls for flexible response and recovery systems. Location allocation models allow planners to propose and develop adaptable models for locating public facilities to maximize social utility. The use of multcriteria models can allow planners to weigh competing objectives against each other. This type of modeling should allow for a more focused distribution points.

The ability to integrate information about a location's vulnerabilities into a model would allow planners to better understand the needs of a location during times of crisis. Having a better understanding of a location's needs allows for a better disaster relief supply chain. The strength and performance of the chain is influenced by how well the anticipated needs are met by the supply chain. .The chain can be made more flexible by taking the established system and transforming it into a hub network, which will allow for two-way and/or multicommodity flow.

Chapter Three

Methodology and Model Development

3.1 Introduction

As discussed much of today's research and policy in disasters and disaster response, in the United States, has its foundation in research that occurred in the post- World War II and Cold War era. Not more so is the historical foundations evident than in the manner in which disaster relief is distributed. The current systems are heavily reliant on a top-down, automobile centric approach to distribution. Relief supplies and equipment are stored at large centrally located warehouses, in some cases there are smaller intermediary regional facilities, and moved to Points of Distribution (POD) for distribution to those who need the supplies. The POD is designed to be a "drive thru" facility where persons requiring supplies enters at one end, in a vehicle, and exits at another end with the needed supplies. This process is shown in Figure 3.1; vehicles enter from the left in the diagram, and exit at the right with loading points for various supplies along the path. Figure 3.2 outlines the relative land area requirements for the various types of distribution

facilities. The distribution model based on “pushing” down the required supplies to a location to which the requiring population must travel to receive the supplies. These facilities require a large expense in land area, manpower, and money to establish and operate that these facilities tend to be located a distance away that does require the reliance of a motor vehicle to receive assistance.

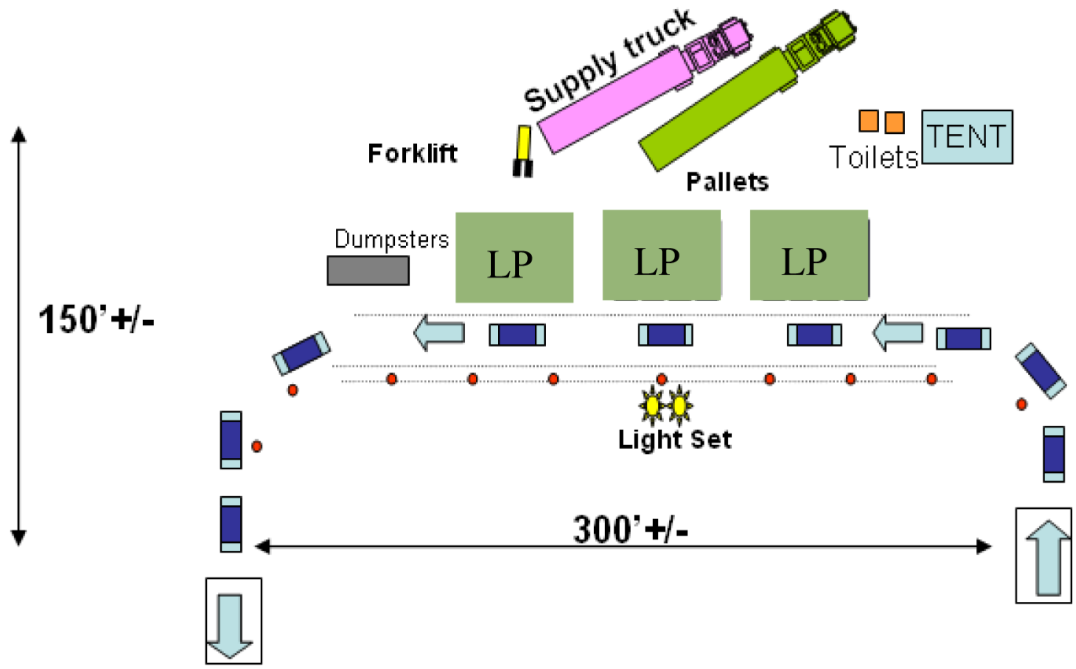


Figure 3.1 Diagram of Point of Distribution. LP = Loading points (FEMA/USACE 2008).

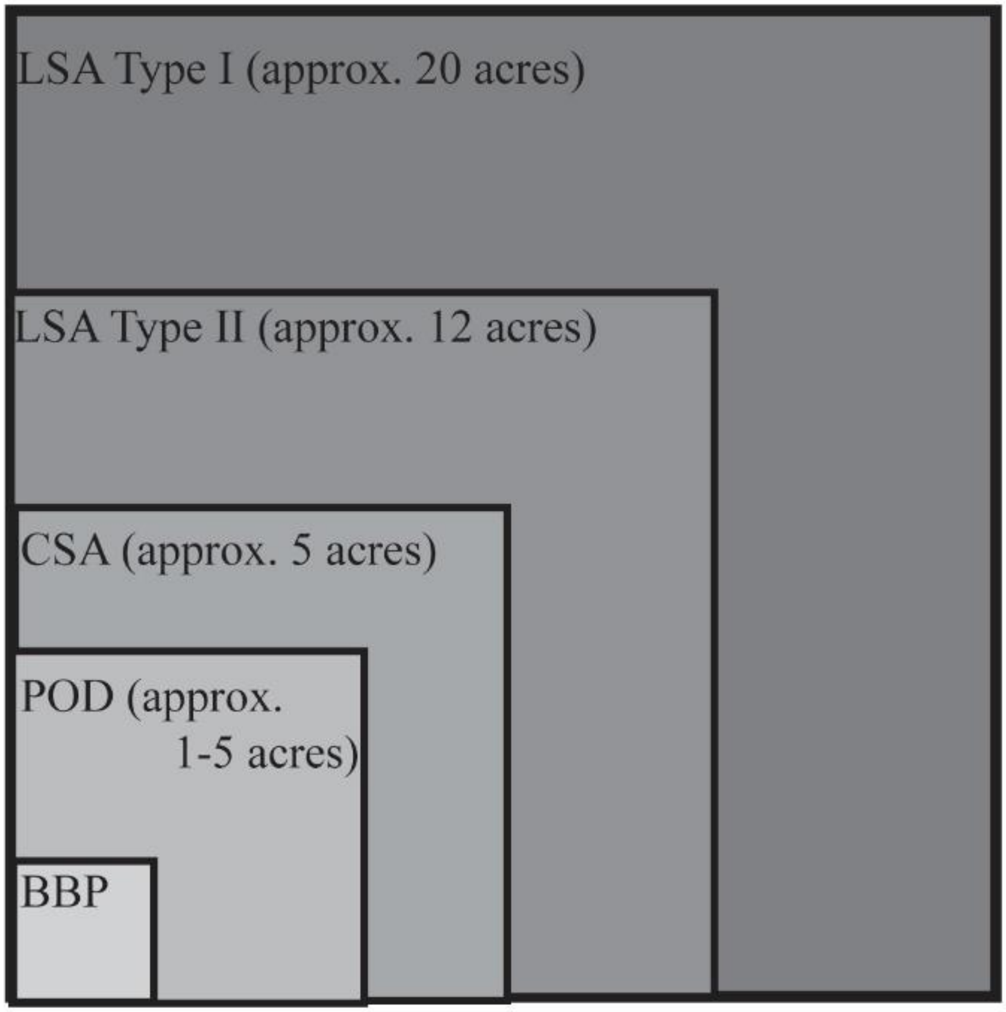


Figure 3.2 Relative area requirements for the different distribution levels as suggested by the State of Florida and FEMA (“County Points of Distribution PowerPoint” 2010).

Horner and Downs (Horner and Downs 2007) proposed a model in which goods went from a large warehouse to a POD and then a Bulk-Breakout Point (BBP). This system is analogous to one that is used by less-than-load (LTL) shipping systems, and is shown in Figure 3.3.

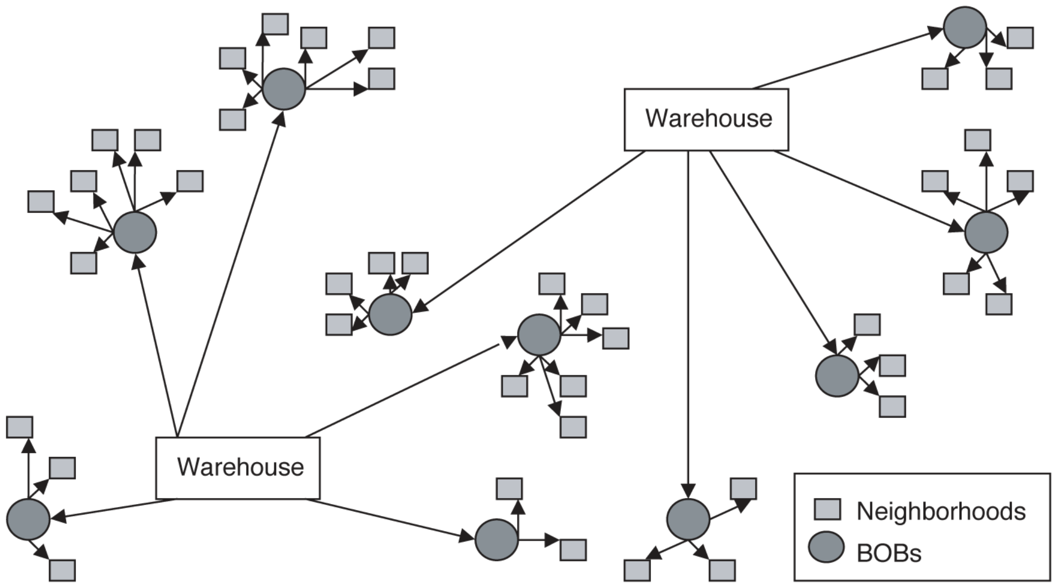


Figure 3.3 Schematic of Horner and Downs model (Horner and Downs 2007). BOBs are equivalent to the proposed BBPs.

The Horner and Downs model relies the same “push” driver to get supplies to the populations that need them. Horner and Downs rely on the metric of minimizing the total demand weighted cost in the system (using distance as the costing factor) in making the decision as to where to locate a facility.

This research’s model is similar to the Horner and Downs model in that it takes a multiobjective approach to solve the problem. The Horner and Downs model is a two objective model. The first objective determines which POD serves which BBP, and the second objective determines the locations of the BBP. The model attempts to minimize the costs within the system. The proposed model will build upon minimizing the total demand weighted costs, and it will take into account the desire to maximize coverage of more vulnerable neighborhoods.

3.2 Model Development

Cohon points out that one of the jobs of an analyst is to narrow the choices for decision makers. He believes that multiobjective modeling allows for such a process to occur (Cohon 2003). That process also allows for the modeling to broken down into smaller pieces to help determine the bounds and limits of the final solution. The first step in the process is to layout the objectives of the model or what goals are going to be achieved by the model. In this model, there will be three objectives. The first objective will involve the relationship between the PODs and the BBPs. This objective will be a straightforward cost-minimizing objective. The next two objectives of the model concern the BBP-neighborhood system. These two objectives are the more complex, and are listed below:

1. To maximize the coverage of the “more” vulnerable neighborhoods
2. To minimize the total demand weighted cost in the BBP-neighborhood system.

What is first observed by the objectives is that they are in conflict with each other. The first objective is a maximization and the second is a minimization. This is a simple conflict to resolve when one considers that a maximization can become a minimization objective by taking the negative of objective (Cohon 2003). However, the use of negative values could lead to errors or confusion in the results and analyst. A convention suggested by Daskin (Daskin 2013) is used to change the first objective to:

1. Minimize the uncovered “more” vulnerable neighborhoods.

This will result in a change the formulation of the coverage matrix as follows:

$$C_{ij} = \begin{cases} 1, & \text{if } dist_{ji} > \text{coverage distance and neighborhood is “more” vulnerable;} \\ 0, & \text{Otherwise.} \end{cases}$$

Planners and analysts decide upon the value of the "coverage distance". This value represents the distance within which planners determined acceptable service can be provided. $Dist_{ji}$ is the distance from a node, j, requiring service and a node, i, providing the service. This formulation is the same as the formulation that was proposed by Church and ReVelle in their discussion about the computational links between the Maximal Covering Problem and the p-Median problem (Church and ReVelle 1976).

3.3 Determining the Bounds and Limitations

Prior to developing a complete outline of a model, an analyst has to determine or understand the possible bounds and limitations of any solutions. An approach to examine this issue is to analyze the problem using smaller, less complex fundamental models. In this case, this specific problem is examined using the three fundamental models:

1. Set Covering Model
2. Maximal Covering Model
3. p-Median Model

The Set Covering Model is considered the fundamental model in solving for public facilities locations. The objective of this model, first proposed by Toregas, Swain, ReVelle, and Bergman (Toregas et al. 1971), is to locate a minimum number of facilities that satisfy a response-time or distant requirement. The model can be stated as:

Minimize:

$$\sum_{j \text{ in } J} a_j X_j \tag{3.1}$$

Subject to:

$$\sum_{j \text{ in } J} C_{ij} X_j \geq 1 \qquad \text{for all i} \tag{3.2}$$

$$X_j = 0,1 \qquad \text{for all j} \tag{3.3}$$

Where:

$$C_{ij} = \begin{cases} 1, \text{ if } dist_{ij} <= \text{coverage distance;} \\ 0, \text{ otherwise;} \end{cases}$$

$$X_j = \begin{cases} 1, \text{ if BBP is located at candidate site j;} \\ 0, \text{ if not; and} \end{cases}$$

$a_j =$ Cost of operating/locating BBP at candidate site j (will be set to $1 in this case).

In the context of this problem, the Set Covering Model will give a starting point or an indication of the upper bound for the number of required BBPs to serve the BBP-neighborhood system.

For development of the proposed model, a randomly generated neighborhood system was created. The system was made of 150 neighborhoods, represented as points, located within an x-y coordinate system. Additionally the points were randomly assigned either as “more” or “less” vulnerable, and the points were given a randomly created demand weight. Figures 3.4 and 3.5 shows the randomly generated neighborhoods.

Table 3.1 Sample of generated neighborhood parameters

Name	X-Coordinate	Y-Coordinate	Demand	Operating Cost	Vulnerability Level
NH1	49.489	94.322	0.880	$1.00	More Vulnerable
NH2	31.593	46.322	4.554	$1.00	Less Vulnerable
NH3	31.446	72.684	17.670	$1.00	Less Vulnerable
NH4	43.943	52.082	9.764	$1.00	Less Vulnerable
NH5	48.386	1.913	17.209	$1.00	Less Vulnerable
NH6	76.794	70.986	3.850	$1.00	Less Vulnerable
NH7	20.544	46.405	14.147	$1.00	Less Vulnerable
NH8	17.251	92.376	10.441	$1.00	Less Vulnerable
NH9	29.037	59.778	4.591	$1.00	Less Vulnerable
NH10	76.206	46.147	15.964	$1.00	Less Vulnerable
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
NH145	49.147	81.033	15.183	$1.00	More Vulnerable
NH146	40.230	57.559	7.508	$1.00	Less Vulnerable
NH147	89.481	18.053	8.169	$1.00	Less Vulnerable
NH148	27.722	32.383	10.801	$1.00	Less Vulnerable
NH149	5.808	65.733	6.654	$1.00	More Vulnerable
NH150	57.378	21.085	21.876	$1.00	More Vulnerable

Table 3.2 Totals of Types of Generated Neighborhoods

	Count	Demand
Less Vulnerable Neighborhoods	64	701.493
More Vulnerable Neighborhoods	86	979.735
Total	150	1681.228

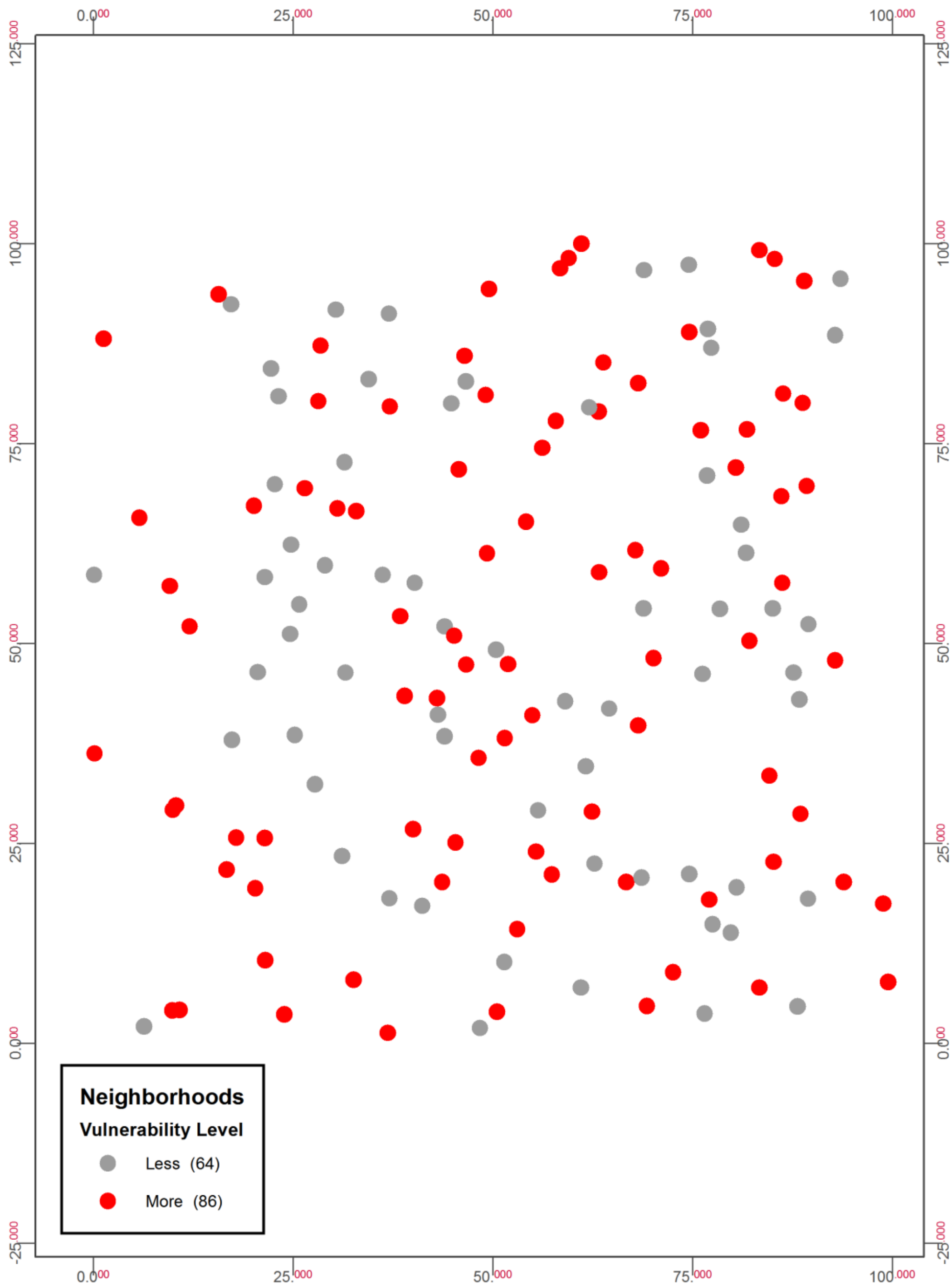


Figure 3.4 Randomly Generated Neighborhoods

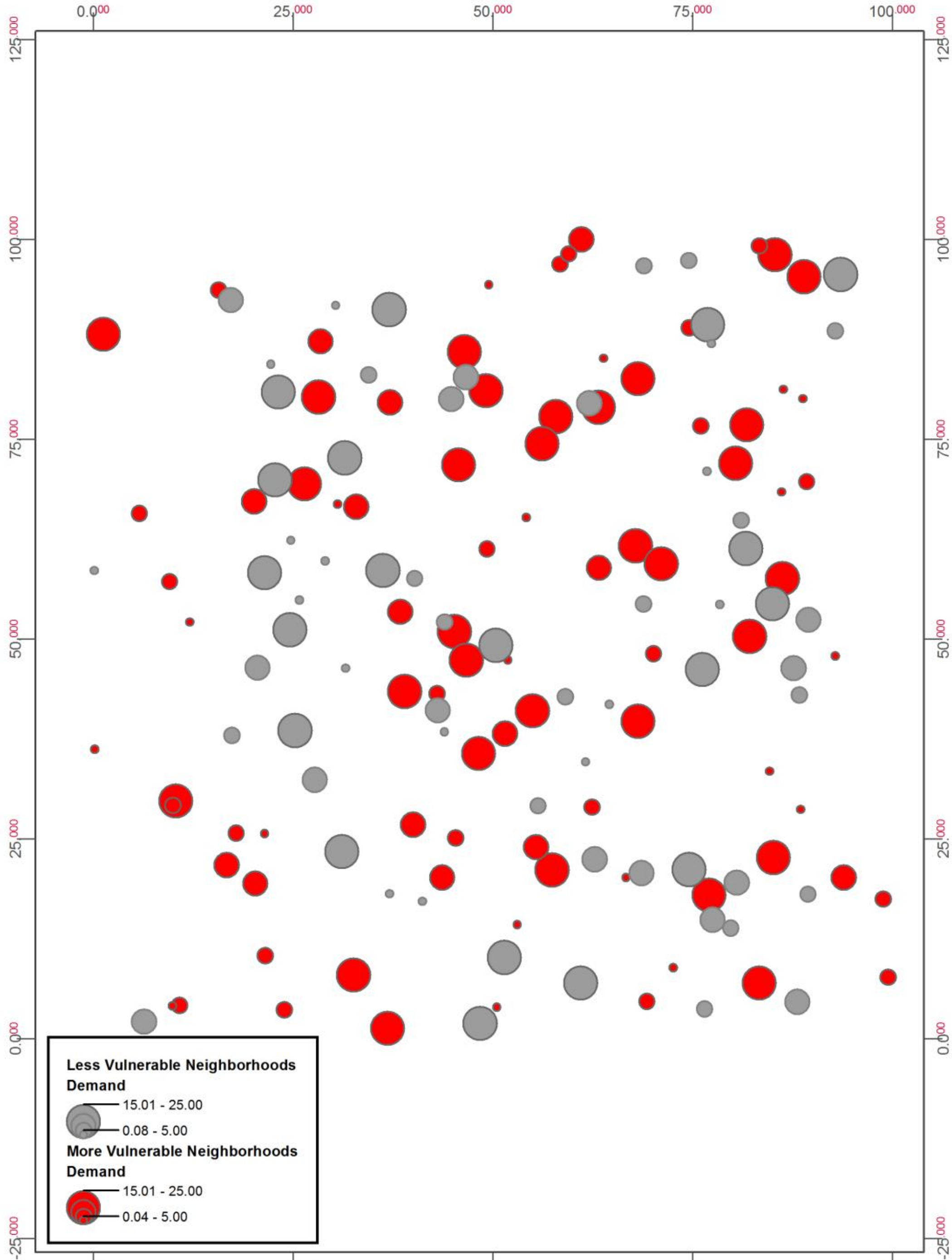


Figure 3.5 Randomly Generated Neighborhoods with generated demand.

The resulting solution for the Set Covering Model located thirty-one facilities as BBPs for the neighborhood system is shown in Figure 3.6.

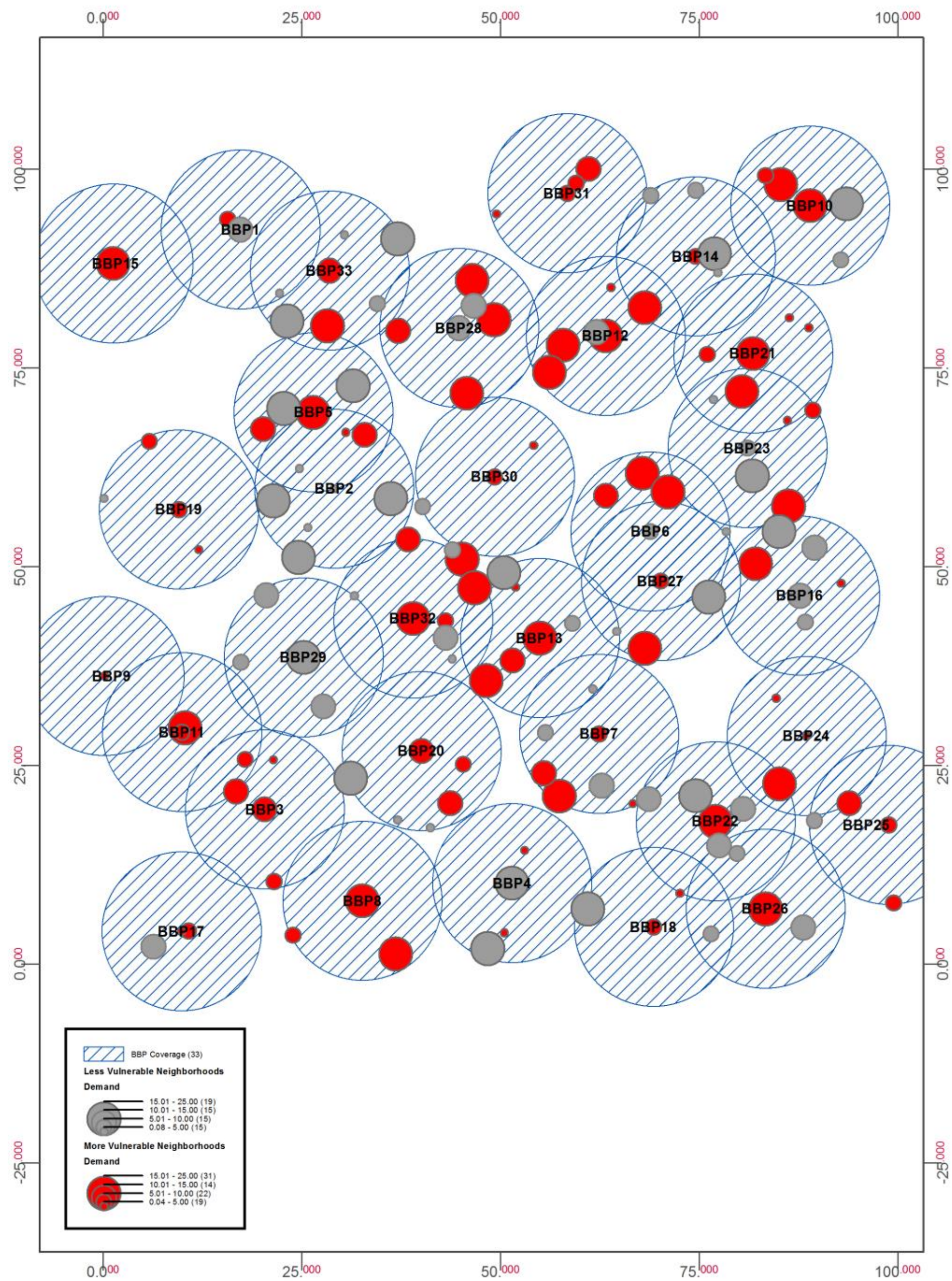


Figure 3.6 Solution to the Set Covering Problem. Note: Blue circle outlines represent relative coverage areas.

The “true” model located in total thirty-three BBPs, as seen in Table 3.3, but two of the locations NH49 and NH27 only service themselves. So, those locations were considered uncovered for this analysis. Therefore, the Set Covering solution produces an upper bound of thirty-one BBPs using a “coverage distance” of 10 distance units. Those thirty-one BBPs covered 98.52% of the total demand (with 98.67% of the neighborhoods covered), this result is summarized in Table 3.4. The model had an average distance of 6.67 distance units from covered neighborhood to BBP, and the distances for the various neighborhood types is shown in Figure 3.7. One drawback of the solution was that fifteen neighborhoods were covered, or serviced, by more than one BBP.

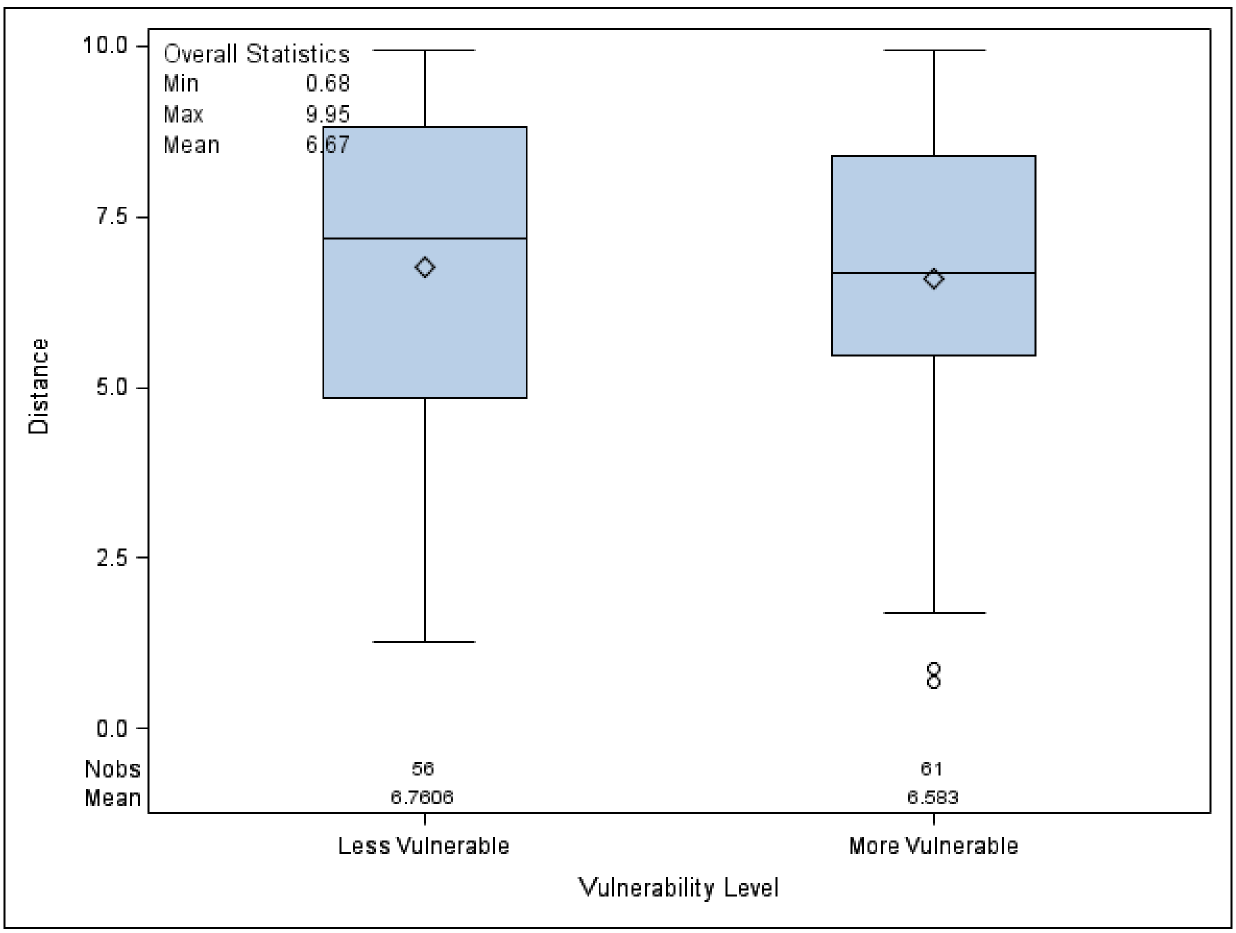


Figure 3.7 Box plots of distance from neighborhood to BBP.

Table 3.3 Bulk Break Points Selected by Set Covering Model

Bulk Breakout Point	X- Coordinate	Y-Coordinate	
NH8	17.251	92.376	
NH9	29.037	59.778	
NH11	20.314	19.411	
NH12	51.461	10.140	
NH15	26.458	69.397	
NH20	68.857	54.385	
NH25	62.372	28.944	
NH26	32.592	7.921	
NH27	0.172	36.196	*
NH28	88.930	95.359	
NH30	9.970	29.152	
NH39	63.221	79.009	
NH41	54.939	40.977	
NH45	74.563	88.968	
NH49	1.299	88.082	*
NH50	87.645	46.342	
NH59	9.914	4.097	
NH70	69.263	4.643	
NH72	9.545	57.169	
NH75	40.036	26.775	
NH80	81.797	76.790	
NH85	77.039	17.945	
NH90	81.060	64.859	
NH92	88.515	28.671	
NH95	98.842	17.469	
NH99	83.330	6.954	
NH110	70.147	48.143	
NH115	44.760	79.976	
NH116	25.205	38.561	
NH121	49.276	61.292	
NH126	58.379	96.905	
NH140	38.976	43.460	
NH141	28.475	87.213	

* Only cover themselves

Table 3.4 Coverage Determined by Set Covering Model Solution

	Covered	Percent Covered	Demand Covered	Percent Demand Covered
Less Vulnerable	64	100	701.493	100
More Vulnerable	84	97.67	954.795	97.46
All Neighborhoods	148	98.67	1656.228	98.52

The Set Covering model offers the first dilemma for decision makers. The solution provides for almost total coverage, well within the coverage requirement of 10 distance units, using 31 BBPs. But, what if the daily cost to operate a BBP was $1,000? That is $31,000 per day over the course of the recovery – which in a post Hurricane Katrina and Sandy world could be weeks to months in time. What if planners had a budget for only half that many BBPs?

Church and ReVelle examined that similar scenario when they developed the Maximal Covering model (Church and ReVelle 1974). In a variation to the usual formulation to the Maximal Covering model, the BBP-neighborhood system was examined using a covering matrix formulation that gave weight to the vulnerability type of the neighborhood. Recalling that when the neighborhood system was generated each neighborhood was given the following assignment:

1 = "more" vulnerable neighborhood

0 = "less" vulnerable neighborhood

And, the definitions of "coverage distance" and $dist_{ji}$ are the same as previously discussed. Therefore, the coverage matrix can be stated as:

$$C_{ij} = \begin{cases} 1, \text{ if } dist_{ji} \text{ <=coverage distance and vulnerability = 1;} \\ 0, \text{ Otherwise.} \end{cases}$$

The Maximal Covering problem can be stated as follows:

Maximize:

$$\sum_{i \text{ in } I} d_i \; X_i \qquad (3.4)$$

Subject to:

$$\sum_{j \text{ in } J} C_{ij} \; Y_j \geq X_i \qquad \text{for all } i \qquad (3.5)$$

$$\sum_{j \text{ in } J} Y_j = p \qquad (3.6)$$

$$X_i = 0,1 \qquad \text{for all } i \qquad (3.7)$$

$$Yj = 0,1 \qquad \text{for all } j \qquad (3.8)$$

Where:

$$c_{ij} = \begin{cases} 1, \text{ if } dist_{ji} <= \text{coverage distance and vulnerability } =1; \\ 0, \text{ otherwise;} \end{cases}$$

$$X_i = \begin{cases} 1, \text{ if neighborhood } i \text{ is covered;} \\ 0, \text{ if not;} \end{cases}$$

$$Y_j = \begin{cases} 1, \text{ if BBP is located at site } j; \\ 0, \text{ if not;} \end{cases}$$

$d_i =$ demand at neighborhood i;and

$p =$ number of BBPs to locate.

In the case of the BBP-neighborhood system, the “coverage distance” was set to a value of 10 distance units. The Maximal Covering Problem was solved using p=15 to maximize the coverage of the “more” vulnerable neighborhoods using fifteen BBPs. The model produced the resulting solution, shown in Figure 3.8 and Table 3.5: Figure 3.9 summarizes the distances of the two types of neighborhoods.

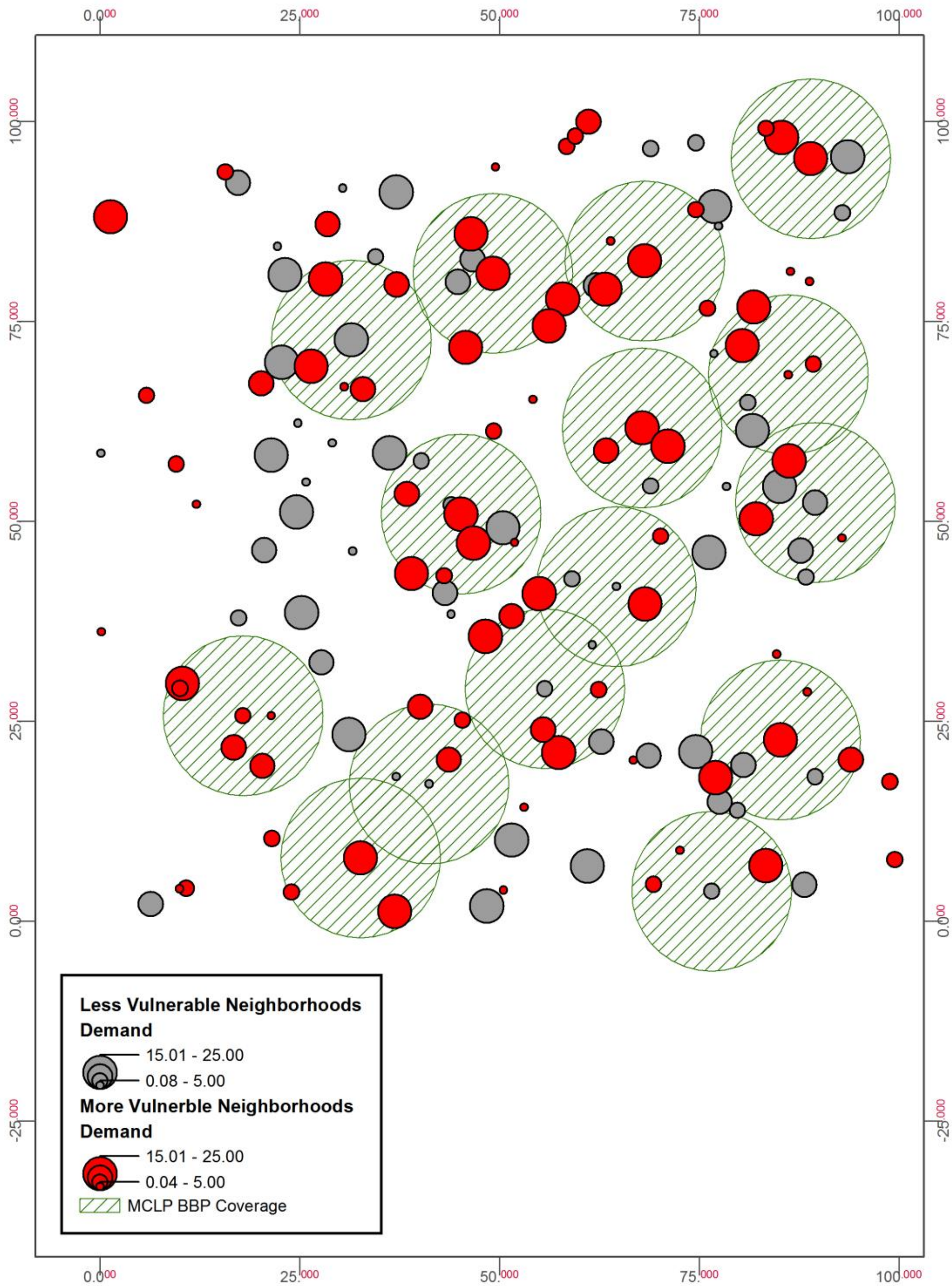


Figure 3.8 Coverage Diagram of Maximal Covering Solution. p=15

The solution found that the maximum demand covered for the “more” vulnerable neighborhoods is 826.87 or 84.4% of the total demand for the “more” vulnerable neighborhoods. Sixty-one or 70.93% of the “more” vulnerable neighborhoods were covered.

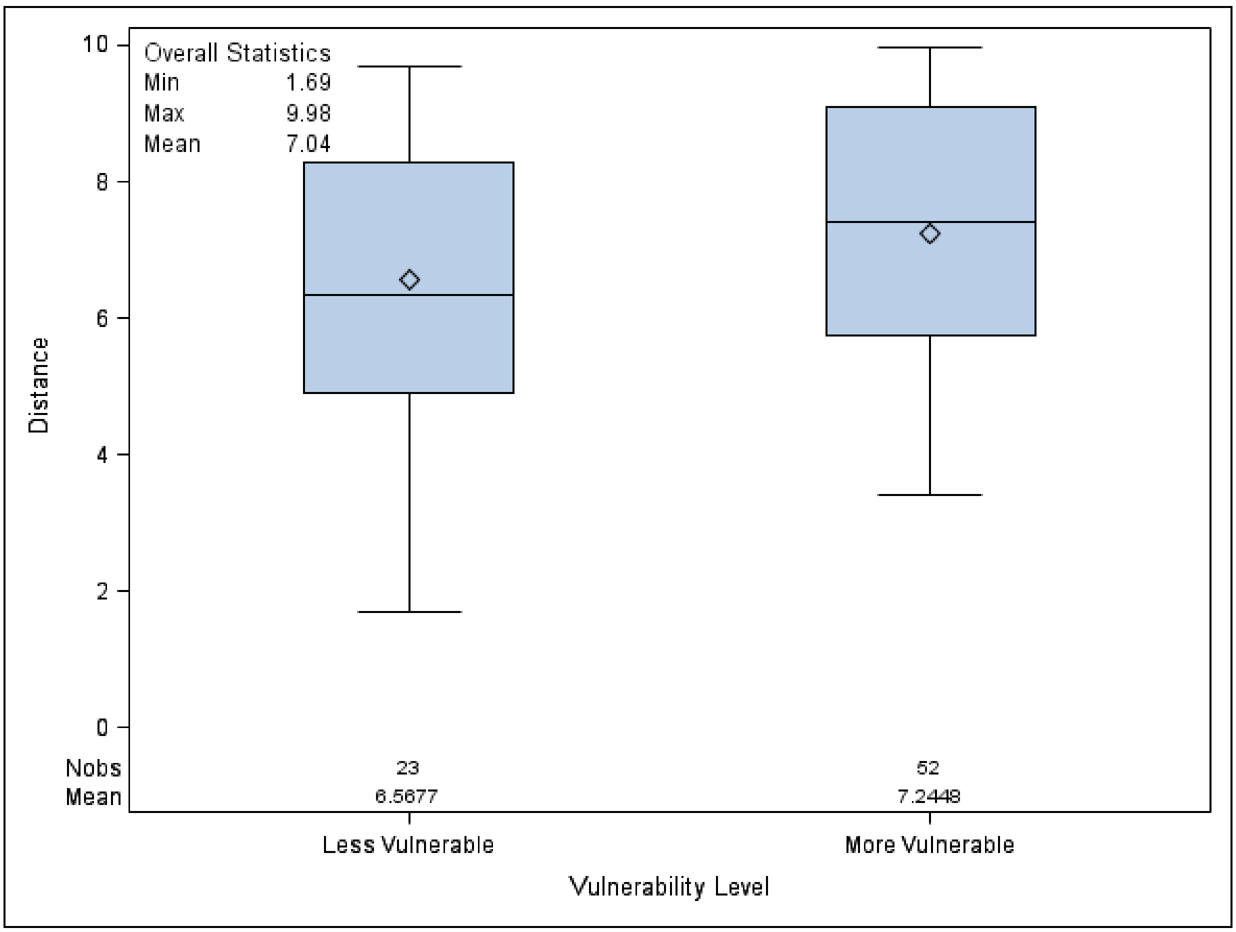


Figure 3.9 Box plot of distance for Maximal Covering Problem.

Table 3.5 Bulk Breakout Points Selected by Maximal Covering solution

BBP	X-Coordinate	Y-Coordinate
NH3	31.446	72.684
NH26	32.592	7.921
NH28	88.931	95.359
NH40	85.129	22.668
NH56	89.501	52.374
NH61	64.586	41.841
NH81	68.155	82.554
NH100	55.660	29.087
NH105	41.152	17.163
NH113	67.831	61.687
NH119	86.123	68.365
NH123	76.523	3.745
NH136	45.175	50.927
NH142	17.903	25.709
NH145	49.147	81.033

Table 3.6 Coverage Determined by Maximal Covering Model Solution

	Covered	Percent Covered	Demand Covered	Percent Demand Covered	Average Distance to BBP
Less Vulnerable	29	45.31	302.869	43.17	5.209
More Vulnerable	61	70.93	826.874	84.41	6.17
Total Neighborhoods	90	60	1129.743	67.20	7.037

The solution found by the Maximal Covering Model offers the insight for the analyst that the coverage of a particular type of neighborhood can be influenced or controlled by the formulation of the model. Table 3.6 shows that more than twice as many “more” vulnerable neighborhoods are covered than “less” vulnerable neighborhoods using the weighting cover

matrix proposed. The Maximal Covering solution also indicates that a more in depth approach to the modeling has to occur. The results show that over 80% of the "more" vulnerable demand is covered, but less than 70% of total demand is covered.

The final fundamental examination of the BBP-neighborhood system was done using the p-Median problem. The p-Median problem developed out of the formative work by Cooper and Hakimi, who worked independently (Cooper 1963; Hakimi 1964). As with the Maximal Covering problem, the p-Median problem uses a predefined number of facilities to locate. The model attempts to minimize the total demand weighted cost (or distance) in the system. The model can be formulated as such:

Minimize:

$$\sum_{i \text{ in } I} \sum_{j \text{ in } J} c_{ij} \; d_i \; X_i \qquad (3.9)$$

Subject to:

$\sum_{j \text{ in } J} X_{ij} = 1$	for all i	(3.10)
$\sum_{j \text{ in } J} Y_j = p$		(3.11)
$X_{ij} - Y_j \leq 0$	for all i and j	(3.12)
$X_i = 0,1$	for all i	(3.13)
$Yj = 0,1$	for all j	(3.14)

Where:

$X_{ij} =$ 1, if demand of neighborhood i is covered by BBP at j; 0, if not;

$Y_j =$ 1, if BBP is located at site j; 0, if not;

$d_i =$ demand at neighborhood i;

$c_{ij} =$ Distance between neighborhood i and BBP site j; and

$p =$ number of BBPs to locate.

The p-Median solution for p =15 is shown in Figure 3.10. Figure 3.11 summarizes the distances for the model in box plots, and Tables 3.7 and 3.8 offer additional insights into the p-median solution. By the nature of the p-Median formulation the model offers 100% coverage of the required demands.

Table 3.7 Bulk Break Out Points selected by p-Median Model Solution, p=15

BBP	X-Coordinate	Y-Coordinate
NH13	79.780	13.857
NH15	26.458	69.397
NH18	80.376	71.991
NH20	68.858	54.385
NH22	68.883	96.660
NH28	88.931	95.359
NH49	1.299	88.082
NH54	16.695	21.727
NH58	36.852	1.259
NH67	24.620	51.176
NH78	62.054	79.510
NH91	85.027	54.372
NH103	46.703	47.306
NH115	44.760	79.976
NH150	57.378	21.085

Table 3.8 Coverage Determined by p-Median Model Solution, p=15

	Covered	Percent Covered	Demand Covered	Percent Demand Covered	Average Distance to BBP
Less Vulnerable	64	100	701.493	100	10.398
More Vulnerable	86	100	979.635	100	10.144
Total Neighborhoods	150	100	1681.128	100	10.251

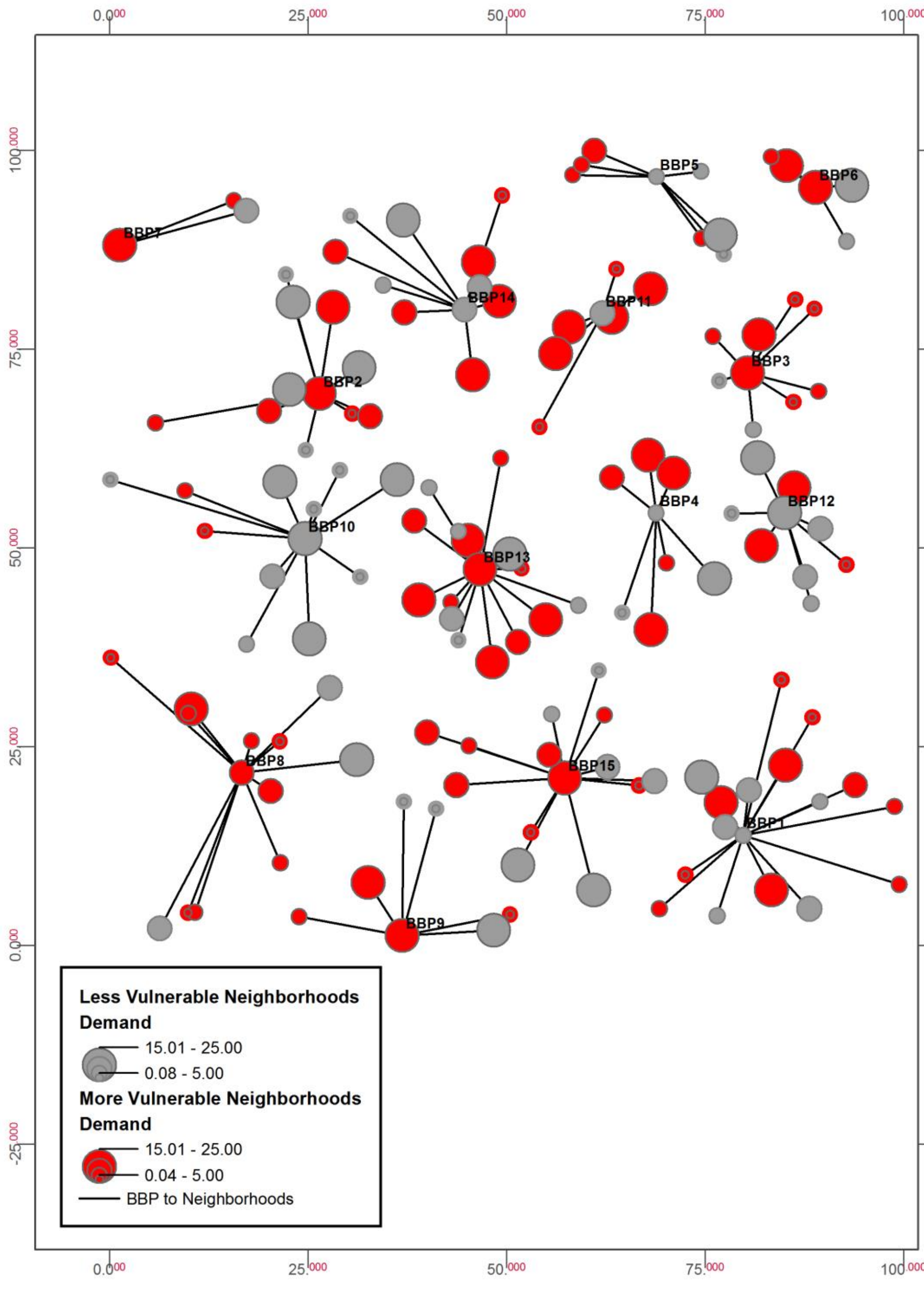


Figure 3.10 Solution of p-Median solution with p=15.

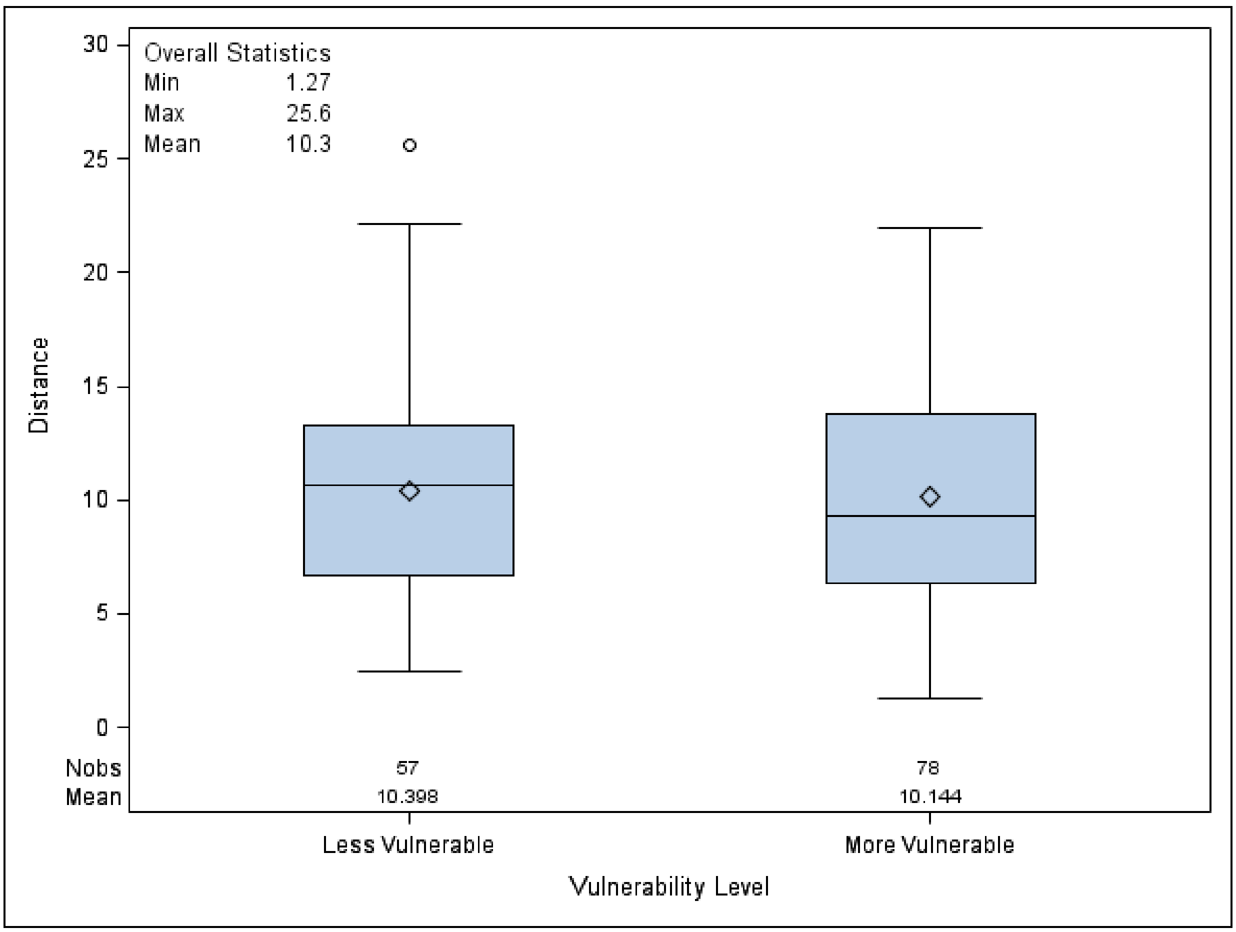
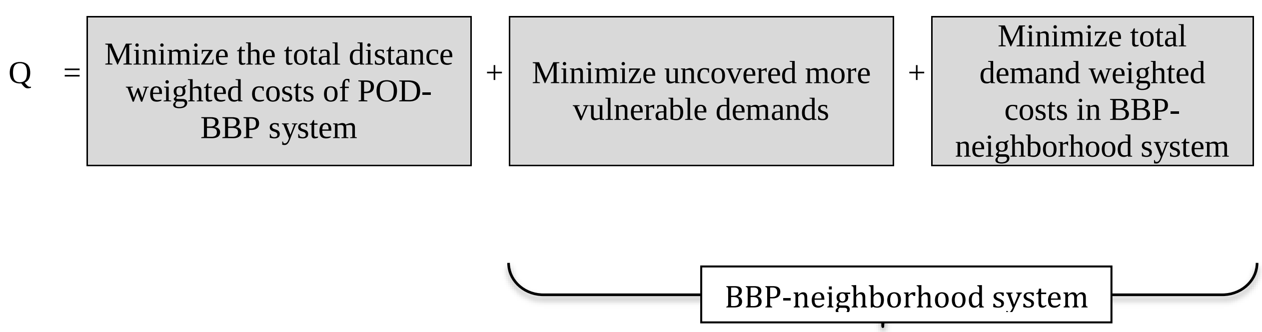


Figure 3.11 Box plots of distance from neighborhoods to BBP.

The p-Median Model solution indicates that the “coverage distance” of 10 distance units for BBP to neighborhood is an acceptable parameter. By adding one more BBP location, or assigning p=16, the average distance from BBP to neighborhood decreases to 10.021 distance units. This is a 2.24% decrease in the distance. The addition of additional two BBP locations, p=17, results in an average distance below 10 distance units or 9.639. This is a 5.97% reduction in the distance. Both p = 16 and p =17 are below the upper bound determined by the Set Cover Model solution of 31 BBPs.

3.4 Building the Multiobjective Model

The proposed model encompasses three objectives. The complete model will look as follows:



The initial focus in this section will continue with the BBP-neighborhood system. Once the proposed model for the BBP – neighborhood system is formulated the objective for the POD – BBP system will be added to the model.

For the time being the POD-BBP system objective will be dropped and result in a two objective model where the objectives of the BBP-neighborhood system are considered.

$$Q_1 = \text{Vulnerable} + \text{Distance}$$

And:

$$\text{Vulnerable} = k(\sum_{i \in I} \sum_{j \in J} d_i c_{ij} X_i)$$

$$\text{Distance} = (1-k)(\sum_{i \in I} \sum_{j \in J} d_i b_{ij} X_i)$$

In the above expansion of the objectives Vulnerable and Distance a factor, k, is added to the formulations. This factor serves two purposes in the model. The first purpose is to allow the model to place emphasis on a particular objective over another. This allows planners to add or remove "importance" to particular objectives in the case of the proposed model the ability to minimize the uncovered "more" vulnerable neighborhoods is seen as more important than the Distance objective. The second purpose for k is to allow all the objectives to be expressed in the same units. In some multicriteria objective models some objectives are measured is distance or time and others are measured in the forms of resources such as dollars or labor requirements. (Cohon 2003).

The BBP – neighborhood system in the proposed model can be expressed as:

Minimize:

$$k(\sum_{i \in I} \sum_{j \in J} d_i c_{ij} X_i) + (1-k)(\sum_{i \in I} \sum_{j \in J} d_i b_{ij} X_i) \quad (3.15)$$

Subject to:

$\sum_{j \in J} X_{ij} = 1$ for all i (3.16)
$\sum_{j \in J} Y_j = p$ (3.17)
$X_{ij} - Y_j \leq 0$ for all i and j (3.18)
$X_i = 0,1$ for all i (3.19)
$Yj = 0,1$ for all j (3.20)

Where:

$$X_{ij} = \begin{cases} 1, \text{ if demand of neighborhood i is covered by BBP at j;} \\ 0, \text{ if not;} \end{cases}$$

$$Y_j = \begin{cases} 1, \text{ if BBP is located at site j;} \\ 0, \text{ if not;} \end{cases}$$

$d_i =$ demand at neighborhood i;

$$c_{ij} = \begin{cases} 1, \text{ if } dist_{ji} <= \text{coverage distance and vulnerability} =1; \\ 0, \text{ otherwise;} \end{cases}$$

$b_{ij} =$ distance from neighborhood i to BBP j; and
$p =$ number of BBPs to locate.

Where $i \in I$ representing all the neighborhoods, and $j \in J$ representing the candidate sites for BBPs – in this model the set of neighborhoods also represents the set of all potential BBP sites. The definitions for "coverage distance" and $dist_{ji}$ are the same as previously established. Objective 3.15 minimizes the uncovered more vulnerable demands and the total demand weighted costs (or distance) in the BBP-neighborhood system. Constraint 3.16 requires that each demand location/neighborhood be assigned to exactly one facility/BBP. Constraint 3.17allows for exactly P number of facilities/BBPs to be located. The linking constraint is seen in 3.18. This constraint states that a demand location/neighborhood can only be assigned to a facility location/BBP if such a facility is located at that location. The standard integrality conditions are found in 3.19 and 3.20.

Once the formulation of for the model is established the value for k can be determined. There are two methods to help determine k. The slope-line method is the first method that was used for this model. In the slope-line method k is determined by the slope of the line connecting two extreme points, and then the model is analyzed using that factor to determine intermediate points to determine additional lines and slopes (Daskin 2013). The slope—line procedure is

outlined in Figure 3.12.The weighting method uses a logical pattern of values to determine a value for k. In the proposed model's case, the values for k were chosen to be between 0 and 1. As with the slope – line method the chosen values for k are put into the model and the resulting solutions are calculated. Tables 3.9 and 3.10 summarizes the determination of k by the two methods.

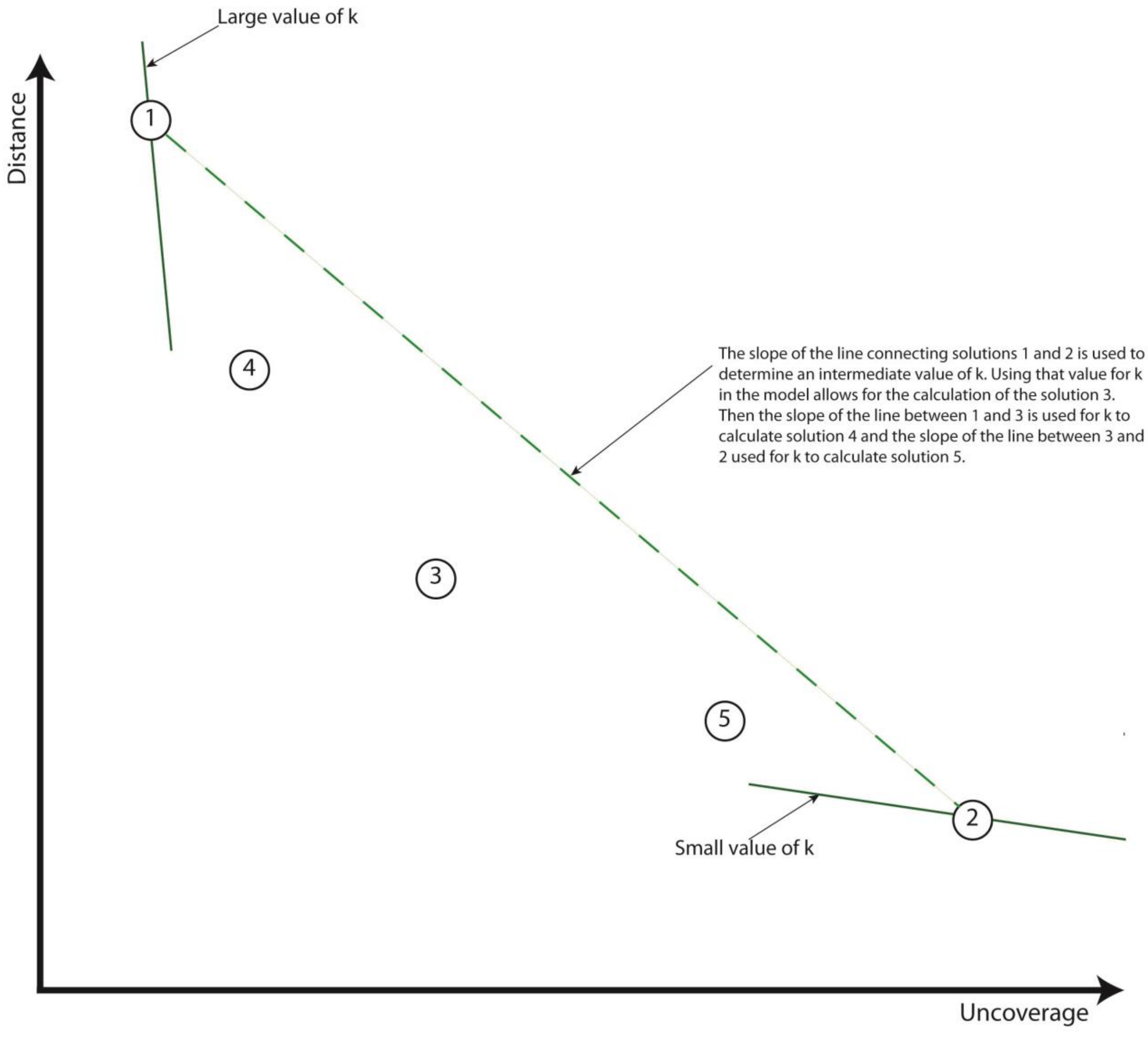


Figure 3.12 Outlines the slope—line method to determine k (adapted from Daskin 2013)

Table 3.9 k factor determined by slope method

Uncovered "more" vulnerable demand	Average Distance BBP-neighborhood	k
152.762	7.202	1
178.964	6.736	8.542
222.964	6.112	4.106
222.964	6.112	4.682
305.461	6.426	0

Table 3.10 k factor determined by weighting method

Uncovered "more" vulnerable demand	Average Distance BBP-neighborhood	k
152.762	7.202	1
178.964	6.736	0.75
222.964	6.612	0.5
222.964	6.612	0.25
305.461	6.426	0

With the determination of the factor k completed, a tradeoff curve between the objectives is constructed. The tradeoff curve allows for the examination in the changes of one objective versus another objective. In the model as the amount of uncovered more vulnerable demand is decreased the average distance between the BBPs and the neighborhoods increases. In Figure 3.13, a shaded area highlights the preferred solution region for the model using the random

generated data. The preferred solution region is determined by planners or analysts as a result their interpretation of the solutions of the model. This actual determination of k is a bit more art than hard determining mathematics. In a real world setting the stakeholders in the solution would be brought together to examine initial solutions, presented by the model, to determine this range. The competing objectives that would be put forth are: Do the stakeholders want a lower average distance to the BBP or do they want less uncovered "more" vulnerable neighborhoods? For further analysis of the model the amount of uncovered "more" vulnerable neighborhoods was chosen to be less than 220, and this results in a k of 0.75 – as determined by the weighted method. Figures 3.14 and 3.15 show the solutions for the model at the extreme values of k = 0 or k = 1.

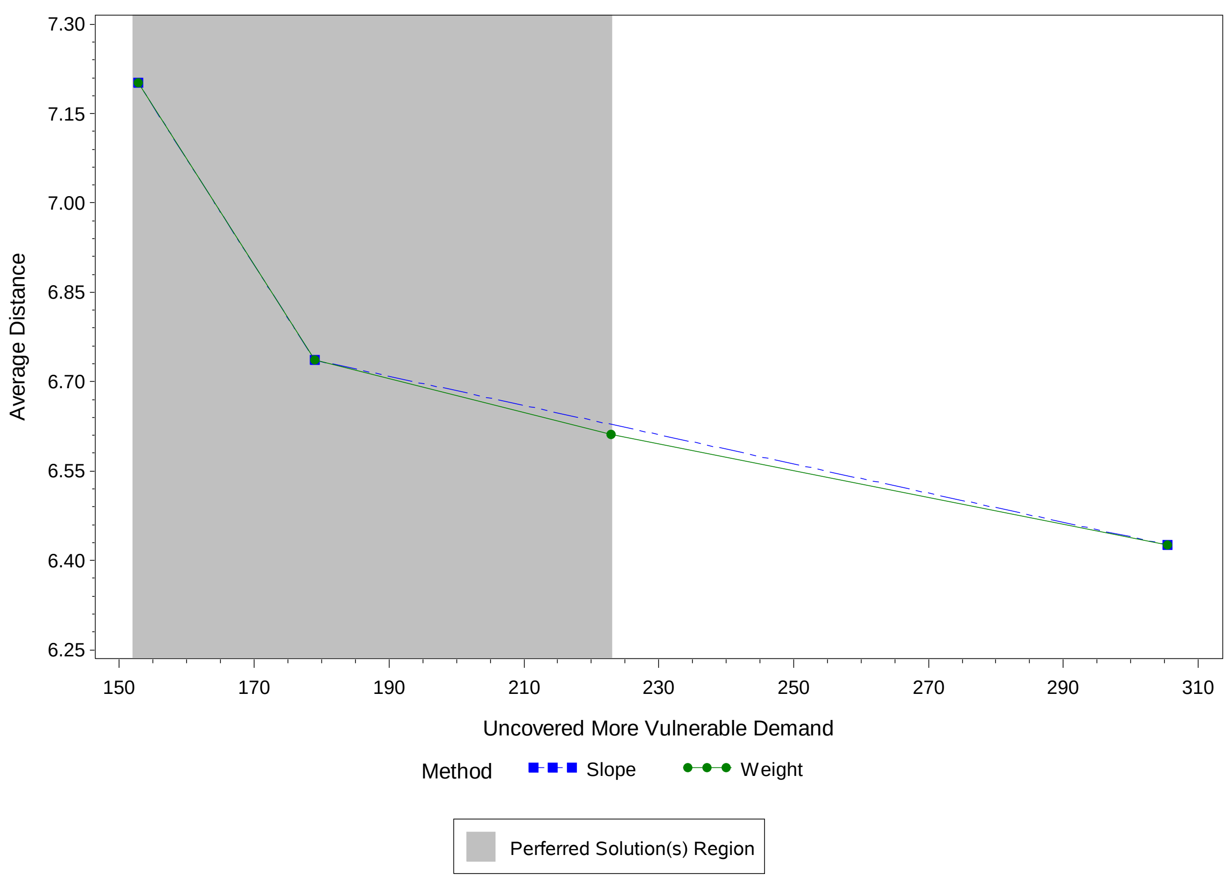


Figure 3.13 Tradeoff Curve for Objectives Vulnerable and Distance**.**

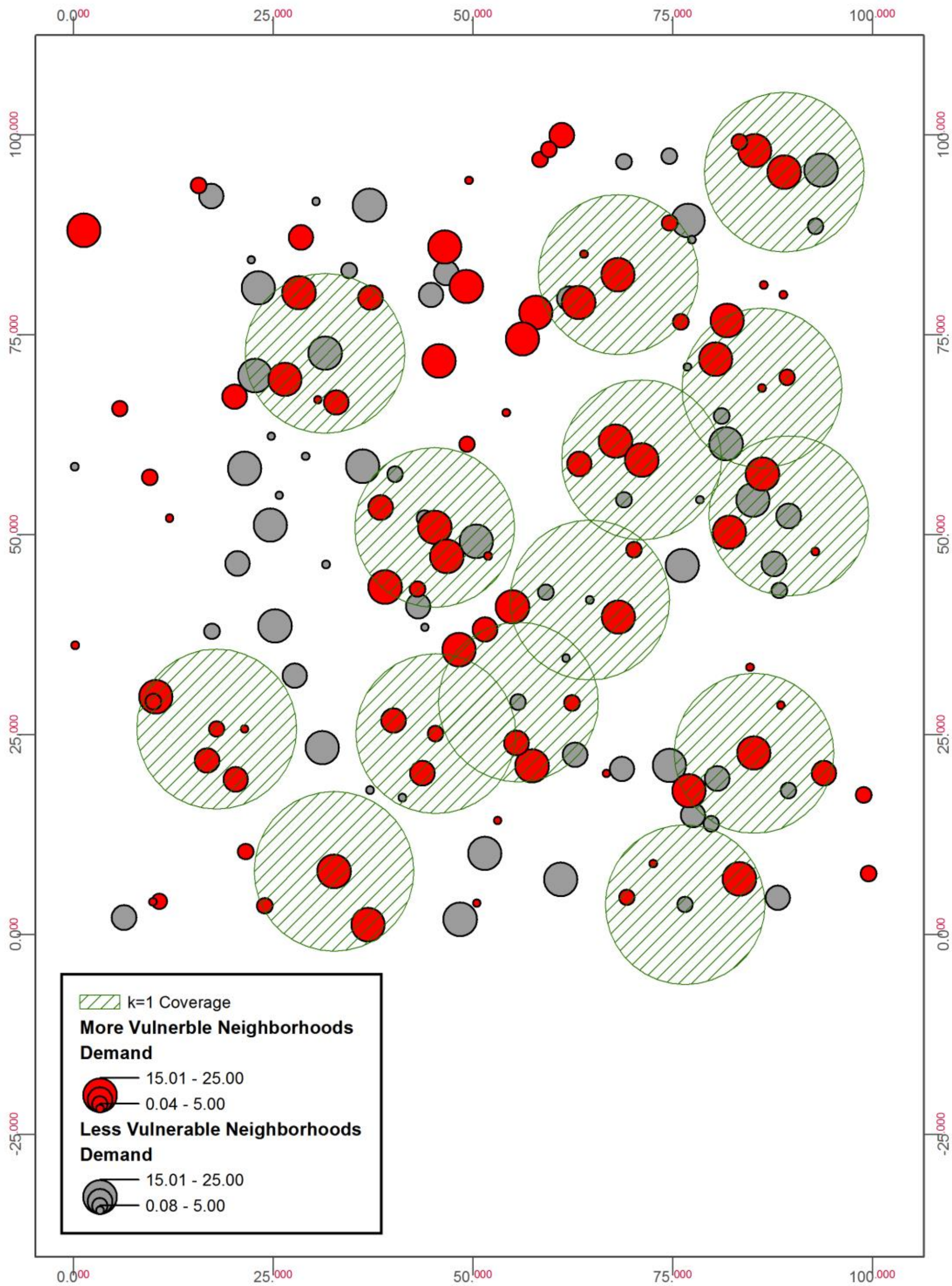


Figure 3.14 Solution for the BBP-neighborhood system with k=1. This is the same solution as found by the MCLP. This is represents the left extreme of the tradeoff curve.

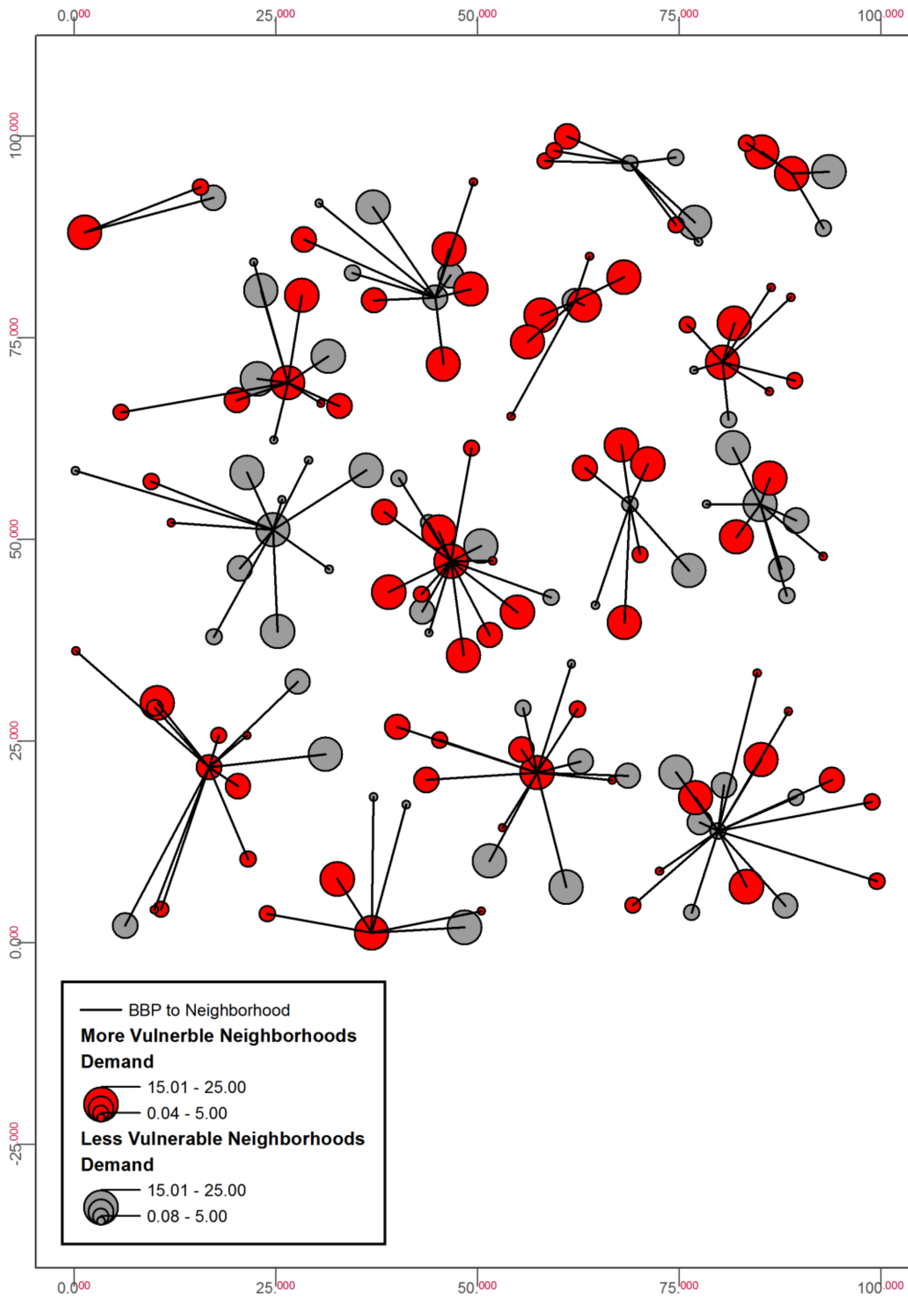


Figure 3.15 This is the solution for the BBP-neighborhood system with k=0. This is the same result as the p-Median solution, and represents the extreme right side of the tradeoff curve.

After examining the tradeoff curve a weighting factor of 0.75 was selected to be used, and the objective can be seen as:

$$Q_1 = 0.75*(\text{Vulnerable}) + (1-0.75)*(\text{Distance})$$

Therefore, solving the model for p=15 results in the following BBPs being selected:

Table 3.11 BBP selected by Model

BBP	X-Coordinate	Y-Coordinate
NH13	79.780	13.857
NH15	26.458	69.397
NH18	80.376	71.991
NH20	68.858	54.385
NH26	32.592	7.921
NH28	88.931	95.359
NH42	48.234	35.642
NH49	1.299	88.082
NH67	24.620	51.176
NH78	62.054	79.510
NH91	85.027	54.372
NH115	44.760	79.976
NH136	45.175	50.927
NH142	17.903	25.709
NH150	57.378	21.085

The resulting solutions for the model are presented in Figures 3.16 and 3.17. Table 3.11 lists the BBPs as selected by the model. In Figure 3.16, the solution is examined as if the coverage restriction of 10 distance units is maintained on the located BBP. This is in fact a pseudo-solution because the true model solution is similar to the p-Median problem solution as seen in Figure 3.10. However, this comparison allows for the examination of the average distance between BBP and neighborhood. With the coverage restriction in place the average distance is

just over 6.6 distance units for the “more” vulnerable neighborhoods. In the “true” solution to the model the average distance in the entire BBP-neighborhood system is 10.4 distance units. This is slightly above the 10-distance unit requirement. Figures 3.18 and 3.19 summarize the distances for the model solutions, of Figures 3.16 and 3.17, as box plots.

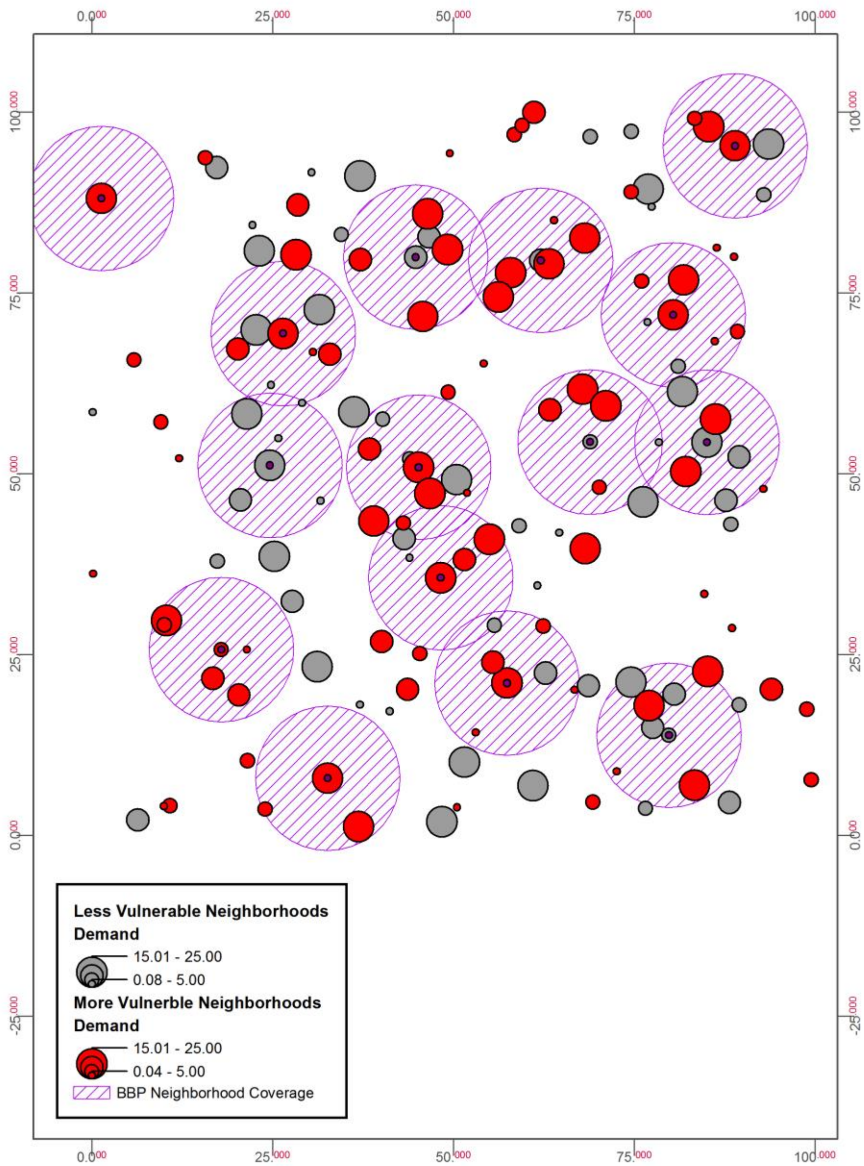


Figure 3.16 BBP-neighborhood system with coverage restriction maintained. Coverage = 10 distance units and p = 15.

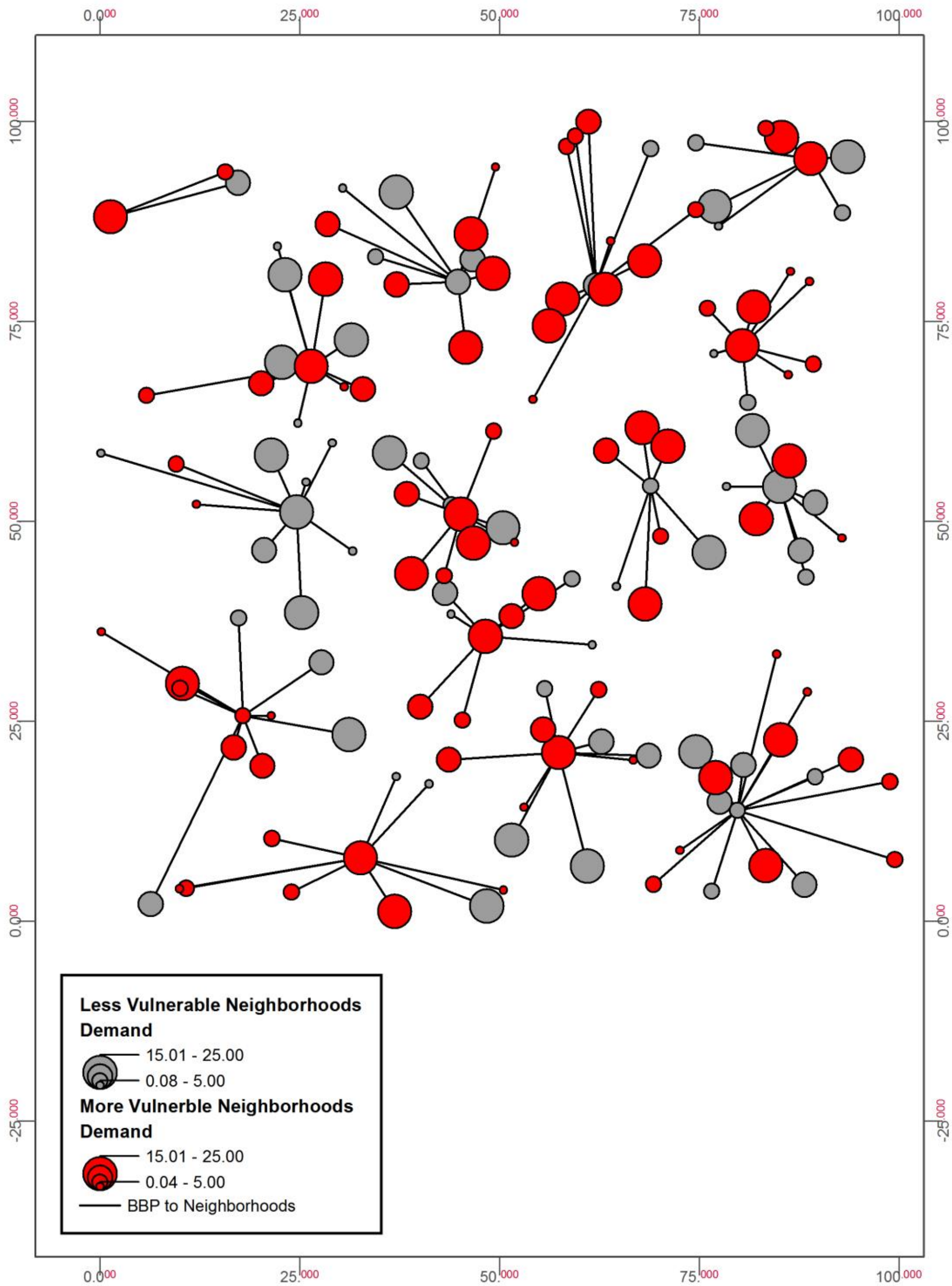


Figure 3.17 BBP-neighborhood system without coverage restriction. p=15

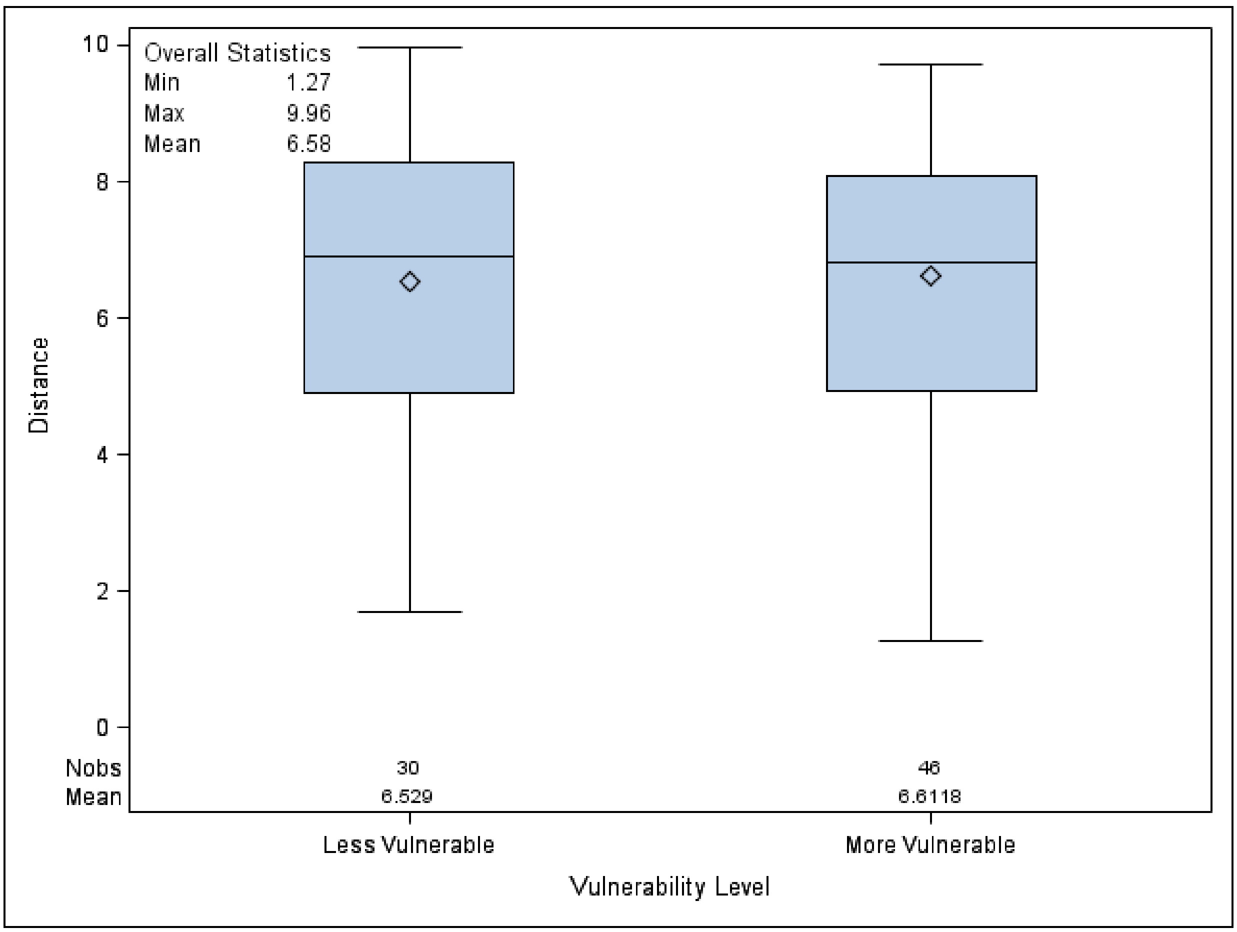


Figure 3.18 Box Plot of model solution distance from BBP to Neighborhood (coverage restriction maintained)

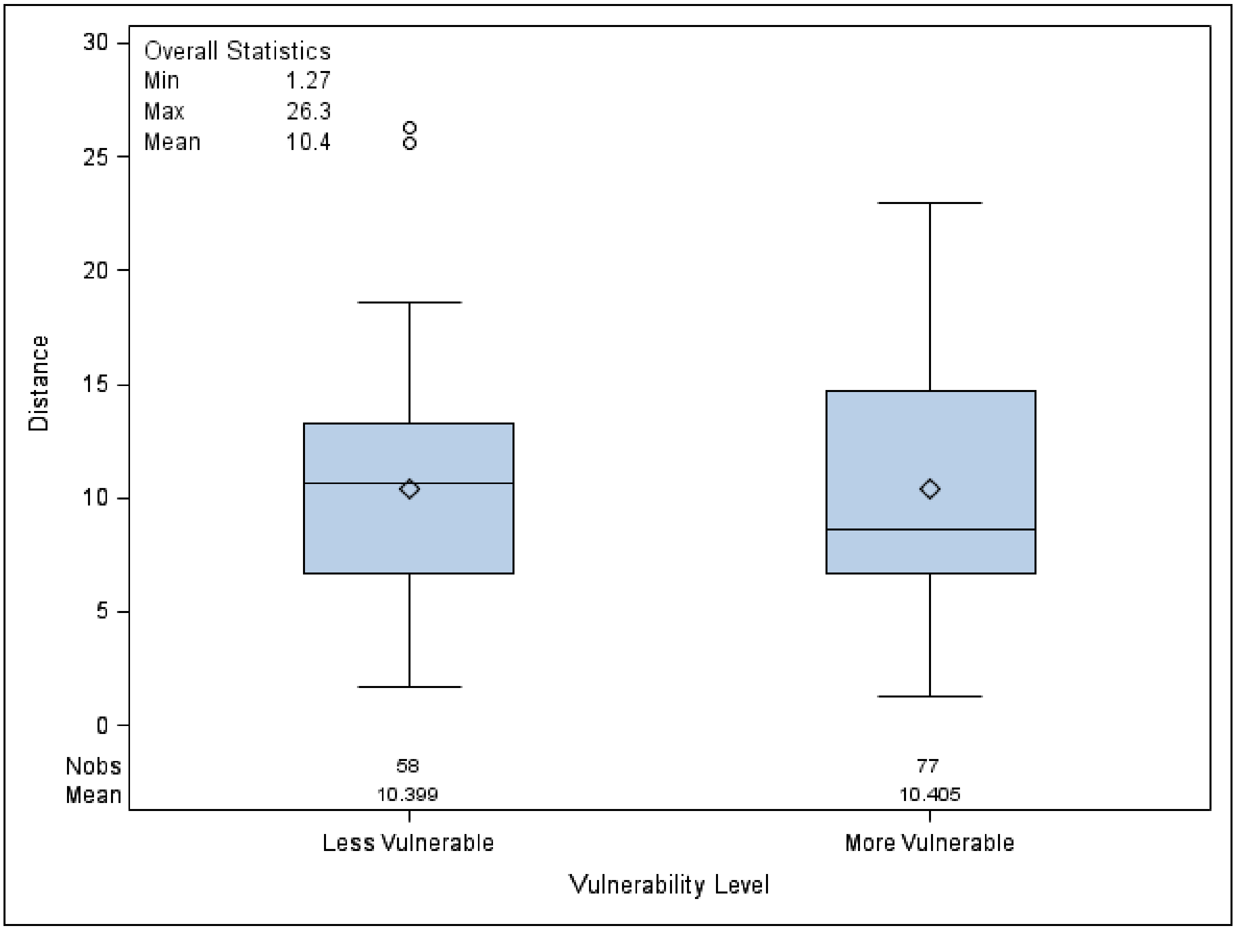


Figure 3.19 Box Plot of distance from BBP to Neighborhood (coverage restriction not maintained)

Tables 3.12 and 3.13 summarize solutions for the two model solutions shown in Figures 3.15 and 3.16. If the model is analyzed as a coverage model, as in Table 3.12, only about 67% of the total demand is covered. In the complete solution, the model accounts for 100% coverage of the demand. This difference in analysis also accounts for the difference in average distances in the system observed.

Table 3.12 Model solution with coverage restriction maintained

	Covered	Percent Covered	Demand Covered	Percent Demand Covered	Average Distance to BBP
Less Vulnerable	36	56.25	385.26	54.92	6.53
More Vulnerable	55	63.95	756.67	77.24	6.61
Total Neighborhoods	91	60.67	1141.93	67.93	6.58

Table 3.13 Model solution without coverage restriction (true solution)

	Covered	Percent Covered	Demand Covered	Percent Demand Covered	Average Distance to BBP
Less Vulnerable	64	100	701.49	100	10.40
More Vulnerable	86	100	979.64	100	10.41
Total Neighborhoods	150	100	1681.13	100	10.40

One of the advantages of solving multiobjective problems, as presented in this research, is the ability to add or remove objectives in a logical, straightforward manner. The discussion, up to this point, has been focused on the BBP – neighborhood system objectives (Q_1). A third objective of the model is the POD – BBP system. Adding the POD – BBP system objective results in the following formulation:

$$\text{Minimize } Q = k_{full} Q_2 + (1-k_{full})Q_1$$

Where:

$Q_2 = \sum_{n \text{ in } N} \sum_{j \text{ in } J} e_{nj}\, o_n\, X2_{nj}$ POD to BBP system

$Q_1 = k(\sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i\, c_{ij}\, X1_i) + (1-k)(\sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i\, b_{ij}\, X1_i)$ BBP to Neighborhood system

The resulting formulation:

Minimize:

$$\sum_{n \text{ in } N} \sum_{j \text{ in } J} e_{nj}\, o_{nj}\, X2_{nj} + k \sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i\, c_{ij}\, X1_i + (1-k) \sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i\, b_{ij}\, X1_i \quad (3.21)$$

Subject to:

$\sum_{j \text{ in } J} X_{ij} = 1$	for all i	(3.22)
$\sum_{j \text{ in } J} Y_j = p$		(3.23)
$X_{ij} - Y_j \leq 0$	for all i and j	(3.24)
$\sum_{n \text{ in } N} X2_{nj} = Y_j$	for all j	(3.25)
$X1_{ij} = 0,1$	for all i	(3.26)
$X2_{nj} = 0,1$	for all n and j	(3.27)
$Yj = 0,1$	for all j	(3.28)

Where:

$c_{ij} =$
- 1, if $dist_{ji}$ > coverage distance and neighborhood is "more vulnerable;
- 0, if not;

$X1_{ij} =$
- 1, if demand of neighborhood i is covered by BBP at j;
- 0, if not;

$$X2_{nj} = \begin{cases} 1, \text{ if BBP } j \text{ is covered by POD at } n; \\ 0, \text{ if not;} \end{cases}$$

$$Y_j = \begin{cases} 1, \text{ if BBP is located at site } j; \\ 0, \text{ if not;} \end{cases}$$

b_{ij} = distance from neighborhood i to BBP j;

d_i = demand at neighborhood i;
e_{nj} = distance between BBP at j and POD at n;
o_n = operating cost of POD at location n; and
p = number of BBPs to locate.

The POD-BBP-neighborhood system is a transshipment model. The objective 3.21 minimizes:

1. The economic cost weighted distance between the PODs and BBPs.
2. The uncovered "more" vulnerable demands.
3. The demand weighted distance between BBPs and neighborhoods.

The set of PODs, N, are predetermined outside of the model – there is no restriction on the number of PODs utilized by the model. The set of neighborhoods, I, requires that each neighborhood's demand is aggregated at a point. The set of BBPs, J, is chosen from the set of neighborhoods. Constraint 3.22 limits that a neighborhood is only assigned to one BBP. Constraint 3.23 assures that only p number of BBPs are sited. Constraint 3.24 is a linking constraint that stipulates that a neighborhood must be designated a BBP to service other neighborhoods. Constraint 3.25 only allows PODs to service actual BBPs. Constraints 3.26-3.28 are the usual integrality constraints.

To examine the full model PODs were randomly generated and added to the randomly generated neighborhoods (Figure 3.20):

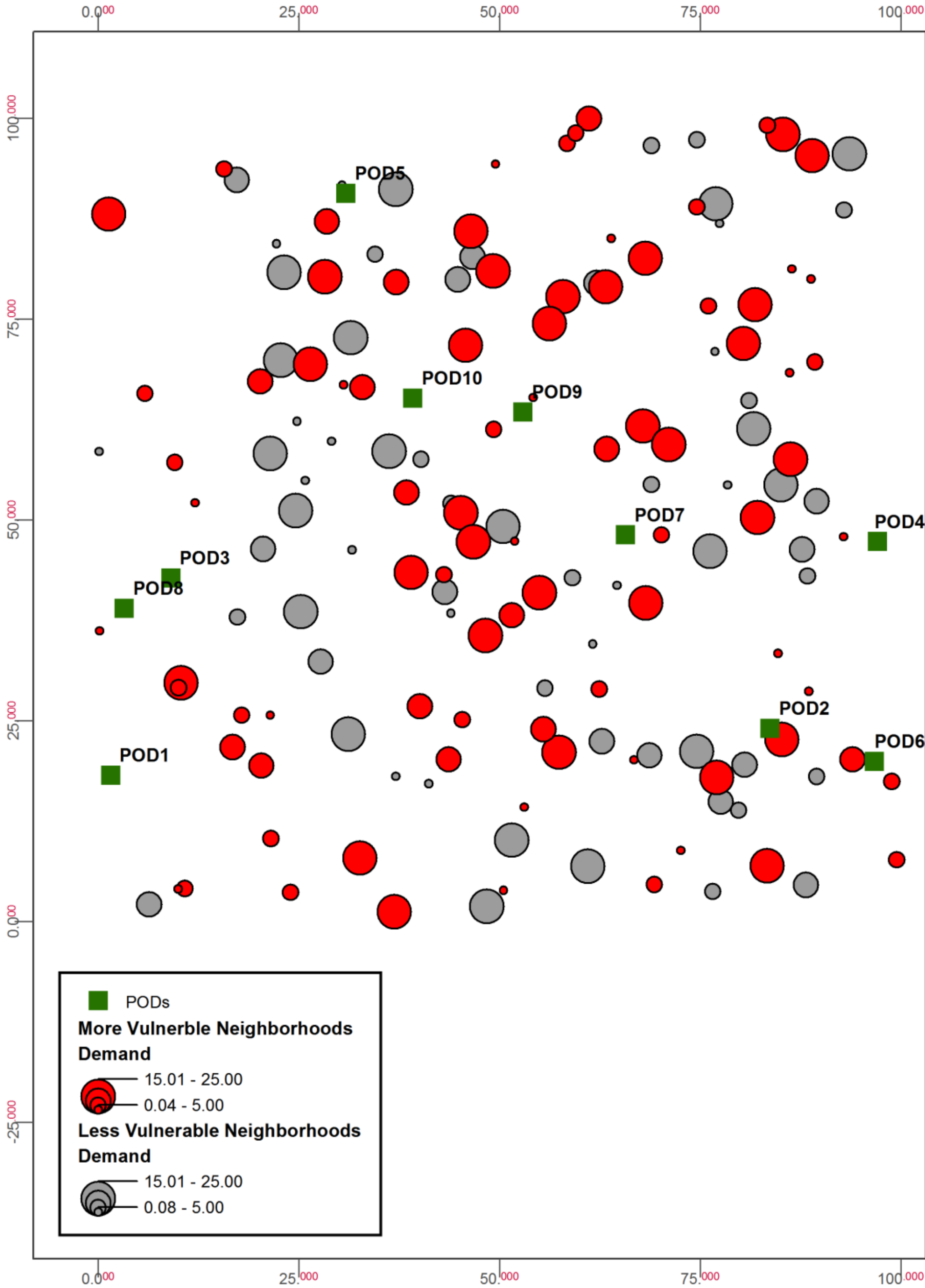


Figure 3.20 Randomly generated PODs are added to the randomly generated neighborhoods.

As with the BBP-neighborhood system, the value for k_{full} was determined for the full model. The examination of values of k_{full} allowed for the selection of 0.5 as an appropriate value and this summarized in Table 3.14. Since, k_{full} was chosen to be the value 0.5 the factor can be dropped from the model formulation because k_{full} equals $1 - k_{full}$ giving equal weight to each objective Q_1 and Q_2 .

Table 3.14 Determining k_{full} for full model

k	Average Distance (POD-BBP)	Average Distance (BBP-neighborhood)	Average Distance (BBP-More vulnerable)	Average Distance (BBP-Less vulnerable)
1	57.28	10.4	10.41	10.4
0.75	21.09	10.4	10.41	10.4
0.5	19.83	10.1	10.3	9.9
0.25	18.09	10.2	10.46	9.85
0	4.27	49.4	50.89	47.36

The full model was then solved using p=15 and 10 randomly generated locations for the POD locations. The model produced the following solution from those parameters (Figure 3.21):

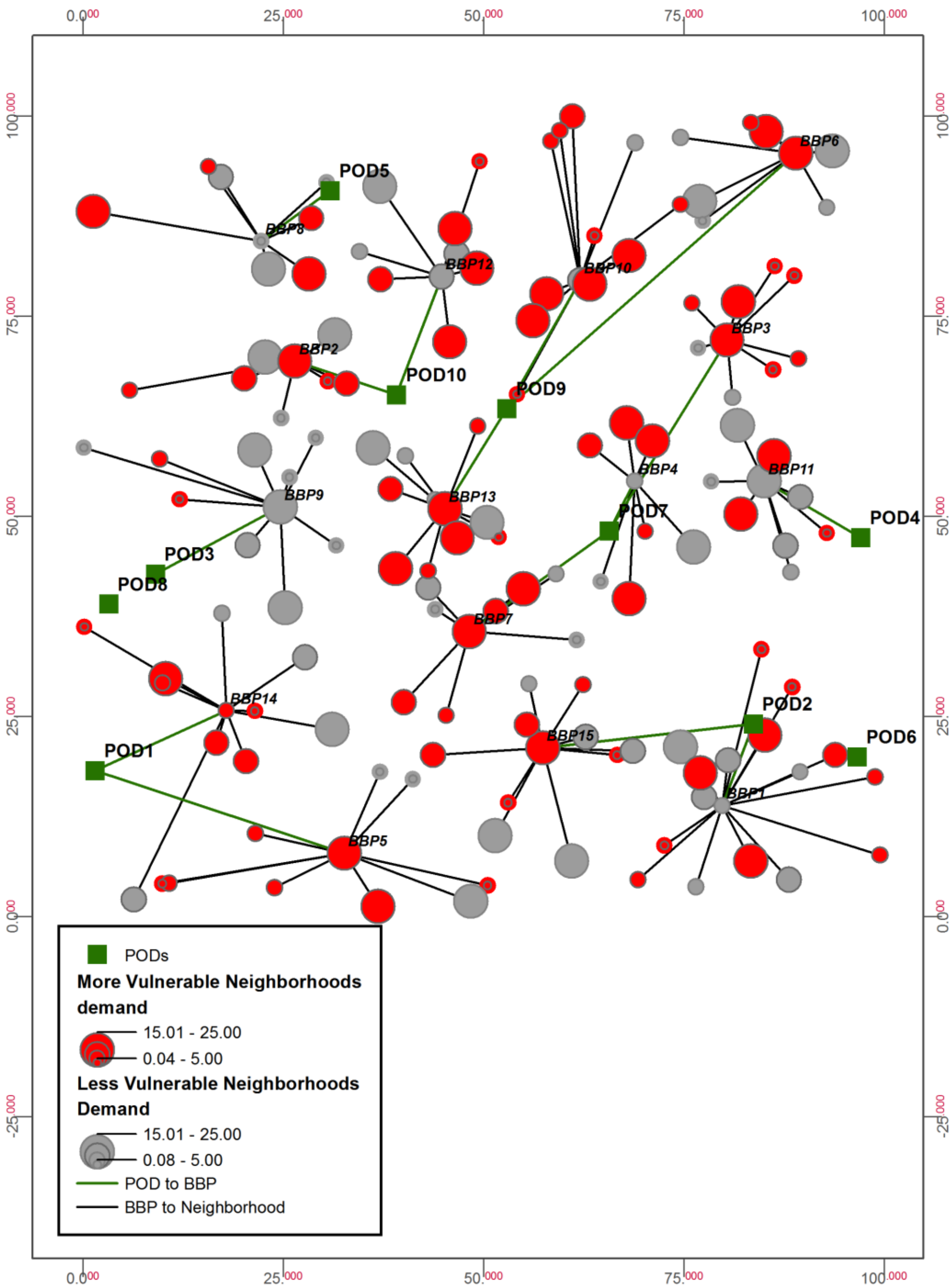


Figure 3.21 The model solution with p=15

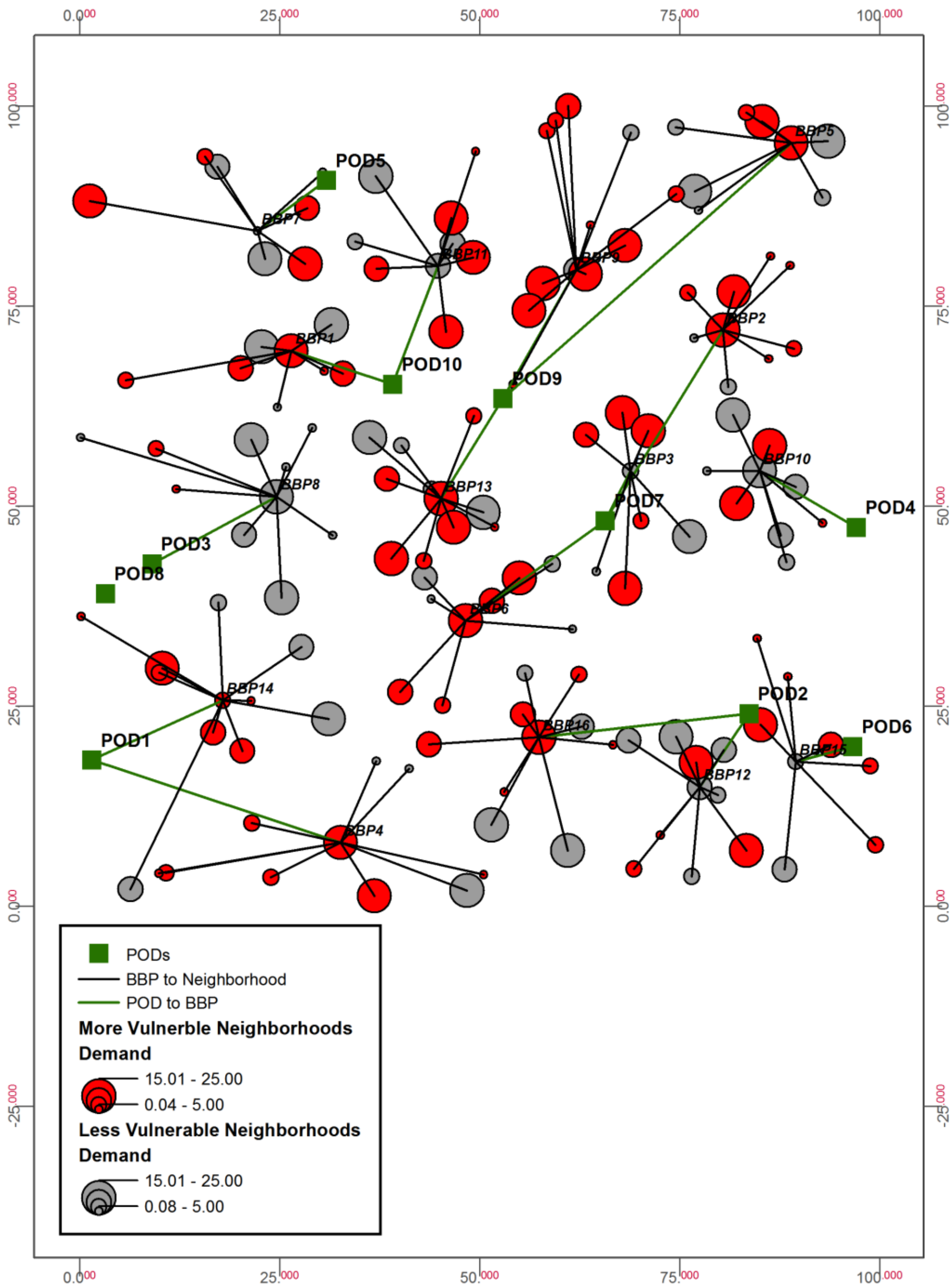


Figure 3.22 The model solution for p=16.

The model only utilizes eight out of the ten available POD for the solution. The model was run an additional time – this time p=16 and all other parameters and data remained the same.

With p=16 the average distances from the BBP to the differing types of neighborhoods was below 10 distance units (Figure 3.22). Table 3.15 summarizes the comparison between p=15 solution and p=16 solution.

Table 3.15 Resulting Average Distances p=15 versus p=16

	Average Distance BBP to Less Vulnerable	Average Distance BBP to More Vulnerable	Average Distance BBP to any type neighborhood	Average Distance POD to BBP
p = 15	9.9	10.3	10.1	19.8
p = 16	9.9	9.8	9.8	19.1

3.5 Additional Refinement to the Model

One of the objectives/goals of the model is to minimize the uncovered “more” vulnerable demands a closer look as to how the BBPs were chosen by the model was analyzed. This was done because if the model could make a “more” vulnerable neighborhood its first choice in selecting a BBP location it would help in minimizing the uncovered “more” vulnerable demands. The randomly generated demands were ranked by the cumulative percentage of the total demand in the system. Table 3.16 lists the cumulative percentage ranking of the demands within the model-testing universe. The demand value was then assigned as “more” or “less” vulnerable. The demands were assigned in a way to favor one vulnerability level or another. For example, in the first run all 86 “more” vulnerable neighborhoods were assigned the top or largest 86 demand levels. This created a scenario in which 57.33% of the total demand was assigned to the “more” vulnerable locations. Two separate testing sets of neighborhoods were determined. The first set was done randomly. In the random set the demand, with its assigned vulnerability level, was assigned a location chosen randomly from the existing generated neighborhood universe. The

second set was created by assigning the demand, with its vulnerability level, done sequentially by the neighborhood naming convention. The model was then run for the different types of location assignments. The randomly assigned locations were run three times because each run produced different locations. Tables 3.17 and 3.18 list examples of randomly and sequentially assigned demands. The sequentially assigned locations were run just once because those locations did not change. The model showed a tendency to locate the most BBPs at neighborhoods with the vulnerability levels that commanded the highest demand levels, but it did not assign all BBPs to that vulnerability level. Table 3.19 summarizes the results of the testing of the model.

Table 3.16 Ranking of Demand

Demand	Cumulative Percent
0.043	0.67
0.325	1.33
0.407	2
0.478	2.67
0.656	3.33
0.880	4
0.919	4.67
1.278	5.33
1.496	6
1.917	6.67
1.980	7.33
2.410	8
2.493	8.67
2.535	9.33
3.464	10
.	.
.	.
.	.
24.488	98.67
24.862	99.33
24.994	100

Table 3.17 Sequentially Assigned Demands

Name	X-Coordinate	Y-Coordinate	Demand	Vulnerability Level
NH1	49.49	94.32	13.73	Less Vulnerable
NH2	3.52	31.59	13.85	Less Vulnerable
NH3	46.32	18.22	14.15	Less Vulnerable
NH4	31.45	72.68	14.72	Less Vulnerable
NH5	70.68	43.94	14.85	Less Vulnerable
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
NH146	16.37	74.53	13.09	More Vulnerable
NH147	97.34	28.02	13.24	More Vulnerable
NH148	83.33	6.95	13.54	More Vulnerable
NH149	70.49	55.66	13.59	More Vulnerable
NH150	29.09	36.82	13.60	More Vulnerable

Table 3.18 Example of Randomly Assigned Demands

Name	X-Coordinate	Y-Coordinate	Demand	Vulnerability Level
NH95	40.19	82.11	13.73	Less Vulnerable
NH110	29.02	37.12	13.85	Less Vulnerable
NH133	68.18	39.72	14.15	Less Vulnerable
NH12	92.38	41.76	14.72	Less Vulnerable
NH137	65.27	88.51	14.85	Less Vulnerable
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
NH107	45.88	9.54	13.09	More Vulnerable
NH74	95.68	87.64	13.24	More Vulnerable
NH104	74.45	69.26	13.54	More Vulnerable
NH101	77.66	38.40	13.59	More Vulnerable
NH109	89.28	69.68	13.60	More Vulnerable

Table 3.19 Sample results of demand loading analysis

Top 57.33%* of Demand Assigned to "More" Vulnerable Neighborhoods

Randomly Assigned Neighborhoods			Sequentially Assigned Neighborhoods	
More Vulnerable BBP	Less Vulnerable BBP		More Vulnerable BBP	Less Vulnerable BBP
13	2			
10	5		11	4
10	5			

*The 86 highest demands are all assigned as "more" vulnerable

Top 40%* of Demand Assigned to "More" Vulnerable Neighborhoods

Randomly Assigned Neighborhoods			Sequentially Assigned Neighborhoods	
More Vulnerable BBP	Less Vulnerable BBP		More Vulnerable BBP	Less Vulnerable BBP
11	4			
12	3		10	5
11	4			

*The 60 highest demands are all assigned as "more" vulnerable

Top 20%* of Demand Assigned to "More" Vulnerable Neighborhoods

Randomly Assigned Neighborhoods			Sequentially Assigned Neighborhoods	
More Vulnerable BBP	Less Vulnerable BBP		More Vulnerable BBP	Less Vulnerable BBP
13	2			
14	1		11	4
14	1			

*The 30 highest demands are all assigned as "more" vulnerable

Bottom 40%* of Demand Assigned to "More" Vulnerable Neighborhoods

Randomly Assigned Neighborhoods			Sequentially Assigned Neighborhoods	
More Vulnerable BBP	Less Vulnerable BBP		More Vulnerable BBP	Less Vulnerable BBP
3	12			
3	12		4	11
1	14			

*The 60 lowest demands were assigned as "more" vulnerable

To have more control as whether the "more" vulnerable demands are covered more readily there needs to be some control within in the model to allow BBPs to be sited at "more" vulnerable neighborhood as oppose to a "less" vulnerable neighborhood. Initially, an operating cost for each potential BBP was added to the costs for each facility. The model has a parameter for the costs, which for the development and analysis of the model was set to the distance between potential sites and neighborhoods, and is represented by b_{ij} in the second objective of Q_1 (refer to 3.21). The operating costs are defined as:

$$OC_j = \begin{cases} M, \text{ is a large number if "less" vulnerable site} \\ 0, \text{ otherwise} \end{cases}$$

And Q_1 becomes:

$$Q_1 = \begin{matrix} k(\sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i c_{ij} X1_{ij}) + \\ (1-k)(\sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i b_{ij} oc_j X1ij) \end{matrix} \qquad \text{BBP to Neighborhood system}$$

Where oc_j is the operating costs of BBP at site j.

The approach did not offer any better control in the ability to be able to influence what type of neighborhood the BBP was sited.

Another way to approach the problem is as a fixed charge problem. In a fixed charge problem a cost, charge, is associated with an aspect of operating a facility. This charge is typically associated with "opening" the facility. The goal is to minimize the total amount of fixed charges when opening multiple facilities. The fixed charge minimization becomes another objective of the model. The objective is defined as:

Minimize: $\sum_{j \text{ in } J} f_j Y_j$

Where:

$$f_j = \begin{cases} M, \text{ if BBP is located at a “less” vulnerable site;} \\ 1, \text{ otherwise.} \end{cases}$$

$$Y_j = \begin{cases} 1, \text{ BBP is located at j;} \\ 0, \text{ if not.} \end{cases}$$

The model with additional fixed charge objective becomes:

Minimize:

$$\begin{aligned} &\sum_{n \text{ in } N} \sum_{j \text{ in } J} e_{nj}\, o_{nj}\, X2_{nj} + \\ &k \sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i\, c_{ij}\, X1_{ij} + \\ &(1\text{-}k) \sum_{i \text{ in } I} \sum_{j \text{ in } J} d_i\, b_{ij}\, X1_{ij} + \\ &\sum_{j \text{ in } J} f_j\, Y_j \end{aligned} \qquad (3.29)$$

Subject to:

$\sum_{j \text{ in } J} X_{ij} = 1$	for all i	(3.30)
$\sum_{j \text{ in } J} Y_j = p$		(3.31)
$X_{ij} - Y_j \leq 0$	for all i and j	(3.32)
$\sum_{n \text{ in } N} X2_{nj} = Y_j$	for all j	(3.33)
$X1_{ij} = 0,1$	for all i	(3.34)
$X2_{nj} = 0,1$	for all n and j	(3.35)
$Yj = 0,1$	for all j	(3.36)

Where:

$c_{ij} =$ 1, if $dist_{ji}$ > coverage distance and neighborhood is "more vulnerable;
0, if not;

$f_j =$ M, is a large number if BBP candidate site at j is a "less" vulnerable neighborhood;
1, if not;

$X1_{ij} =$ 1, if demand of neighborhood i is covered by BBP at j;
0, if not;

$X2_{nj} =$ 1, if BBP j is covered by POD at n;
0, if not;

$Y_j =$ 1, if BBP is located at site j;
0, if not;

$b_{ij} =$ distance from neighborhood i to BBP j;
$d_i =$ demand at neighborhood i;
$e_{nj} =$ distance between BBP at j and POD at n;
$o_n =$ operating cost of POD at location n; and
$p =$ number of BBPs to locate.

Table 3.20 Comparing Distances between Operating Cost and Fixed Charge

Using Operating Cost parameter	
Average Distance from BBP to Less Vulnerable Neighborhoods	21.4
Average Distance from BBP to More Vulnerable Neighborhoods	22.8
Average Distance from BBP to any type Neighborhood	22.2
Average Distance POD to BBP	20.2

Using Fixed Charge objective	
Average Distance from BBP to Less Vulnerable Neighborhoods	9.8
Average Distance from BBP to More Vulnerable Neighborhoods	10.7
Average Distance from BBP to any type Neighborhood	10.3
Average Distance POD to BBP	18.8

The results of testing the both the operating cost and fixed cost approaches are summarized as comparisons in Table 3.20. The distance from the BBPs were lower in the fixed cost approach. Figures 3.23 and 3.24 show the spatial relationship of the POD-BBP-Neighborhood links for each approach. As can be seen both approaches favor the siting of BBPs in "more" vulnerable neighborhoods. The operating cost approach allows several BBPs to be sited so that they are only serving the neighborhood they are located, and these self-serving sites were not apparent in the fixed cost objective. The fixed cost approach offers the ability to pinpoint with certainty that the model will only site BBPs in "more" vulnerable neighborhoods.

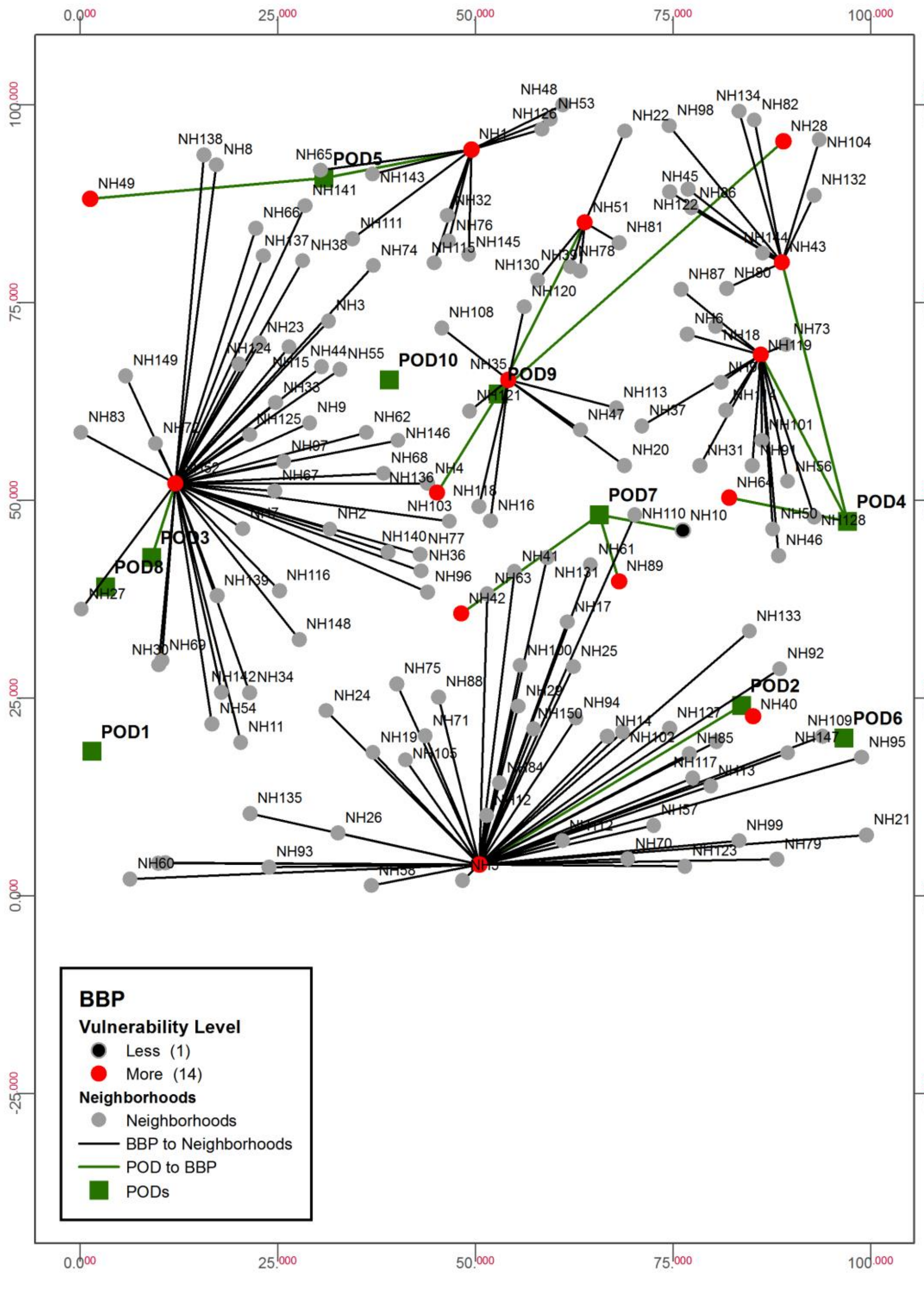


Figure 3.23 Using an operating cost parameter in attempt to influence siting of BBPs (p = 15).

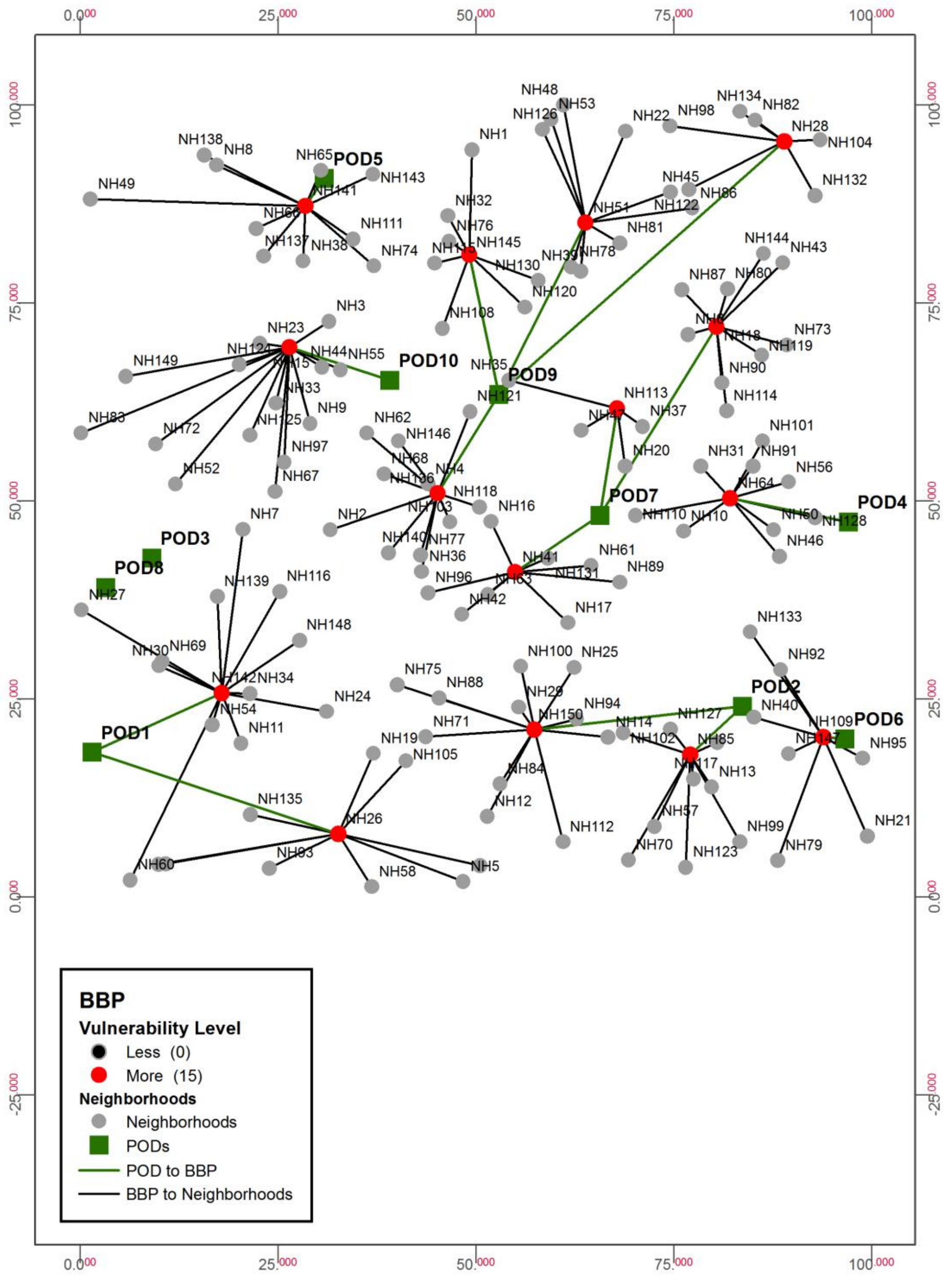


Figure 3.24 Using fixed charge objective approach to influence siting of BBPs (p = 15).

3.6 Summary

The resulting model can be summarized as follows:

Q	=	Minimize the total distance weighted costs of POD-BBP system	+	Minimize uncovered “more” vulnerable demands	+	Minimize total demand weighted costs in BBP-neighborhood system	+	Minimize the fixed facility costs

The results of the foundational model indicate that the ability to cover the demand for disaster relief supplies within a defined set of parameters and emphasize the ability to cover “more” vulnerable neighborhoods. As with similar models, this model allows for the delivery of goods down to smaller demand points beyond the traditional “points of distribution.” To move the formulation of the model further it will be analyzed using data and conditions for an area of the State of Connecticut. Additional examination of the proposed model will include a simulation of an actual disaster event, and the transformation of transshipment points into origin-destination pairs to formulate a hub network.

Chapter Four

Study Area and Data

4.1 Introduction

Place is a simple everyday term that people use throughout their daily lives. Yet, place is a complex, fundamental geographical concept encompassing the concepts of location, locale, and "sense of place (Cresswell 2015). A place's location is its physical point on the earth. Along with the fixed describing point, the location includes the geophysical and climatic descriptors associated with a place's natural environment or surroundings. The locale is how a place defines the space that it occupies. People delineate space by the use of boundaries to identify countries, states, counties and cities or towns. The buildings, roads, and other infrastructure, which the people inhabiting a place use to interact or associate with each other within the place, further define the space. The sense of place is where history, culture and society come together to define how it is to live in a particular place.

"Sense of place" is also the result of the interactions between people and their environments. In today's modern world, people's environments include both the natural and built environment, and in people's daily lives, there may not be a distinction between location and locale. If people's daily lives can be defined by the interactions between their environment and themselves, then a disaster can be seen as a collision between people and their environment. The different types of disasters that may occur within a place's space can further enhance an understanding of a place.

4.2 Location

The location for this study is the coastal region of the State of Connecticut. Connecticut is located in the northeast portion of the continental United States and is one of six states that make up the region called "New England." Connecticut's geographical location is shown in Figure 4.1. It is within moderate traveling distances to New York City and Boston. The state is fully contained within the highly urbanized region of the Eastern United States seacoast known as the "Northeast megalopolis" (Gottmann 1964). The "spine" of the region is made up of the roadways of U.S. Route 1 and Interstate 95. Gottmann (1964) saw the region as an area of about 600 miles long, spanning north from Boston to Washington, D.C. in the south and having a population of about 30 million. Today, the region is from southern Maine to Wilmington, North Carolina (Schned, n.d.). Figure 4.2 shows the extent of this highly urbanized region along the eastern seacoast of the United States. Connecticut contributes five cities with populations in excess of 100,000 to the region.

Connecticut is about 5,543 square miles in total area with 4,842 square miles in land area. A factor in this research and the application of the model developed in Chapter Three is the length of the coastline. The state has a coastline of about 96 miles (Beaver 2006). However,

estimates of this measurement can be as high as 618 miles when a formulation is used to include smaller coves and inlets, which is an approach used by NOAA ("General Coastline and Shoreline Mileage of the United States" 2016). By comparison with other states, Connecticut is 48th in land area and 17th in coastline length.

Figure 4.1 Location of the State of Connecticut in relation to the northeast United States and the New England region.

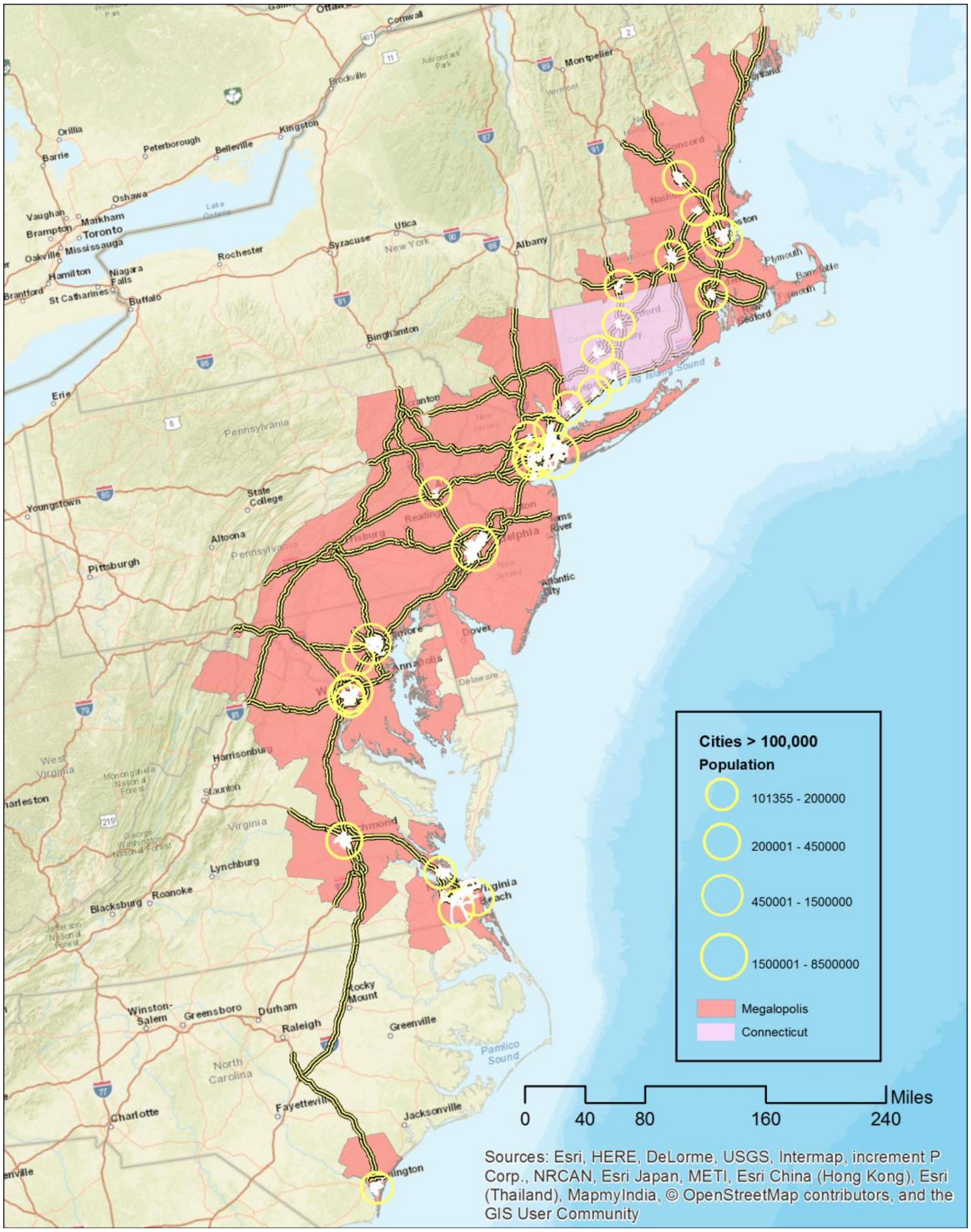


Figure 4.2 Gottman's Megalopolis, adapted from research by The Regional Planning Agency (Schned, n.d.)

4.3 Locale

Connecticut is divided into 169 cities and towns. The geographical boundaries of the counties, cities and towns can be seen in Figure 4.3. Cities and Towns are the primary component

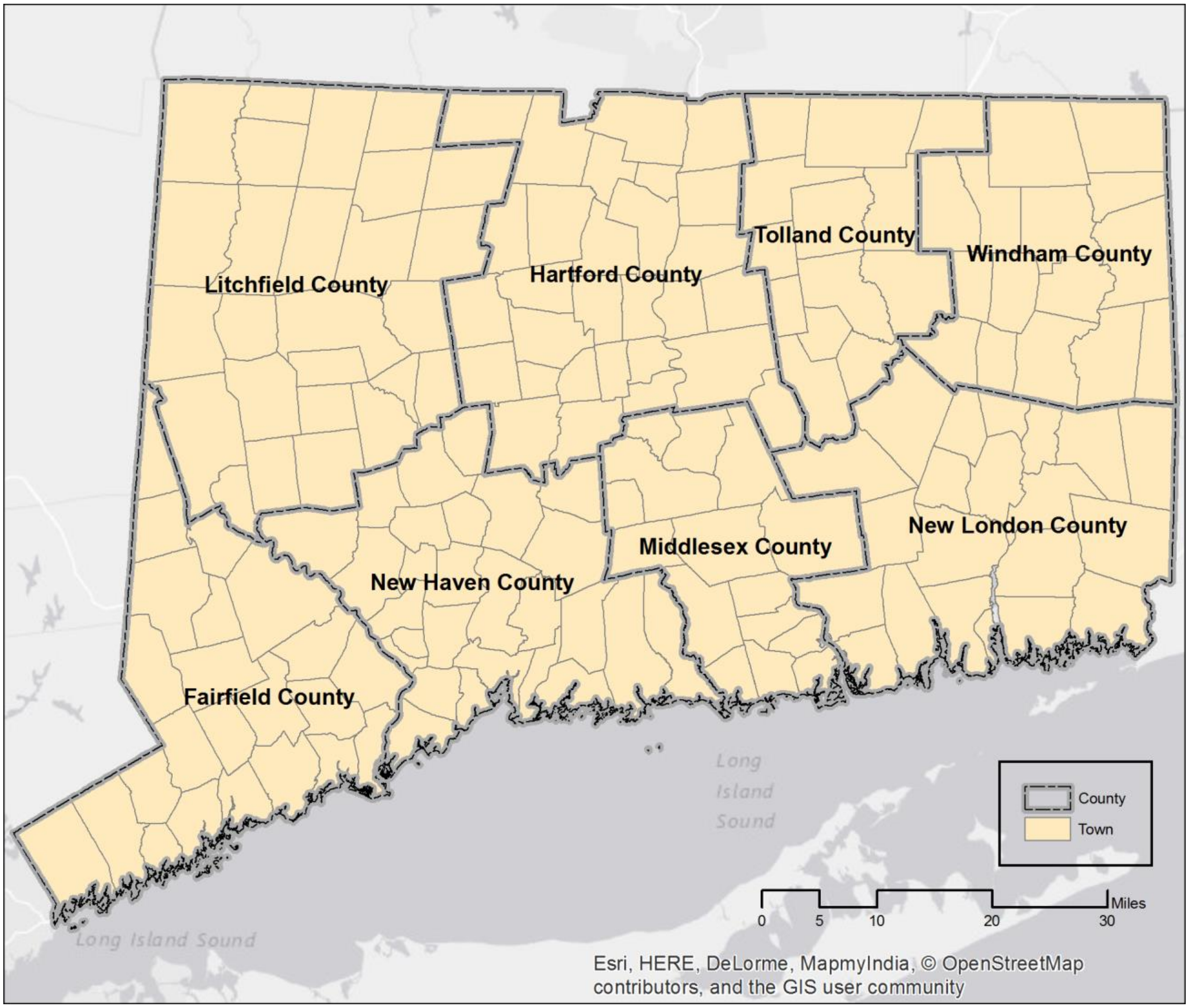


Figure 4.3 Connecticut Counties and Towns. Connecticut has 8 counties and 169 cities and towns (Source: U.S. Census Bureau 2010)

of local governance in the state. Towns or Cities may operate under a framework defined by State statute or can define their own character by enacting charters. However, in doing so they must operate any services they provide to their citizens within the limits and bounds of State statutes as such statutes apply to all Cities and Towns. The State's relationship with Cities and Towns was established by the Home Rule Act of 1957 and State constitutional provisions. The constitutional provision allows Cities and Towns to operate without fear of the Connecticut

General Assembly enacting any type of legislation that could potentially affect a single City or Town (League of Women Voters of Connecticut 2010).

There is no intermediary form of government between the City/Town level and the State level. Connecticut's eight counties are used for statistical and record keeping purposes, and do not serve any political purposes. Connecticut abolished the formal county government system in 1960. Cities and Towns have taken on the governmental functions that were previously carried out by the counties (League of Women Voters of Connecticut 2010).

Though Connecticut no longer has a formal county government system, its Cities and Towns have sufficient history and experience in using cooperative programs for various services and resources. A commission to study and analyze such programs has been in existence since 1985 (Russell, West, and Van Ausdall 2000). Cities and Towns can enter into inter-municipal agreements to cooperate in all sorts of services such as transportation, health boards, education, and planning. Figure 4.4 shows examples of the geographical extent of three types of regional agreements: planning, health, and education. In 2000, the state Office of Policy and Management (OPM) estimated that there were more than 9,000 agreements between various Cities and Towns to share all types of resources and services and in Figure 4.5, the breakdown between educational programs and other types of programs is illustrated. Several cities and towns have arrangements to share things like public works equipment, computer systems, and communications systems. There are various organizations and arrangements for police and fire mutual aid and police/fire task forces among different Cities and Towns, but the OPM report found only one "joint organization for civil preparedness," and the organization covered just three towns (Russell, West, and Van Ausdall 2000). One drawback to the current system is that the regional cooperative arrangements can be temporary and subject to change. For example, because of

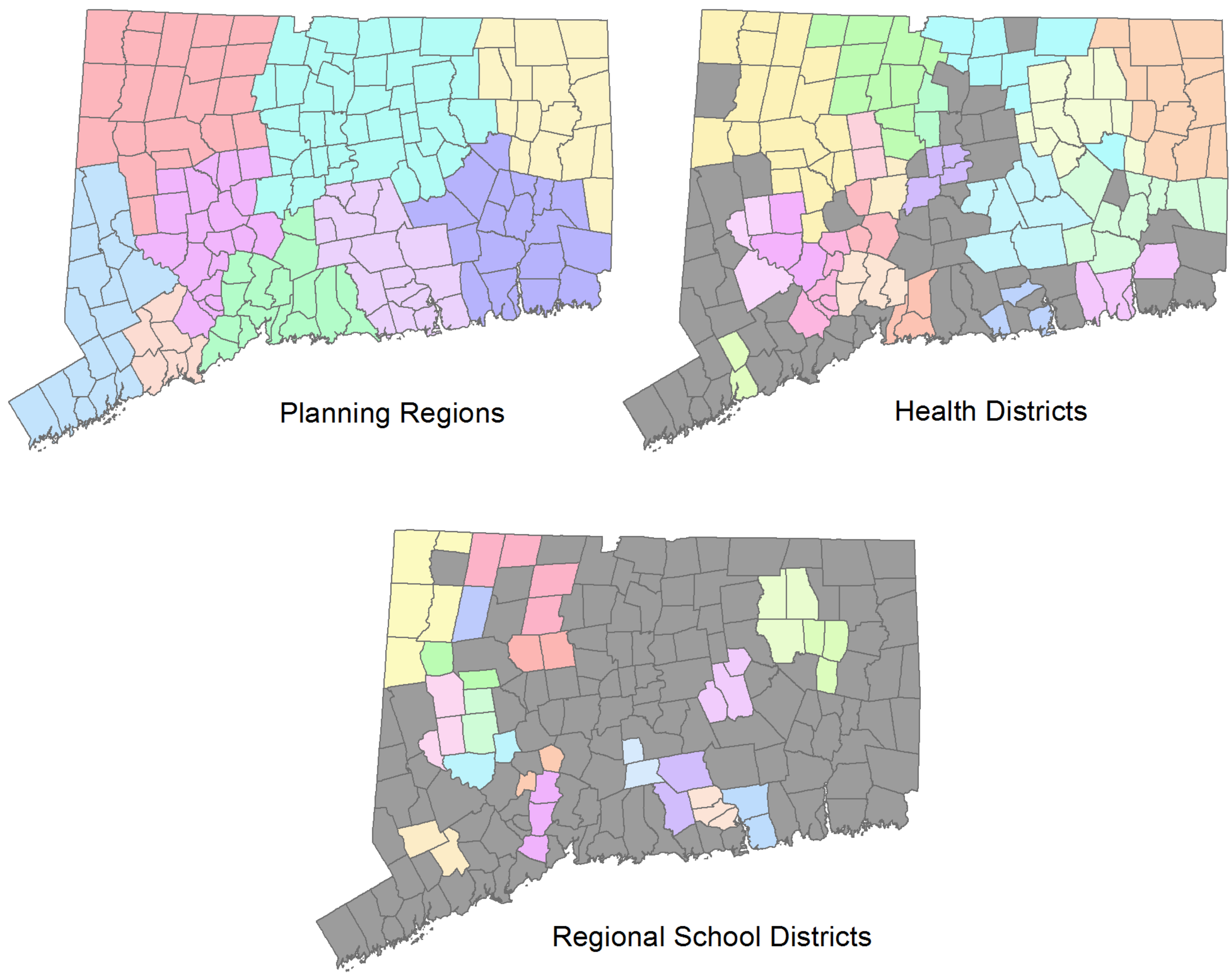


Figure 4.4 Sample of several types of existing regional cooperative arrangements within Connecticut. Towns shaded in gray are independent (Russell, West and Van Ausdall, 2000).

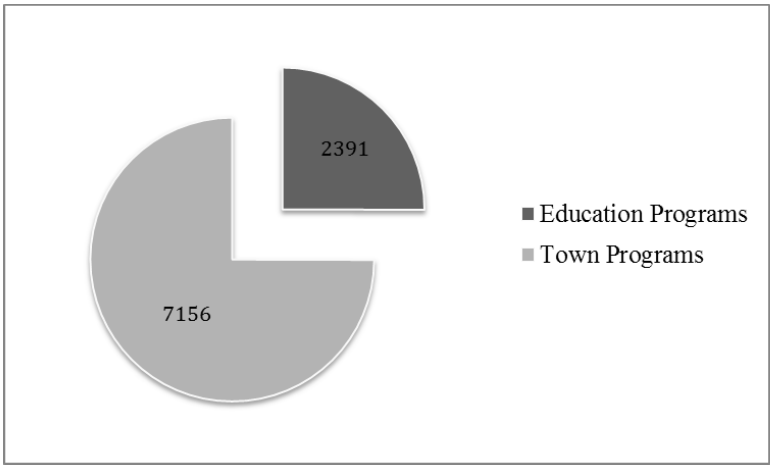


Figure 4.5 Number of statewide town cooperative programs. In the Connecticut, there are 9457 programs. The average number a town participates in is 56 with a high of 96 (Windsor) and a low of 33 programs (Stafford and Union) (Russell, West, and Van Ausdall, 2000)

budget constraints the state Office of Policy and Management reduced the number of regional planning agencies from ten to five (Note that the Planning Region map, in Figure 4.7, shows the original 10 planning regions prior to the 2013 budget cuts because many of new regions have not been finalized). Cities and Towns must have membership in regional agencies authorized by the State to advocate for regional planning type activities. Membership in such an agency must align with a City's or Town's particular focus or planning framework. Many communities had concerns about their choices because of the change (Tuz 2013).

Aligned with the ideals of Home Rule the disaster supply relief system in Connecticut is primarily a local City or Town function. This system for distributing disaster relief supplies calls for locating Points of Distribution (POD) within each City or Town. The result is a system of 271 PODs, with each individual City or Town having the ability to locate them as they see fit – presumably to meet the needs of that particular community. Figure 4.6 shows the geographical distribution of the PODs throughout the state. Each Town is responsible for staffing each site and equipping the sites as suggested by the state emergency management officials (State of CT Commodities and Resource Support Group 2012).

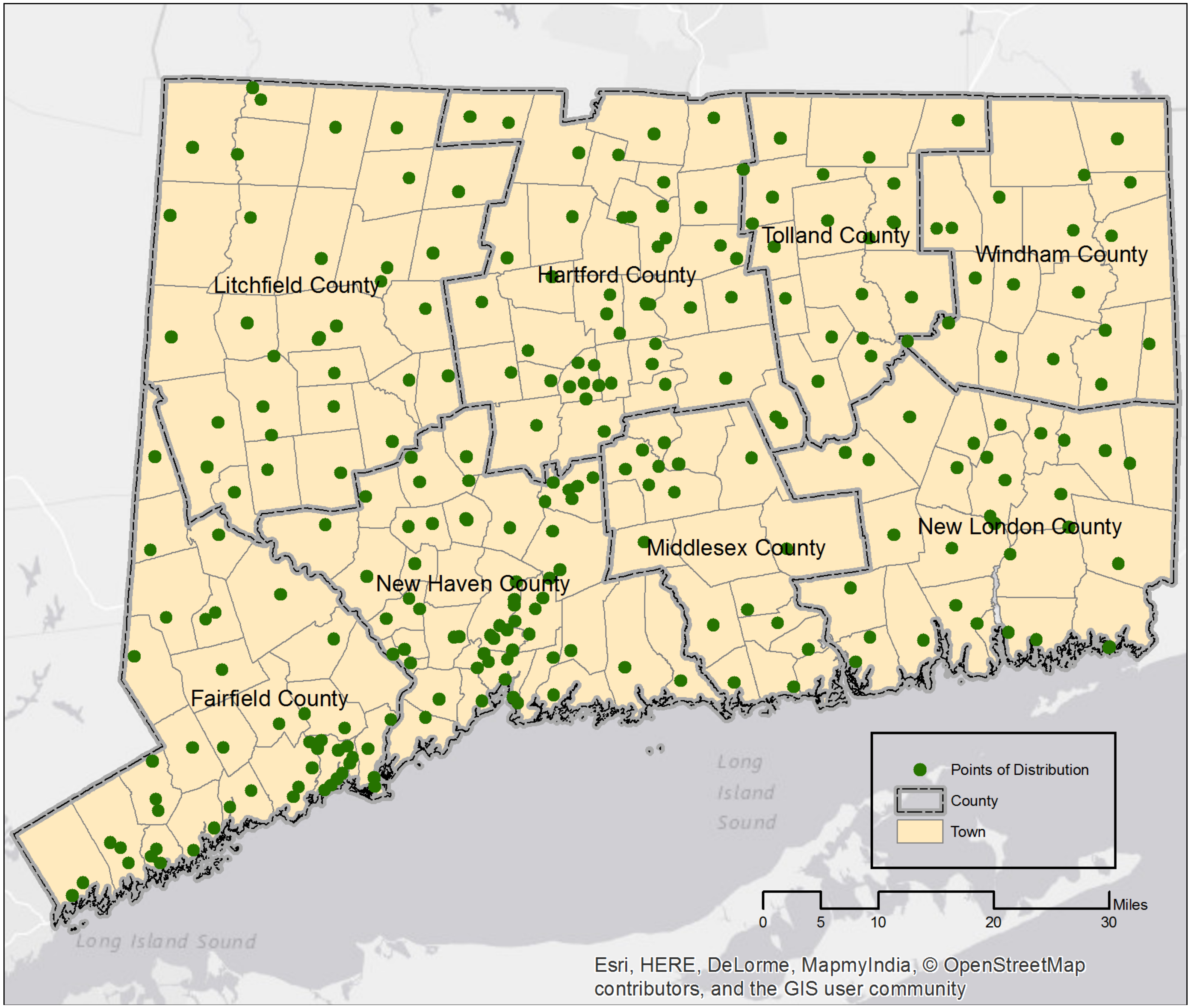


Figure 4.6 Location of established Points of Distribution (PODs) in Connecticut (State of CT Commodities and Resource Group, 2012

Some states, such as Florida, offer counties and local governments exacting specifications for the various types of staging areas and PODs. There is also a hierarchy of the differing types of distribution areas (see Figure 4.7) that may lead to some efficiencies ("County Points of Distribution PowerPoint" 2010). FEMA and US Army Corp of Engineers suggest three sizes of PODs. These three sizes are suggested to be able to handle various amounts demand as outlined in Table 4.1 (FEMA/USACE 2008).

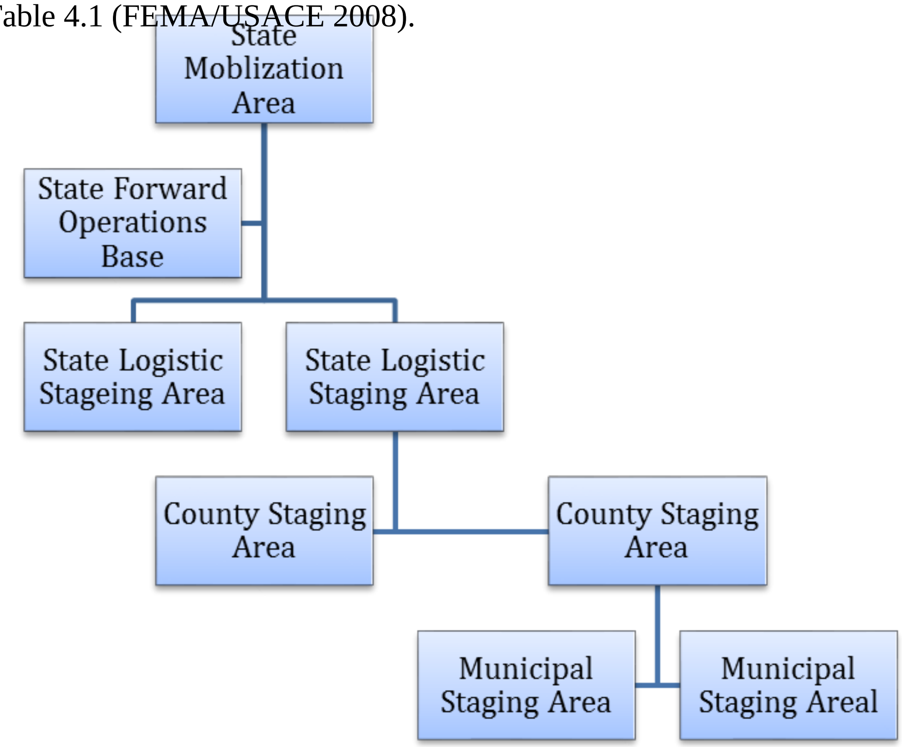


Figure 4.7 Hierarchy of State of Florida Distribution System (FL SERT, 2010)

Table 4.1 POD Types and Volume

TYPE	PERSONS/DAY	VEHICLES/HR	STAFFING (TOTAL INC. DAY & NIGHT)
I	20,000	560	88
II	10,000	280	40
III	5,000	140	23

(USACE 2016)

All of Connecticut's PODs are Type III. The layout and spatial organization of a Type III POD is shown in Figure 4.8. For many of the smaller communities this size POD is sufficient to handle the expected volume. However, in the larger Cities and Towns, this size POD may not be large enough, and those same Cities and Towns may not have enough proposed locations to handle the volume. The State does not offer guidance or regulation on the number of PODs that should be required by each community.

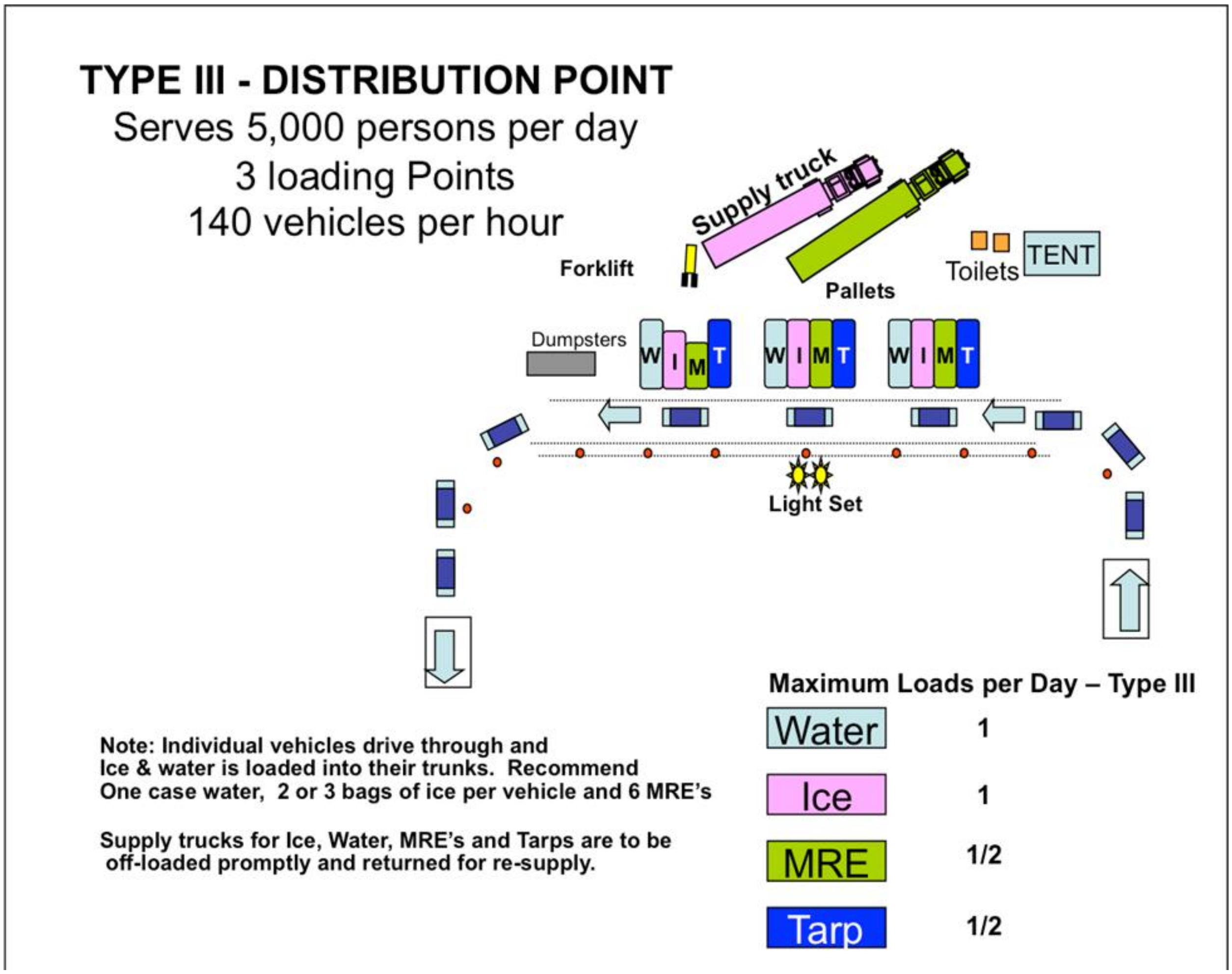


Figure 4.8 Diagram of Type III POD specified by Connecticut. (Source: USACE 2016)

Connecticut's proposed POD system was analyzed using ArcGIS Business Analyst. The reasoning behind this analysis was to determine if the current system of PODs had sufficient geographical coverage for the state. Figures 4.9, 4.10, and 4.11 are the results of the ArcGIS analysis of the POD locations. The analysis determined that there appears to be sufficient geographical coverage of the current system. The locations of the PODs were entered in as if they were store locations and demand rings were constructed around each location that contained a population of 5,000. Even though 5,000 persons is the daily volume capacity, the demand area would not be much beyond that population-delineated region. During an actual event the demand may be artificially low because of the lack of access to the located or operational POD, for example if the particular event is on one side of a community and traveling to a POD on the other side of a community is limited or not possible because of obstructed roads. Distribution guidelines allow for each vehicle to receive a daily allotment of the available supplies, and those amounts could be adjusted less if the vehicle cannot carry all the supplies. A pedestrian would receive even less supplies.

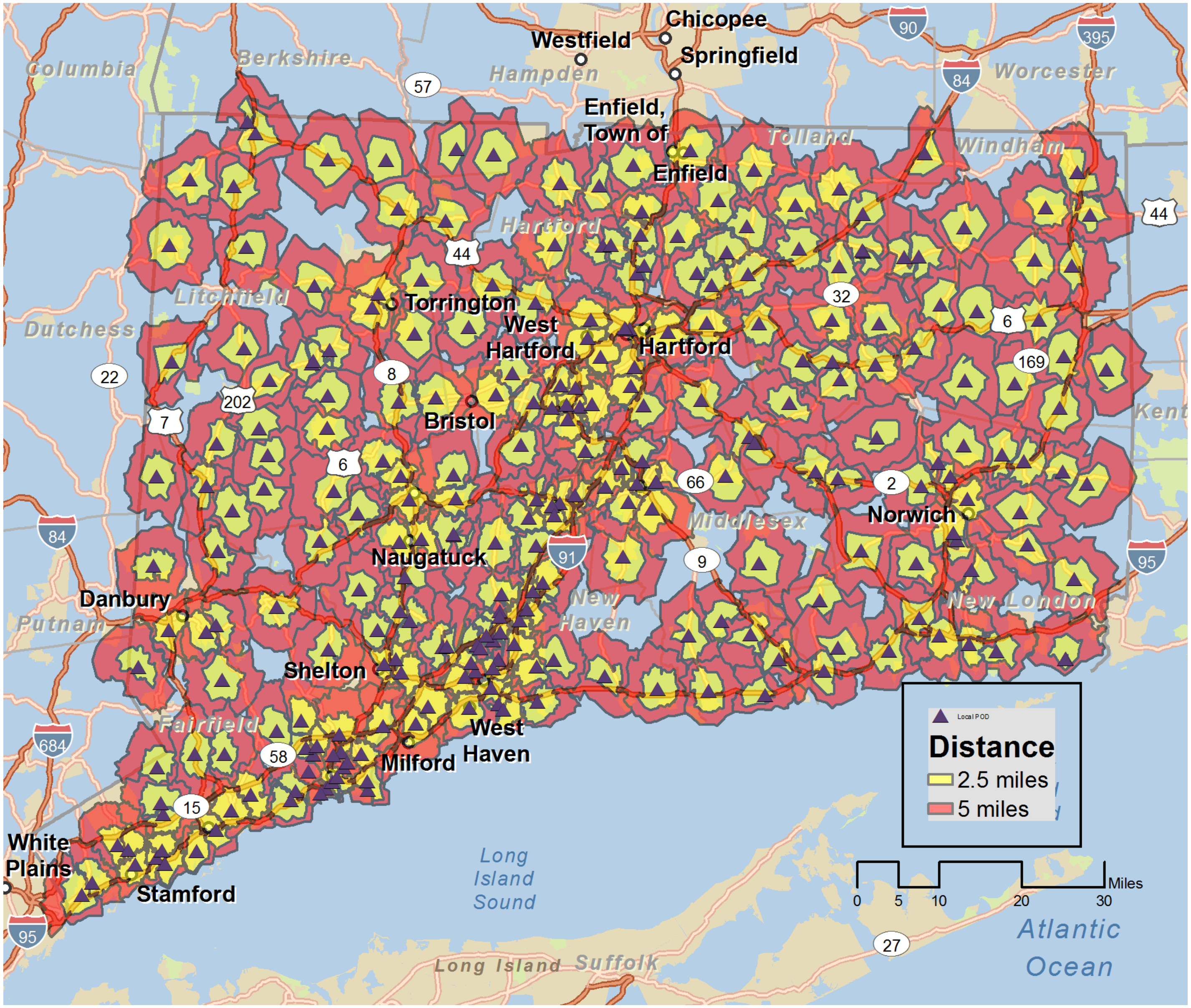


Figure 4.9 Driving distance threshold analysis of PODs by ArcGIS Business Analyst

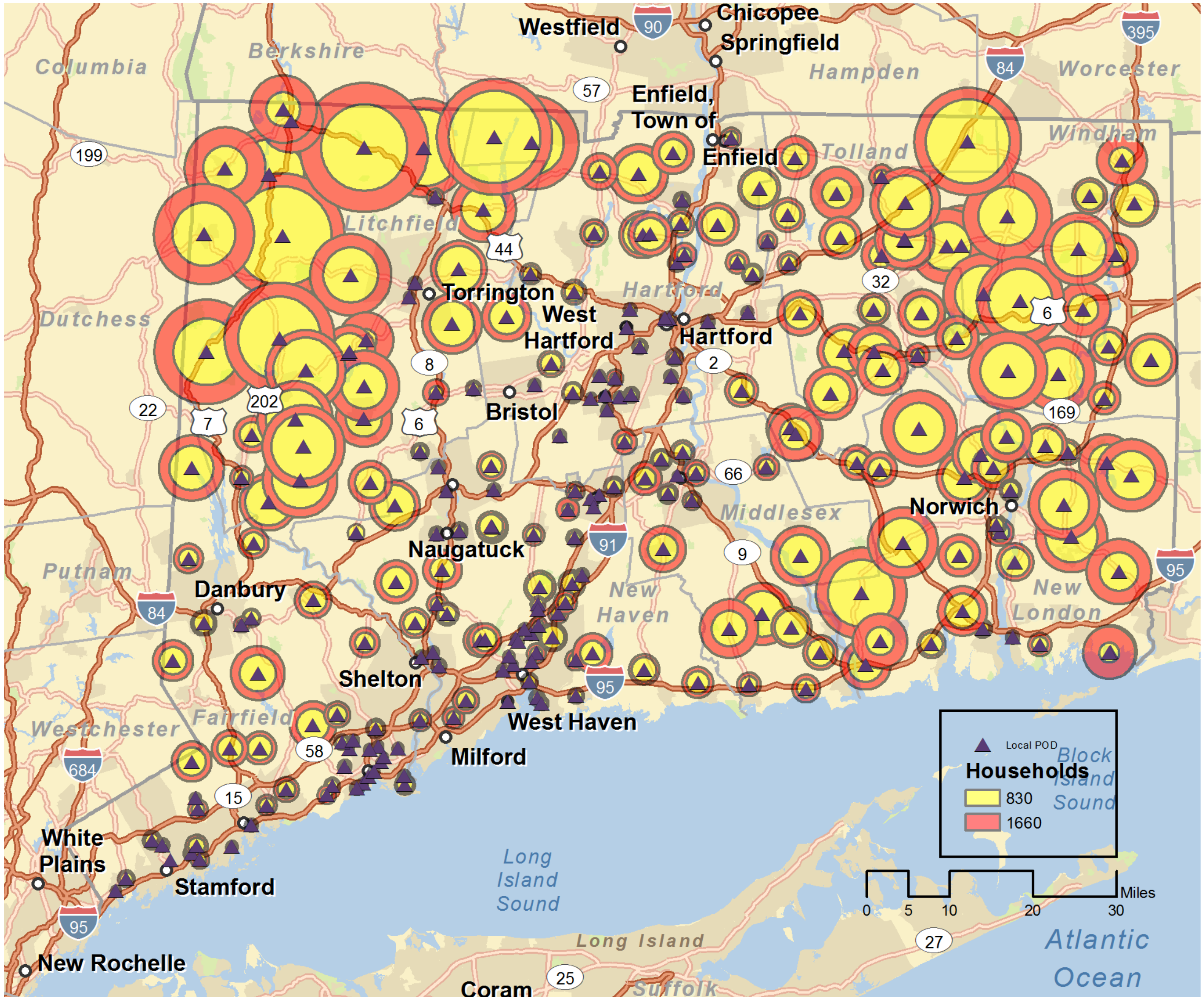


Figure 4.10 Number of households are used a threshold in this analysis of the POD locations by ArcGIS Business Analyst. 1660 households is equivalent to population of 5,000 people.

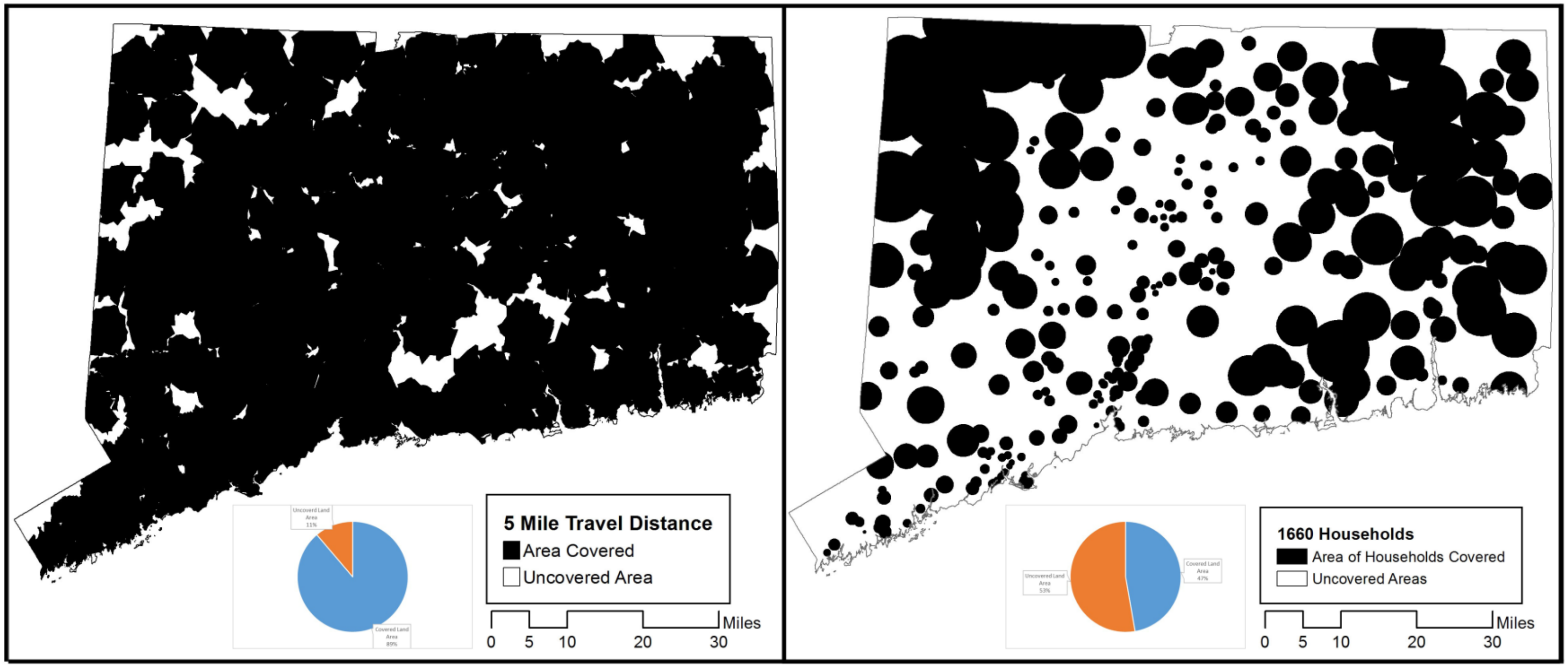


Figure 4.11 Figure-Ground examination of coverage of current PODs. The 5 mile travel distance rings cover much of the state. Using the 1660 household threshold leaves much of the state uncovered. Blue in the pie charts represent covered land area and orange is the uncovered land area. For the 5 Mile Travel Distance: 11% uncovered and 89% covered. For 1660 Households: 53% uncovered and 47% covered

A long-term event would possibly require multiple trips, on a daily basis, to the POD for relief supplies for each affected household. An example of the scale of supplies that could be required is Figure 4.12. The figure shows the path of Hurricane Wilma and the affected area in Florida, and the amount of relief supplies distributed. Hurricane Wilma was the last Category 3 hurricane to make landfall along the U.S. east coast in over ten years. Accordingly, FEMA suggests that supply a Type III POD would require deliveries from at least three separate trucks: one truck for water, one truck for ice and one truck for food and tarps (requirements of tarps and food can be met with a half truck respectively). Under the current system, even if only a handful PODs are opened, a large fleet of trucks would be required to move supplies from a large-scale staging area located in East Hartford.

When developing the model in Chapter Three, one of the beliefs was there may be some inefficiencies in Connecticut's current disaster relief supply system. The model was designed to cover a larger area than a single town. Since, Connecticut has no county or intermediary government between the local and State levels for the purposes of testing the model a large region is needed. As established, Connecticut does have a hodgepodge of cooperative arrangement among some towns; therefore, such a cooperative region for use during a disaster event would not be out of the norm for the Cities and Towns in the State. The development of a region can be quite complex, requiring the examination of similarities, dissimilarities, and methods or measure of connections between places, but this not the focus of this research. A simpler approach was utilized by using a common geophysical characteristic to develop a region. Connecticut has a coastline of about 100 miles long, and the coast was chosen as the foundation for the testing region

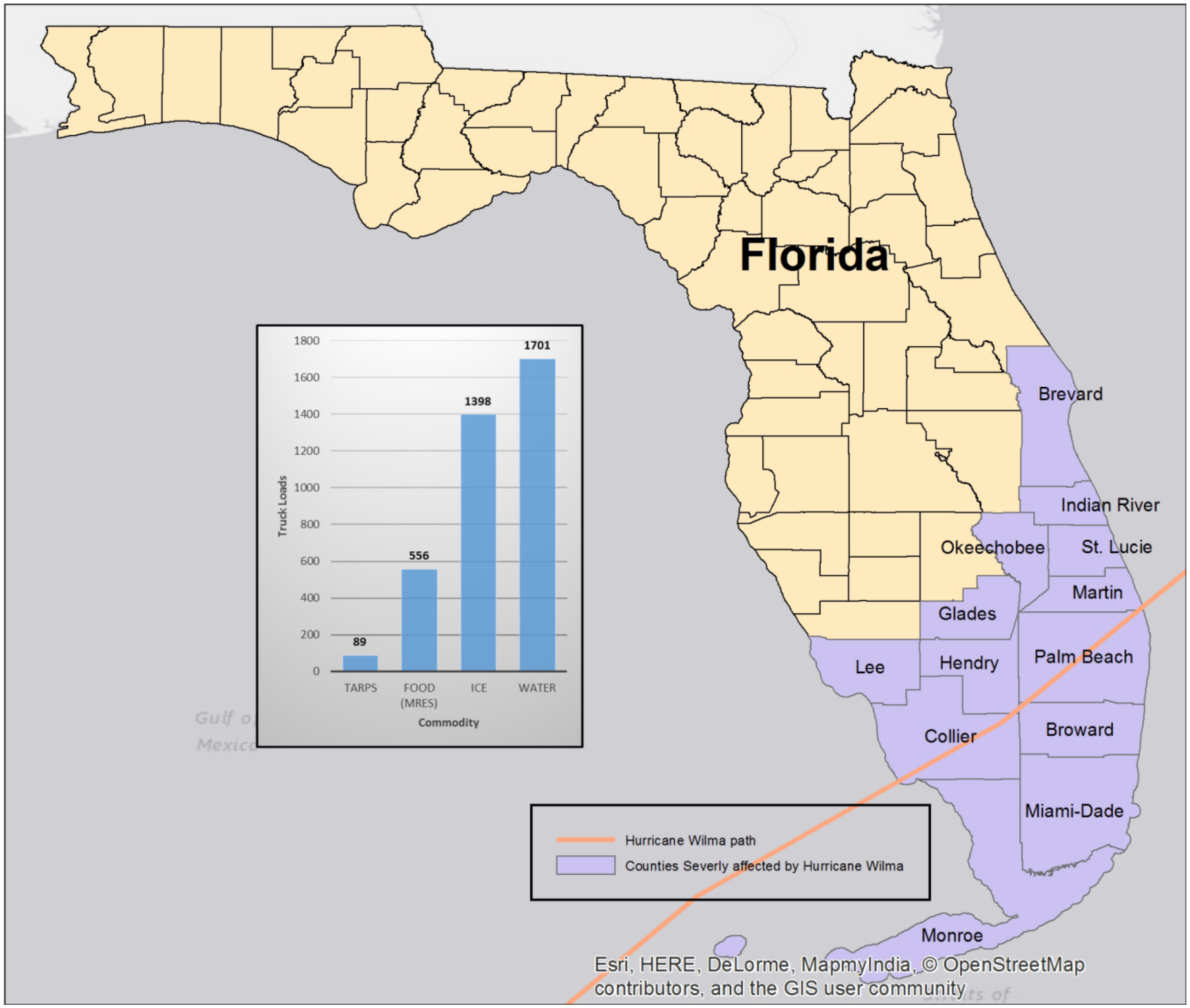


Figure 4.12 Logistic requirements example for Hurricane Wilma (Oct. 2005). The hurricane severely affected 13 counties. There were 96 PODs set up in those counties and they were operational for about 16 days. Those PODs served a population of about 4.8 million people, which was about 65% of the affected counties' population. Those PODs provided over 8 million gallons of water, 11,700 meals, and over 27,000 tons of ice. (Source: FL SERT 2010)

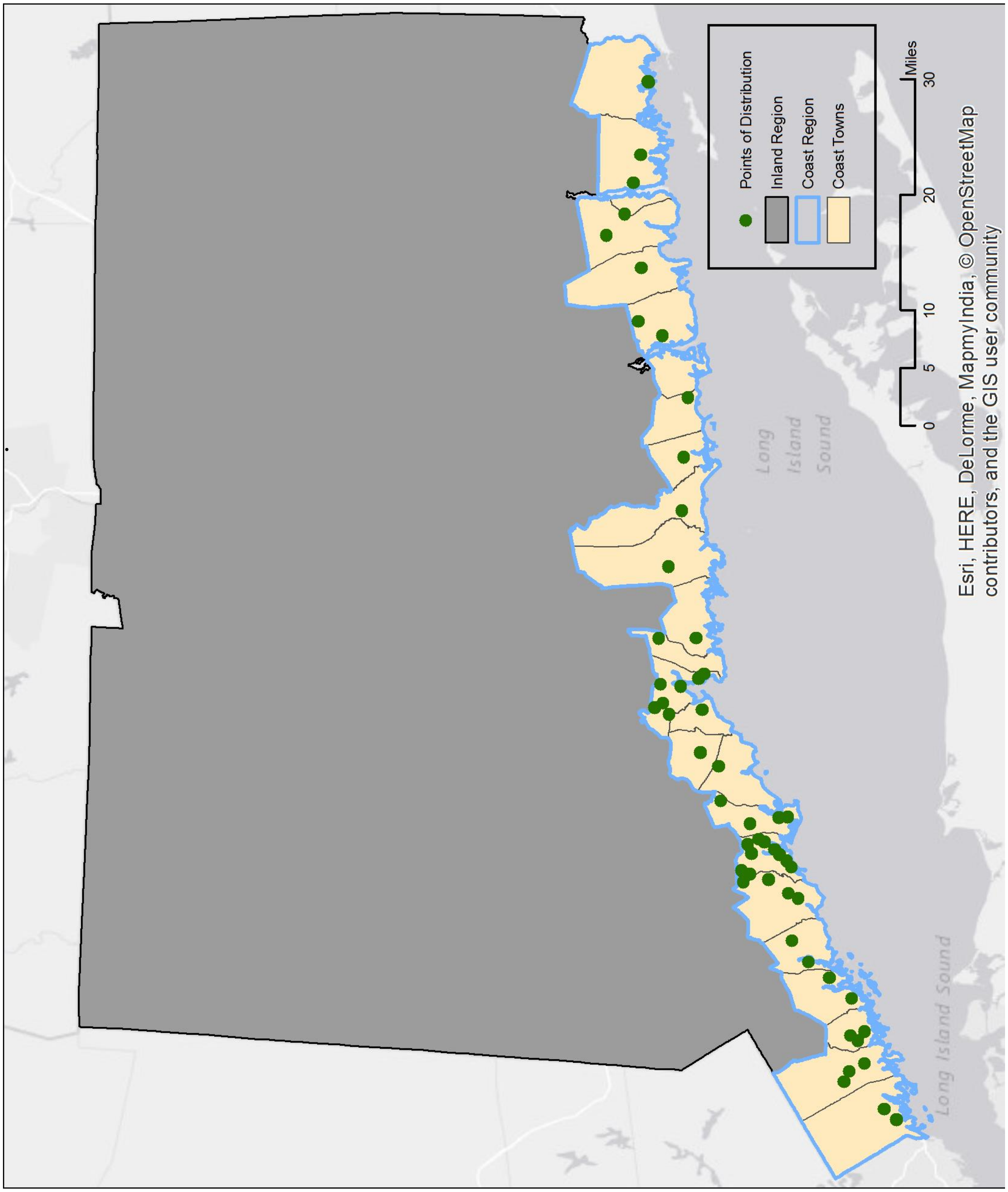


Figure 4.13 Proposed Coastal Cooperative Region (CCR) for use with proposed model.

To test the model a region compromising the towns along Connecticut's shoreline will be utilized. The region will be made up of 25 towns along the shore from the New York state line to the Rhode Island state line. The region has a population of 1,084,541. Table 4.2 illustrates how the region compares with existing county geographical areas. The region, like the "megalopolis" shares a framework the major roadways of Interstate 95 and US Highway 1. The region will use the existing PODs system, as they are located within the region. However, the model will anticipate that the PODs will need to service areas outside of the town in which the PODs are located. Figure 4.14 shows the proposed Coastal Cooperative Region (CCR).

Table 4.2 Comparing Sizing of Model Region with existing CT Counties

Region	Number of Towns	Population (2010 US Census)	Land Area (sq. mi.)	Density (uniform persons/sq.mi.)
Connecticut	169	3,574,097	4845.4	737.6
Fairfield Cnty	23	916,829	625.9	1464.8
Hartford Cnty	29	894,014	735.5	1215.5
Litchfield Cnty	26	189,927	920.0	206.4
Middlesex Cnty	15	165,676	369.3	448.6
New Haven Cnty	27	862,477	605.8	1423.7
New London Cnty	21	274,055	666.1	411.4
Tolland Cnty	13	152,691	410.1	372.3
Windham Cnty	15	118,428	512.8	230.9
Ave. County	21	446,762	605.7	721.7
Model Region	25	1,084,541	604.5	1794.1

(U.S. Census Bureau 2010)

4.4 Sense of Place

In Cresswell's outline of Agnew's description of place the "sense of place" is defined as the intangible understanding of the makeup or composition of a location. This composition is a combination of the place's location and locale. To get a "sense of a place" one has to understand the foundational elements of a location as perceived by the people who interact with that location. These elements take the form of history, culture and traditions. In understanding the "sense of place", concerning disasters, there are two major blocks of understanding that have to be examined. The first is a historical and predictive understanding of what types of disasters have occurred and what types might occur. Hewitt and Burton believed that any location could experience many different types of natural hazards and subsequent disasters (Hewitt and Burton 1971). What has happened in the past may help inform as to what could happen in the future. The second element of a place is the locations socioeconomic composition. This element helps planners determine what type of aid or resources could be required by a place in the event of a disaster.

Understanding the types of disasters that can occur and what types of hazards that may have an impact on a population can be key to understanding how to plan for such events. During Connecticut's over 400 hundred year history the State has experienced almost every type of hazard. Table 4.3 lists some examples of such events. Additionally, Figure 4.16 shows the types of extreme weather events, as cataloged by NOAA, from 1955 until 2014 (NOAA 2015). Connecticut has also had 31 federal disaster declarations in the same period as seen in Figure 4.15 ("Disaster Declarations by Year" 2013).

Table 4.3 Examples of Connecticut Disasters

Hazard	Dangerous Agents	Connecticut Examples
Natural	Atmospheric	1978 Blizzard
		1989 Windsor Locks Tornado
		2011 Hurrican Irene
	Hydrological	1936 Flood
		1955 Flood
	Geological	1791 Moodus
		1925 Hartford
Technological	Destructive Process	1902 Downtown Waterbury Fire
		1983 Mianus River Bridge Collapse
		1987 L'Ambiance Plaza Collapse
	Installations	1963 Norwich Dam Break
		2010 Middletown Kleen Energy Plant explosion
Social	Weapons	1993 Unabomber bombing Yale University
		2012 Sandy Hook School Shooting

(CT State Library 2015)

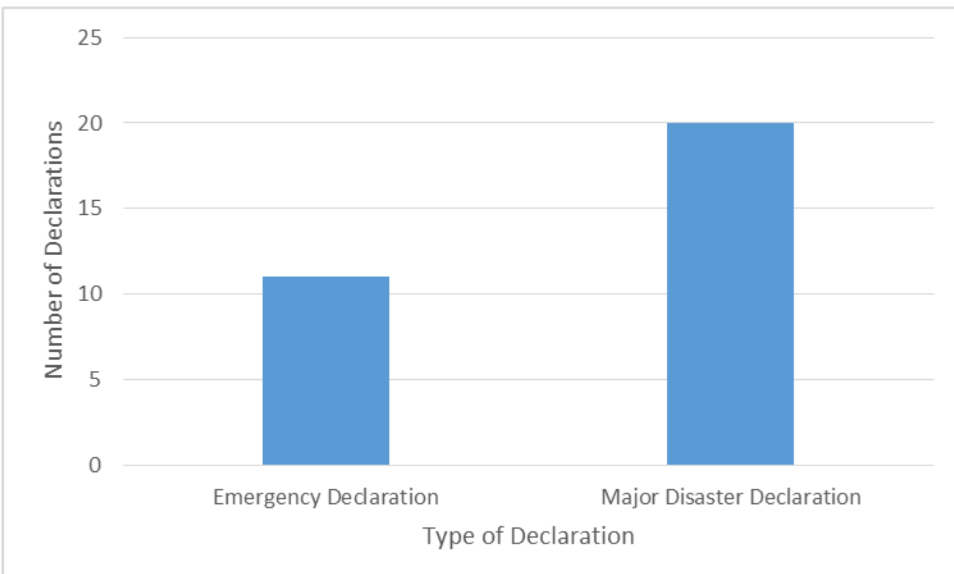


Figure 4.14 Number of federal disaster declarations for the State of Connecticut 1954 to 2014 ("Disaster Declarations by Year, 2015)

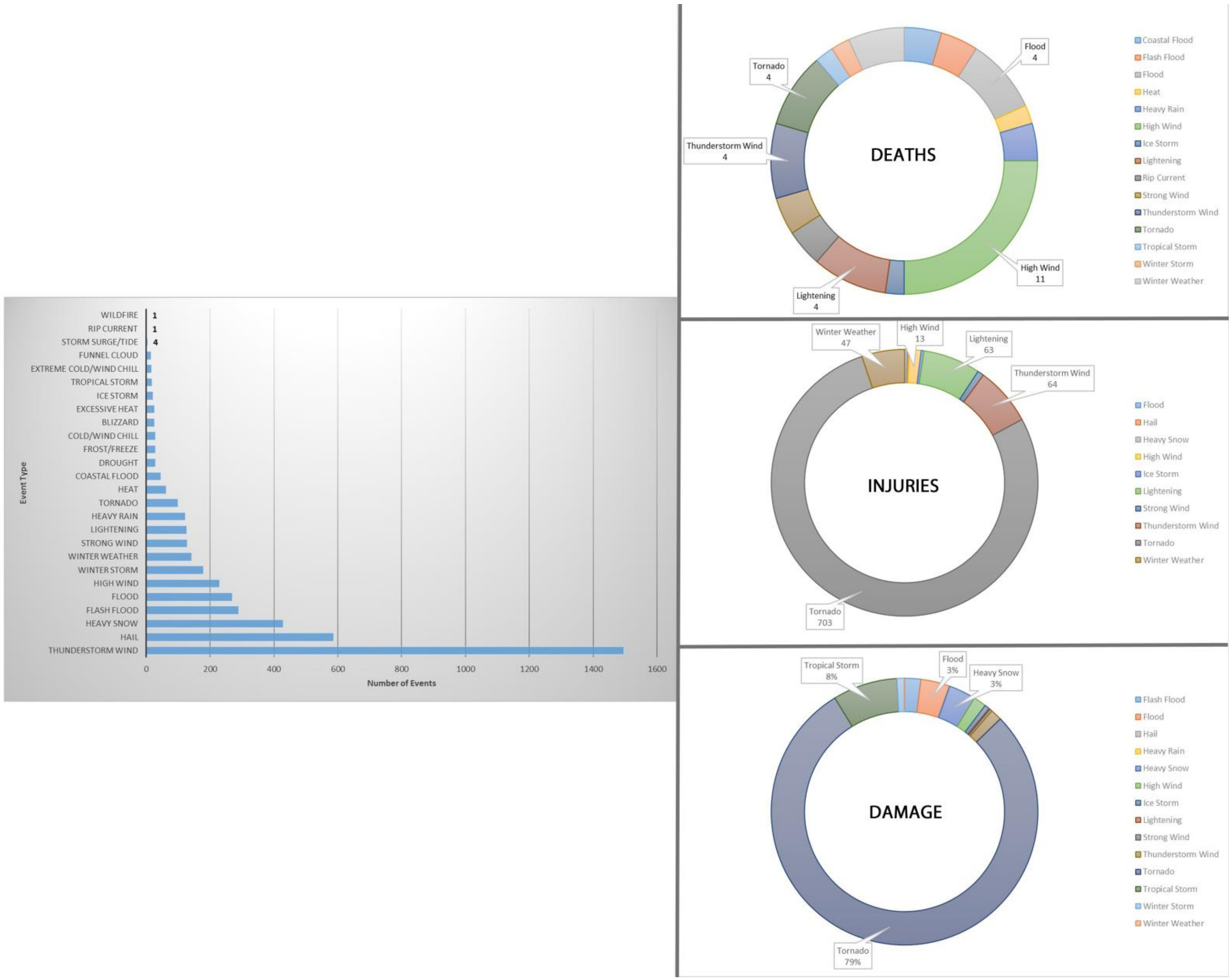


Figure 4.15 Extreme weather events in Connecticut from 1955 to 2014 (NOAA, 2015)

Over the period, 1955 to 2014, wind events have been the most prevalent weather event, more specifically thunderstorm wind events. Thunderstorm wind events accounted for 1497 of the recorded extreme weather events. This amount of those type of events is nearly three times the next closest weather event, hail. A similar trend can be seen for deaths, injuries and damage where wind type events account for the highest in those categories. As Hewitt and Burton pointed out over 45 years ago a location has to be prepared for a multitude of hazards and disaster types (Hewitt and Burton 1971). Hewitt pointed out the complexity in attempting to determine the probability of such events (Hewitt 1970). Therefore, planners need to have an understanding that "if it has happened before…it can happen again." Planners need to have plans and systems in place to adapt and be flexible to varying hazards and events.

Several researchers (Baker 1991; Cutter 2005; Fothergill, Maestas, and Darlington 1999; Morrow 1999) suggest that an understanding of the population and socioeconomic composition of that population is important to disaster research and preparedness of an area. This understanding offers insights as to the type and amount of assistance that a location may require after a disaster. As a whole the State of Connecticut, when compared to other states, is ranked highly with regards to personal economic indicators. Table 4.4 summarizes some of these indicators for the State. The State is highly ranked in both median household income and per capita personal income. Similarly, the State ranks high with regards to average annual income, and home values of the State are higher than the United States as a whole by a factor of over 150%. Connecticut performs above the United States average in terms of educational attainment pertaining to high school graduation and the percent of the population with a bachelor's degree.

Table 4.4 Selected Data Rankings for Connecticut

Category	Value	Rank	Year	Notes
Average Annual Pay	$58,029	2nd	2007	
Personal Income per capita	$56,272	1st	2008	
Median Household Income	$68,595	3rd	2008	
Persons Below Poverty	9.3%	45th	2008	US percentage 14.8%
Median Home Value	$274,500		2010-2014	US median value $175,500
Persons who are High School graduate or Higher	89.5%		2010-2014	US percentage 86.3%
Persons with Bachelor's Degree or Higher	35.6%	2nd	2008	

(U.S. Census Bureau 2010)

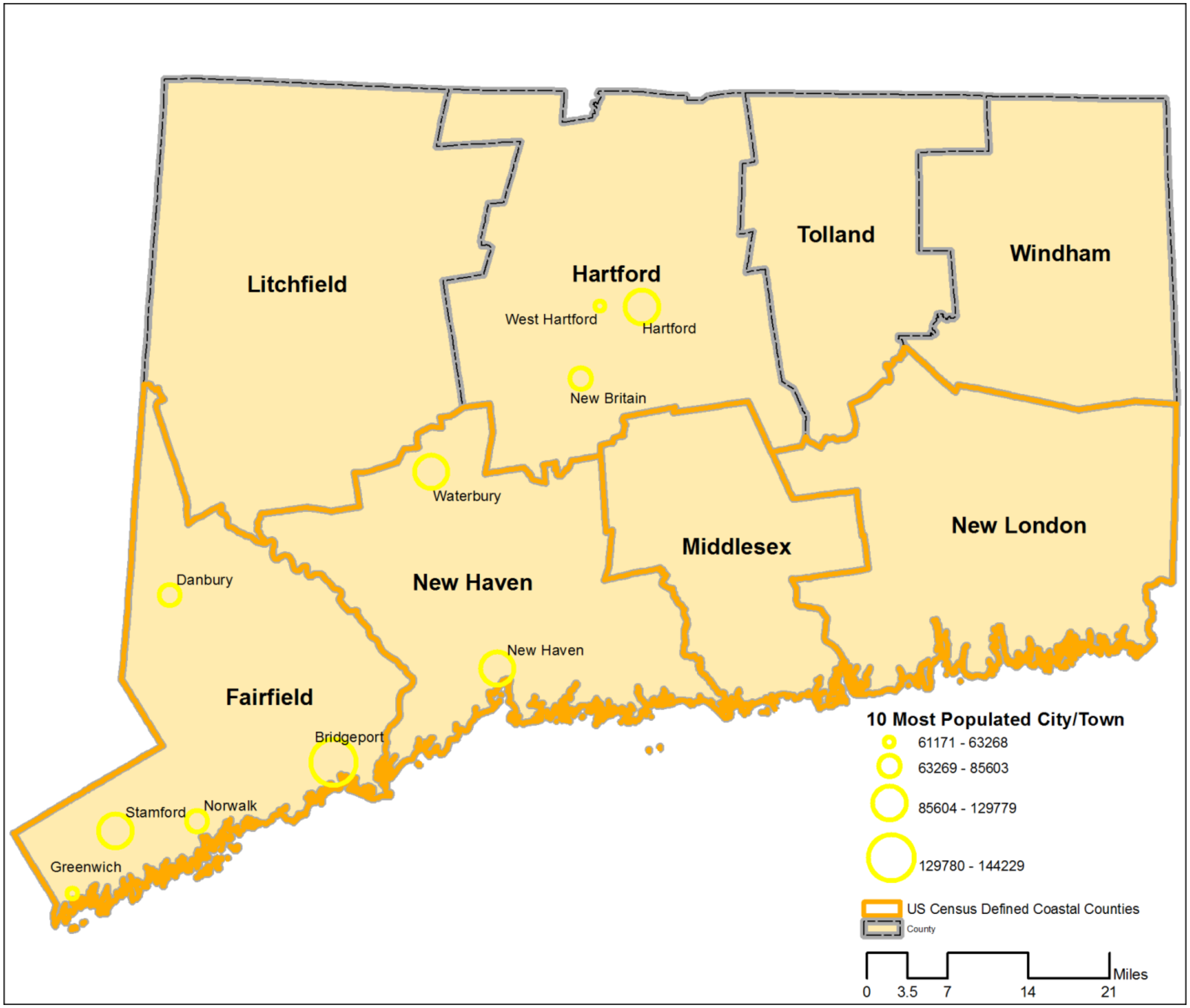


Figure 4.16 Coastal Counties in Connecticut as defined by the U.S. Census Bureau (Source: U.S. Census Bureau 2010)

The State's coastal counties follow similar population growth as those seen in coastal counties in the United States. Figure 4.17 highlights the counties in Connecticut that the U.S. Census Bureau classifies as "coastal counties." In 2010, the U.S. Census Bureau found that less than 10% of the United States' 3,142 counties were on a saltwater coast, and those counties accounted for 29% of the United States' population(Wilson and Fischetti 2010). In Connecticut the four coastal counties, Fairfield, Middlesex, New Haven, and New London, account for about 62% of the State's 2012 population, and those counties contain 7 out of 10 of the most populous cities and towns in the State. In Figure 4.18, the percentage of population of inland and coastal counties in the State is shown over time. The population density of the coastal counties in Connecticut has also increased over the same time period, and this trend can be seen in Figure 4.19.

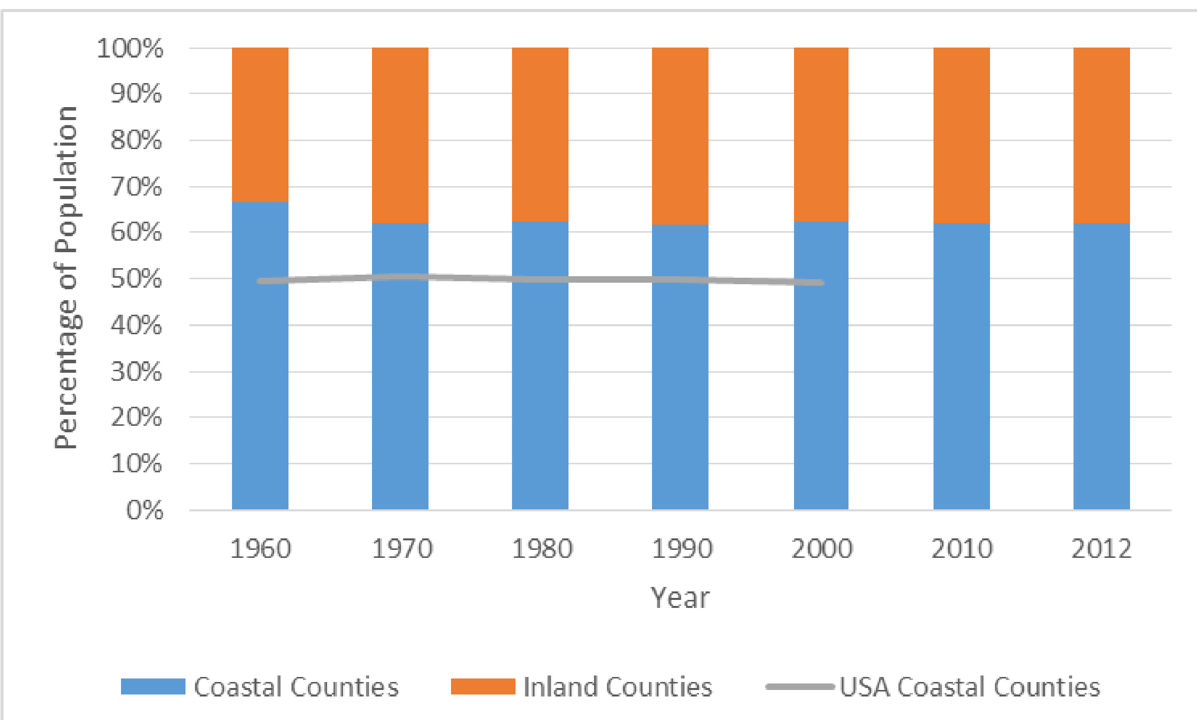


Figure 4.17 Percentage of population in coastal and inland counties in Connecticut (Source: U.S. Census Bureau 2010)

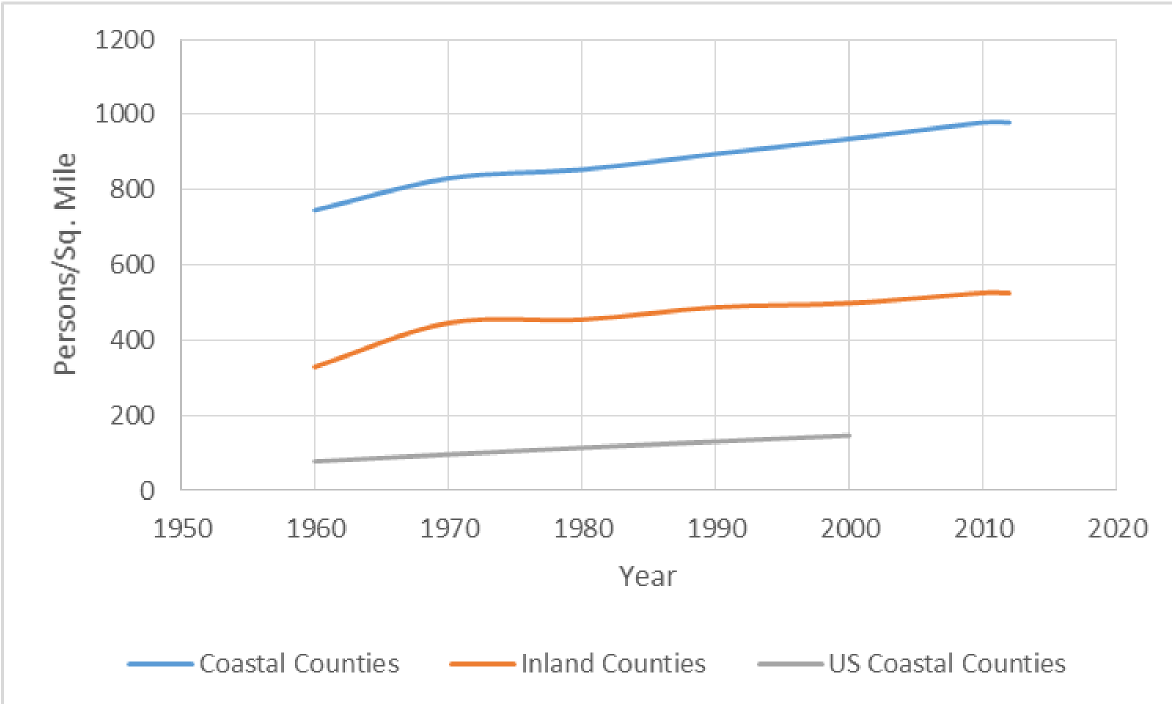


Figure 4.18 Population Density of coastal and inland counties in Connecticut (Source: U.S. Census Bureau 2010)

Two economic factors that were key in the motivation in developing the proposed model are: (1) percentage of households that receive public assistance and (2) percentage of households that do not have access to a vehicle. Public assistance is seen as an indicator as to whether or not a household would require disaster assistance or have a tendency not to evacuate (Baker 1991; Fothergill and Peek 2004). Horner and Downs, in one of their models, used public assistance measurements as a way to define and quantify demand for relief supplies (Horner and Downs 2010). The access to a vehicle is central to the current distribution system. The current system is designed around the ability of people to drive to a location and drive through the POD. As they drive through the POD, their vehicle is loaded with various available supplies (food, water, and tarps) at load points. For people without vehicles the current system is not effective. The distribution of households without vehicles and households on public assistance is seen in Figures 4.20 and 4.21.

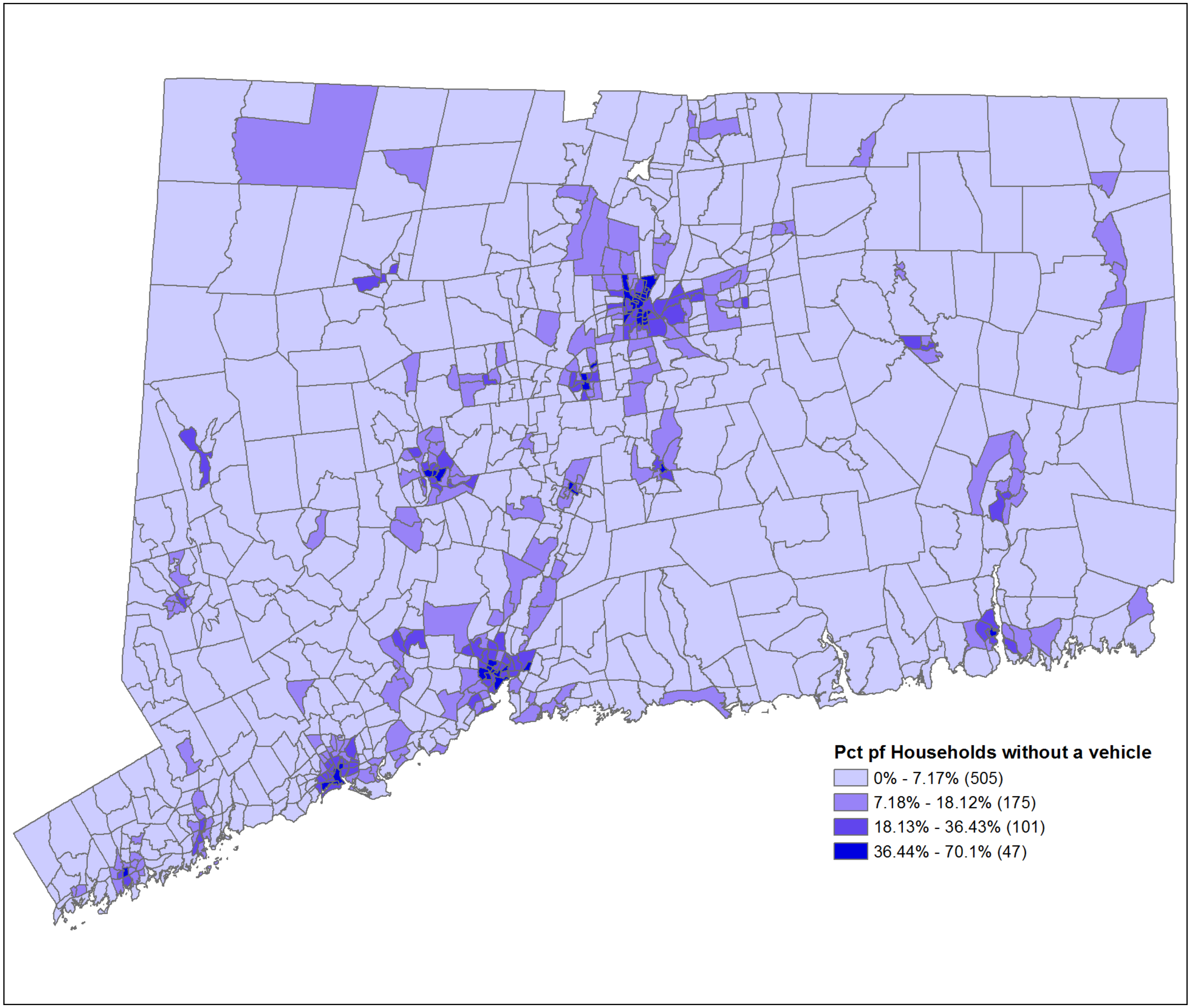


Figure 4.19 Percent of households without a vehicle in census tracts in Connecticut

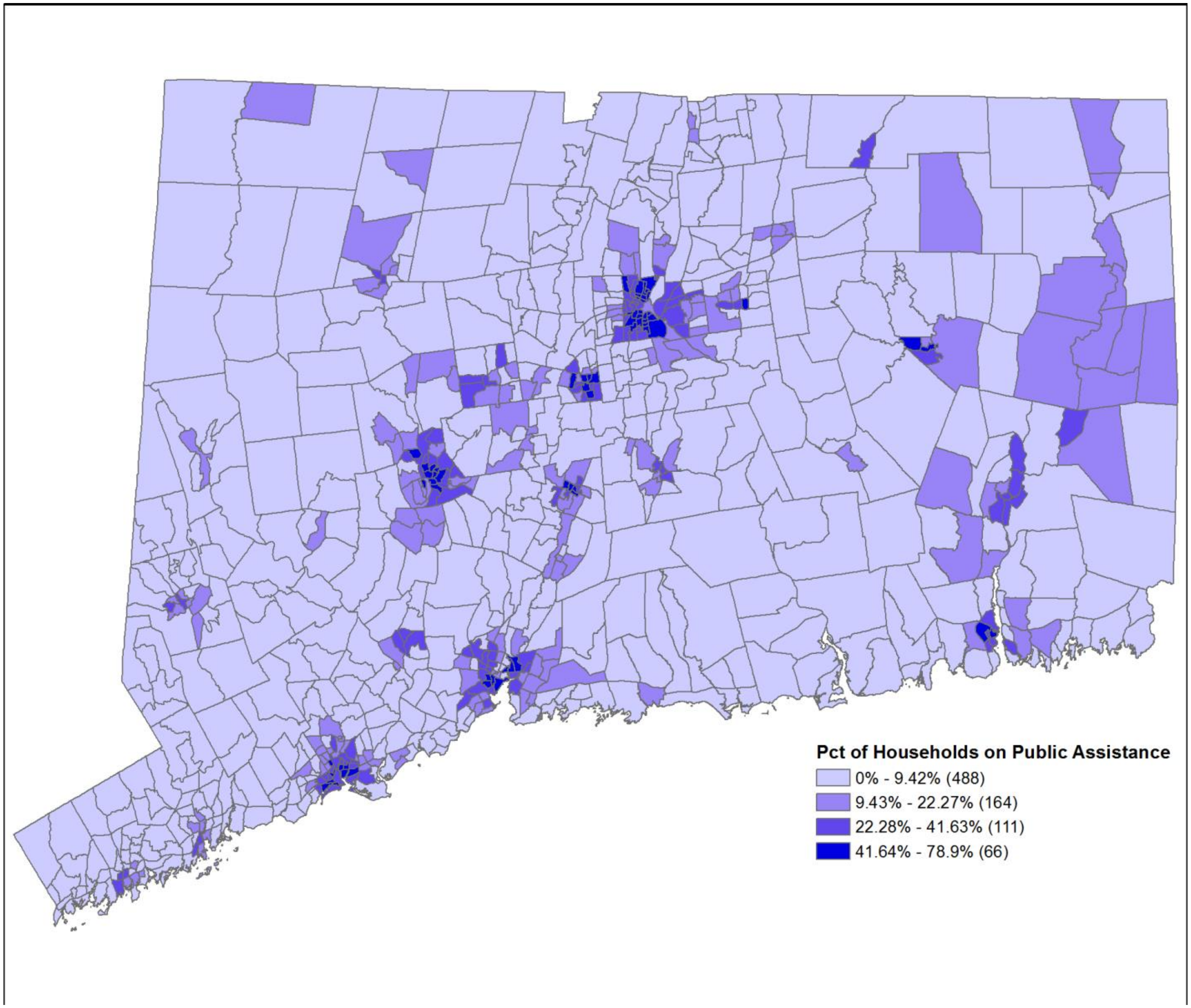


Figure 4.20 Percent of households on Public Assistance in census tracts in Connecticut (Source: U.S. Census Bureau 2010)

As discussed in Chapter Two there a several actual and proposed methods to determine and develop vulnerability indices to hazards. Cutter and Heinz Center succinctly compiled a list of such factors, a sample of these factors is shown in Table 4.5 (Cutter, Boruff, and Shirley 2003; “Human Links to Coastal Disasters” 2002). From this list of indicators and other similar ones Cutter, et. al. developed the Social Vulnerability Index (SOVI®) (Cutter, Boruff, and Shirley 2003). The goal of this research is not to “create” a new index or approach, but to integrate such information into a model for the distribution of relief supplies and aid. For modeling purposes the Social Vulnerability Index (SOVI®) maintained by the Hazards and Vulnerability Research Institute at the University of South Carolina will be utilized. This index is the same one proposed and develop by Cutter, et. al. The index utilizes 27 to 29 variables to determine the level of social vulnerability for a geographic area. A summary of the variables used for Connecticut’s SOVI® is in Table 4.6. The index is developed using factor analysis to reduce the number of variables that explain a large portion of the variance. The resulting variables are then placed into an additive model using Z scores to compute a summary score (Hazards and Vulnerability Research Institute 2014). The index will be used at the census tract level for the state of Connecticut. To measure a particular geographical area’s index value the area is ranked by 5-quantiles or quintiles within a larger area. Figure 4.22 shows how a particular areas vulnerability changes relative to its grouping. These differences for Connecticut and this research’s CCR is shown in Figure 4.23 and Table 4.7. Figure 4.24 shows the ranking system that will be utilized within the proposed model.

There is a drawback to the use of the SOVI®, and the drawback is that it offers a snapshot in time of an areas social vulnerability. However, many of the factors remain consistent, over time changes in data gathering and availability occurs. These changes make it difficult to compare the index over time periods. A strong argument has been presented for the

statistical integrity of the index over varying area sizes (Schmidtlein et al. 2008), but changes in available data at the time the index is formulated may cause problems with it translating over time periods. Similar problems occur with changes of area delineation, data available at the state or county level is not necessarily available at the tract or block levels.

Table 4.5 Some Vulnerability Factors

Characteristic	Description	Influence on Vulnerability
Socioeconomic Status	This gives indication of how a place can absorb losses. Encompass things like a places wealth, political power and safety net infrastructure	High wealth and/or power (+) Low wealth (-)
Age	Age composition of a place may affect the movement out of harm's way.	Elderly (+) Children (+)
Commercial and Industrial Development	The value and density of these give insight into the economic health of a place	High density (+) High value (+/-)
Infrastructure and lifelines	Weakened or aged sewer systems, water systems, bridges, highways and communications have a ripple effect through a disaster	Infrastructure (+)
Housing stock	The type, value and density of housing available in a place	Mobile homes (+)
Rural/Urban	Rural areas may be poorer with fewer resources. Urban areas may have higher densities making evacuation difficult	Rural (+) Urban (+)

This is not an exhaustive list of all the factors that might go into formulating a vulnerability index to hazards. This a representative list as compile from a longer list developed by the Heinz Center. ("Human Links to Coastal Disasters" 2002)

Table 4.6 Components of SOVI®

Component	Cardinality	Name	% Variance Explained	Dominant Variables
1	+	Ethnicity and Class	31.795	Percent with Less 12th Grade Education
				Percent Hispanic
				Percent Poverty
				Percent Housing Units with No Car
				Percent Female Headed Households
				Percent Renters
				Percent of Civilian Unemployed
				Percent Employment if Service Industry
				Percent Speaking English as 2nd Languge w/ limited prof.
				Percent Black
				Percent Native American
				Per Capita Income
				Median Age
				Percent of Children living in Married Couple Families
2	-	Wealth	13.138	Percent of Households earning > 200K
				Median House value
				Per Capita Income
				Median Gross Rent
3	+	Age	9.465	Percent of population < 5 yrs old or 65+ yrs old
				Percent of Households receiving Social Security
				Median Age
				Percent of population living in nursing facilities
4	+	Gender (Female)	5.584	Percent of Females in Labor force
				Percent of population female
5	-	Ethnicity (Asian)	5.584	Percent Asian
6	+	Unoccupied Housing	5.081	Percent of Unoccupied Housing Units
				Persons per Unit
	Cumulative Variance Explained		71.177	

Tract level 2006-10 Social Vulnerability Component Summary for the State of Connecticut. The dominate variables are listed within each component in the order of each variables dominance. The cardinality indicates whether that component adds to or subtracts from the tracts vulnerability (Hazards and Vulnerability Research Institute 2014).

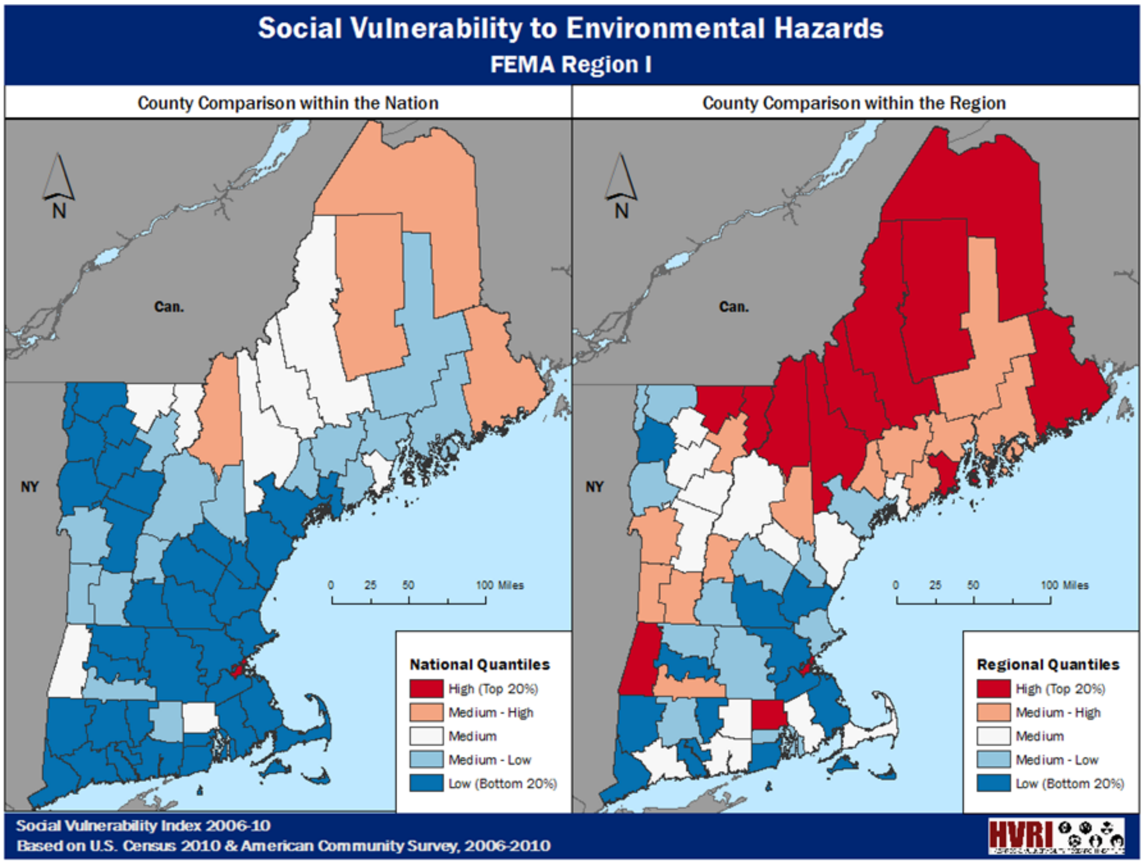


Figure 4.22 Comparison of how SOVI ranking can differ with regards to the larger overall group it is compared within (Hazards and Vulnerability Research Institute 2014)

Table 4.7 Comparison of different SOVI® Rankings

Ranking	Number of rank (ranked among all state tracts)	Number of rank (ranked among all coastal tracts)
High	21	24
Medium High	55	61
Medium	115	89
Medium Low	53	63
Low	15	24

The universe in which the SOVI® is ranked effects the quantities ranked in each rank.

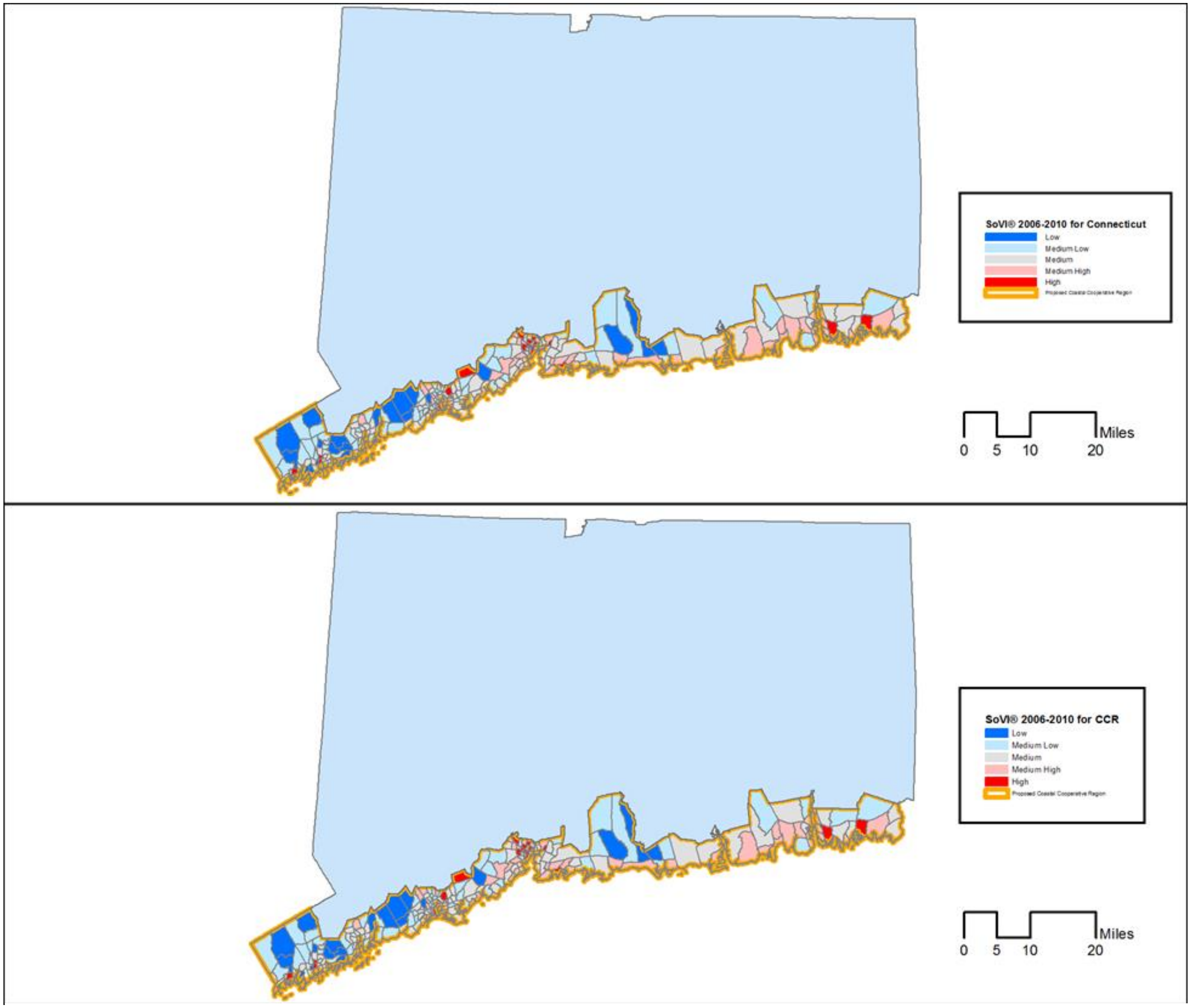


Figure 4.22 Comparison of using quintile ranking index for entire state versus ranking for the tracts in the CCR (Hazards and Vulnerability Research Institute 2014)

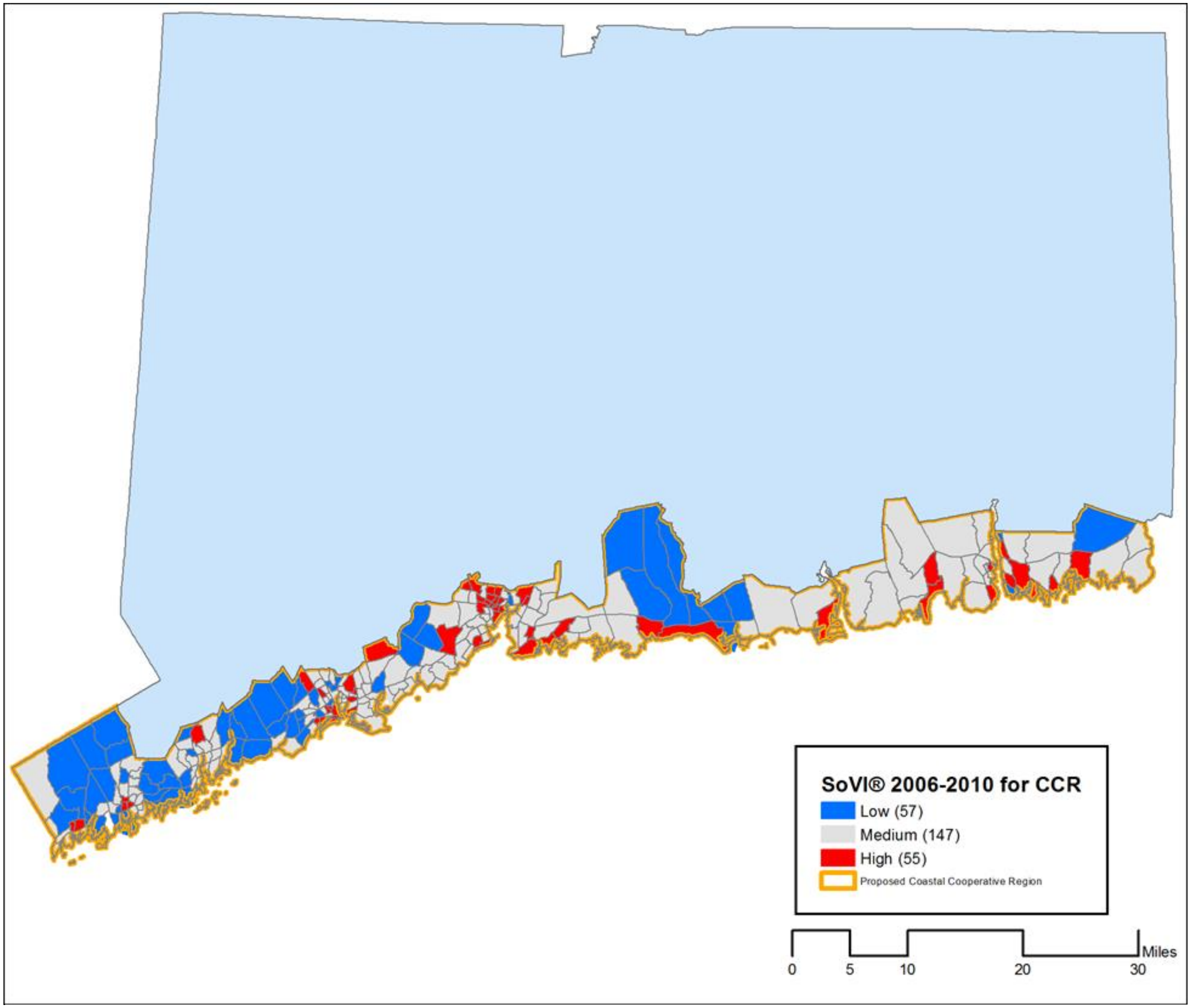


Figure 4.23 Tertile ranking for the CCR. This is the ranking that will be used in the proposed model (Hazards and Vulnerability Research Institute 2014)

4.5 Summary

In examining the state of Connecticut, it was found that the proposed model could be beneficial to the state in the event of a disaster. Connecticut has a history of all types of disasters. The state is located in a highly urbanized densely populated area of the United States. The state contains counties that have continued population growth and increases in density. Connecticut by some measures is consider a "rich" state. However, examination of some economic factors points to some extremely poor areas within the state. There are sixty-six census tracts that have well over 40% of households receiving public assistance, with some of those tracts located in one of the richest counties in the country. Similarly, in forty-seven tracts over 36% of the households do not have a vehicle. This factor is important because the current distribution system depends on people who require supplies to have access to a vehicle.

Though it is complex to develop a measure of a population's vulnerability to a disaster there have been attempts. The SOVI® is one of the more comprehensive attempts. The index can be used at varying geographical scales. However, it cannot be compared across differing geographies because the components of the index may change. This is because differing levels of data are available at differing geographies. The index is also a snapshot in time, and it cannot be compared over periods. The reason is the same as for differing geographies – the components may be slightly different over different periods. The index does offer an ability to test the concept of the proposed model. The index provides a compact way to enter vulnerability levels into the model.

Moving forward the information in this chapter will be utilized in Chapter Five. In Chapter Five, the proposed model will be tested using the SOVI® for Connecticut at the census

tract level, and actual population demands. The proposed model will use as its foundation the proposed CCR, from this chapter, and the located PODs.

Chapter Five

Model Testing and Analysis

5.1 Introduction

In this, chapter theoretical and reality are merged. The proposed model, developed in Chapter Three, will be used to build a disaster relief supply chain for a region in the State of Connecticut. Data that was presented in Chapter Four will be used within the framework of the proposed model. The proposed model to locate distribution facilities will utilize actual census and road network data, for the proposed Coastal Cooperative Region (CCR). Once the model is tested for an event affecting the entire region, the model will be further tested using a simulated disaster event, and the resulting locations of transshipment points are used as a foundation for a hub network.

The discussion in the chapter outlines the four aspects of how the proposed model is tested. The chapter has a brief overview of how ArcGIS is used to develop a road network using publicly available data sources. The chapter furthers the discussion about the adequacy of the

current POD system that was introduced in Chapter Four. Throughout the chapter, the general performance of the proposed model is examined under changing parameters.

5.2 Overview of Model Testing

The disaster relief logistic model developed in Section 3.4 (Equations 3.29 – 3.36) in Chapter Three had a multi-criteria objection function which balanced the following competing goals against one another: 1) minimize the total distance—weighted costs of the POD—BBP system; 2) minimize the number of uncovered “more” vulnerable demand sites; 3) minimize the total demand – weighted costs in the BBP—neighborhood system and 4) minimize the total fixed facility costs of the BBPs. The relationships of the objectives is outlined in Figure 5.1.

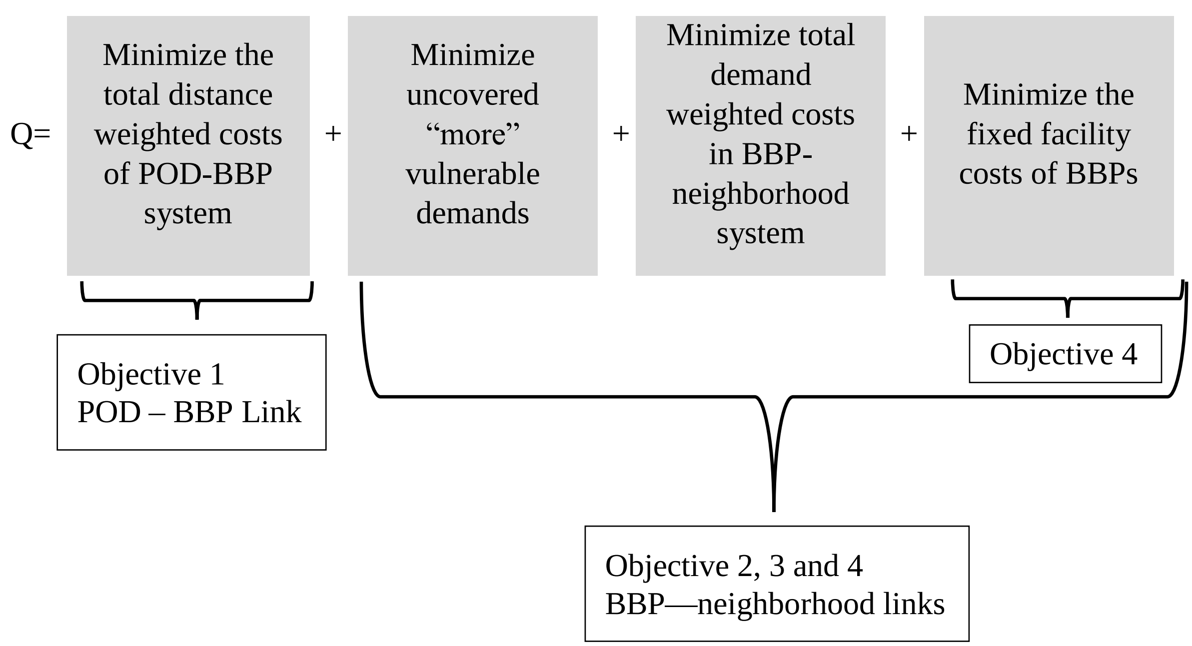


Figure 5.1 Relationships of objectives in proposed model

During the testing process of the proposed model, using “real” or “live” data the entire model was tested, but during the different phases the performance of particular objectives was the focus of the analysis. In the initial phases of testing, it was assumed that the entire CCR was affected by a disaster event. The performance of the first objective, the POD – BBP link, was the focus of the first phase of testing. In this testing phase, a large pool of available POD locations could be made smaller. The next phase of testing objectives two, three and four were the focus of the testing. In this phase the BBP – neighborhood links were examined under varying parameters. The range of number of BBPs to locate or p value was varied from 5 to 85. As with the POD – BBP link analysis the model was tested with all available POD locations and then with smaller sets of POD locations. In addition to varying the p value, a cost factor multiplier was tested on the BBP – neighborhood link. The third phase of testing took values for p and the set of POD locations, found in phases one and two, and used those parameters to be tested in a simulated disaster event. Using publicly available software, from FEMA, the historic 1938 hurricane was recreated. In this phase, a smaller set of affected census tracts in the CCR was tested. The final phase of testing entailed taking the results from the simulated event and transforming those locations into a hub network.

The final goal of the phases one through three was to build a distribution network, as shown in Figure 5.2. In the figure, the LSA is outside of the proposed model. The network assumes that goods move from the LSA to PODs efficiently, and within the model, the goods travel from the PODs to the BBPs, then onto neighborhoods. Neighborhoods are the demand points, and BBPs are chosen from the set of neighborhoods. The POD locations are known.

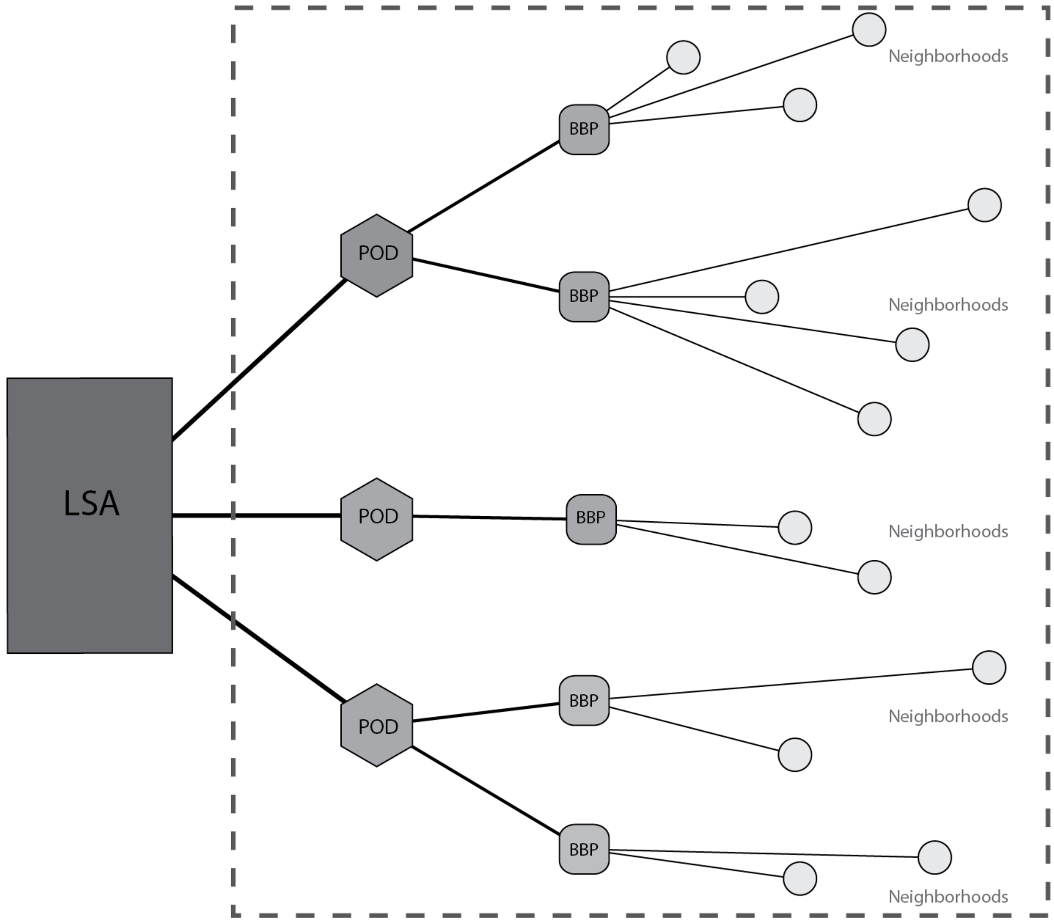


Figure 5.2 Diagram shows the Logistic Staging Area (LSA) to PODs to BBPs to Neighborhoods system. The parts contained within the gray dashed box are those considered by the proposed model.

5.3 Developing the Network

To test the proposed model a network was developed using ArcGIS Network Analyst. At the foundation of the network was a road network from OpenStreets obtained from ArcGIS Online Services (as seen in Figure 5.3). . This street network was publicly available, and the network contained the minimum requirements for a street network that could be used by ArcGIS Network Analyst Toolbox. ArcGIS transformed the street network into a network dataset. This transformation turns the street map into a system of nodes and junctions from which the ArcGIS Network Analyst Toolbox can use to perform calculations. Figure 5.4 shows the nodes, edges and junctions produce to complete the network dataset.

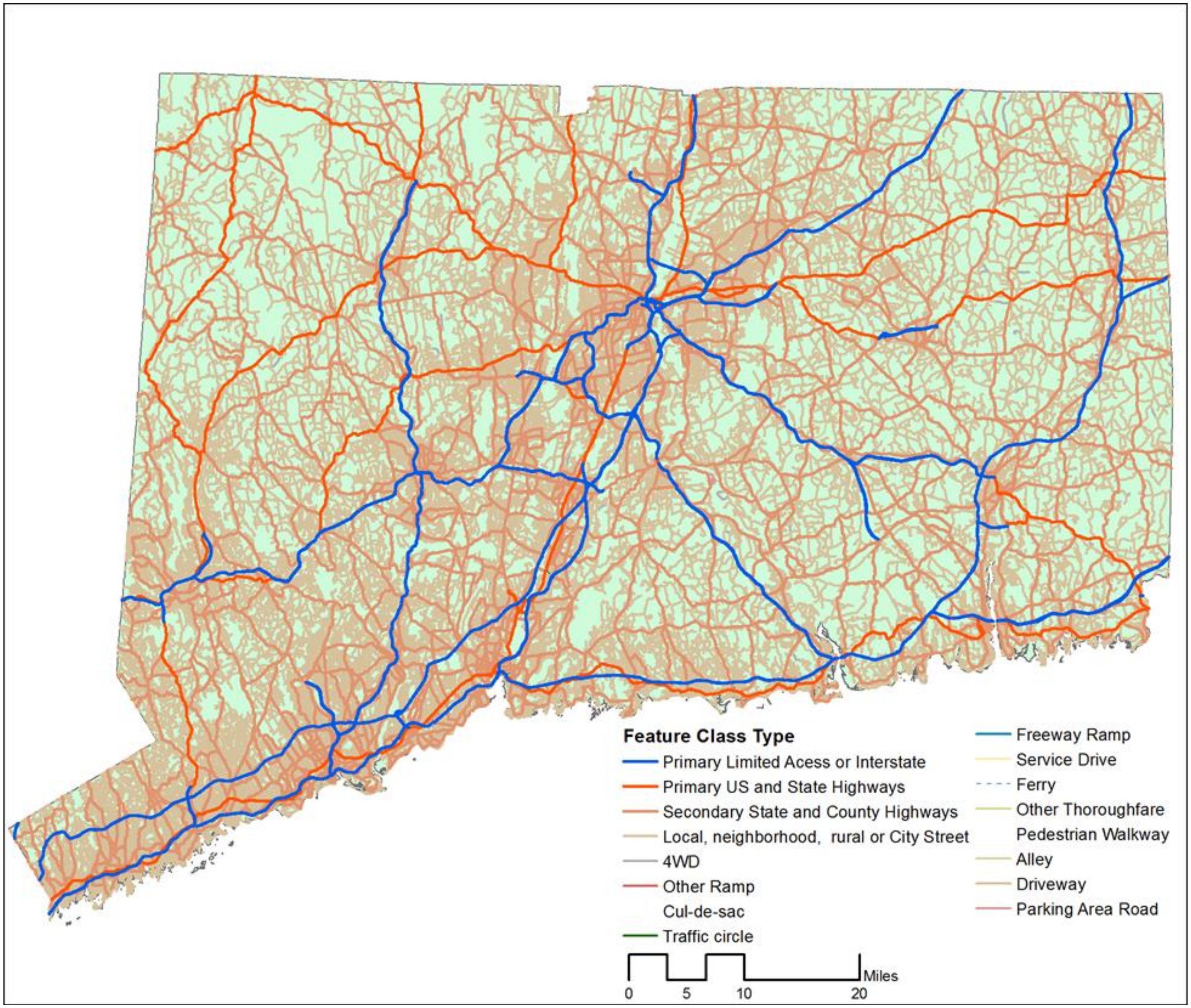


Figure 5.3 OpenStreets network obtained from ArcGIS Business Analyst. This network was used to develop a network dataset in ArcGIS. That dataset was used as the foundation of developing an origin and destination matrix

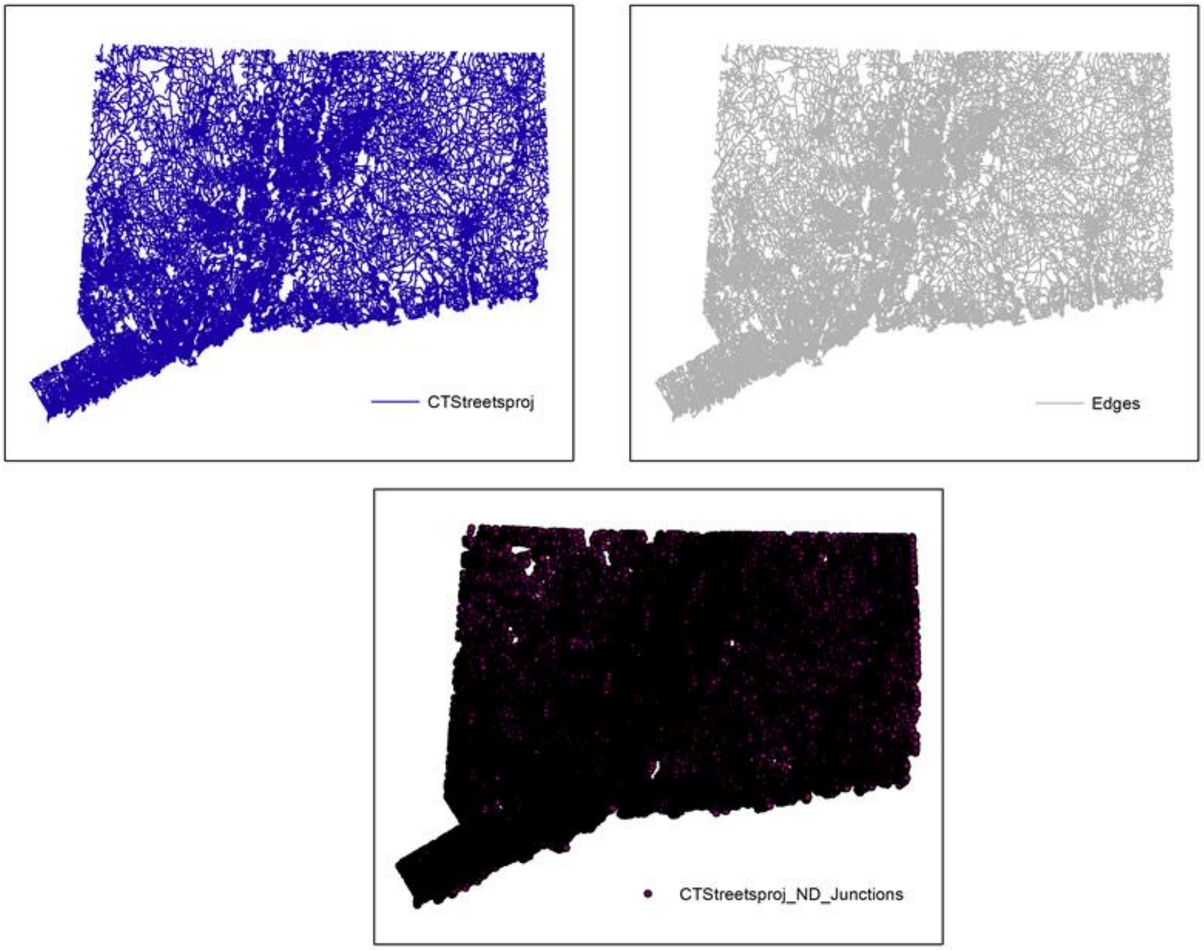


Figure 5.4 Various components of the Network dataset created by ArcGIS for use in the Network Analysis Toolbox

5.4 Points of Distribution System

To integrate the proposed system for disaster relief supplies into the current system the use of the current Points of Distribution System (PODs), utilized by the state of Connecticut, was decided as the starting point of the model. Recalling from Figure 5.2 the proposed model attempts to take goods from the Logistical Staging Area (LSA), operated to by the state, to the PODs and down the Bulk Breakout Points (BBP) and finally to the neighborhoods. The proposed model moves the goods from the PODs to BBPs and on to the neighborhoods. The leg from the LSA to the POD is left for future analysis.

As discussed in Chapter Four the current system encompasses 271 locations, with fifty-five of those locations are located within the CCR. Figure 5.5 shows the location of all the PODs statewide, and Figure 5.6 highlights the ones located in the proposed CCR. Each of these locations is considered a FEMA Class III POD. A Class III POD is defined as having a capacity of 5,000 person/day or about 1660 households (FEMA/USACE 2008). However, for this model the capacity of the PODs is not under consideration. The PODs, under the proposed model, will transform into transshipment points as oppose to "drive-thru" pick up locations. It is anticipated that the PODs will still function at some level as pick up locations – but that is not factored into the proposed model. The candidate POD sites were located on the network using actual street addresses obtained from the State of Connecticut and those addresses were geocoded by ArcGIS. Table 5.1 offers a sample of the format the locations' addresses.

Table 5.1 Sample of POD addresses used for geocoding

Name	Street	City	Zip
Walmart Lot	120 Commercial Parkway	Branford	06405
Food World Parking Lot	345 Huntington Turnpike	Bridgeport	06610
Shaw's Supermarket Parking Lot	500 Sylvan Avenue	Bridgeport	06606
.	•	•	•
.	•	•	•
.	•	•	•
Bedford Middle School	88 North Avenue	Westport	06880
Kings Highway Elementary School	125 Post Road W	Westport	06880

(State of CT Commodities and Resource Support Group, 2102)

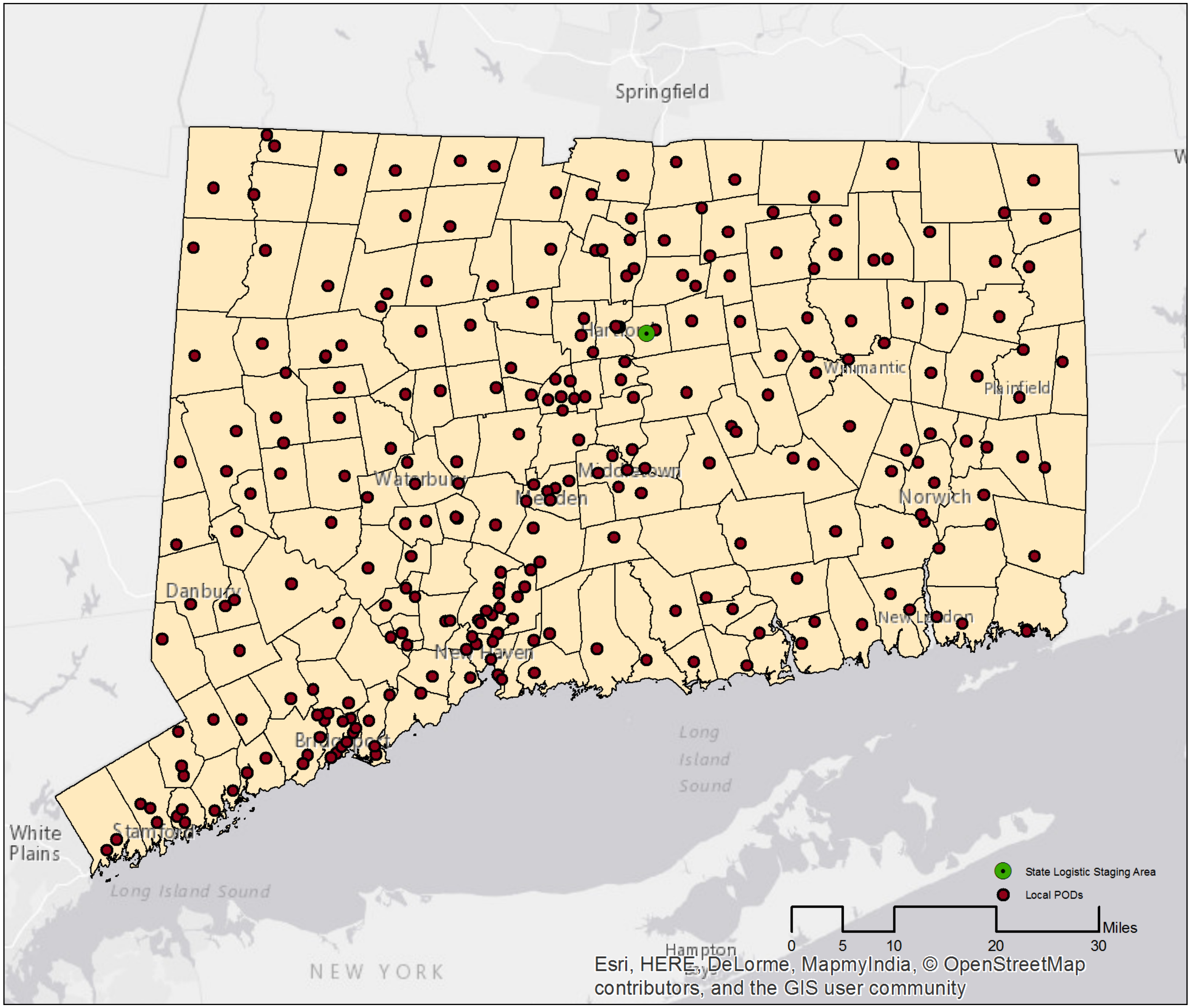


Figure 5.5 Location of all PODs within the state of Connecticut (State of CT Commodities and Resource Support Group 2012).

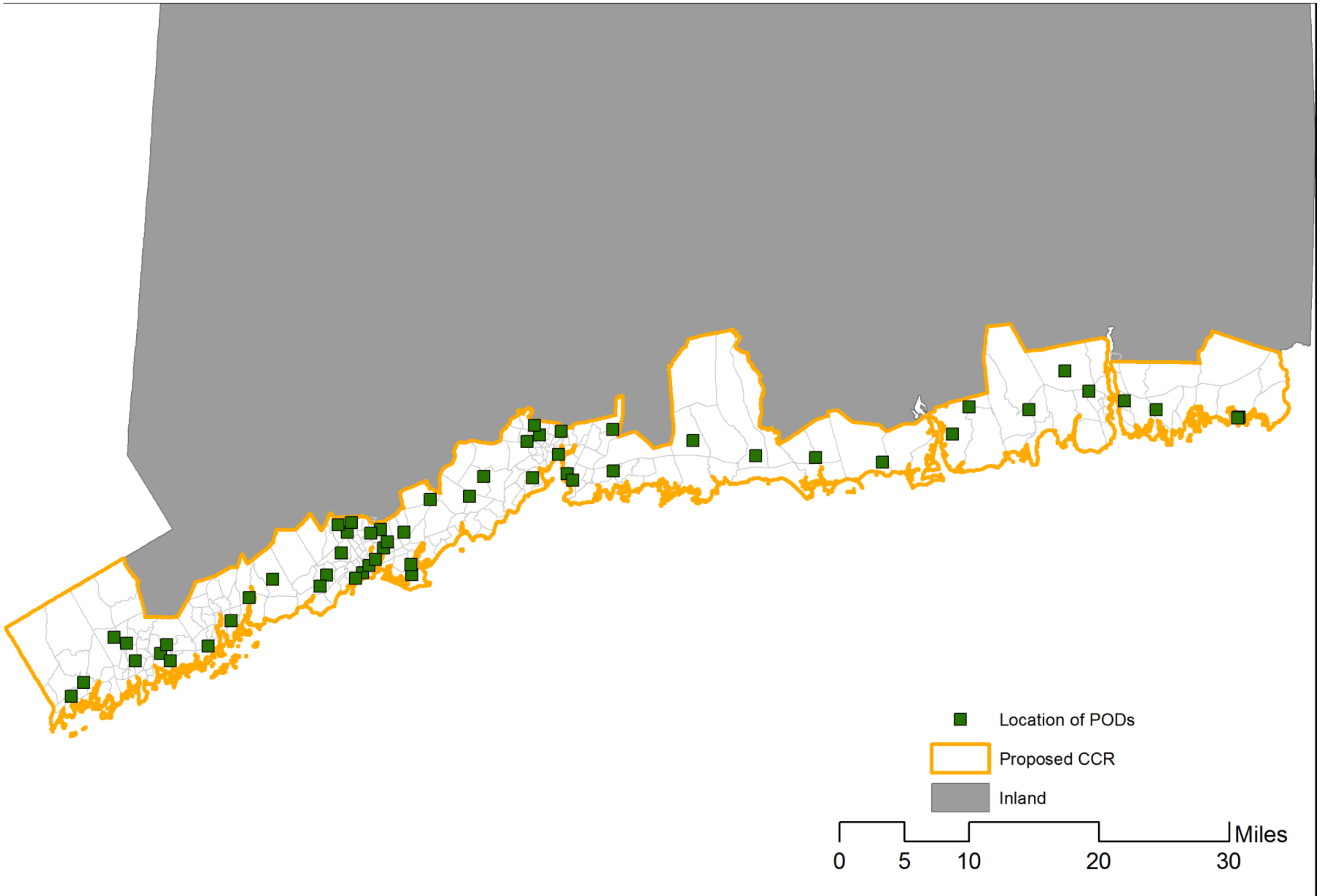


Figure 5.6 Location of established PODs within the CCR.

Trade Area analysis of the current POD system was examined in Chapter Four. Using ArcGIS Business Analyst 2014 descriptive trade areas for each location was established. A descriptive trade area is one in which the customers are described in spatial and aspatial ways. What the Business Analyst did when given the spatial distribution of the potential stores (PODs) was that it used internal data sources regarding population and households to estimate a trade area for each POD. This analysis was carried out in two ways, and examined visually for any patterns. The first analysis was conducted using number of households as the threshold. As would be expected the PODs located in more densely populated urban areas had smaller trade areas then more rural less populated areas. The second analysis was performed using driving distance. This analysis revealed much more geographical coverage than the household threshold – however, there may also be much more overlap among trade areas, which could indicate inefficiencies in the siting of the PODs. Figures 4.9 and 4.10 further this discussion.

The purpose of the analysis was to see if in fact the current POD system had adequate coverage. Visually, as the discussion in Chapter Four reinforces, it does appear that the current system does have adequate geographical coverage. However, the current system is an automobile centric "drive thru" distribution plan. This adequate coverage does confirm that the current POD system forms can form a foundation for the proposed model.

Since, the proposed model uses the current PODs primarily as a transshipment point from the LSA to the BBP it was determined that the number of PODs the model could choose from could be less than the current number of available locations. The proposed model was run using all fifty-five available POD locations within the CCR. The number of PODs utilized by the model reached a maximum of thirty-nine. Figure 5.7 summarizes the relationship among Number of BBPs; Number of PODs sited and distances and Figure 5.8 shows the model run with p=80

and availability of all PODs. This result offered insight that the model could function with less than the fifty-five PODs available. Further evidence of this type of reasoning was found in a restriction used by a similar model by Horner and Downs (Horner and Downs 2007). Their restriction on the POD universe was as follows:

PODs < defined number of BBPs < Neighborhoods

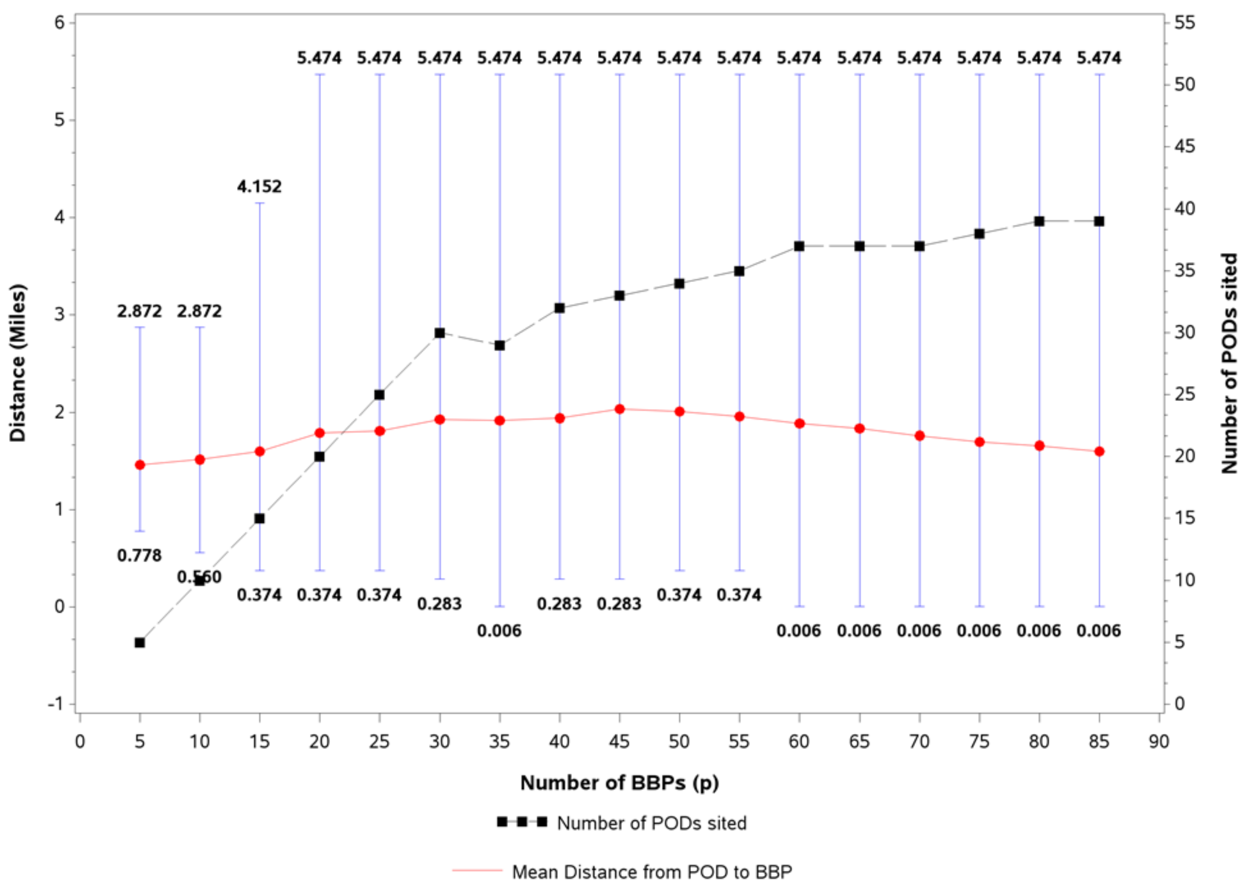


Figure 5.7 Graph shows the relationship between number of BBPs, PODs and distances. Blue "candlesticks" show the distance range from POD to BBP for each BBP or p

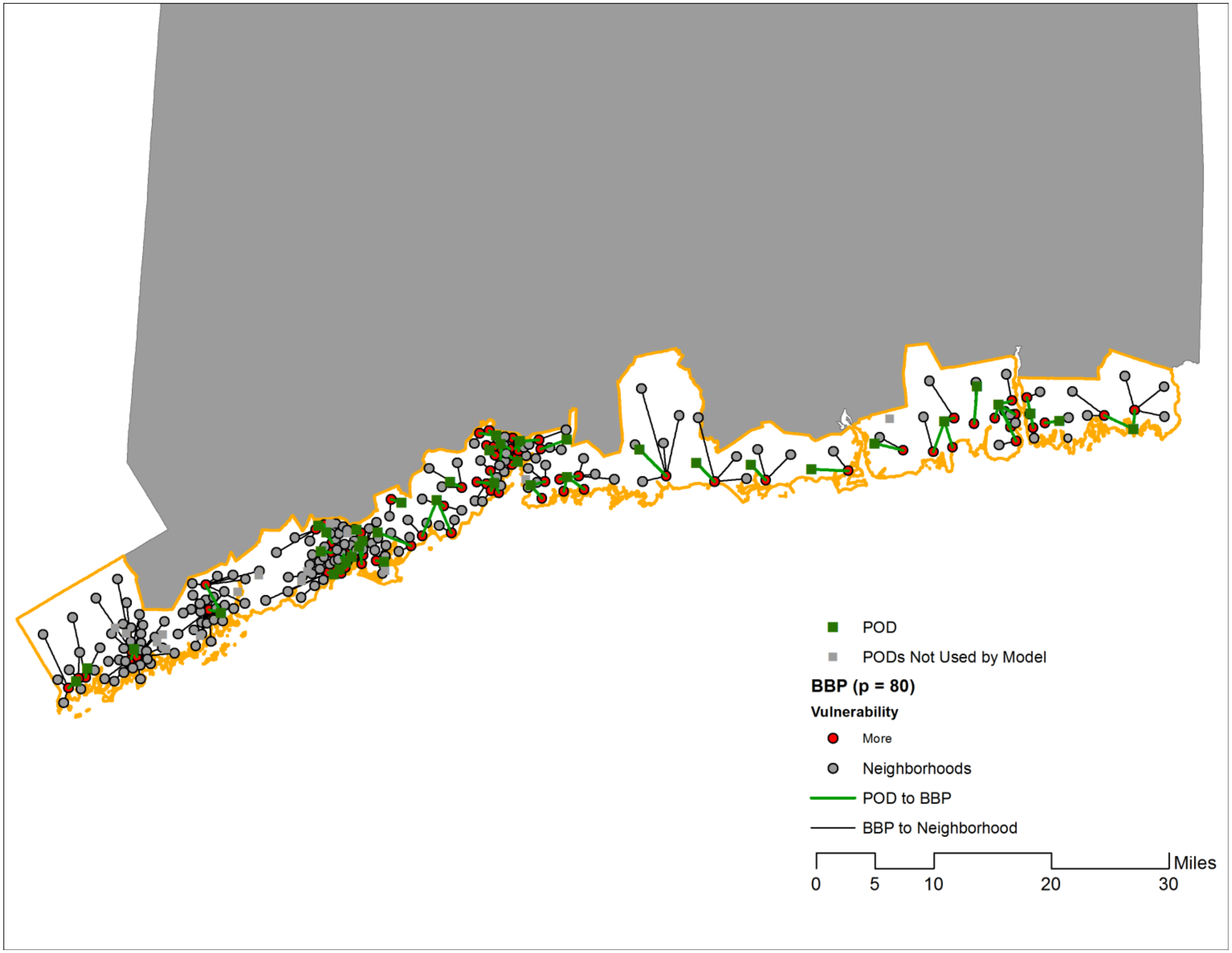


Figure 5.8 Example of the model run with all POD locations available to be sited (p=80). All BBPs are sited in neighborhoods that are more vulnerable and the system uses 39 PODs out of the 55 available.

During the model development, for this research, the lack of such a restriction did not appear to cause any difficulties in the proposed model's performance. The Horner and Downs restriction does offer guidance that a smaller set of PODs could be used within the proposed model. In the same model, Horner and Downs placed a restriction of the number of intermediary distribution points each POD will service. They define it as a "user defined number locations" that is served by each respective POD location. For this research's model, this type of restriction does not seem appropriate, because as Horner and Downs illustrate in their model, such a restriction will cause unanticipated distances between PODs and the intermediary or BBP locations. In other words, the model will "force" a POD site to service a BBP to meet the service restriction, and will affect the efficiency or true optimization of the system. Table 5.2 shows the average distance from POD to potential BBP locations for various sets of POD locations. These average distances were determined from the Origin-Destination Matrix generated by ArcGIS Network Analyst using candidate POD sites as Origins and candidate BBP sites as Destinations.

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Table 5.2 Average Distance to BBP for various POD sets

POD Location Candidate Sets	**Average Distance to candidate BBP Site (Miles)**
All available candidate POD sites	34.23
PODs located at 18 more vulnerable candidate sites	31.69
PODs located at 9 more vulnerable candidate sites	27.37
PODs located at 4 more vulnerable candidate sites	30.94

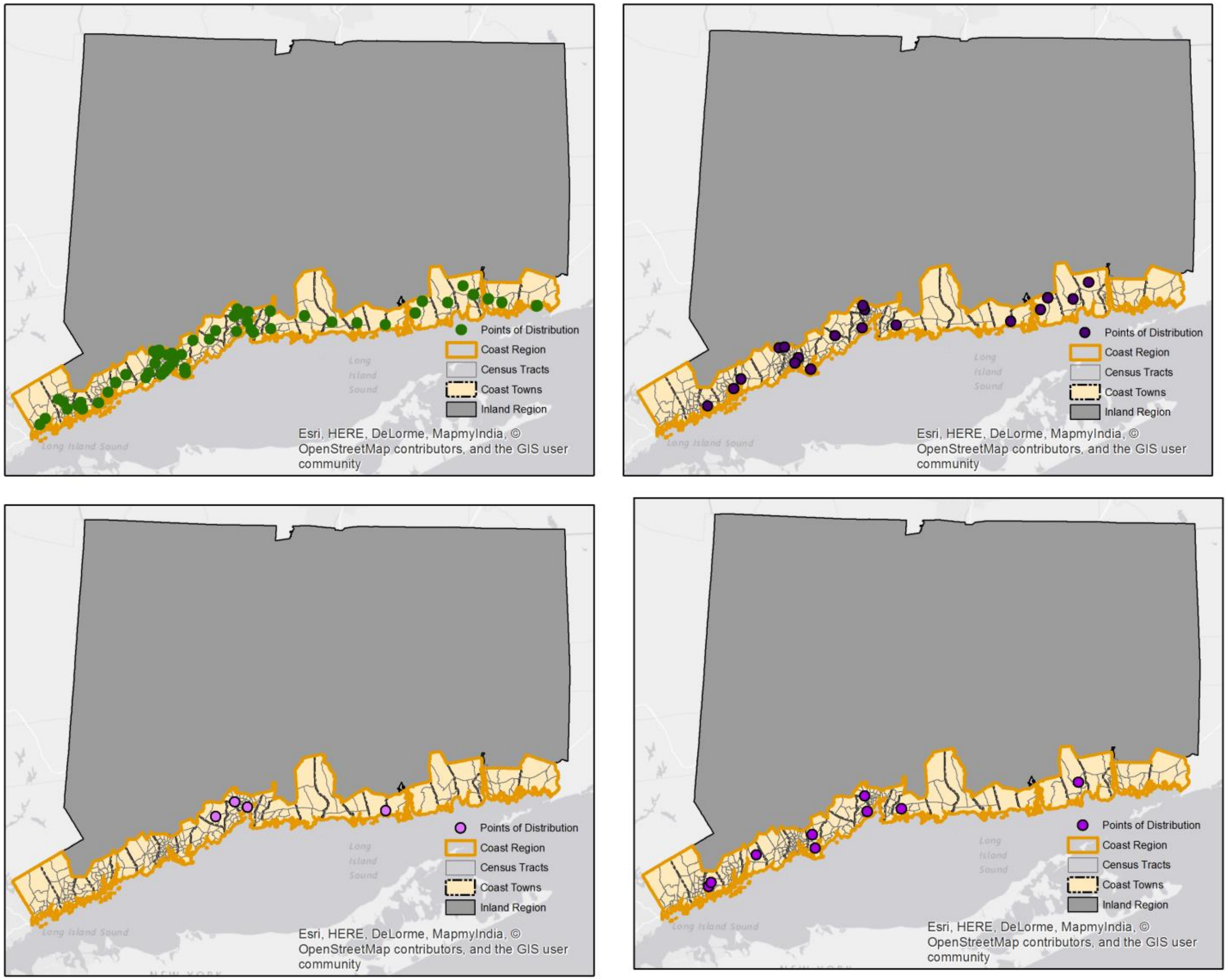


Figure 5.9 Randomly selected POD locations Clockwise from the upper left corner are all the available locations, 18 randomly selected locations; 9 selected locations; and 4 locations

The universe of PODs was further shrunk by randomly selecting eighteen, nine, and four POD locations from all the available locations in the CCR (as seen in Figure 5.9). At this time in the application of the model, some "soft" operational parameters were needed to be established. These parameters would put the model's efficiency within context. The first such parameter was that BBP could be serviced by a POD within a mean distance between 5 and 15 miles on the network. Figure 5.10 and Table 5.3 summarizes the results of the various testing of the different POD location sets.

When examining the socioeconomic indicators of the CCR a particular pattern was observed. This pattern was apparent in the examination of More Vulnerable neighborhoods in relation to other More Vulnerable neighborhoods. Both cluster and hot spot analysis show that the areas of concentration of More Vulnerable neighborhoods is in the western part of the CCR. With this pattern in mind three additional sets of POD locations were developed. In each of these sets, the PODs located in the tracts with the highest vulnerability scores were used as locations for the model to choose. The sets were comprised of eighteen, nine, and four locations; Figure 5.11 shows the locations for each respective set. Since these sets were chosen for a specific characteristic, being located within a more vulnerable neighborhood, the spatial distribution of each set of POD locations was examined to determine if the set was similar in distribution as to the original set of fifty-five. The spatial distribution of set of PODs located within neighborhoods that are more vulnerable is shown in Figure 5.12. The spatial distribution for the sets containing eighteen and nine available PODs was similar to the set of fifty-five. The set containing four PODs had distribution too narrow and orientated too far west. Figure 5.13 is the locations of the candidate POD sites that will be used in further testing of the proposed model. This is the set of eighteen candidate sites located in tracts that are more vulnerable.

Table 5.3 Range of POD-BBP distance and number POD sited

Available PODs (to be sited)	Range of Mean Distance (Miles)	Range of PODs sited
All	1.458 - 2.035	5 - 39
18 More Vulnerable	4.833 -6.795	5 - 18
9 More Vulnerable	9.804 - 14.385	4 - 9
4 More Vulnerable	12.485 - 16.929	4
18 Random	3.993 - 6.190	5 - 16
9 Random	6.069 - 8.716	4 - 9
4 Random	14.976 - 20.837	3 - 4

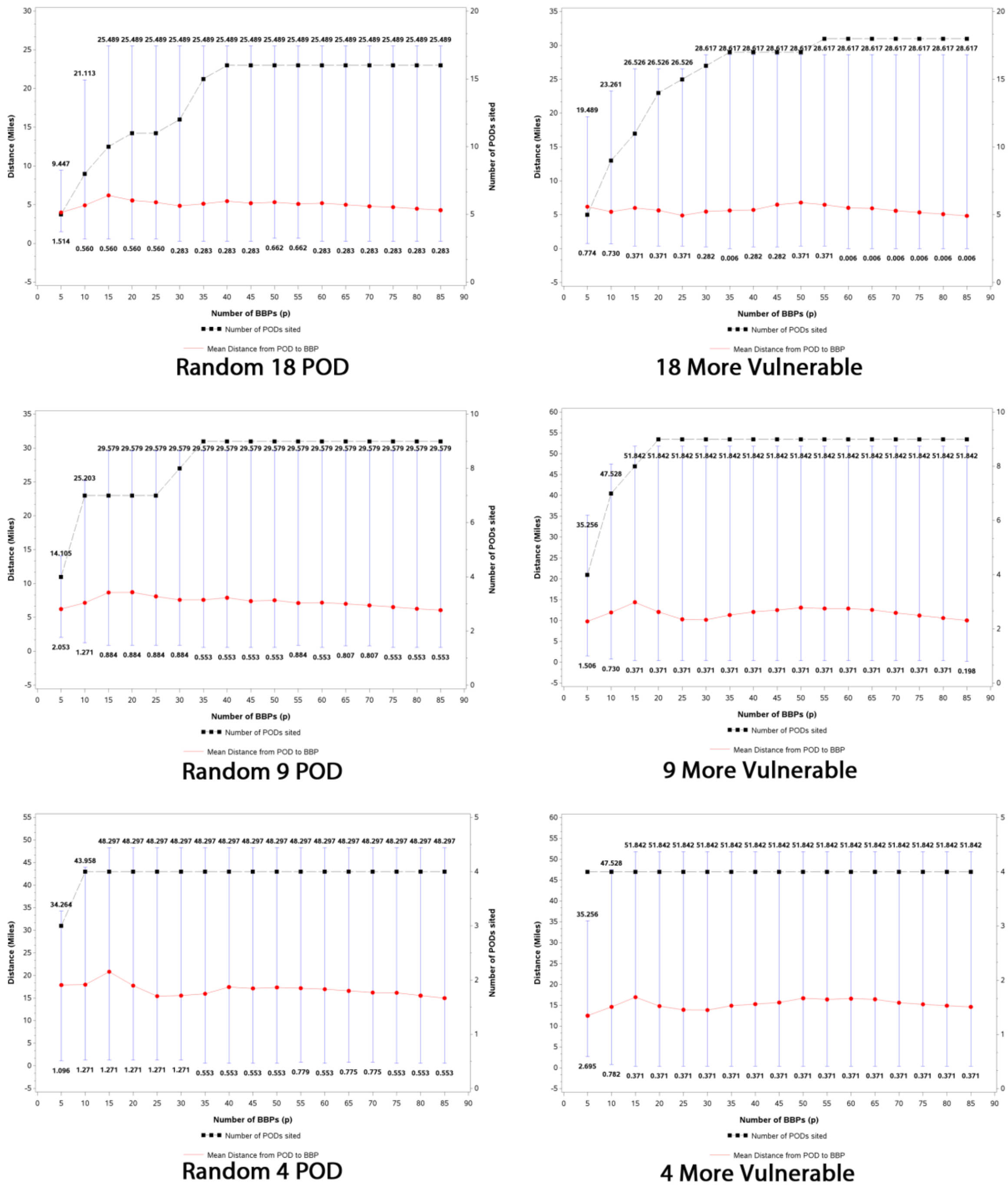


Figure 5.10 Testing of Various POD sets

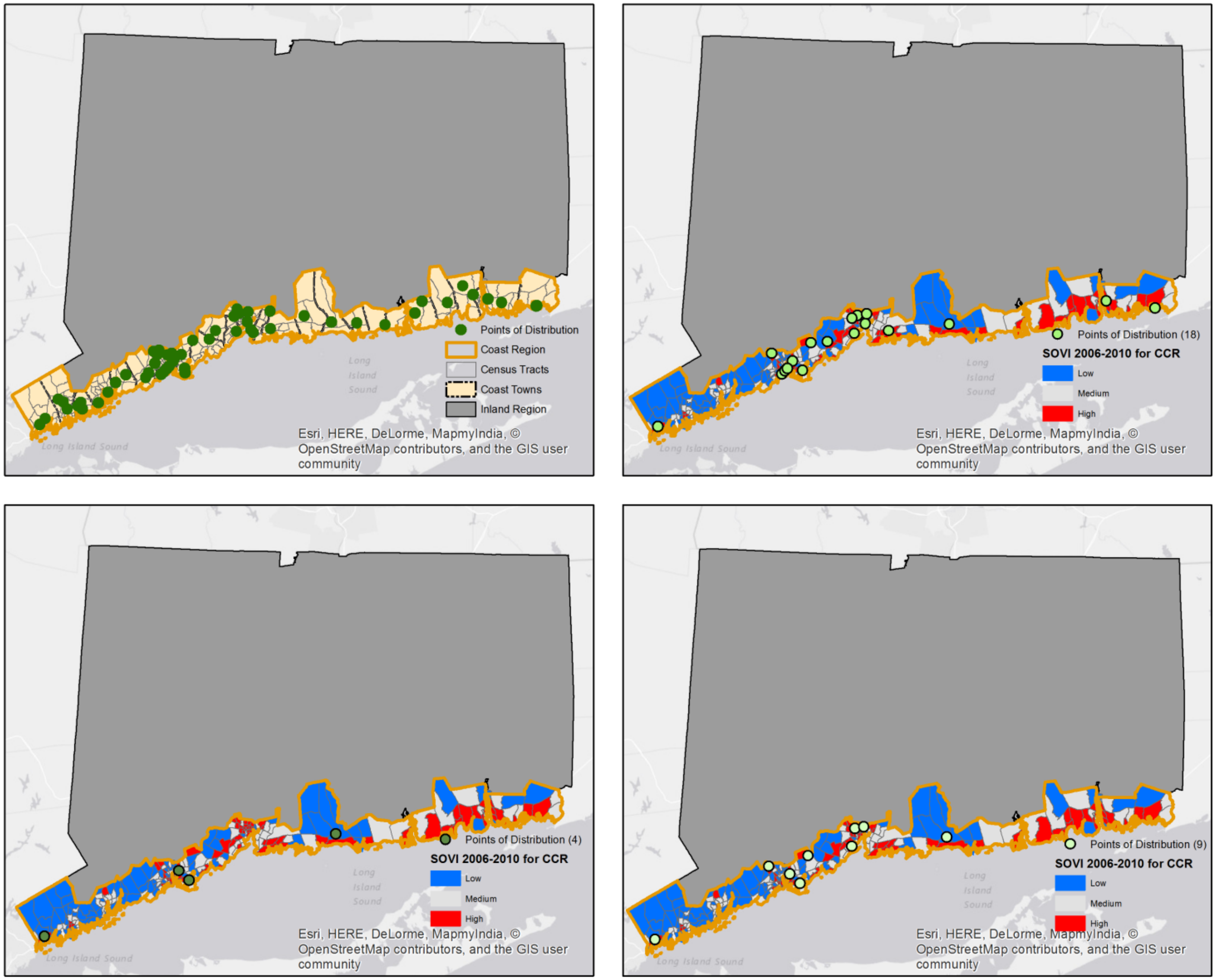


Figure 5.11 PODs sets determined by PODs located in neighborhoods that are more vulnerable

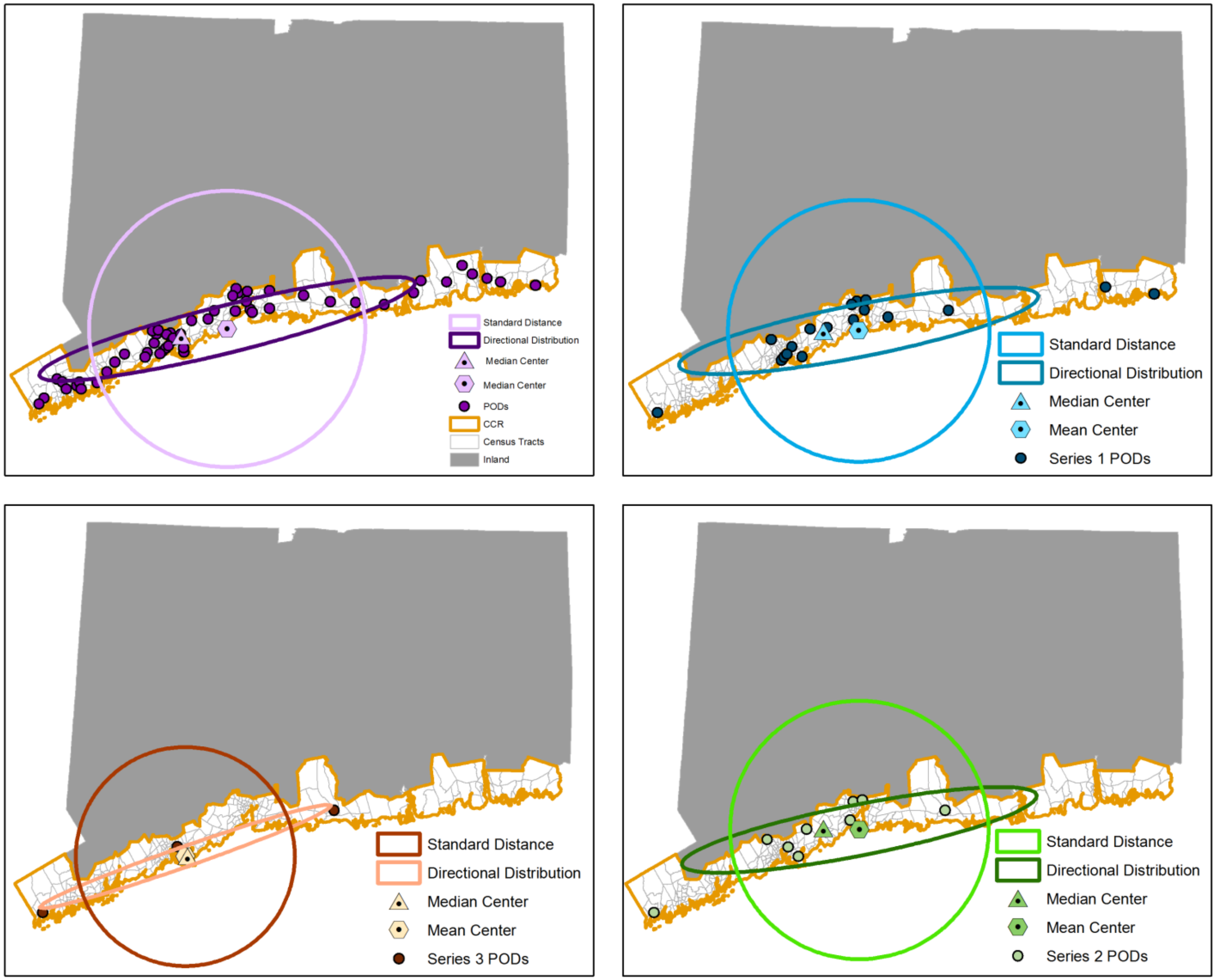


Figure 5.12 Spatial distribution of various sets of PODs. Clockwise from upper left corner: All available PODs; set of 18 located in more vulnerable neighborhoods; set of 9 located in more vulnerable neighborhoods; and set of 4 located as such

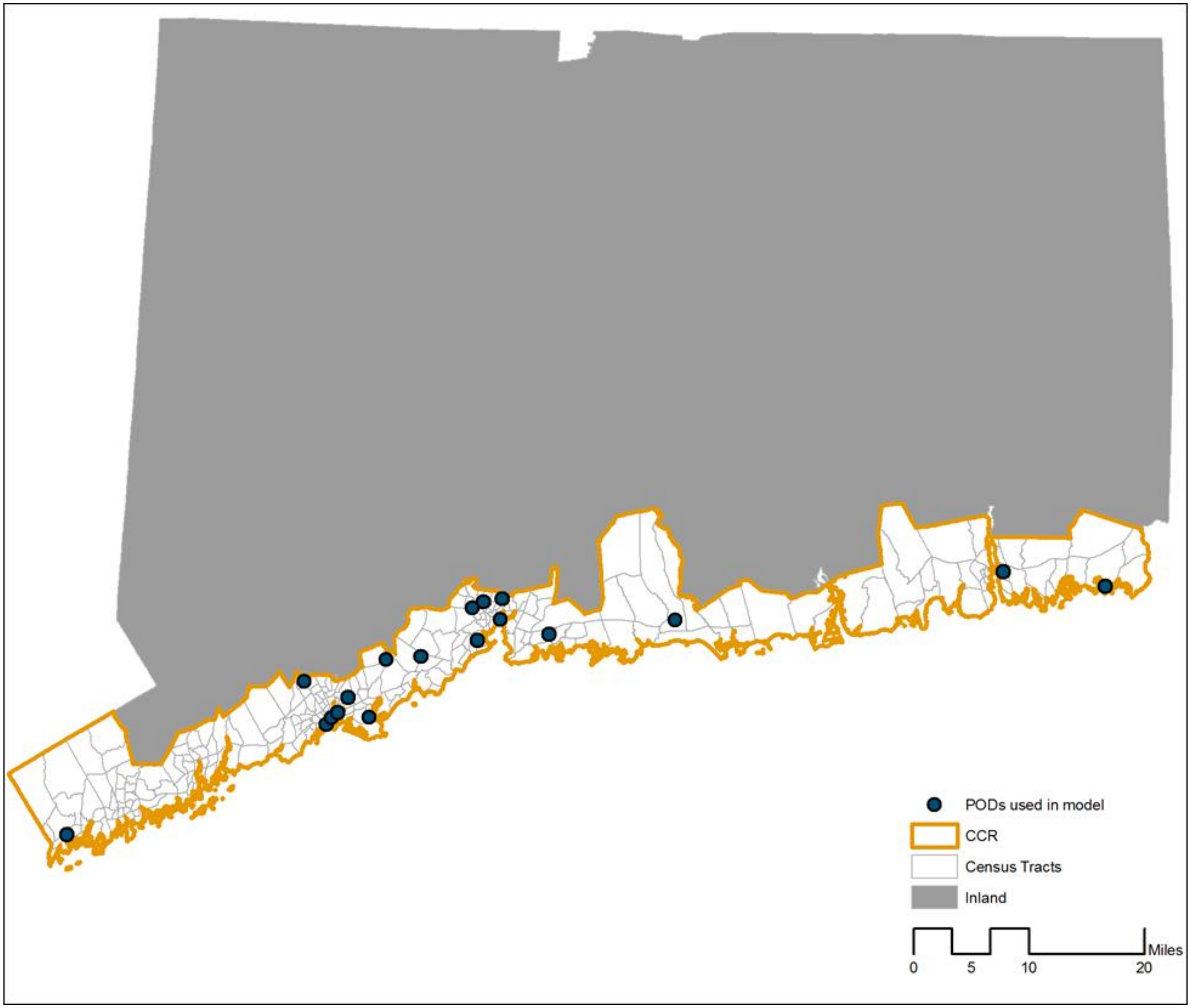


Figure 5.13 POD candidate location set determined to be best for the model. With a range of average distance of BBP to Neighborhood link of about 4.8 to 6.8 miles, and min/max range of about 0.4 to 28 miles.

During the research of the current POD system a casual examination of the current locations was done, and what was found was that some of locations may not be suitable to be POD sites or up to FEMA standards. Though site suitability is not the focus of this research it must be understood, that under the proposed model, site requirements may have to be more strictly followed. The proposed system does believe that the POD locations could fulfill both missions of being a traditional drive through POD and a transshipment point. These goals can only be achieved if the site locations are sized properly and have the appropriate amenities to allow both operations. For now, mathematical examination of this ability will be left for future research, but does offer additional in sight as to why a smaller set of POD locations can be utilized.

5.5 Building the Bulk-Breakout-Points to Neighborhood network

Once the universe of PODs was examined, the system of neighborhoods was developed. Since, there was no standard geography for a neighborhood within the cities and towns of the CCR the geographical unit of the census tract was chosen to represent a neighborhood. The census tract boundaries that were used were obtained from the 2010 U.S. Census, and the shapefiles used in ArcGIS were from the U.S. Census Bureau. These files were obtained through the NHGIS system (Minnesota Population Center 2011). The census tracts for Connecticut are shown in Figure 5.14. For the proposed model, the demand was aggregated at the centroid of each census tract. The centroid locations were calculated within ArcGIS 10.3 for each tract. ArcGIS, using the Network Analyst Toolbox to the street network dataset, then attached the centroid. Figure 5.15 shows the centroid locations with their demand. The attachment parameters were set such that every centroid was attached to the network. At this point one census tract, in the area of the Town of East Lyme, was dropped from the modeling universe. This particular

census tract appears to be associated with a state prison, and did not have any demand or SOVI data associated. The Network Analyst Toolbox calculated an Origin-Destination Distance Matrix using those locations. This matrix was calculated in a similar manner as the one created for the PODs to tract centroids

Even though the previous discussion of the proposed model determined that a set of eighteen candidate POD sites located in tracts that are, more vulnerable would be a sufficient set of candidate sites for the model, the next analysis of the proposed model will take a step back. In the following, the examination the proposed model will be used with the entire set of fifty-five candidate POD sites. In a later model developed by Horner and Downs (Horner and Downs 2010) they suggested that the distance from BBP to Neighborhood by multiplied by some large number. This cost factor, in their rational, was a way to make the BBP to Neighborhood link in the model more prominent. They suggested a value of about 200. They theorized that the BBP to Neighborhood link would create about 200 more trips than the POD to BBP link in their model. Following their logic, the proposed model was tested using a cost factor of 240, and Figure 5.16 shows that the proposed model behaves similarly regardless of the addition of a cost factor. Figure 5.17 shows that the cost factor has little influence on the distances between neighborhoods and BBPs as sited by the proposed model. This is done by examining the slope and general trend of the average distances of more vulnerable neighborhoods to BBP, less vulnerable neighborhoods to BBP and all neighborhoods to BBP

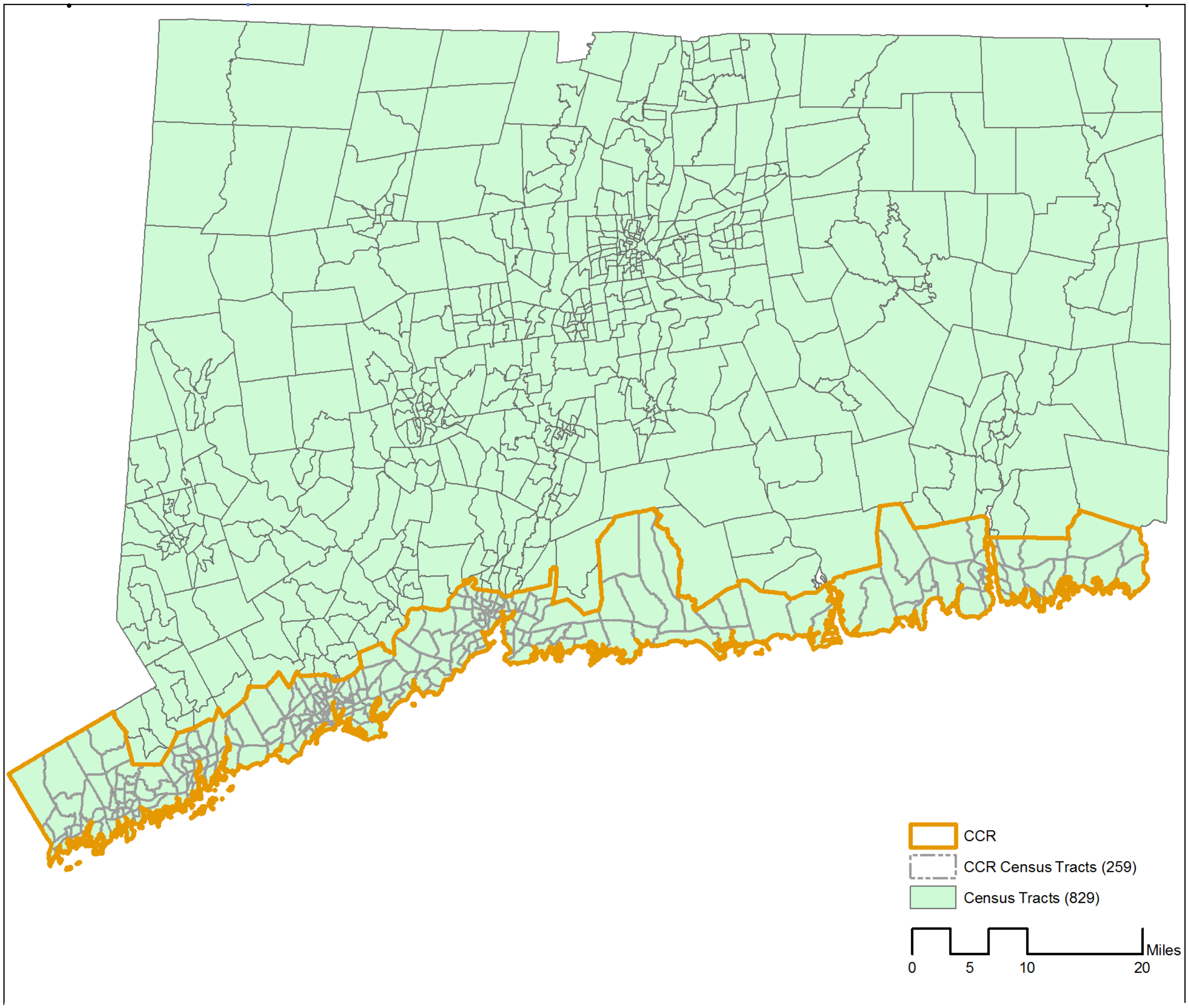


Figure 5.14 Census Tracts for the State of Connecticut to be used as “neighborhoods” in proposed model.

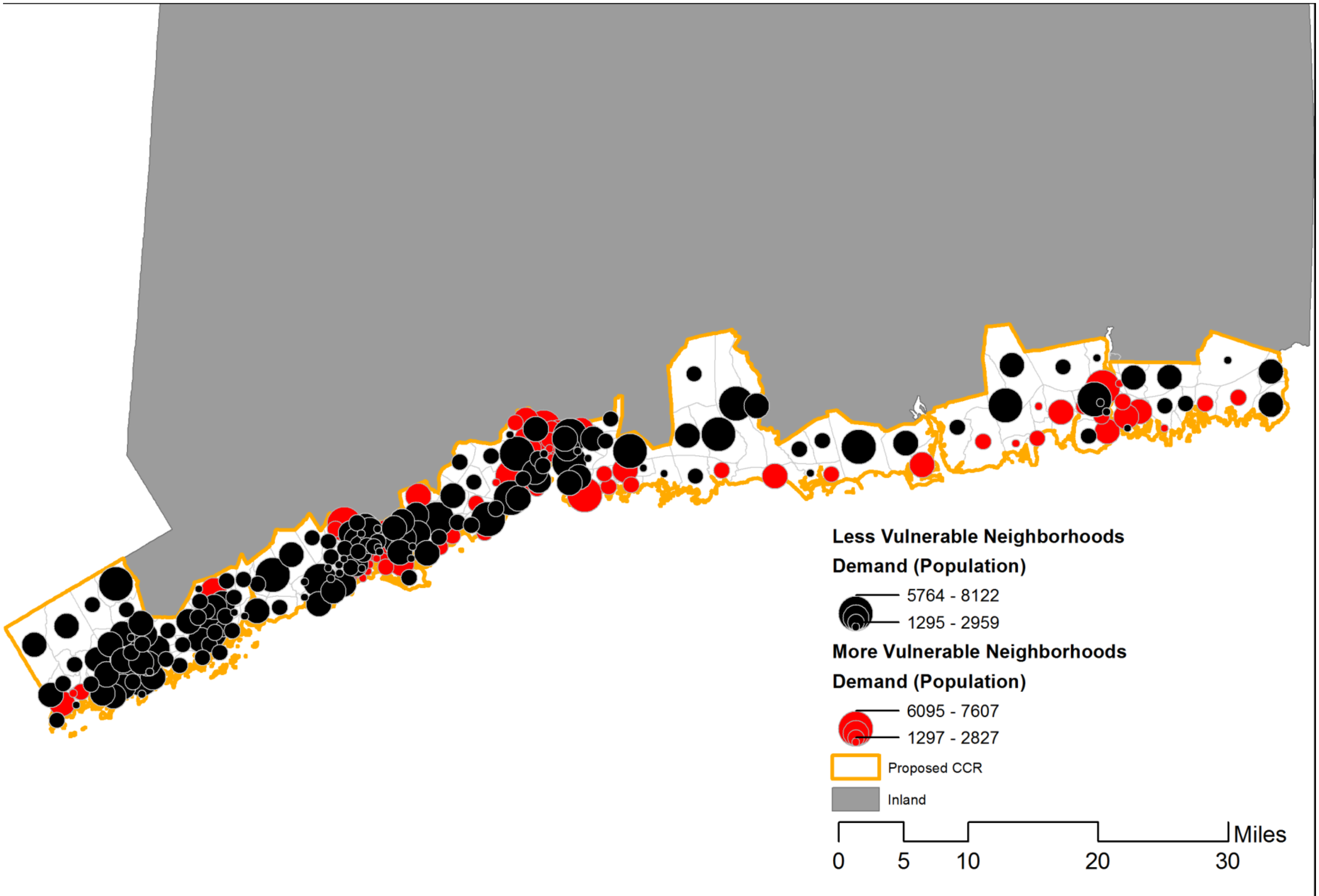
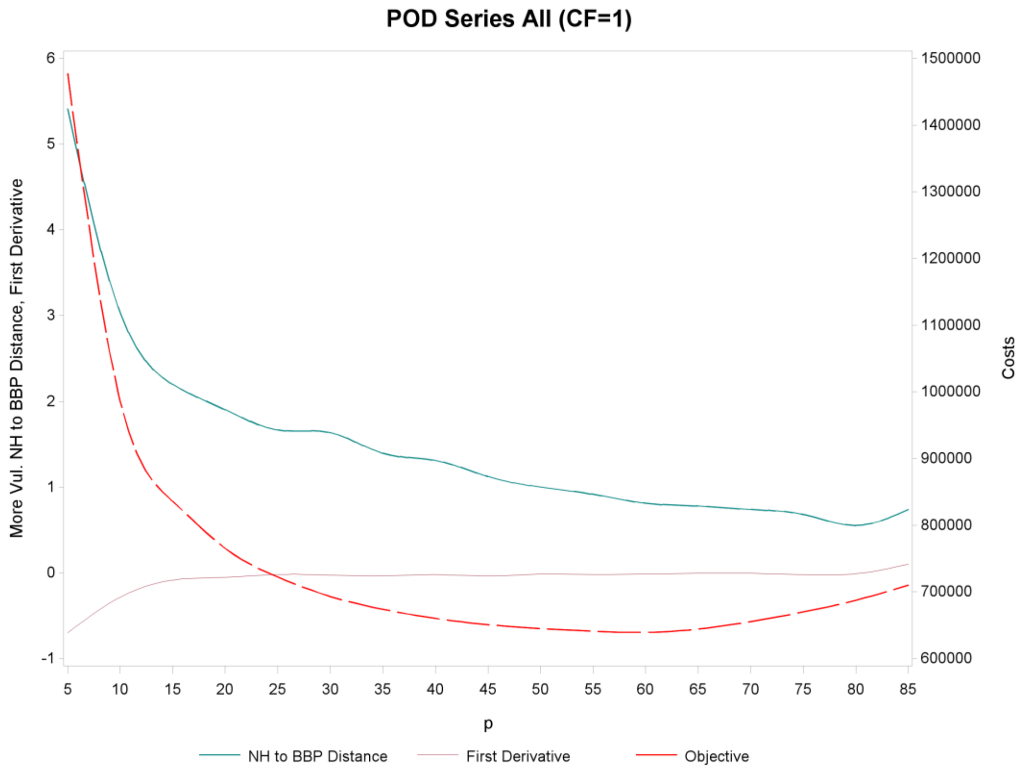


Figure 5.15 Census Tract centroids with demand represented as population



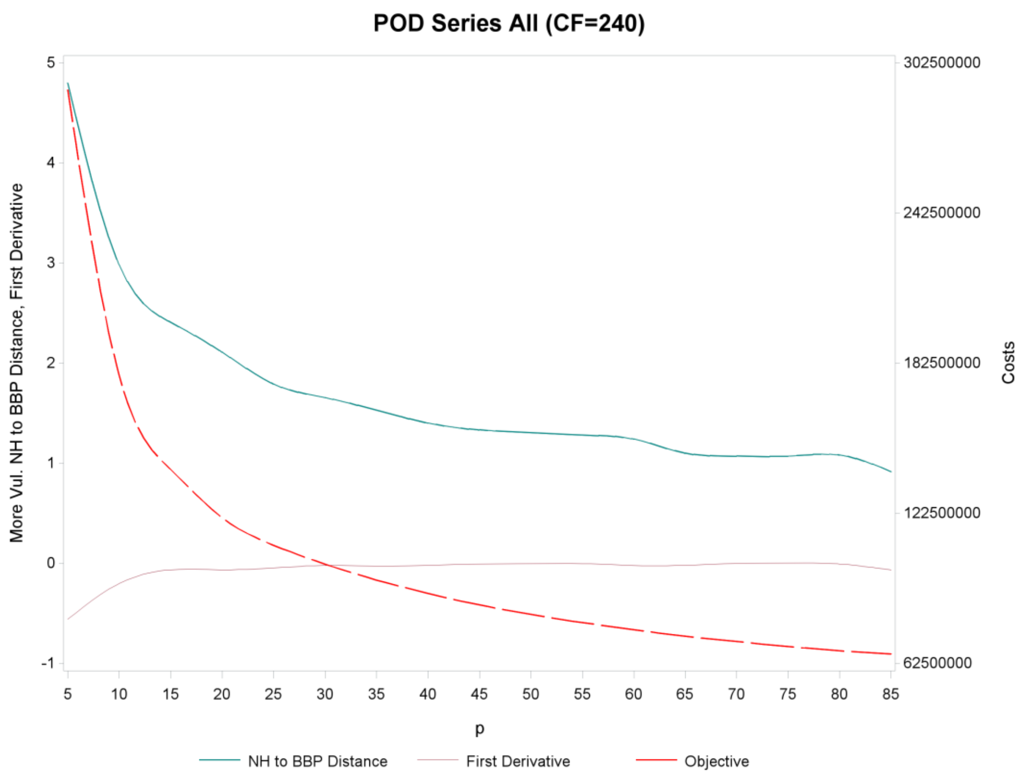


Figure 5.16 Graphs show the behavior of the model's objective (red dashed line), average distance from BBP to more vulnerable neighborhoods (green solid) and first derivative of the average distance BBP to neighborhood line measures rate of change of the average distance.

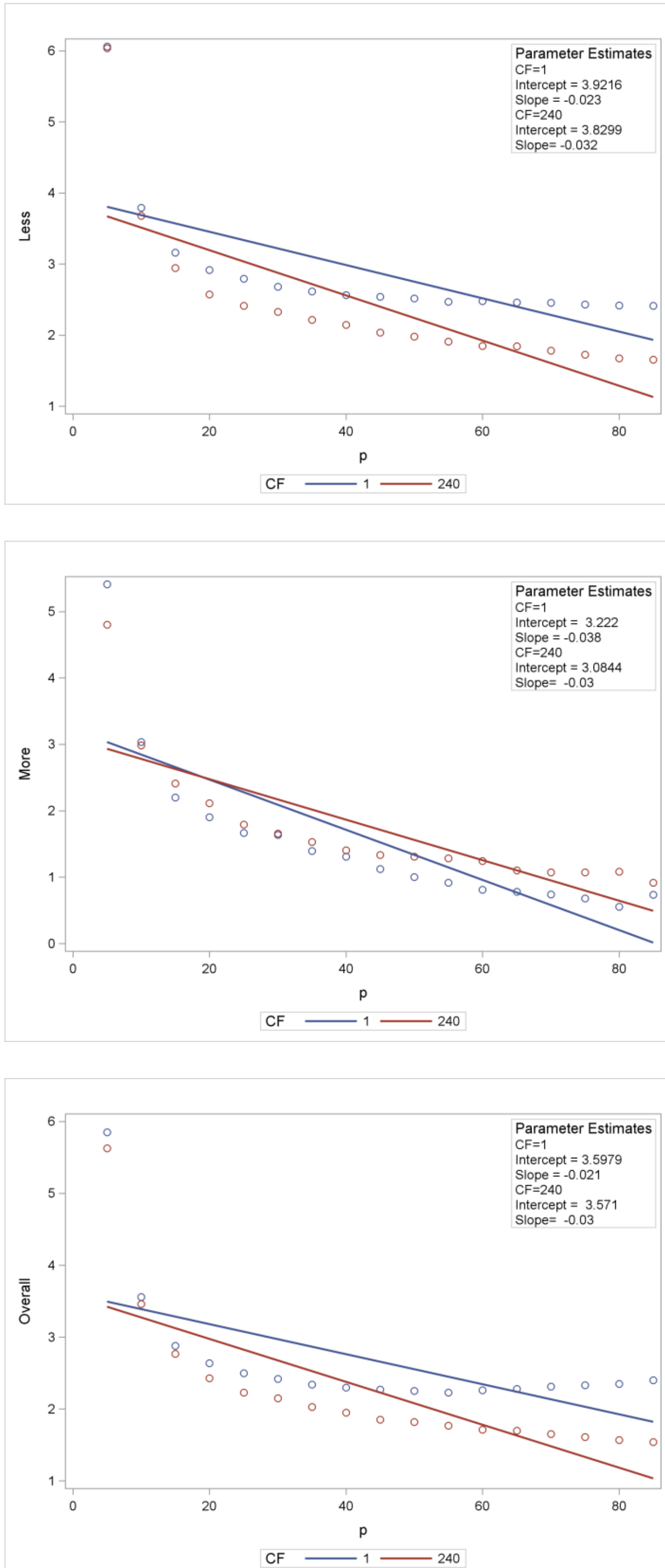


Figure 5.17 Graphs show the behavior of the average distance of the BBP to neighborhood link of the model

After the examination presented in Figures 5.16 and 5.17 there does not appear that the proposed model requires any adjustments to what was developed and proposed in Chapter Three. Thus, an examination of the model's performance, concerning, the BBP-Neighborhood linkage will continue. Remembering that one of the goals is to maximize coverage of more vulnerable neighborhoods, it was determined, that one of the ways to obtain that goal was to site BBPs in more vulnerable neighborhoods. So, in examining an extreme, where the model sites eighty-five BBPs (or p = 85 and the CCR contains eighty-six neighborhoods as defined as more vulnerable) would seem an ideal solution. However, at p = 85 the model sites numerous "orphan" BBPs. Orphan BBPs are BBP sites that only service the neighborhood they are sited in – they do not have any network connection to any other neighborhoods. This is not necessarily a fatal fault because part of the proposed model has a coverage aspect. Figure 5.18 is the entire solution of the model for p = 85 and all fifty-five POD candidate sites, and Figure 5.19 is the set of sited BBPs. Table 5.4 summarizes the number "orphan" BBPs for the various p values.

Table 5.4 Number of "Orphan" BBPs

p Value	Number of Orphan BBPs Sited
5 -- 40	0
45	2
50	4
55	6
60	8
65	11
70	13
75	13
80	18
85	28

Figure 5.18 Solution with p = 85 with using all fifty-five candidate PODs

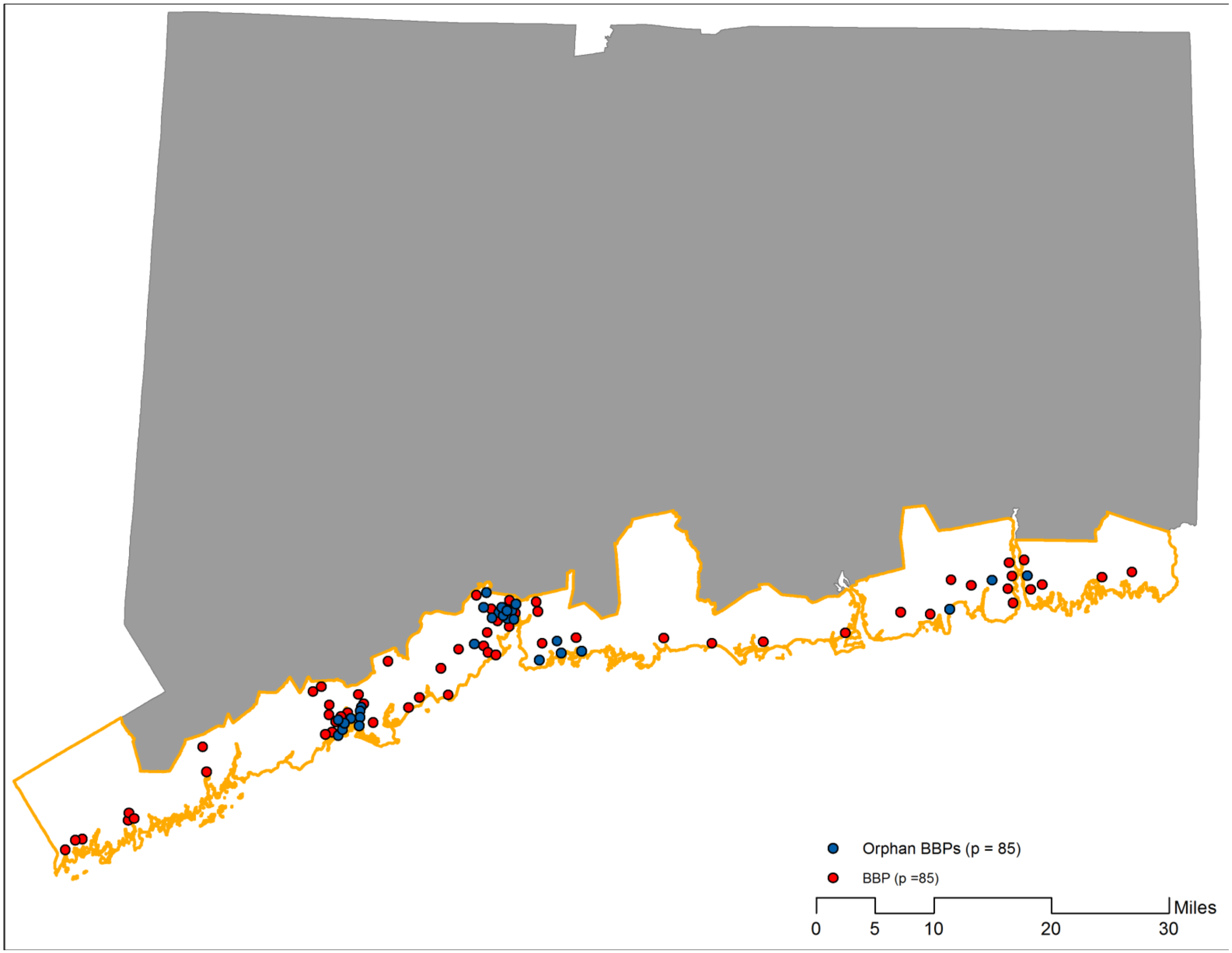


Figure 5.19 Set of sited BBPs for solution p = 85

5.6 Examination of a complete solution

The step-wise analysis of the proposed model has led to some general conclusions about the performance of the model. The first being the most intuitive is that as more BBPs are added, or as p increases, the average distance along the BBP-Neighborhood links decreases. However, it was also found that as p increases beyond 40 the model begins to site “orphan” BBPs. Though this does necessarily point to a fault in the model, it may lead to inefficiencies if resources are scare to staff and equip such locations. Analysis of the POD candidate sites indicated that the model could function without having to use all available candidates, and in fact, the model did not utilize more than thirty-nine candidate sites. The candidate POD sites were set at eighteen located in the more vulnerable tracts (as seen in Figure 5.13).

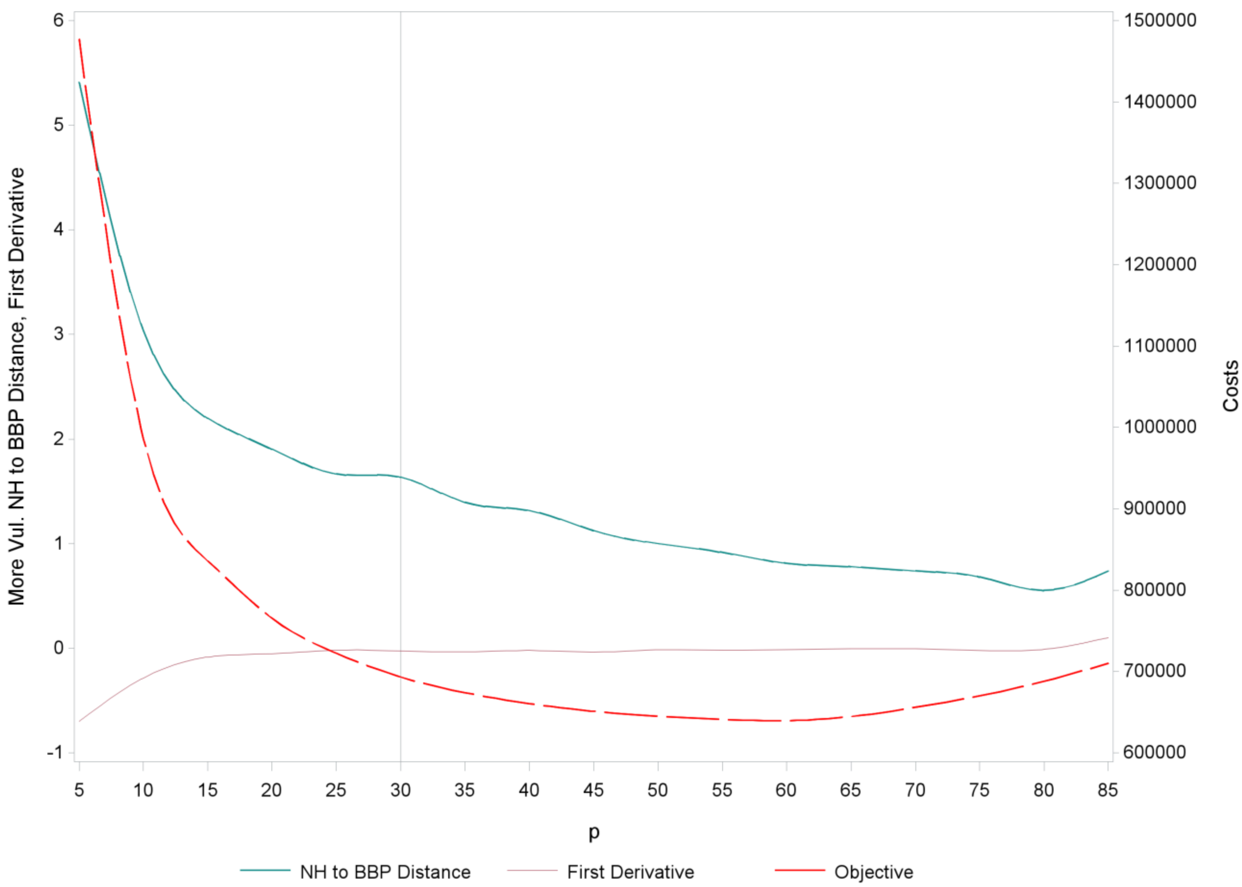


Figure 5.20 Solution for 18 candidate POD sites. p= number of BBPs sited by the model

In Figure 5.20 is a graph that summarizes the model when the eighteen POD sites are utilized. The objective behaves similar to the objective seen in Figure 5.16., and the BBP-Neighborhood link behaves similarly. The BBP-Neighborhood link behavior stayed consistent throughout all the model testing. The model gave very similar results for changes in the parameters of the model for that link. There were slight variations when the cost factor multiplier was introduced into the model, but for the most part the link was consistent. The BBP-neighborhood distance is less for neighborhoods that are more vulnerable compared to those that are less vulnerable. The first derivative of the average distance BBP-Neighborhood line is shown in Figure 5.20. This shows that the biggest rate of change in the average distance is between p = 5 and 10, and then the rate of change remains constant to p=85. Examination of the objective4 line on the graph shows that the objective, or costs, begin to rise after about p = 60. This rise in costs is attributed to the fixed cost objective in the model. Ideally, as the model sites more BBPs the model should become more efficient or the costs continue to decrease, however the presence of the fixed cost objective continues to add costs to the model. The average distance BBP to neighborhood line is "lumpy" because of the way the average was calculated. Neighborhoods that had BBPs located in them were considered to have a distance of zero, and those neighborhoods were not included in the set of neighborhoods for averaging purposes. Table 5.5 shows the results of the model for values of p. Figure 5.21 shows the solution to the model for p = 30, and Figure 5.22 summarizes the distances for the solution.

Table 5.5 Solution summary for 18 candidate POD sites

p	objective	BBP- Neighborhood Less Vulnerable Link (ave. distance, miles)	BBP- Neighborhood More Vulnerable Link (ave. distance, miles)	BBP- Neighborhood All Link (ave. distance, miles)	BBPs located in Less Vulnerable Neighborhoods	BBPs located in More Vulnerable Neighborhoods	Average Distance from POD to BBP (miles)
5	1477638	6.0613	5.4105	5.85	0	5	6.1836
10	986090.8	3.791	3.0376	3.56	0	10	5.4379
15	835882.8	3.1625	2.1987	2.88	0	15	6.0115
20	765174.2	2.9168	1.903	2.64	0	20	5.6428
25	722231.8	2.792	1.6662	2.5	0	25	4.894
30	693074.3	2.6793	1.6362	2.42	0	30	5.4724
35	673847.4	2.6153	1.3945	2.34	0	35	5.6331
40	660295.1	2.5616	1.3158	2.3	0	40	5.7179
45	650920.8	2.5399	1.1236	2.27	0	45	6.4894
50	644916.8	2.5154	1.0008	2.25	0	50	6.7951
55	641102.1	2.4682	0.9163	2.23	0	55	6.4702
60	639378.3	2.4789	0.8123	2.26	0	60	6.0215
65	644453	2.4609	0.7798	2.28	0	65	5.9575
70	655716.7	2.4566	0.7387	2.31	0	70	5.5885
75	670022	2.4326	0.681	2.33	0	75	5.3491
80	687761.2	2.4162	0.5539	2.35	0	80	5.0918
85	710024.2	2.4141	0.7354	2.4	0	85	4.8326

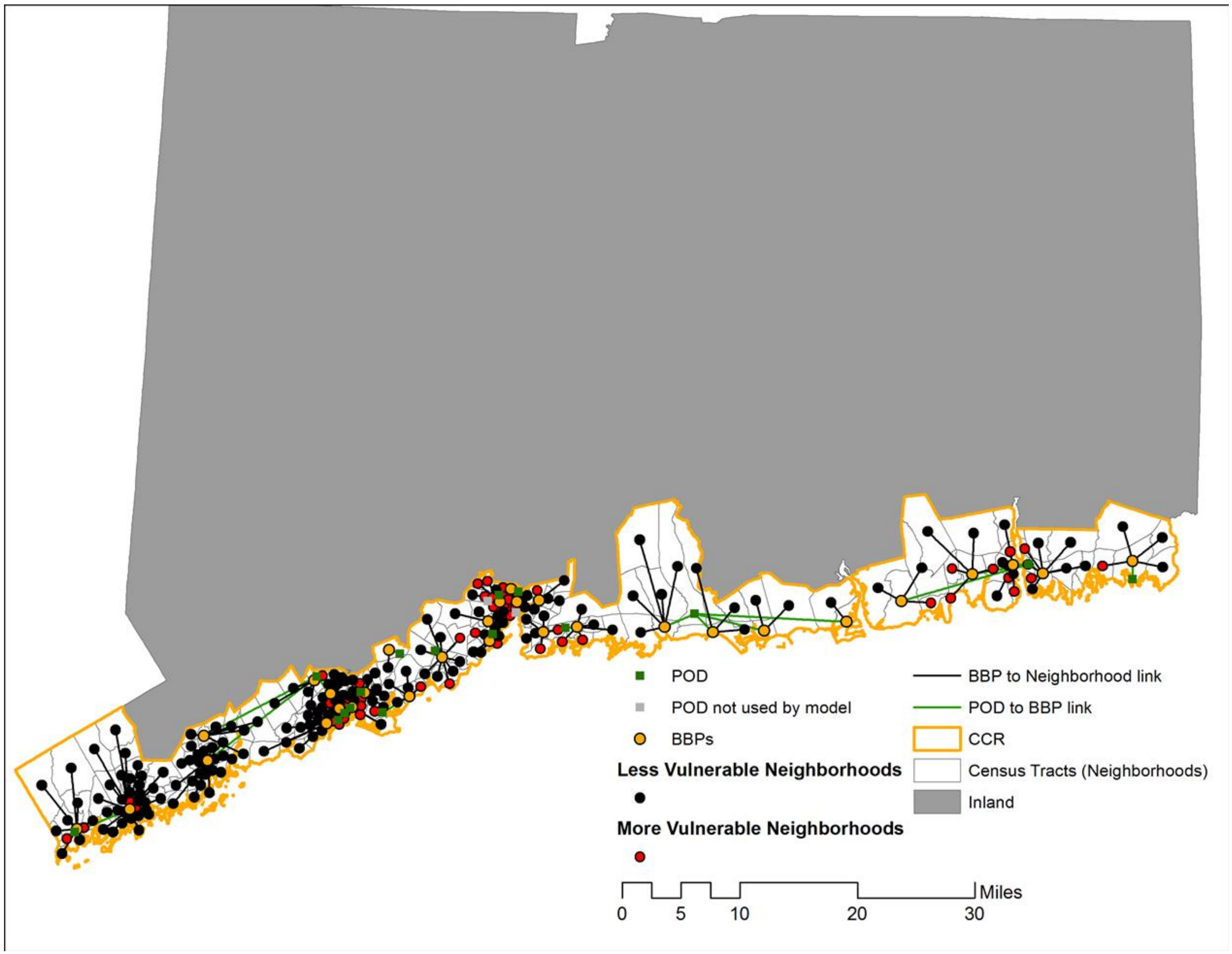


Figure 5.21 Solution for p = 30 and 18 POD set

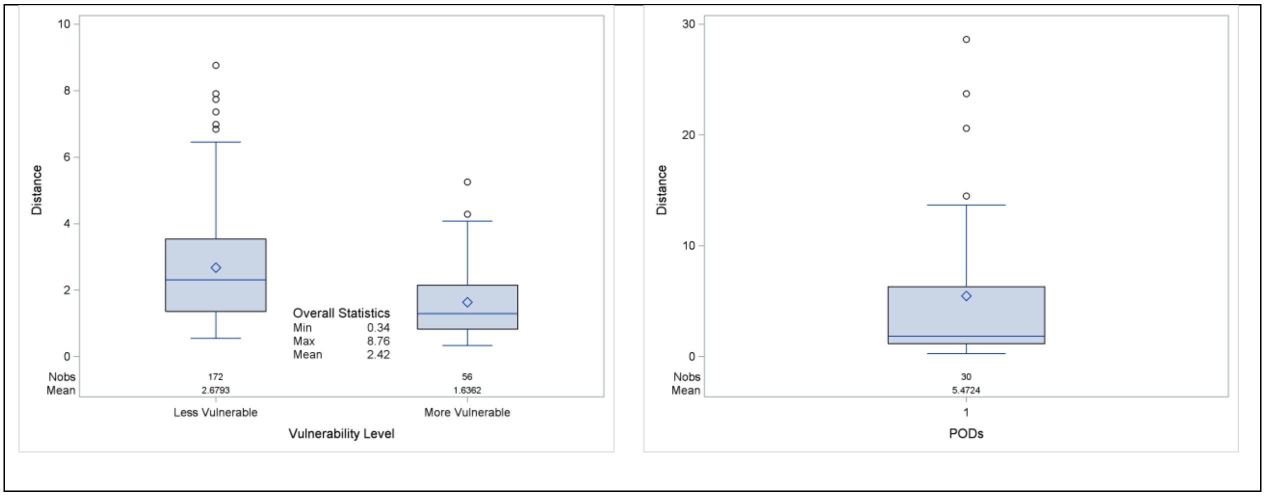


Figure 5.22 Box plots of distances for p=30 and 18 set POD solution.

Once the model solution can be visualized, the next question that needs to be examined is what are the demands placed on each individual site. This analysis is particularly important, about disaster relief, because planners need to have an idea how the system may react because of secondary event. . Since, the model is uncapacitated there are no upper bounds of each sited POD or BBP. Traditionally, a chart such as a pie chart, as seen in Figure 5.23, can be used for this analysis. However, the tree maps, seen in Figure 5.24, are more informative. The tree maps display the relative relationship among PODs, BBPs and Neighborhoods.

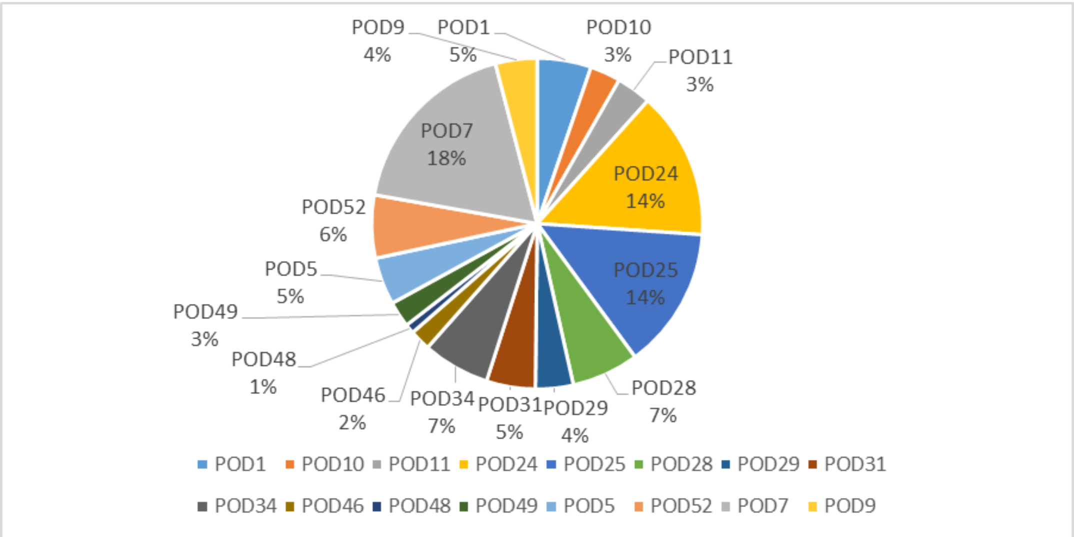


Figure 5.23 Summary of the demand filled by each POD location. The percentage of demand ranges for 18% of the demand to 1%.

Figure 5.24 Tree maps of number of neighborhoods and demand served by each POD. Heavier lines signify POD, lighter dark lines are BBPs and gray lines are neighbor

5.7 Simulation Test of the Model

Taking the analysis of the proposed, an additional step the model was tested using the results of a simulated disaster. Using a software program developed by FEMA called “HAZUS-MH” the proposed CCR was used as the geographical region of study for a potential disaster. The disaster chosen was the historical 1938 Hurricane. The 1938 Hurricane was one of the most devastating storms to strike the New England region. The storm made landfall on Sept. 21, 1938, and Figure 5.25 shows the historical forecast from that day.(“U.S. Daily Weather Maps | NOAA Central Library” 2016), and Table 5.6 summarizes some the key facts about the storm (US Department of Commerce 2016)

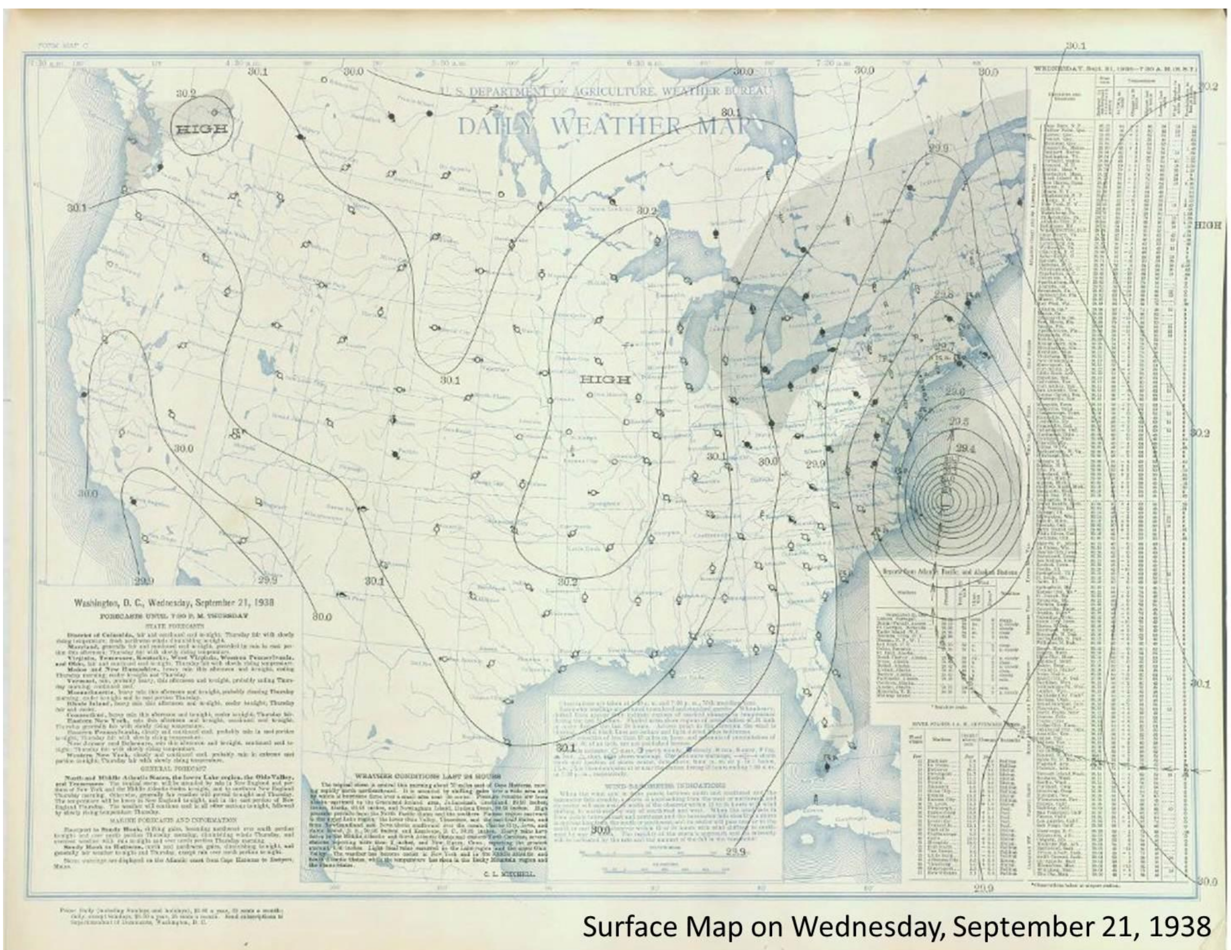


Figure 5.25 Historical forecast of 1938 Hurricane from the National Weather Service (“U.S. Daily Weather Maps| NOAA Central Library” 2016)

Table 5.6 1938 Hurricane Quick Facts

- Category 3 Hurricane when made landfall at Connecticut on Sept. 21, 1938
- 564 deaths and 1,700 injuries related to the storm along its path through New England
- 8900 buildings destroyed and >15,000 damaged
- Catastrophic fires in New London and Mystic area because of downed power lines

(US Department of Commerce 2016)

The historical path of the storm is shown in Figure 5.26. HAZUS used that path and internal data describing building stock and population to determine the expected extent of damage from such a storm. Table 5.7 offers a snapshot of the region as described by HAZUS. In the simulation, HAZUS determined that at least 71,500 buildings in the CCR will have at least minor damage, and there will be about 1130 homes destroyed. The simulation estimates that 2,434 households will be displaced and 508 of those households will seek temporary shelter. Table 5.8 shows the potential economic losses determined by the simulation.

Table 5.7 CCR Snapshot by HAZUS

Geographical Size	616 sq. miles
Census Tracts	259 (258 will actually be used to test model)
Total Households	413,000
Total Population	1,082,448
Total Buildings	347,000

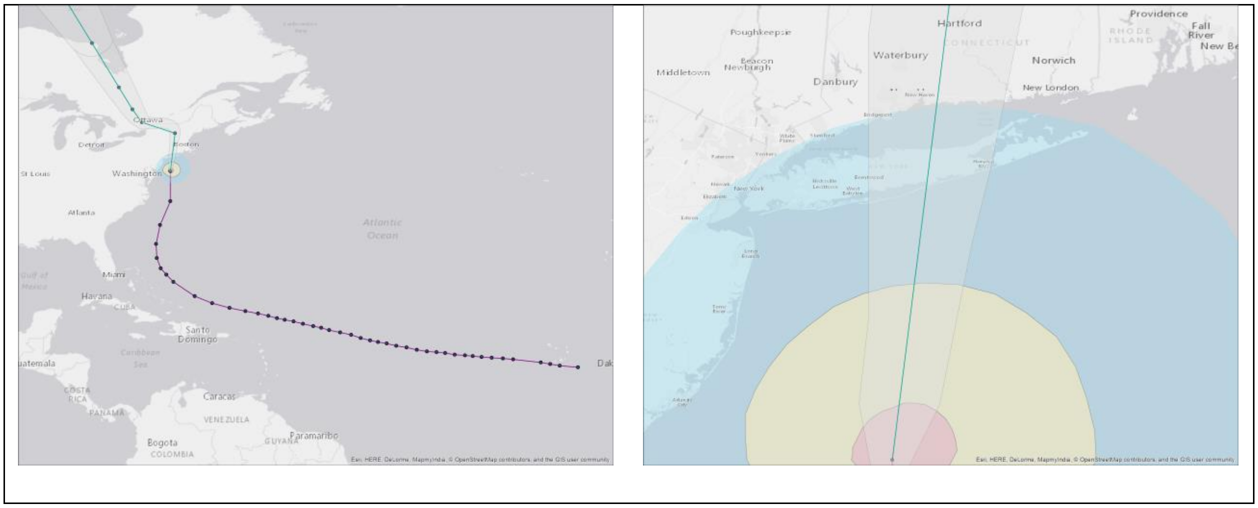


Figure 5.26 Path of 1938 Hurricane. The left is the overall path of the storm and the right shows the storm just before landfall. These maps were created using HAZUS-MH and Hurrevac

Table 5.8 Potential Economic Losses (Thousands of Dollars)

Category	Area	Residential	Commercial	Industrial	Others	Total
Propety Damage	Building	2,418,161.51	255,986.81	63,579.53	66,134.50	2,803,862.35
	Content	705,563.05	99,827.99	44,020.54	29,895.93	879,307.51
	Inventory	0.00	1,610.40	5,561.58	248.04	7,420.02
	Subtotal	3,123,724.56	357,425.20	113,161.65	96,278.47	3,690,589.88
Business Interruption Loss	Income	178.14	25,132.57	650.23	5,433.17	31,394.11
	Relocation	184,810.49	37,678.96	4,081.97	12,211.44	238,782.86
	Rental	101,835.28	19,974.94	629.08	1,228.42	123,667.72
	Wage	417.34	23,596.73	1,059.66	20,571.95	45,645.68
	Subtotal	287,241.25	106,383.20	6,420.94	39,444.98	439,490.37
	Total	3,410,965.81	463,808.40	119,582.59	135,723.45	4,130,080.25

After the simulation was completed the program generates shapefiles for the various solved and simulated parameters, and to test the model the parameters for the following were examined: the probability of at least minor damage to a residential building; short term sheltering requirements; displaced households; and tree debris. From those shapefiles a Damage Scorecard was developed. Each census tract in the CCR was ranked 0 or 1 for each of the parameters, and those rankings can be seen in Figure 5.27. The rankings were added across the four parameters

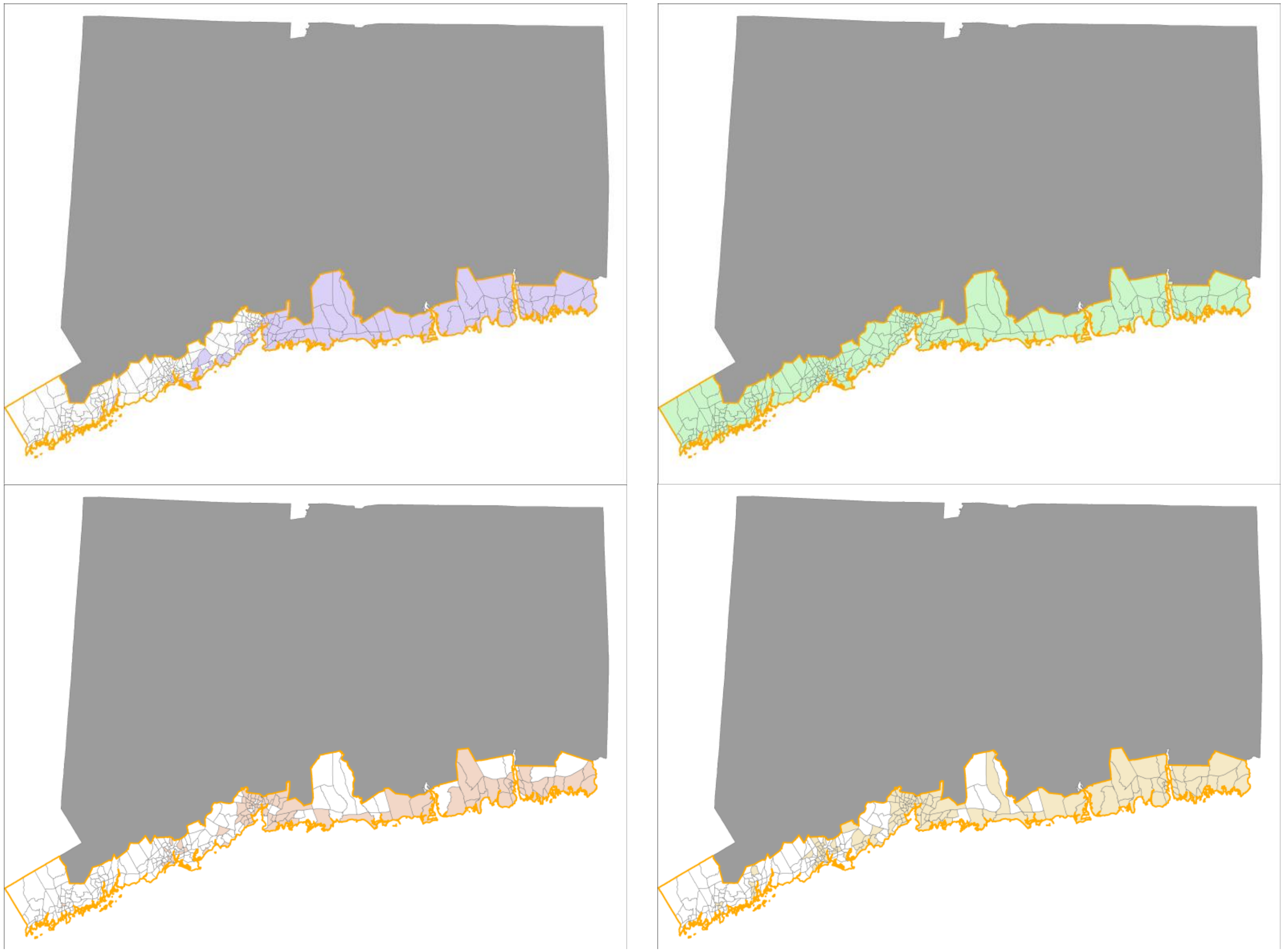


Figure 5.27 Clockwise, starting upper left tracts with > 14 tons of tree debris; Tracts with at least 1 household in temporary shelter; Tracts with at least 1 displaced household; and Tracts with probability > 38% that residential building will be damaged

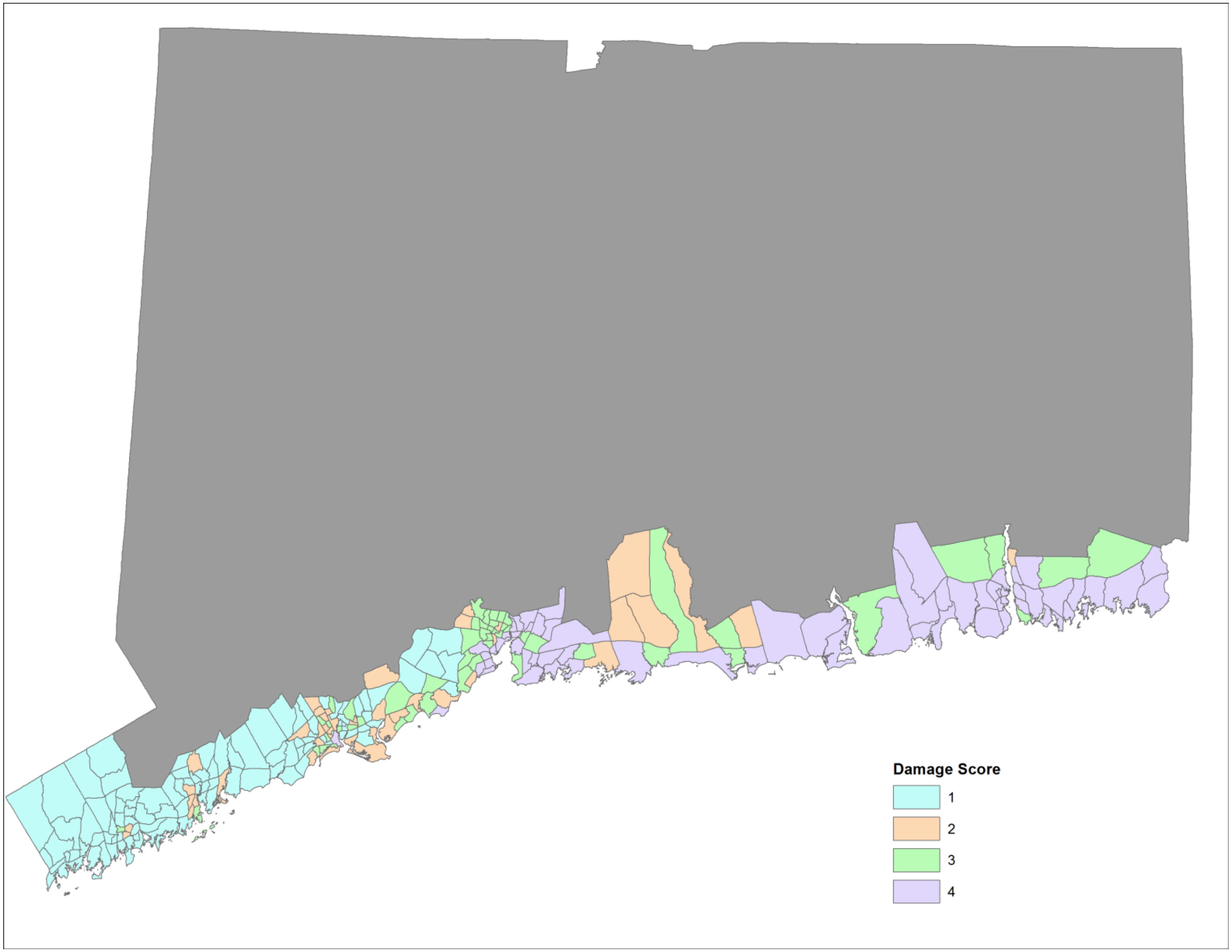


Figure 5.28 Damage Scorecard developed from the HAZUS simulation of the 1938 Hurricane

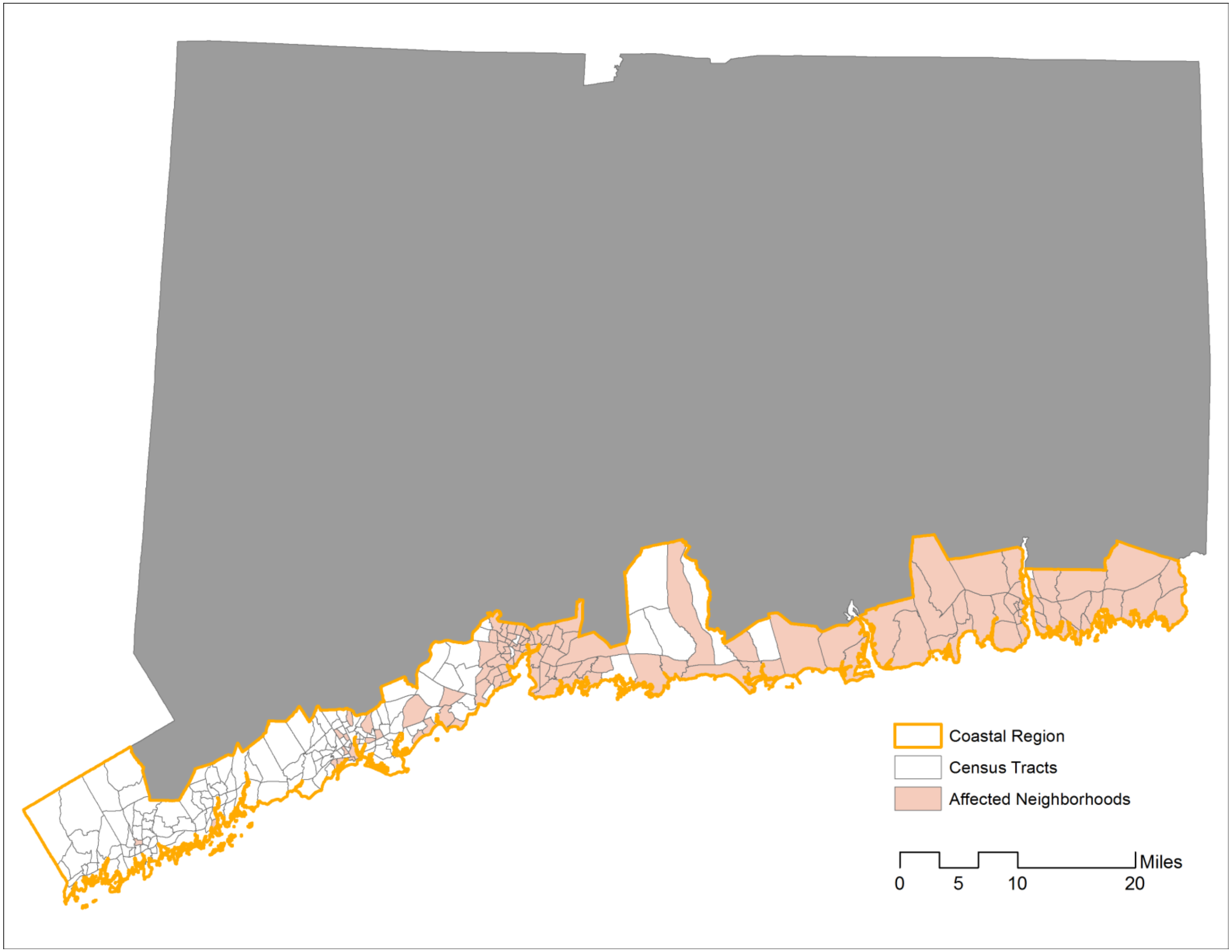


Figure 5.29 Affected neighborhoods in the 1938 Hurricane scenario

to get a final score and the Damage Scorecard is shown in Figure 5.28. Figure 5.29 shows the "affected" neighborhoods for the 1938 Hurricane scenario that will be used to further test the model.

The proposed model was then run in a similar manner as earlier in the Chapter. "Unaffected" tracts had their demand set to zero, but their locations were still kept in the pool to choose for potential BBP sites. The eighteen POD set in the more vulnerable neighborhoods was used for the candidate POD sites. The solution to the model for p = 25 is shown in Figure 5.30, and Figure 5.31 shows the boxplots for p=25 solution.

The disaster simulation offered two insights regarding the proposed model. The first insight was that the simulated disaster had more affected tracts in the eastern end of the CCR. During the model development, it was found that there were a greater number of more vulnerable tracts in the western end of the CCR. The model was developed to maximize the ability to service the more vulnerable tracts. However, this western "tilt" was not necessarily a factor in the simulated disaster, and the proposed model was able to perform as expected. The second insight was that a few of the BBPs were sited in more vulnerable neighborhoods that were not consider affected by the disaster. This may have been because the model still had the bias towards locating BBPs in more vulnerable neighborhoods, remembering that unaffected neighborhoods had a demand of zero, but were still in the pool of candidate sites for BBPs. Future investigation could possibly resolve whether that bias in the model should be removed. However, in a disaster situation, there may be some advantage to locating some BBPs in relatively unaffected neighborhoods, and some post event conditions may still affect neighborhoods that are more vulnerable even if they are not directly affected.

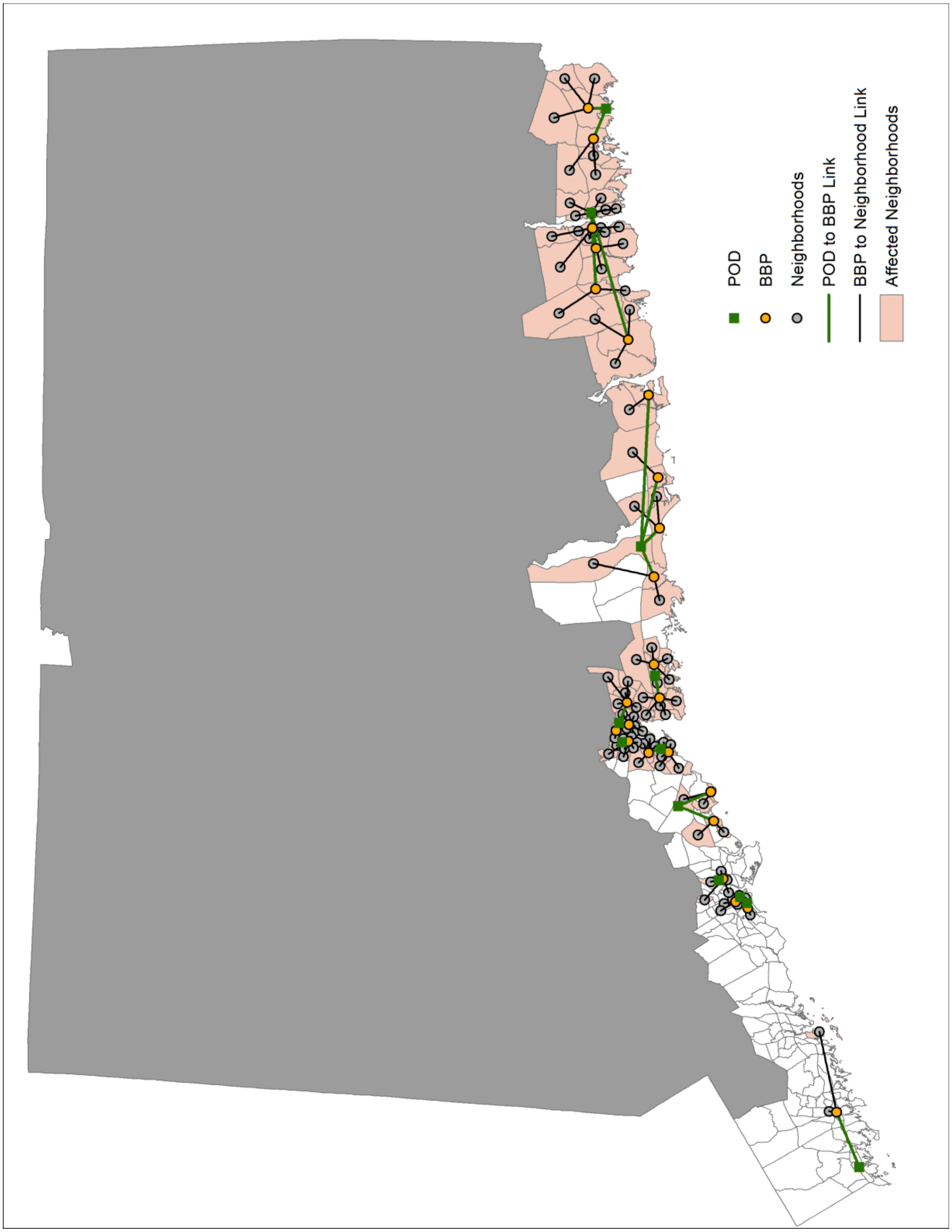


Figure 5.30 Solution for the 1938 Hurricane scenario with p = 25.

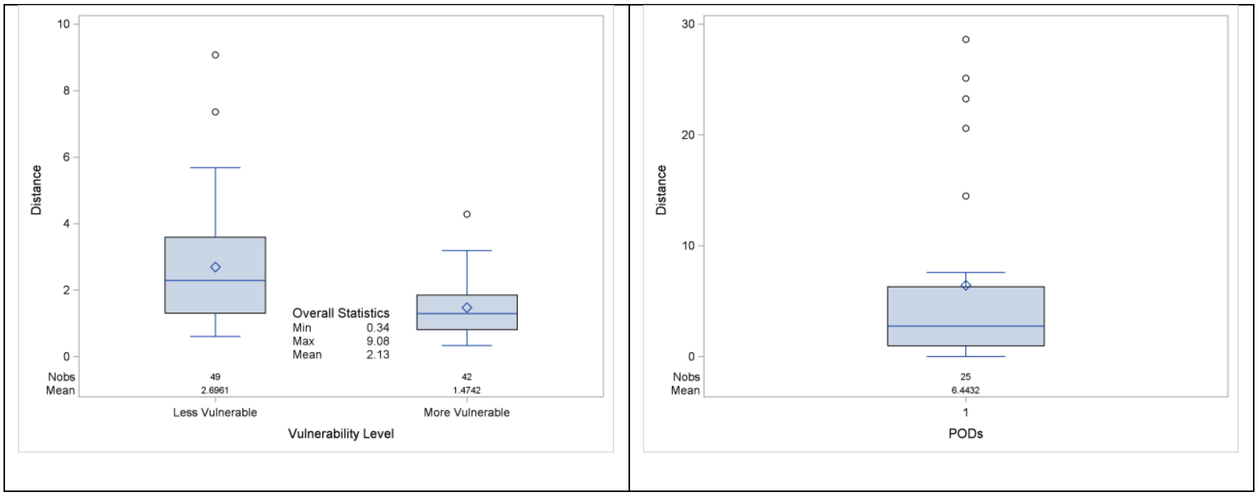


Figure 5.31 Box plots of the p = 25 solution for the 1938 Hurricane scenario.

5.8 Transforming Transshipment points to Hubs

Hubs are facilities that act as transshipment and sorting points in a many-to-many distribution system. Hubs do not serve each demand directly, but service the origin-destination pairs by concentrating the flow of goods to take advantage of economies of scale. This consolidation occurs on the routes from the origin to the hub, between hubs, and from the hub to the destination. There are two types of hub networks: single allocation and multiple allocation. In a single allocation system, the traffic coming into and out of a demand node is allocated to a single hub. A multiple allocation system allows that a demand node can receive traffic from more than one hub. To develop a hub network three things are assumed: (1) the hub network is complete with connections between every hub pair; (2) there is an economies of scale incorporated into the cost by discount factor (α) for using the inter-hub connection; and (3) no direct service is allowed between two non-hub nodes (Alumur and Kara 2008).

Transforming the transshipment points located using the proposed model may some advantages. In the proposed model those points are treated as facilities in which a service or good is provided at that location. The facilities are located in way as to meet an expected

demand. The hub network focuses on the flow between origin-destination pairs. Campbell argues that the origin-distance pairs are analogous to demand nodes in the p-median model (Campbell 1996). The other observation is that the flow from origin A – destination B is unique, and it must be accomplished in that manner. An example of this air travel, passengers or freight that want to travel from New York to Los Angeles must be the same from the beginning to the end of the trip. A hub network can better stretch transportation resources. A fully connected network has N(N-1) connections, where the number of nodes is N. So, for network, with N=9, there are 72 origin-destination pairs. This would require a fleet of 12 vehicles, where each vehicle could service 6 pairs a day. If one node was made into a hub, the network now has 2(N-1) connections. Therefore, with the same fleet of trucks, thirty-seven nodes could be serviced.

To see if the POD-BBP system could be changed to a hub network some changes were made to the system. The hub network attempted is a single allocation network as suggested by the following formulation:

Minimize:

$$\sum_{i \text{ in } I} \sum_{j \text{ in } J} \sum_{k \text{ in } K} \sum_{m \text{ in } M} W_{ij} \; X_{ijkm} \, Cijkm \qquad (5.9)$$

Subject to:

$\sum_{k \text{ in } K} Y_k = p$		(5.10)
$\sum_{k \text{ in } K} \sum_{m \text{ in } M} X_{i,j,k,m} = 1$	for all i and j	(5.11)
$Z_{ik} \leq Y_k$	for all i and k	(5.12)
$Z_{ik} + Z_{jm} - 2\, X_{ijkm}$	for all i, j, k,m	(5.13)
$X_{ijkm} = 0,1$	for all i, j, k, m	(5.14)
$Y_k = 0,1$	for all k	(5.15)
$Zik = 0,1$	for all i, k	(5.16)

X_{ijkm} = 1 if demand from location i met by location j is routed via hubs at locations k and m in that order;

C_{ijkm} = Total cost from location i to location j via hub k and hub m;

$= C_{ik} + C_{mj} + \alpha C_{km}$ and α is hub discount factor

W_{ij} = Flow from location i to location j;

Y_k = 1 if location k is a hub and 0 otherwise;

Z_{ik} = 1 if location I is allocated to the hub k and 0 otherwise; and

p = number of hubs to locate.

(Campbell 1994)

The locations for the PODs and BBPs, as determined by the proposed model, were arranged into origin/destination pairs and the PODs made up the candidate Hub locations. The hub network required a flow into and out each node, so the demand for the neighborhoods serviced by a BBP was aggregated at the BBP. The demand would represent the flow from the POD to the BBP. To simulate the flow from the BBP to the POD the aggregated demand was divided by twelve, and Table 5.9 shows a sample of data. No travel between BBPs is accounted for in the simulation. The POD and BBP locations were determined from the proposed model p = 25 for the 1938 Hurricane simulation. Figure 5.32 shows the solution for a three Hub network.

Table 5.9 Sample of OD pairs and Hubs for 3 Hub Solution

Origin	Hub 1	Hub 2	Dest	Flow (O →D)
NH122	POD10	POD10	POD10	1192.75
NH122	POD10	POD10	POD24	1192.75
NH122	POD10	POD10	POD29	1192.75
NH122	POD10	POD10	POD5	1192.75
NH122	POD10	POD10	POD9	1192.75
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
POD10	POD10	POD10	NH207	21558
POD24	POD10	POD10	NH91	10723
POD29	POD10	POD10	NH122	14313
POD5	POD10	POD10	NH70	5349
POD9	POD10	POD10	NH234	24384

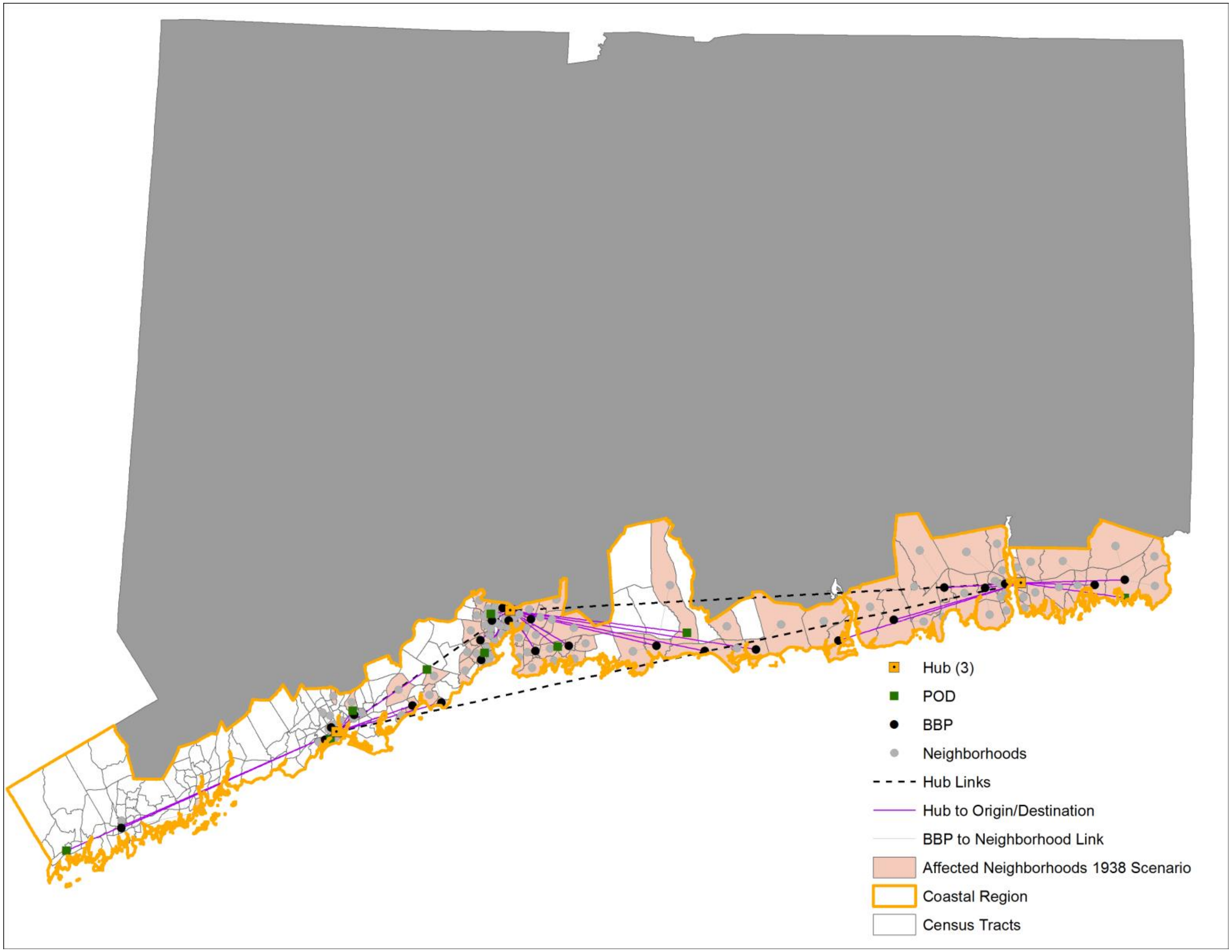


Figure 5.32 Hub network solution for 1938 Hurricane Scenario

Using Campbell's formulation, a three Hub network was developed. Thirty-seven origin-destination pairs consisting of BBP to POD links was used. In the hub network supplies would come from the LSA to the POD. Travel to a hub then on to the BBPs, and from the BBPs on to the neighborhoods. The BBP to Neighborhood link was outside of the hub network. The hub network requires in and out flows along the network. The outflows of BBPs into the PODs was simulated. That assumption was developed because of the location of the CCR. The CCR has a spine of several major roadways, and it would not be unconceivable that relief supplies could enter the CCR from east or west along Route 1 or Interstate 95. The supplies could enter into the hub network at any node, or one type of supplies could be delivered to one location and another type at another. In the latter case, the supplies would move to the hub for consolidation and sorting. A fully connected network with thirty-seven nodes has 1,332 connections or 666 origin-destination pairs, and by creating a three Hub network, those are reduced to 34 origin-destination pairs and 3 hub-to-hub pairs.

5.9 Summary

The proposed model was able to move from using generated data sets to the use of actual data sets. Actual data for demand, location, and network distances was established from the region of study. The model was able to integrate information about the social vulnerability of a neighborhood using the SOVI®. This information was used by the model to influence the siting of BBPs to neighborhoods that are more vulnerable. The model was also able to use that information to influence distances from more vulnerable neighborhoods and distribution points. The model produced results that were expected and the average distances from more vulnerable neighborhoods to BBPs were lower than average distances from less vulnerable neighborhoods. This was the overall objective of the model. The model did produce unanticipated results as p

became greater than forty. The model would begin to site “orphan” BBPs. Therefore, as the p value becomes greater than forty, the objective and average distances may make the model appear to become more efficient. This apparent efficiency may not be actual because, as p increases beyond forty, the model begins to locate “orphan” BBPs.

The first stage of the model testing, using actual data, assumed that an event would affect all neighborhoods in the CCR. However, a real disaster would not necessarily affect all the neighborhoods. A computer simulation of a historical disaster was created. The 1938 Hurricane was recreated, and the results of the hurricane on today’s CCR was examined. The affected census tracts were used within the proposed model. The model was able to develop solutions for the distribution system. Building from the locations of the BBPs and PODs found for the 1938 Hurricane scenario a 3 Hub network was developed. Using an established integer formulation for a single allocation hub network the proposed model could be converted into a hub network.

Chapter Six

Summary and Conclusion

6.1 Review of the study

This research provides a modelling foundation from which information concerning a geographical area's social vulnerability could be taken into account when siting distribution points for disaster relief supplies. There is a long history in the design and use of location allocation models. These models have been developed to meet the needs of both the public and private sector. As the world becomes more complex and interconnected advancements in location models become critical in developing systems to deliver products and services to people in a variety of conditions.

A straightforward, simple method of integrating social vulnerability information into a multi-criteria location model was presented in this research. This method was a departure from earlier research in which models focused on population or household demand weighted measurements. Earlier models estimated demand by anticipated percentages of the population,

whereas this research allows an area's demand importance to be influenced or weighted by its social vulnerability measurement. There is a growing body of research in the geographical analysis of hazards and disasters recognizing that there needs to be adaptable, flexible solutions to the aftermath of disasters. By being able to understand both the potential environmental and social vulnerabilities and inequalities of a place, systems could be better integrated to deliver services and supplies during such crisis.

This study developed a proposed model that attempted to solve this integration of information problem. The model took a known index of social vulnerability, SOVI®, and used that information to guide it in locating distribution points. A stepwise development of the model was presented in Chapter Three. Through this approach, the model was able to utilize well-known location allocation models and concepts. In doing so, the model was able to present a goal of maximizing coverage of more socially vulnerable neighborhoods, and was able to minimize the distances in the overall system for all the neighborhoods. The model was solved using linear programming techniques and commercially available solvers through SAS.

Testing of the final model was done on an actual location, and this location was described in Chapter Four. Proposed in Chapter Four was a geographical area called the Coastal Cooperative Region (CCR) for the State of Connecticut. This region would be used as the geographical area in which the model was tested. After the model was tested for an event that was assumed to effect the entire region it was then tested for a simulated event. Using publicly available software the 1938 Hurricane was recreated, and the storm's potential effects on today's region were examined. Those results were used to test the proposed model.

6.2 Assessment of the Model

The proposed model built on the work of Horner and Downs (Horner and Downs 2007; Horner and Downs 2010), and throughout the testing the model behaved as expected. The model was able to integrate information about a census tract's social vulnerability. The model used that information to influence the locating of distribution points. As discussed, in the previous section, the model presented a multobjective approach. The final model contained four objectives: 1) minimize the total—distance weighted costs of the POD—BBP system, 2) minimize the uncovered "more" vulnerable demands; 3) minimize total—demand weighted costs in BBP-neighborhood system, and 4) minimize the fixed facility costs of the BBP (refer back to Figure 5.1 for relationship among the objectives). The model was able to balance those competing goals to produce plausible results. To achieve the final model the development was carried out in a step--wise fashion. This stepwise development led to the determination of the weighting factors k and M; with k being a weighting factor to balance the initial objectives of the model and M being the factor to influence more vulnerable neighborhoods as sites for BBPs. Those factors were kept the same when the model used actual data from the CCR. It was anticipated that the factors would have to be adjust with the use of actual data. However, the model performed as expected, and as it did using the generated data during development.

When developing the CCR there were a set of PODs available. The belief was that the model would utilize all the available PODs. The model only used a maximum of thirty-nine PODs, and from these results, the decision was made to produce a smaller set of PODs from which the model could choose. The spatial distribution was examined and the first goal was to maintain the similar distribution pattern as the original set. A final set of eighteen PODs was chosen. These PODs were located in neighborhoods that were more vulnerable. This set was also

selected because it appeared that many of the neighborhoods that were more vulnerable were located towards the western end of the CCR. The belief was that this would make the model more efficient, and it did assist when the entire was tested as being effected by a disaster.

To further test, the proposed model a simulated disaster was created. The historic 1938 Hurricane was recreated using software available from FEMA. In this simulation about half of the CCR census tracts were determined to significantly affected by the storm, and most of those tracts were located in the eastern portion of the CCR. The proposed model was run using the eighteen POD set used for the general testing. The model produced an acceptable solution.

The final analysis of the proposed model did not offer any novel formulation of classical location models. In the final analysis the POD—BBP transshipment points were transformed as origin-destination pairs. By thinking of them as origin—destination pairs allowed for the model to be transformed into a hub network. Using the p =25 solution for the 1938 Hurricane scenario 37 origin – destination pairs were established. Using limited computer facilities, the model was able to produce a 3-hub network using an integer formulation of the p – hub problem.

6.3 Directions for Future Research

Future research can extend the models of this study in four additional areas: information integration, time, uncertainty, and reliability. The kernel of this research is the belief that information concerning a location's social vulnerability can be used to help influence decisions by location allocation models for disaster relief. Further methods of integration could be examined. Can additional socio-economic factors be utilized to better pinpoint locations in need? Can sources such as remote sensing and imagery be utilized to determine an areas vulnerability? Can those same sources by used to determine a sites suitability for locating a distribution point?

Time is a large factor in disaster research. In a post- World War Two world much of the emphasis on the idea of time concerned preparedness and response, and in a post-Katrina world time, as a factor, in recovery is important. Recoveries are now seen as large endeavors that require large amounts of time, and over the recovery period, the needs of community recovering change. Research in how disaster relief supply chains have to accommodate for these changes is an important area that requires examination.

Building on the ideas of additional information integration and time is research into uncertainty and reliability. The concept of uncertainty is a major factor in disaster research many of the questions of an event involve uncertainty – what will the extent of the event be? how long will the event last?; how many people will need immediate, short – term or long term assistance? The level of uncertainty surrounding a disaster is high, and techniques to better understand the uncertainty and to plan with it are strong areas of future research. Finally, the reliability of systems is important in disaster relief and future research is needed in assessing the failure of particular locations designated by model parameters.

Works Cited

Aalst, Maarten van. 2006. "The Impacts of Climate Change on the Risk of Natural Disasters." *Disasters* 30 (1): 5–18. doi:10.1111/j.1467-9523.2006.00303.x.

"A Stronger, More Resilient New York." 2013. New York, NY: City of New York, PlaNYC Office of the Mayor. http://www.nyc.gov/html/sirr/html/report/report.shtml.

Adger, W. Neil. 2006. "Vulnerability." *Global Environmental Change* 16 (3): 268–281. doi:10.1016/j.gloenvcha.2006.02.006.

Altay, Nezih, and Walter G. Green. 2006. "OR/MS Research in Disaster Operations Management." *European Journal of Operational Research* 175 (1): 475–493. doi:10.1016/j.ejor.2005.05.016.

Alumur, Sibel, and Bahar Y. Kara. 2008. "Network Hub Location Problems: The State of the Art." *European Journal of Operational Research* 190 (1): 1–21. doi:10.1016/j.ejor.2007.06.008.

ASCE. 2015. "ASCE 2013 Report Card for America's Infrastructure." *Www.infrastureréporcard.org*. Accessed January 27. http://www.infrastructurereportcard.org.

Baker, Earl J. 1979. "Predicting Response to Hurricane Warnings: A Reanalysis of Data from Four Studies." *Mass Emergencies* 4 (1): 9–24.

———. 1991. "Hurricane Evacuation Behavior." *International Journal of Mass Emergencies and Disasters* 9 (2): 287–310.

———. 2011. "Household Preparedness for the Aftermath of Hurricanes in Florida." *Applied Geography* 31 (1): 46–52. doi:10.1016/j.apgeog.2010.05.002.

Barrows, Harlan H. 1923. "Geography as Human Ecology." *Annals of the Association of American Geographers* 13 (1): 1–14.

Baumol, William J., and Philip Wolfe. 1958. "A Warehouse-Location Problem." *Operations Research* 6 (2): 252–263.

Beaver, Janice C. 2006. "U.S. International Borders: Brief Facts." Government Report rs21729. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/misc/RS21729.pdf.

Belardo, S., J. Harrald, W. A. Wallace, and J. Ward. 1984. "A Partial Covering Approach to Siting Response Resources for Major Maritime Oil Spills." *Management Science* 30 (10): 1184–1196. doi:10.1287/mnsc.30.10.1184.

Bernert, Eleanor H., and Fred C. Iklé. 1952. "Evacuation and the Cohesion of Urban Groups." *American Journal of Sociology*, 133–138. doi:10.1086/221111.

Burton, Ian, Robert W. Kates, and Gilbert F. White. 1968. "The Human Ecology of Extreme Geophysical Events." http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1077&context=fmhi_pub.

———. 1993. *The Environment as Hazard*. 2nded. New York, NY: Guilford Press.

Campbell, James F. 1994. "Integer Programming Formulations of Discrete Hub Location Problems." *European Journal of Operational Research* 72 (2): 387–405. doi:10.1016/0377-2217(94)90318-2.

———. 1996. "Hub Location and the P-Hub Median Problem." *Operations Research* 44 (6): 923–935. doi:10.1287/opre.44.6.923.

Carr, Lowell J. 1932. "Disaster and the Sequence-Pattern Concept of Social Change." *American Journal of Sociology*, 207–218. doi:10.1086/216030.
Caunhye, Aakil M., Xiaofeng Nie, and Shaligram Pokharel. 2012. "Optimization Models in Emergency Logistics: A Literature Review." *Socio-Economic Planning Sciences* 46 (1): 4–13. doi:10.1016/j.spes.2011.04.004.
Church, Richard L., and Alan Murray. 2009. *Business Site Selection, Location Analysis, and GIS*. Hoboken, NJ: John Wiley and Sons.
Church, Richard L., and Charles S. ReVelle. 1974. "The Maximal Covering Location Problem." *Papers in Regional Science* 32 (1): 101–118. doi:10.1007/BF01942293.
———. 1976. "Theoretical and Computational Links between the P-Median, Location Set-Covering, and the Maximal Covering Location Problem." *Geographical Analysis* 8 (4): 406–415. doi:10.1111/j.1538-4632.1976.tb00547.x.
Cohon, Jared L. 2003. *Multiobjective Programming and Planning*. Mineola, NY: Dover Publications, Inc.
Comfort, Louise K. 2006. "Cities at Risk Hurricane Katrina and the Drowning of New Orleans." *Urban Affairs Review* 41 (4): 501–16. doi:10.1177/1078087405284881.
Cooper, Leon. 1963. "Location-Allocation Problems." *Operations Research* 11 (3): 331–343. doi:10.1287/opre.11.3.331.
"County Points of Distribution PowerPoint." 2010. Florida State Government. *Www.floridadisaster.org*. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiYg9CjwtTLAhUDWz4KHfq0AIQQFggcMAA&url=http%3A%2F%2Fwww.floridadisaster.org%2Fciem%2F2010%2Fpresentations%2FCounty%2520Points%2520Of%2520Distribution%2520(POD)%2520REVISED%2520100410.ppt&usg=AFQjCNFyCaPSkICQNxBGL7XuUdCyLM9Bew&bvm=bv.117218890,d.cWw.
Cova, Thomas J. 1999. "GIS in Emergency Management." In *Geographical Information Systems: Principles, Techniques, Applications, and Management.*, edited by P.A. Longley, M.F. Goodchild, D.J. Maguire, and D.W. Rhind, 845–858. New York, NY: John Wiley & Sons. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.134.9647&rep=rep1&type=pdf.
Cresswell, Tim. 2015. *Place: An Introduction*. 2nd ed. Malden, MA USA: John Wiley & Sons.
CT State Library. 2015. "Disasters in Connecticut." State library. *Dates of Disasters in Connecticut*. December 7. http://libguides.ctstatelibrary.org/hg/disasters.
Cutter, Susan. 1996. "Vulnerability to Environmental Hazards." *Progress in Human Geography* 20: 529–539.
———. , ed. 2001. *American Hazardscapes: The Regionalization of Hazards and Disasters*. Washington, DC: John Henry Press.
———. 2005. "The Geography of Social Vulnerability: Race, Class, and Catastrophe." *Understanding Katrina: Perspectives from the Social Sciences*. http://understandingkatrina.ssrc.org/Cutter/.
Cutter, Susan, Bryan Boruff, and W. Lynn Shirley. 2003. "Social Vulnerability to Environmental Hazards." *Social Science Quarterly* 84 (2): 242–261. doi:10.1111/1540-6237.8402002.

Daskin, Mark S. 2013. *Network and Discrete Location: Models, Algorithms, and Applications*. 2nd ed. Hoboken, NJ: Wiley.
Dekle, Jamie, Mariel Lavieri, Erica Martin, Hülya Emir-Farinas, and Richard Francis. 2005. "A Florida County Locates Disaster Recovery Centers." *Interfaces* 35 (2): 133–139.
"Disaster Declarations by Year." 2013. *Www.fema.gov*. Accessed March 10. http://www.fema.gov/disasters/grid/year.
Drezner, T. 2004. "Location of Casualty Collection Points." *Environment and Planning C: Government and Policy* 22 (6): 899–912. doi:101.1068/cl13r.
Erikson, Kai T. 1976. *Everything in Its Path*. New York, NY: Simon and Schuster.
FEMA/USACE. 2008. "IS-26 Guide to Points of Distribution (PODS)." FEMA/US Army Corp of Engineers.
Fothergill, Alice, Enrique Maestas, and JoAnne DeRouen Darlington. 1999. "Race, Ethnicity and Disasters in the United States: A Review of the Literature." *Disasters* 23 (2): 156–173. doi:10.1111/1467-7717.00111.
Fothergill, Alice, and Lori A. Peek. 2004. "Poverty and Disasters in the United States: A Review of Recent Sociological Findings." *Natural Hazards* 32 (1): 89–110. doi:10.1023/B:NHAZ.0000026792.76181.d9.
Fritz, C. E. 1961. "Disaster." In *Contemporary Social Problems: An Introduction to the Sociology of Deviant Behavior and Social Disorganization*, edited by Robert K. Merton and Robert A. Nisbet, 651–94. New York, NY: Harcourt, Brace and World.
"General Coastline and Shoreline Mileage of the United States." 2016. Government agency. *Office of Coastal Management*. Accessed May 16. https://coast.noaa.gov/data/docs/states/shorelines.pdf.
Gilbert, Claude. 1995. "Studying Disaster: A Review of the Main Conceptual Tools." *International Journal of Mass Emergencies and Disasters* 13 (3): 231–240.
Goldman, A. J. 1969. "Optimal Locations for Centers in a Network." *Transportation Science* 3 (4): 352–360. doi:10.1287/trsc.3.4.352.
Gottmann, Jean. 1964. *Megalopolis The Urbanized Northeastern Seaboard of the United States.* Vol. 8. The MIT Press Paperback Series. Cambridge, MA: The MIT Press.
Gutjahr, Walter, and Pamela Nolz. 2016. "Multicriteria Optimization in Humanitarian Aid." *European Journal of Operational Research* 252 (2): 351–66. doi:10.1016/j.ejor.2015.12.035.
Haghani, Ali, and Sei-Chang Oh. 1996. "Formulation and Solution of a Multi-Commodity, Multi-Modal Network Flow Model for Disaster Relief Operations." *Transportation Research Part A: Policy and Practice* 30 (3): 231–250. doi:10.1016/0965-8564(95)00020-8.
Hakimi, S. Louis. 1964. "Optimum Locations of Switching Centers and the Absolute Centers and Medians of a Graph." *Operations Research* 12 (3): 450–459. doi:10.1287/opre.12.3.450.
Haley, K. B. 1963. "The Siting of Depots." *The International Journal of Production Research* 2 (1): 41–45. doi:10.1080/00207546308947811.
Hazards and Vulnerability Research Institute. 2014. "Social Vulnerability Index 2006-2010 at the Census Tract Level for Connecticut." Software service content. *SoVI 2006-2010 for Connecticut*. https://www.arcgis.com/home/item.html?id=1e33d8a662354a0abfa2447b4c4b9d2a.

Hewitt, Kenneth. 1970. “Probabilistic Approaches to Discrete Natural Events: A Review and Theoretical Discussion.” *Economic Geography*, 332–349.

———. 1983. “Place Annihilation: Area Bombing and the Fate of Urban Places.” *Annals of the Association of American Geographers* 73 (2): 257–284. doi:10.1111/j.1467-8306.1983.tb01412.x.

———. 1995. “Excluded Perspectives in the Social Construction of Disaster.” *International Journal of Mass Emergencies and Disasters* 13 (3): 317–39.

———. 1997. *Regions Of Risk A Geographical Introduction to Disasters*. Essex England: Addison Wesley Longman.

Hewitt, Kenneth, and Ian Burton. 1971. *The Hazardousness of a Place: A Regional Ecology of Damaging Events*. Toronto, Canada: University of Toronto Press.

Horner, Mark W., and Joni A. Downs. 2007. “Testing a Flexible Geographic Information System-Based Network Flow Model for Routing Hurricane Disaster Relief Goods.” *Transportation Research Record: Journal of the Transportation Research Board* 2022 (1): 47–54. doi:10.3141/2022-06.

———. 2010. “Optimizing Hurricane Disaster Relief Goods Distribution: Model Development and Application with Respect to Planning Strategies.” *Disasters* 34 (3): 821–844. doi:10.1111/j.1467-7717.2010.01171.x.

“Human Links to Coastal Disasters.” 2002. The H. John Heinz III Center for Science, Economics and the Environment.

Kovács, Gyöngyi, and Karen Spens. 2007. “Humanitarian Logistics in Disaster Relief Operations.” *International Journal of Physical Distribution & Logistics Management* 37 (2): 99–114. doi:10.1108/09600030710734820.

Kreps, Gary A. 1984. “Sociological Inquiry and Disaster Research.” *Annual Review of Sociology*, 309–330.

Kuehn, Alfred A., and Michael J. Hamburger. 1963. “A Heuristic Program for Locating Warehouses.” *Management Science* 9 (4): 643–666.

League of Women Voters of Connecticut. 2010. “Connecticut: A Guide to State Government.”

Leventhal, Gerald S. 1980. “What Should Be Done with Equity Theory? New Approaches to the Study of Fairness in Social Relationships.” In *Social Exchange: Advances in Theory and Research*, edited by Kenneth Gergen, Martin Greenberg, and Richard Willis, 27–55. New York, NY: Plenum Press. http://www.eric.ed.gov/ERICWebPortal/recordDetail?accno=ED142463.

Lieberman, Neil. 2014. “The Risks of Aging Infrastructure.” *American City & County*, November.

Liu, Jiyin, Chung-Lun Li, and Chun-Yan Chan. 2003. “Mixed Truck Delivery Systems with Both Hub-and-Spoke and Direct Shipment.” *Transportation Research Part E: Logistics and Transportation Review* 39 (4): 325–39. doi:10.1016/S1366-5545(03)00005-X.

Marsh, Michael, and David Schilling. 1994. “Equity Measurement in Facility Location Analysis: A Review and Framework.” *European Journal of Operational Research* 74 (1): 1–17. doi:10.1016/0377-2217994090200-3.

McGuire, Martin, and Harvey Garn. 1969. “The Integration of Equity and Efficiency Criteria in Public Project Selection.” *The Economic Journal*, 882–893.

Mete, Huseyin Onur, and Zelda Zabinsky. 2010. “Stochastic Optimization of Medical Supply Location and Distribution in Disaster Management.” *International Journal of Production Economics* 126 (1): 76–84. doi:10.1016/j.ijpe.2009.10.004.
Mileti, Dennis. 1999. *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Washington, DC: Joseph Henry Press.
Mileti, Dennis, and Lori Peek. 2000. “The Social Psychology of Public Response to Warnings of a Nuclear Power Plant Accident.” *Journal of Hazardous Materials* 75 (2): 181–194. doi:10.1016/S0304-3894(00)00179-5.
Minnesota Population Center. 2011. “National Historical Geographic Information System: Version 2.0.” https://www.nhgis.org.
Morrill, Richard, and John Symons. 1977. “Efficiency and Equity Aspects of Optimum Location.” *Geographical Analysis* 9 (3): 215–225. doi:10.1111/j.1538-4632.1977.tb00575.x.
Morrow, Betty Hearn. 1999. “Identifying and Mapping Community Vulnerability.” *Disasters* 23 (1): 1–18. doi:10.1111/1467-7717.00102.
“National Disaster Response Framework.” 2011. Washington, DC: FEMA. http://www.fema.gov/pdf/recoveryframework/ndrf.pdf.
“National Response Framework.” 2008. Washington, DC: Department of Homeland Security/FEMA. http://www.fema.gov/pdf/emergency/nrf/nrf-core.pdf.
NOAA. 2015. “Storm Events Database.” Federal government agency. *Storms Events Database*. December. http://www.ncdc.noaa.gov/stormevents/.
“NOAA: Billion-Dollar Weather/Climate Disasters.” 2013. Government agency. *NOAA*. Accessed March 20. http://www.noaanews.noaa.gov/stories2011/20111207_novusstats.html.
O’Brien, Geoff, Phil O’Keefe, Joanne Rose, and Ben Wisner. 2006. “Climate Change and Disaster Management.” *Disasters* 30 (1): 64–80. doi:10.1111/j.1467-9523.2006.00307.x.
Ogryczak, Włodzimierz. 2000. “Inequality Measures and Equitable Approaches to Location Problems.” *European Journal of Operational Research* 122 (2): 374–91. doi:10.1016/S0377-2217(99)00240-4.
O’Kelly, Morton E. 1986a. “Activity Levels at Hub Facilities in Interacting Networks.” *Geographical Analysis* 18 (4): 343–356. doi:10.1111/j.1538-4632.1986.tb00106.x.
———. 1986b. “The Location of Interacting Hub Facilities.” *Transportation Science* 20 (2): 92–106.
———. 1987. “A Quadratic Integer Program for the Location of Interacting Hub Facilities.” *European Journal of Operational Research* 32 (3): 393–404. doi:10.1016/S0377-2217987080007-3.
———. 1992. “Hub Facility Location with Fixed Costs.” *Papers in Regional Science* 71 (3): 293–306. doi:10.1007/BF01434269.
———. 1998. “A Geographer’s Analysis of Hub-and-Spoke Networks.” *Journal of Transport Geography* 6 (3): 171–186. doi:10.1016/S0966-6923(98)00010-6.
O’Kelly, Morton E., and Harvey Miller. 1994. “The Hub Network Design Problem: A Review and Synthesis.” *Journal of Transport Geography* 2 (1): 31–40. doi:10.1016/0966-6923(94)90032-9.
O’Rourke, Thomas D. 2007. “Critical Infrastructure, Interdependencies, and Resilience.” *The Bridge* 37 (1): 22.

Perrow, Charles. 1981. “Normal Accident at Three Mile Island.” *Society* 18 (5): 17–26. doi:10.1007/BF02701322.
Quarantelli, Enrico. 1954. “The Nature and Conditions of Panic.” *American Journal of Sociology*, 267–275. doi:10.1086/221536.
Quarantelli, Enrico Louis. 1987. “Disaster Studies: An Analysis of the Social Historical Factors Affecting the Development of Research in the Area.” http://dspace.udel.edu:8080/dspace/handle/19716/1335.
Ransikarbum, Kasin, and Scott J. Mason. 2016. “Goal Programming-Based Post-Disaster Decision Making for Integrated Relief Distribution and Early-Stage Network Restoration.” *International Journal of Production Economics* 182: 324–341. doi:10.1016/j.ijpe.2016.08.030.
Revelle, Charles, David Marks, and Jon Liebman. 1970. “An Analysis of Private and Public Sector Location Models.” *Management Science* 16 (11): 692–707. doi:10.1287/mnsc.16.11.692.
ReVelle, Charles, and Ralph Swain. 1970. “Central Facilities Location.” *Geographical Analysis* 2 (1): 30–42. doi:10.1111/j.1538-4632.1970.tb00142.x.
Russell, David W., Brian E. West, and Richard Van Ausdall. 2000. “Local Government Cooperative Ventures in Connecticut.” Hartford, CT: CT Advisory Commission on Intergovernmental Relations/CT OPM. http://www.ct.gov/opm/cwp/view.asp?a=2985&q=383076.
Santos, Fernanda, and Clifford Kraus. 2013. “Emerging From the Rubble in a Texas Town.” *New York Times*, April 19. http://www.nytimes.com/2013/04/20/us/texas-explosion.html.
Savas, Emanuel S. 1978. “On Equity in Providing Public Services.” *Management Science* 24 (8): 800–808. doi:10.1287/mnsc.24.8.800.
Schmidtlein, Mathew C., Roland C. Deutsch, Walter W. Piegorsch, and Susan L. Cutter. 2008. “A Sensitivity Analysis of the Social Vulnerability Index.” *Risk Analysis* 28 (4): 1099–1114. doi:10.1111/j.1539-6924.2008.01072.x.
Schned, Dan. n.d. “Northeast.” *America2050*. http://www.america2050.org/northeast.html.
Smith, Adam B., and Richard W. Katz. 2013. “US Billion-Dollar Weather and Climate Disasters: Data Sources, Trends, Accuracy and Biases.” *Natural Hazards* 65 (3). doi:10.1007/s11069-013-0566-5.
Smith, David Marshall. 1981. *Industrial Location: An Economic Geographical Analysis*. New York, NY: John Wiley & Sons.
State of CT Commodities and Resource Support Group. 2012. “State of Connecticut. Commodities Distribution Standard Operating Procedure (Draft).” Dept. of Emergency Services and Public Protection/ Div. of Emergency Management and Homeland Security. http://www.ct.gov/demhs/lib/demhs/eppi/draft_commodities_sop.pdf.
Stein, S. M., James Menakis, M. A. Carr, S. J. Comas, S. I. Stewart, Helene Cleveland, Lincon Bramwell, V. C. Radeloff, and others. 2013. “Wildfire, Wildlands, and People: Understanding and Preparing for Wildfire in the Wildland-Urban Interface-a Forests on the Edge Report.” http://www.treesearch.fs.fed.us/pubs/43016.
“Swiss Re Provides Expert Input for New York City Study.” 2013. Corporate website. *Swissre.com*. June 24.

http://www.swissre.com/rethinking/climate_and_natural_disaster_risk/Swiss_Re_provides_expert_input_for_New_York_City_study.html.
Toregas, Constantine, and Charles ReVelle. 1972. "Optimal Location under Time or Distance Constraints." *Papers in Regional Science* 28 (1): 133–144. doi:10.1007/BF01961457.
Toregas, Constantine, Ralph Swain, Charles ReVelle, and Lawrence Bergman. 1971. "The Location of Emergency Service Facilities." *Operations Research* 19 (6): 1363–1373. doi:10.1287/opre.19.6.1363.
Tuz, Susan. 2013. "Regional Planning Agencies Fret over Mergers." *Connecticut Post*, September 2. http://www.ctpost.com/local/article/Regional-planning-agencies-fret-over-mergers-4781937.php.
USACE. 2016. "Inter-Governmental Plans: Commodities Planning and Distribution." http://www.englink.usace.army.mil/igp/commodities.htm.
U.S. Census Bureau. 2010. "Census Data." http://www.census.gov.
"U.S. Daily Weather Maps | NOAA Central Library." 2016. Accessed August 31. http://www.lib.noaa.gov/collections/imgdocmaps/daily_weather_maps.html.
US Department of Commerce, NOAA. 2016. "NWS Boston - The Great Hurricane of 1938." Accessed August 31. http://www.weather.gov/box/1938hurricane.
Wagner, J. L., and L. M. Falkson. 1975. "The Optimal Nodal Location of Public Facilities With Price-Sensitive Demand." *Geographical Analysis* 7 (1): 69–83. doi:10.1111/j.1538-4632.1975.tb01024.x.
Wallace, Anthony FC. 1956. *Tornado in Worcester: An Exploratory Study of Individual and Community Behavior in an Extreme Situation*. 392. National Academy of Sciences, National Research Council.
Wesolowsky, George, and William Truscott. 1975. "The Multiperiod Location-Allocation Problem with Relocation of Facilities." *Management Science* 22 (1): 57–65. doi:10.1287/mnsc.22.1.57.
"West Virginia Oil Train Derailment Threatens Water Supply." 2015. National news website. *Www.cbsnews.com*. February 17. http://www.cbsnews.com/news/west-virginia-oil-train-derailment-threatens-water-supply/.
White, Gilbert F. 1945. "Human Adjustment to Floods. A Geographical Approach to the Flood Problem in the United States." Dissertation. Chicago, IL: University of Chicago, Dept. of Geography.
Widener, Michael, and Mark Horner. 2011. "A Hierarchical Approach to Modeling Hurricane Disaster Relief Goods Distribution" 19 (4): 821–28. doi:10.1016/j.jtrangeo.2010.10.006.
Wilson, Steven G., and Thomas R. Fischetti. 2010. "Coastline Population Trends in the United States: 1960 to 2008." Washington, DC: US Census Bureau.
Wisner, Ben. 1993. "Disaster Vulnerability: Scale, Power and Daily Life." *GeoJournal* 30 (2): 127–140.
Wisner, Ben, J.C. Gaillard, and Ilan Kelman. 2012. "Framing Disaster Theories and Stories Seeking to Understand Hazards, Vulnerability and Risk." In *The Rutledge Handbook of Hazards and Diaster Risk Reduction Management*, Chapter 3. London, UK: Routledge.
Zeigler, Donald, Stanley Brunn, and James Johnson Jr. 1981. "Evacuation from a Nuclear Technological Disaster." *Geographical Review*, 1–16.

Zeigler, Donald, and James Johnson. 1984. “Evacuation Behavior in Response to Nuclear Power Plant Accidents.” *The Professional Geographer* 36 (2): 207–215. doi:10.1111/j.0033-0124.1984.00207.x.
Zelinsky, Wilbur, and Leszek Kosinski. 1991. *The Emergency Evacuation of Cities*. Savage, MD: Rowman & Littlefield.

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