FATALITIES DUE TO HURRICANE KATRINA'S IMPACTS IN LOUISIANA

A Dissertation

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by

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Dedication

This dissertation is dedicated to the people of southeast Louisiana who lost their homes and family members to the 2005 flood disasters.

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Abstract

This dissertation presents a comprehensive analysis of the loss of life in Louisiana associated with Hurricane Katrina and the catastrophic failure of the federal hurricane protection system. While Louisiana officials attribute 1,464 deaths to this disaster, a Louisiana Katrina Victim Database compiled for this dissertation lists 1,575 victims whose death can be linked to circumstances related to the disaster. First, this dissertation presents a comprehensive assessment of the multiple hazards impacting a dynamic population within southeast Louisiana. This is followed by a comprehensive descriptive analysis of victims' characteristics. Both of these assessments point to an important conclusion: circumstances matter in interpreting the observed trends in victims' characteristics. Drawing inferences from the available data, three categories of circumstances of death are identified: (i) direct flood deaths, (ii) emergency circumstances deaths, and (iii) evacuation/displacement deaths. As a whole and within each category, age is the most important demographic attributes with nearly 60% of deceased victims over 65 or older. However, the role of other demographic attributes varies between different categories of circumstances, with flood victims being predominantly African-American males and evacuation/displacement deaths being predominantly Caucasian females. Deaths directly related to flood exposure constitutes one major class or category of victims. Using the available data, these victims are identified, and then merged with population data to calculate and map the direct flood fatality rate (FFR). The overall mortality among the flood exposed population for this event was approximately 1%, which is similar to findings for historical flood events. The FFR is then used as the dependent variable in a regression analysis meant to build upon previous research in modeling flood deaths. In a final step, a set of regressions examine the influence of (i) the flood hazard characteristics and (ii) the population vulnerability characteristics in determining the FFR. It was found that water depth and flow velocity explain much of variance in the observed FFR, with age and race also being significant. These results provide important insights into the deaths caused by this complex disaster along with the relationship between flood mortality and the characteristics of the flood and the affected population.

Chapter 1: Introduction and Problem Statement

1.1 Introduction

Hurricane Katrina and levee failures that occurred during this disaster event resulted in an unprecedented flood catastrophe for modern America. In Louisiana over 1,500 people lost their lives to the immediate and short term effects of the flood (Boyd 2006, Louisiana Department of Health and Hospitals 2006, Louisiana Family Assistance Center 2006). Furthermore Stephens et al. (2007) estimated that many thousands of deaths may be linked to the long term impacts of the flooding in New Orleans. This dissertation examines the loss-of-life associated with the impacts of Hurricane Katrina in Southeast Louisiana, with particular emphasis on the direct flood deaths that resulted from levee failure flooding in Orleans and St. Bernard parishes.

Hurricane Katrina essentially consists of a meteorological event characterized by its central pressure, trajectory, and wind field. However, the Hurricane Katrina disaster largely resulted from the cascading effects of the windstorm. In particular, the sea surface response to the wind storm consisted of a storm surge that exerted damaging loads on levees around New Orleans. In turn, numerous levee failures caused catastrophic flooding of a large urban area along with an acute regional breakdown of basic public safety systems, an extended displacement emergency, and a long-term medical crisis.

The Physical Event

After passing over Miami as a Category 1 hurricane, Katrina entered the Gulf of Mexico as a tropical storm early on Friday, August 26, 2005. Over the next two days, Katrina would move west and strengthen. The storm crossed over the Mississippi River delta in southeastern Louisiana early Monday morning as an officially designated Category 3 storm with landfall windspeeds officially logged at 127 mph (Knabb, Rhome, and Brown 2006). The storm then continued north and made final landfall near the Louisiana-Mississippi Gulf Coast around 11:00 a.m. on Monday, August 29, 2005. This massive windstorm tore roofs off of houses, generated destructive wind borne debris, and spawned forty-three confirmed tornados (Knabb, Rhome, and Brown 2006). As an indicator of the windstorm's extent and strength, most of Mississippi, all of southeast Louisiana, and parts of southern Alabama lost power.

While awesome in its power, the worst impacts resulted not directly from the windstorm but from the sea level response to this atmospheric forcing. Storm surges consist of extreme high tides that result from surface winds and decreased air pressure associated with tropical weather systems. Generally speaking storm surges are the most lethal aspect of hurricane disasters and Katrina was no exception to this trend. Based on the limited data available, an estimated that 175 persons drowned directly due to storm surge flooding along the Mississippi[1] while 45,000

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[1] Information on deaths in Mississippi has been very limited, and with no known official break down by location or cause. The Wikipedia site on "The Effects of Hurricane Katrina on Mississippi" (http://en.wikipedia.org/wiki/Effects_of_Hurricane_Katrina_in_Mississippi, visited March 2, 2011) lists 189 deaths for Mississippi's three coastal counties: Harrison County – 126, Hancock County – 51, and Jackson County - 12. While the majority of these victims were almost certainly surge related, some of these may have been wind deaths. The three counties just north of these, which endured just wind effects, experienced 18 deaths.

homes flooded there (Department of Homeland Security 2006). The surge inundated the entire Mississippi coast and peaked at 28 ft. (8.5 m) near Bay St. Louis (Knabb, Rhome, and Brown 2006).

West of the Mississippi coast, much of southeast Louisiana escaped the direct impacts of the storm surge due to the system of levees, floodwalls, and floodgates that formed the Southeast Louisiana Hurricane Protection System. Again reflecting the cascading effects of this disaster, the surge overwhelmed this poorly designed and constructed system and over fifty levee breaches and other structural failures occurred. For days after landfall, floodwaters poured into metro New Orleans. Over 160,000 homes flooded (DHS 2006) and an estimated 600 to 700 people died due to direct exposure to flood waters in the New Orleans region (see Chapter 6).

Preparation and Response

Catastrophic and deadly flooding of New Orleans had been predicted for many years, and the pre-disaster planning anticipated much of the scenario that unfolded. Evacuation of all of southeast Louisiana was seen as the most effective way to saves lives, but it was also known that not everyone would be willing and able to evacuate beforehand (Hurlbert and Beggs 2002, Hurlbert and Beggs 2003, Howell and Bonner 2005).

The evacuation of Southeast Louisiana for Hurricane Katrina began early Saturday morning. Adhering to the regional, phased evacuation plan, the coastal parishes evacuated first since the only routes out of these parishes went through the City. While heavily criticized for his handling of the evacuation of New Orleans, Mayor Ray Nagin, like other local leaders, followed the regional evacuation plan when timing the evacuation call for his parish. Nagin even took the unprecedented step of calling for a mandatory evacuation for New Orleans. By the onset of hazard conditions Sunday evening, over 90 percent of the “at risk population” in Southeast Louisiana had evacuated (Louisiana Office of Homeland Security and Emergency Preparedness 2006). In New Orleans, over 80 percent of the population evacuated, and an additional 10,000-12,000 people sheltered in the Superdome, which was the city’s designated refuge of last resort (Louisiana National Guard 2005). Similarly, residents from other parishes filled their designated refuges of last resort with thousands of additional residents.

While comprehensive in its level of traffic management and coordination, the evacuation of southeast Louisiana prior to Hurricane Katrina was not complete. In New Orleans, it is estimated (see Chapter 4 & 7) around 80,000 people stayed in their homes or the homes of friends and family, while the available data indicates nearly 7,000 people remained in St. Bernard parish. As these two parishes would soon suffer catastrophic flood conditions, these evacuation and sheltering shortcomings set the stage for an unprecedented flood disaster for modern America.

The flooding and large population trapped in the flooded areas necessitated a massive urban search and rescue operation. Dozens of local, state, and federal agencies participated along with private sector organizations and concerned citizens. Rescues saved around 65,000 people from floodwaters over the following ten days (Louisiana Office of Homeland Security and Emergency

Preparedness 2006). Following the initial rescue, individuals were taken to nearby drop-off points, and then transported to overcrowded and undersupplied to local shelters. Finally, hundreds of buses and aircraft evacuated the distressed population to shelters out of the region. Once the initial emergency response ended, the tough tasks of rebuilding and recovery began, as did the difficult task of recovering the remains of the deceased victims.

General Impacts

Hurricane Katrina resulted in general impacts throughout the Gulf Coast region with a number of acute impacts felt in the greater New Orleans region. The President declared parts of four states, Louisiana, Mississippi, Alabama, and Florida, as Major Disaster areas (see Table 1.1). In southeast Louisiana, where the five parishes that make up the metro New Orleans region were hard hit by flooding from numerous levee breaches, the Federal Office of Gulf Coast recovery counted 304,000 homes, 65 percent of the total housing units, as eligible for Federal assistance due to wind or flood damage (Department of Homeland Security 2006). In Orleans and St. Bernard parishes, an estimated 400,000 residents lived within flooded areas (see Table 1.2). The National Hurricane Center (NHC) estimates that 1.2 million were under evacuation orders (Beven et al. 2008), of which approximately half would endure extended displacement. Estimates of total direct damage range $81 billion (Beven et al. 2008) to over $100 billion (Lipton 2006, Bennedetto 2006). The Center for Research on the Epidemiology of Disasters (CRED), global clearinghouse of reliable disaster data, lists a damage value of $125 billion (Center for Research on the Epidemiology of Disasters 2010). Again, a reflection of the cascading nature of this disaster, the President declared emergencies for two other states, Texas and Arkansas, despite no significant direct impacts there.

No official and complete listing of Katrina victims has been provided by government sources. The NHC’s Tropical Cyclone report states:

> “The total number of fatalities known, as of this writing, to be either directly or indirectly related to Katrina is 1833, based on reports to date from state and local officials in five states: 1577 fatalities in Louisiana, 238 in Mississippi, 14 in Florida, 2 in Georgia, and 2 in Alabama. The total number of fatalities directly related to the forces of Katrina is estimated to be about 1500 spread across four states, with about 1300 of these in Louisiana, about 200 in Mississippi, 6 in Florida, and one in Georgia. Especially for Louisiana and Mississippi, the number of direct fatalities is highly uncertain and the true number will probably not ever be known. Several hundred persons are still reported missing in association with Katrina.” (Beven et al. 2008, p 1140)

For their parts, Wikipedia resembles the NHC figures but includes three victims from Ohio and Kentucky, while CRED lists 1,833 but does not break them down by state. Table 1.3 compares deaths by state from the NHC and Wikipedia. For its part, the final statistics published on the state Department of Health and Hospitals’ website on August 2, 2006 states “there have been 1,464 deceased victims of Hurricane Katrina from Louisiana,” (Department of Health and Hospitals 2006) while evidence presented in Chapter X suggests that there are 50 – 200 additional victims[2].

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[2] The lower limit reflects the approximately 50 victims that were found in flood debris in Orleans parish after the state published their final statistics. The upper limit reflects approximately 20 victims listed on a commemorative plaque in St. Bernard parish that are not listed in the state records along with the 130 missing persons.

Table 1.1: Federal Declarations for Katrina by State. The type of declaration specifies what types of aid the states are eligible to receive and the effective date refers to the date after which disaster related expenses by the states are eligible for reimbursement.

Affected State	**Federal Declarations**	**Effective Date**
Louisiana	Major Disaster, Emergency	Aug. 27
Mississippi	Major Disaster, Emergency	Aug. 29
Florida	Major Disaster, Emergency	Aug. 28
Alabama	Major Disaster, Emergency	Aug. 29
Texas	Emergency	Sept. 2
Arkansas	Emergency	Sept. 2

Source: Federal Emergency Management Agency (2010).

Table 1.2: Housing damage in Greater New Orleans. All columns except for the last refer to counts of housing units.

Parish	Total Housing Units	Inside Floodplain	Outside Floodplain	Total Flood	Wind	Wind & Flood	Damaged Units as a Percentage of Total Units
Jefferson	176,234	28,125	2,612	30,737	63,076	93,813	53.23%
Orleans	188,251	85,889	21,490	107,379	26,965	134,344	71.36%
Plaquemines	9,021	2,989	1,463	4,452	2,760	7,212	79.95%
St Bernard	25,123	7,242	12,820	20,062	167	20,229	80.52%
St Tammany	69,253	11,808	3,646	15,454	33,338	48,792	70.45%
Total	**467,882**	**136,053**	**42,031**	**178,084**	**126,306**	**304,390**	**65.06%**

Source: Department of Homeland Security (2006).

Table 1.3: Katrina Deaths by State.

State	Deaths (NHC)	Deaths (Wikipedia)
Alabama	2	2
Florida	14	14
Georgia	2	2
Kentucky		1
Louisiana	1,577	1,577 (135 Missing)
Mississippi	238	238
Ohio		2
Total	**1,833**	**1,836 (135 Missing)**

Sources: NHC column from Knabb, Rhome, and Brown (2006) and Wikipedia column from http://en.wikipedia.org/wiki/Hurricane_katrina#Impact (Accessed 9/24/2010).

Fatalities Associated with Katrina's Impacts in Louisiana

Hurricane Katrina and the subsequent flooding resulted in a diverse set of impacts throughout southeast Louisiana. Some of these impacts were felt immediately in the areas that experienced the destructive forces of wind and water. Other impacts spanned both distance and time. While the state officially counts 1,464 Katrina related deaths, other evidence described later in this section points to a much larger number.

A number of adverse health impacts resulted directly from exposure to flood waters. Most notably, these include deaths due to drowning. Somewhat surprisingly, drowning only accounts for an estimated 250 - 350 Katrina related deaths in Louisiana, though this rough estimate rests solely on inferences from the circumstances surrounding the death (described in Chapter 6). For many of these victims, flood waters came quickly, rose fast, and overwhelmed their ability to take protective action. In addition to drowning deaths, many people survived the initial flood exposure threat by seeking refuge in attics, roofs, and elevated structures, but later succumbed to the adverse conditions and died because of starvation, dehydration, exacerbation of chronic health problems, or lack of medical treatment. This set of circumstances accounts for an estimated 250 deaths. Together these deaths are labeled as "direct flood deaths" because the circumstances of death are directly related to the presence of flood waters at the victim's immediate location. "Direct flood deaths" is one of three categories that the author used to help interpret the data supplied on victims of the disaster.

Reflecting the cascading nature of Katrina's impact, the health impacts of the flood were not confined to the flooded areas or to those that experienced exposure to flood waters. Some people died in high rise apartment complexes. A number of individuals died in hospitals. While some, but not all, of these buildings were surrounded by floodwaters, these deceased victims never made contact with floodwaters and the circumstances of death are not directly related to flood exposure. Instead of flood exposure, the circumstances of death for these victims are linked to the emergency conditions that resulted from wind and flood damage within the heavily impacted zone. These deaths are termed "emergency circumstances deaths," a second category that the author had to utilize to categorize these deaths. Some of these victims died on floors well above the flood level, while others died at locations outside the flood zone but still within the region that experienced significant damage and disruption to basic public safety infrastructure and services.

Finally, a number of people died post-evacuation and well outside of the flooded areas, but their circumstances of death can still be linked to the impacts (or projected impacts) of Hurricane Katrina. In fact, the first Katrina related deaths in Louisiana occurred a full day before landfall and 90 miles outside of New Orleans; three nursing home residents died of dehydration during transit when their nursing home evacuated to Baton Rouge (Staff Reports 2005). In all, approximately 500 people died between August 28, 2005 and before October 1, 2005 from circumstances linked to Katrina induced displacement. These deaths are termed "evacuation and displacement" deaths, the third category used to interpret the circumstances of death for the roughly 1,500 victims.

The Louisiana Department of Health and Hospitals (DHH) set October 1, 2005 as the cut-off date for a death to be considered Katrina related, and all of the 1,464 Katrina victims counted by the state died between August 28 and that date (Louisiana Family Assistance Center 2006). However, this date largely reflects the operational goals and constraints of DHH, and there is no reason to believe that deaths affiliated with Hurricane Katrina's impacts stopped on this date. To investigate this possibility, the New Orleans City Health Department compiled obituary postings in the local paper and, when controlling for population changes, estimated 1,600 excess deaths during the first six months of 2006 (compared to the first six months of 2002 and 2003) (Stevens et al. 2007). These deaths are attributed to the long-term impacts of the storm on the mental/physical health of the survivors, the destruction of public safety infrastructure, and the inevitable accidents associated with recovery and rebuilding. When this data is extrapolated over the roughly two year initial recovery period, it is estimated that in New Orleans as many as 10,000 excess deaths are associated with Katrina's destruction of basic public safety infrastructure in New Orleans[3].

This dissertation focuses on loss-of-life caused by circumstances related to Hurricane Katrina and the levee breaches that occurred during this storm. My research on flood fatalities, which began before the Katrina disaster, focused initially on the deaths directly and immediately caused by exposure to flood waters. However, as trends in the fatalities due to this disaster became apparent, the research expanded to include loss-of-life that extended well beyond the geographic and temporal domain of the flood hazard conditions. Indeed, of the nearly 1,500 deaths officially counted by the State of Louisiana, only around 600 constitute deaths resulting from exposure to floodwaters and many more are estimated to have died due to circumstances only indirectly related to the flood waters.

Interpreting the Katrina Disaster

Interpreting the Katrina disaster has proven difficult. On one hand, it is difficult to find a precedent for the complex interaction of physical, engineered, and social systems. At the same time, this event had produced a massive amount of data to process and filter. One fact became apparent early-on: the static view of disasters where a single "at-risk" population experiences a limited set of hazards would not be sufficient to interpret the outcomes of this event. Likewise, no single cause can fully explain these disaster outcomes.

Beyond just a single hazard, this disaster can only be characterized by a cascading series of hazards that impacted a dynamic population (see Figure 1.1). The acute trigger of the disaster was a tropical weather system and its sea level response. However, the central cause of the catastrophic destruction and loss-of-life in southeast Louisiana was the failure of the federally designed and constructed levee system to contain a storm surge that it should have been able to contain.

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[3] The Stephen et al. (2007) study covers the period from January to June 2006 and estimated 393 excess deaths per month during this period. Extrapolated over the initial 2 year recovery period using this rate yields an estimated 9,423 excess deaths. During this period, repopulation was rapid while the recovery of health care services was slower.

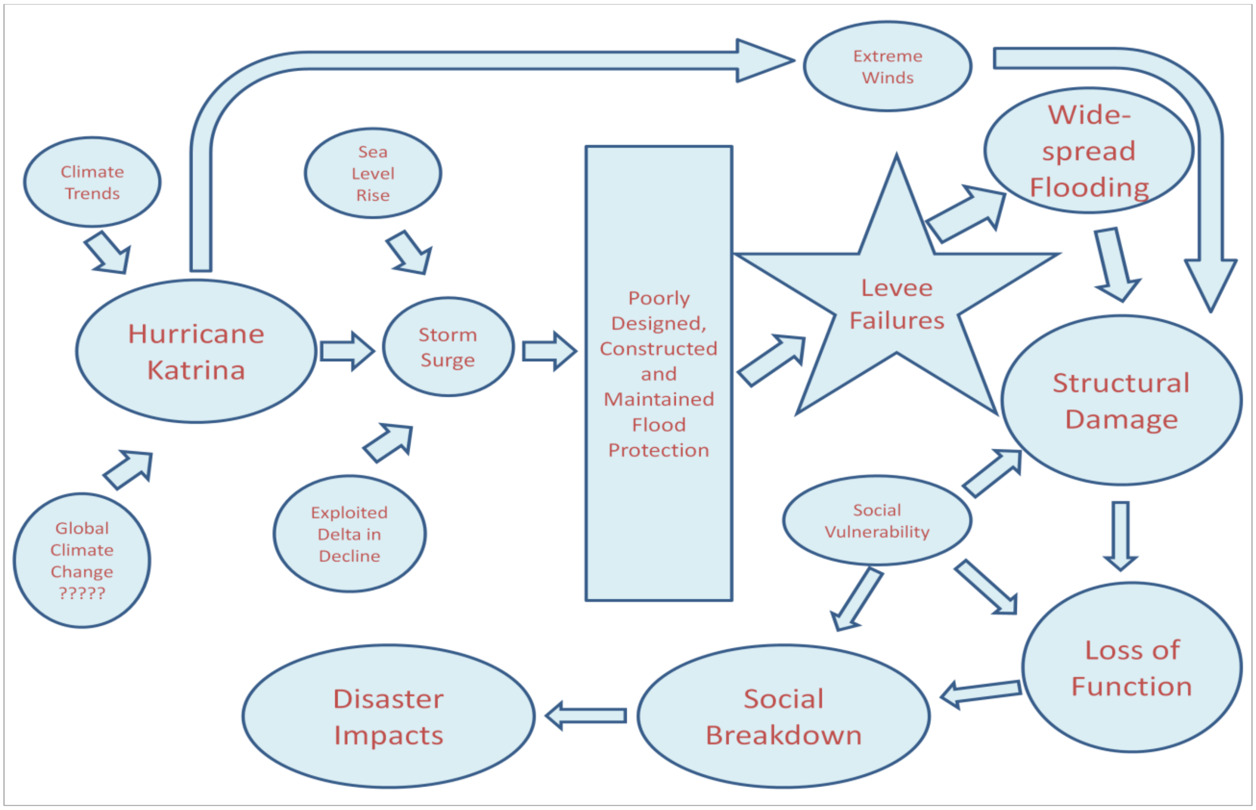


Figure 1.1: The cascading series of events that resulted in the Katrina disaster.

Still, digging deeper into the trigger and central cause listed above reveal other processes that contributed to the disaster. Global climate change possibly contributed to the strength and size of the hurricane, while global sea level rise most certainly contributed to height of the storm surge. Likewise, the failures in the federal levee system fit a broader pattern of unsustainable exploitation of Mississippi Delta, the carving up of coastal wetlands for oil and gas canals, and failure of the federal government to invest in coastal restoration while earning billions of dollars in revenue every year for royalties, navigational fees, and other services provided by the deltaic ecosystem. The construction of and subsequent failure to maintain the Mississippi River-Gulf Outlet exemplifies these trends best, though the landscape bore many marks of these unsustainable federal landuse policies. It could be further argued that this exploitation was aided by the cultural and political marginalization of Louisiana's population.

All of these factors contributed to a cascading series of events characterized by numerous physical and social hazards impacting all or portions of a dynamic population. Just as the storm surge exerted overwhelming loads on the levees and floodwalls, the flooding that ensued exerted overwhelming loads that broke New Orleans' basic public safety systems and infrastructure. This breakdown was felt in the hospitals and nursing homes along with the overcrowded shelters and the many spontaneous "lily pads," a term used to describe the nearest high ground where citizens rescued from flood waters waited for ground transportation. For each of these cases, different segments of the population suffered a set of hazards specific to the circumstance. At the same time, the fire department was unable to respond to fires that raged through the city, including an industrial facility near the river. This breakdown also brought violence throughout the city, with even the mayor being threatened by a mob (Forman 2007). Both a Sewerage and Water Board facility (Forman 2007) and the 1st District Police station received gunfire (Peristein and Lee 2005).

The cumulative effects of these cascading hazards are best represented by the breakdown of the New Orleans Police Department (NOPD). Seventy percent of force lost their homes to the flood, and three districts lost their headquarters (Peristein and Lee 2005). When floodwaters overtook the police headquarters on Broad Street, 30 dispatchers and dozens of officers evacuated (Peristein and Lee 2005). The 911 center also flooded, while windborne debris took out the communications tower (Peristein and Lee 2005). One officer was shot in the head by a looter (Peristein and Lee 2005). Initially, it was reported that two officers committed suicide (Peristein and Lee 2005). However, questions have recently been raised about one of those deaths.

The breakdown of the NOPD created a new hazard for the roughly 90,000 people that remained in New Orleans. In total, NOPD officers were involved in seven separate police shooting incidents, which injured seven and killed four (Peristein and Lee 2005, Thompson, McCarthy and Maggi 2009). In many of these cases, civilians searching for supplies where perceived as threatening looters by police officers. Most perversely, the death of Officer Lawrence Celestine, which was originally reported as a suicide, may have actually been an execution by fellow officers involved in two of the police killings (Paulsen 2010, Editorial Page Staff 2010). These events are hard to imagine in any modern American city, no matter the depth of urban decay, crime and police corruption. These events are best understood in the context of a larger group of hazards related to the acute regional emergency characterized by widespread breakdowns of basic public safety infrastructure and systems once the flood engulfed 80 percent of the city.

1.2 Geographic Hazards and the Vulnerability of New Orleans

Sitting in the heart of the Mississippi River Deltaic Plain and just 6.5° north of the Tropic of Cancer, Southeast Louisiana is exposed to many weather and water hazards. In addition to the region’s well known experience with hurricanes, the area’s humid sub-tropical climate means that floods from heavy rainfall and mid-latitude cyclonic storms are common occurrences. While historically an important hazard for the region, a system of levees and spillways along the Mississippi reduced the likelihood of a river flood in New Orleans. Still, located on a low lying river delta and surrounded by water and wetlands, New Orleans has experienced a number of wind and flood related disasters. Given the record of past experience along with the widespread knowledge of the area’s wetland destruction, it was known prior to Katrina that New Orleans would inevitably experience a catastrophic storm surge flood.

In additional to the general awareness that New Orleans’ location exposed the city to severe weather and floods, awareness also grew regarding the region’s population and infrastructure high vulnerability to disaster. For the inner city population of New Orleans, poverty, poor education, and lack of personal transportation created numerous obstacles when preparing for and responding to catastrophe. In addition, the 2000 Census counted over 150,000 persons over 65 and over 250,000 persons with disabilities within the New Orleans Metropolitan Statistical

Area (US Census 2002) (which includes heavily populated Orleans, Jefferson, Plaquemines, and St. Bernard parishes along with three other nearby parishes).

In addition to the vulnerability of the population, the infrastructure in the region also created vulnerabilities. The drainage system, while one of the world's most complex, was often times overwhelmed by heavy precipitation (Keim and Muller 1992). It was common for a neighborhood to experience street level flooding. Additionally, significant rainfall flooding was not uncommon. As just one example, in May 1995, a two-day rainstorm dropped 20 inches of rain on the region, flooding 56,000 homes and businesses and causing six deaths (Scallan 2005). Just about everyone understood that if a May storm could cause this much death and destruction, then a hurricane induced storm surge could cause catastrophic damage.

Other aspects of the region's flood protection left the region's population exposed to wind and flood hazards. First documented in the late 1960s, the loss of important coastal wetlands had been thoroughly studied in years prior to Katrina. In years, months, and weeks before the storm, researchers had also begun to assess the integrity of levees and floodwalls, particularly as it relates to subsidence.

When considered in the context of political, economic, and social systems, a story of persistent environmental exploitation and injustice emerges. Some 150 years ago, southeast Louisiana was a large expanse of marshes, swamps, and bayous. New Orleans and the surrounding communities benefitted from the hurricane and storm surge protection that these robust coastal wetlands and cypress swamps provided (Colten 2005, van Heerden and Bryan 2006, Shaffer et al. 2009). This natural flood protection system had resulted from the previous 12,000 years of sedimentation by the Mississippi river. However, in the 1850s, human modifications to the landscape started to reverse the natural process of land creation. Looking to tame the mighty Mississippi river and to further exploit it for navigation, federal engineers decided to pursue a "Levee's Only" policy for maintaining the river (McQuad and Scheifstein 2006, Pabis 2000). This decision meant that the many distributaries of the Mississippi river would be isolated from the coastal wetlands that had been sustained by the fresh water and nutrients delivered by the river and that had protected New Orleans from hurricanes and storm surges. With this hydrologic barrier in place, the coastal wetlands slowly started to die as erosion was greater that sedimentation.

In years that followed, many other decisions and actions contributed to the destruction of the coastal wetlands. Following the 1927 Mississippi River flood, federal engineers continued and strengthened the "Levee's Only" policy. Additionally, over the years the federal government dug many new navigation canals throughout the region, including the Inner Harbor Navigational Canal, the Intracoastal Waterway, the Mississippi River Gulf Outlet, the Harvey Canal, and the Houma Navigational Canal. Additionally, oil and gas companies dug many hundreds of additional smaller navigational canals through the wetlands. These canals both contributed directly to wetland loss by physically removing vegetation and soils, and they also provided an avenue for saltwater intrusion which resulted in freshwater marshes dying. Other factors contributing to the wetland loss include regional subsidence, global sea level rise, and polluted agricultural runoff.

For many decades, coastal scientists had worked on plans to restore the wetlands. When Hurricane Katrina hit in 2005, the Coast 2050 plan had widespread support from local and state governments, coastal scientists, environmental organizations, and the state's Congressional delegation. However, despite the fact that the region generated billions in GDP annually and many billions of annual direct revenue, from taxes, tariffs, and mineral royalties, for the Federal treasury, federal government rejected the plan because it deemed the $14 billion price tag, spread over 30 years, too costly (Walsh 2004). In the mean time, emergency managers increasingly became aware that the risk of a storm surge flood disaster continuously grew as the protection provided by the coastal wetlands continuously decreased.

Given the known threat, plans were developed at a variety of levels to prepare for the "Big One" (Walsh 2004, p. 1) that "Filled the Bowl" (Maestri 2003, p. 48). Within the state and local governments, large-scale evacuation in the face of a threatening hurricane was seen as the best strategy to preserve life. However, the limitations of approach were also known. Insufficient highway capacity was one of these limitations. Access to the urban core of New Orleans (where the majority of the population would have to evacuate from) was limited to only four highways and five secondary roads. Additionally, access to some of the outlying coastal communities was limited to only a single low-lying, two lane road that went through urban New Orleans first and tended to flood early when hurricanes approached.

Limited access to personal transportation also complicated planning for large-scale evacuation. The 2000 Census had revealed that approximately 51,000 households (27.2 percent of the total number) in Orleans parish lacked access to a personal vehicle. In surrounding Jefferson, St. Bernard, and Plaquemines parishes approximately 10 percent of households lacked personal transportation. Many of these same households contained elderly persons and persons with physical and mental disabilities, making both convincing them to leave and then helping leave a difficult task.

For these reasons and other similar reasons, New Orleans had earned a place near the top of FEMA's list of possible catastrophes within the United States (Berger 2005). Perhaps surprising to some, the attention given the "New Orleans" scenario meant that a small network of disaster planners, government officials, and academic researchers had anticipated how much of the catastrophe would unfold. Indeed, the 2004 "Hurricane Pam" disaster planning exercise produced a detailed scenario that described much of what would happen along with a detailed plan to provide for the needs of the affected population.

Given the available knowledge, many have asked why did this catastrophe occur? While the subject of considerable debate, no simple, definitive answer has emerged. One common theme throughout the debate has been the "failures at all levels of government" (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, p. 1) While noting that many shortcomings of government response were seen during the Katrina experience, this participant-observer contends that government at all levels did not fail to prepare for or respond to the catastrophe created by Hurricane Katrina. Chapter 4 presents the undeniable evidence of thorough planning and a robust response by local, state, and federal governments. For the time being, the reader might want to note that during testimony before the House committee investigating the Katrina disaster, Colonel Smith (2005), of Louisiana's Office of Homeland Security and Emergency Preparedness, described this success by comparing two numbers: Hurricane Pam predicted 60,000 deaths, while Hurricane Katrina witnessed 60,000 rescues. While the pre-storm evacuation is certainly one of the factors that prevented 60,000 deaths, the 60,000 rescues also represented the limitation of the evacuation. Many would call this shortcoming a failure, a sentiment traced to much publicized testimony by Micheal Brown before the House committee that "my biggest mistake was not recognizing by Saturday [August 27] that Louisiana was dysfunctional" and later stating “My mistake was in [not] recognizing that, for whatever reasons, ... Mayor Nagin and Governor Blanco were reticent to order a mandatory evacuation” (Barrett 2005, p. 1). Interestingly, when asked by the committee what he would consider a successful evacuation, Brown stated eighty percent or better compliance. Further, as described in Chapter 4, instead of being “reticent,” Nagin and Blanco were simply following a staged evacuation plan where timing was crucial and where successfully implementing this plan facilitated the success evacuation of over 1 million people.

Perhaps a better answer to that question is that disasters occur, they occur often, and they often overwhelm governments capability to protect citizens. While governments and the private sector may limit the consequences of disaster through planning and preparedness, it is unreasonable to expect these steps to prevent every disaster and catastrophe. Denial is one of the basic human emotions when responding to traumatic experiences. It is also a significant obstacle to learning from these experiences. The current author contends that denial of the observed fact that disasters occur, occur often, and often overwhelm government’s capability to protect citizens leads to unreasonable expectations of government capabilities when disasters place citizens at risk and also hinders disaster plans based on rational, evidence based analysis.

1.3 The U.S. and Global Disaster Experience

A number of disasters from around the world help illustrate the above assertion that disasters occur, occur often, and often overwhelm government’s capability to protect citizens. Similarly, a cursory examination of U.S. disaster experience in the Twentieth Century reveals that disasters with thousands of fatalities are not unheard of in modern America.

Catastrophes from Around the World

The 2004 Indian Ocean Tsunami is the most lethal disaster in recent memory, though not necessarily the deadliest on record. It provides a good starting point for a discussion of recent flood catastrophes. Resulting from a large under sea earthquake just off the coast of Indonesia, this tidal wave traversed the Indian Ocean bringing death and destruction to the coastline of 15 nations from two continents. The exact number of deaths is unknown. CRED (2009) lists 226,408, though others speculate is could be as high as 400,000 (Anonymous 2005). Nearly 2.4 million people were affected, and damage totaled nearly $10 billion (Center for Research and Epidemiology of Disasters 2009). Indonesia was hardest hit, with an estimated 165,708 deaths, 532,898 affected and $4.5 billion in damage (Center for Research and Epidemiology of Disasters 2009). Sri Lanka suffered the second largest losses with an estimated 35,399 deaths and over 1 million affected (Center for Research and Epidemiology of Disasters 2009). In India, an estimated 16,389 people perished, while nearly 654,512 were affected. Of note, for all three of these countries the number of people affected by the tsunami, in the 500,000 – 1,000,000 range, is comparable to the number of people affected by Hurricane Katrina, but clearly the number of deaths is much different.

While most enshrined in recent memory, the 2004 Tsunami was not the only disaster with hundreds of thousands of deaths. In fact, a dataset on disasters (described below) lists nine additional flood or tropical cyclone disasters since 1900 that killed 100,000 people or greater. Five of these are floods in China, a large country that has experienced many large floods. The other four are tropical cyclones in Asia. One of these occurred in China, a 1922 typhoon that killed 100,000 people (Center for Research and Epidemiology of Disasters 2009). The three others occurred along the coast of the Indian Ocean: an unnamed 1971 cyclone that killed 300,000 in Bangladesh, the 1991 Cyclone Gorky that killed 138,000 in Bangladesh, and the 2008 Cyclone Nargis that killed 138,000 in Myanmar (Burma) (Center for Research and Epidemiology of Disasters 2009).

The CRED maintains and updates weekly an Emergency Events Database, called the EM-DAT, which provides "essential core data on the occurrence and effects of over 16,000 mass disasters in the world from 1900 to present." Most of the disaster statistics presented in this section were obtained from the CRED Website on July 13, 2009. The dataset utilizes a country level of analysis and lists disaster events as cases (multiple countries impacted by a single disaster are listed as separate cases) and includes official estimates of deaths, injuries, persons made homeless, and cost of damage.

According to this data source, floods were the most common disaster type with 3,500 events listed in the dataset, while windstorms, with 3,200 events listed, were the second most common. These flood events resulted in 6.9 million deaths, making floods the third deadliest disaster type. Droughts caused 11.7 million deaths over 562 events, while 1,175 epidemics caused 9.5 million deaths. Table 1.4 compares the occurrence and impacts of floods relative to other disaster types during the period 1900 to present. Importantly, these statistics are skewed by a handful of mega-catastrophes that comprise large portion of each total.

Deadly disasters were a recurrent theme of the Twentieth Century. The CRED dataset lists 293 natural disasters that caused 1,500 or greater deaths, which includes Hurricane Katrina with 1,833 deaths. This list spans over 110 years, implying that on average 2.6 disasters of this magnitude occur a year. Of these, 38 were floods, indicating that on average a flood of this magnitude occurs once every 2.9 years somewhere on the Earth. Table 1.5 shows the occurrence of disasters of this magnitude by disaster type. Of the 293 disasters with 1,500 or greater fatalities, 41 occurred in China, 35 occurred in India, and 21 occurred in Bangladesh. Given that this region accounts for nearly one-third of the world's population, it is not surprising that one-third of the deadliest disasters occurred in these three countries. The United States accounts for just under 5% of the world's population but only 1.3% of the deadliest natural disasters, an indication that disasters of this magnitude are less prevalent for the U.S. population. Why they are less prevalent is subject to continuing debate, though it seems clear that the U.S., a wealthy country with considerable technological and institutional capabilities, is better able to prepare for and respond to hazardous events that would overwhelm other governments and populations.

Table 1.4: Total number of events, deaths, persons affected, and cost of damage by disaster type. "Count of" is the number of events for which a value is listed. A number of cases contain incomplete data. For example, there are 11,139 – 7,796 = 3,343 cases for which the number if fatalities is not listed. Source: EM-DAT (Source: CRED EM_DAT, obtained July 13, 2009).

Disaster Type	Count of Type	Count of Killed	Sum of Killed	Count of Total Affected	Sum of Total Affected	Count of Est. Damage (US$ Million)	Sum of Est. Damage (US$ Million)
Drought	562	62	11,708,267	344	1,967,461,701	150	84,352
Earthquake	1,120	831	2,311,491	856	158,505,819	384	452,526
Epidemic	1,175	994	9,551,813	980	42,294,664	1	0
Extreme temperature	361	296	108,938	95	91,552,895	50	55,031
Flood	3,513	2,518	6,911,005	2,834	3,075,858,315	1,236	432,290
Insect infestation	83			2	2,200	5	230
Dry Mass movement	52	49	4,919	23	26,150	3	204
Wet Mass movement	517	489	55,040	271	11,182,912	60	7,019
Storm	3,206	2,351	1,373,104	1,855	807,640,334	1,513	739,369
Volcano	210	83	95,979	159	5,094,972	33	3,040
Wildfire	340	123	3,287	166	5,885,437	99	45,585
Grand Total	**11,139**	**7,796**	**32,123,843**	**7,585**	**6,165,505,399**	**3,534**	**1,819,646**

Table1.5: Summary statistics by disaster type for all natural disasters with 1,500 or greater killed, 1900 – June 2009. Source: EM-DAT (Source: CRED EM-DAT, obtained July 13, 2009).

Disaster Type	Number of Events	Total Killed	Maximum Killed (in a single event)
Drought	20	11,701,000	3,000,000
Earthquake (seismic activity)	106	2,231,739	242,000
Epidemic	43	9,426,940	2,500,000
Extreme temperature	6	69,261	20,089
Flood	38	6,724,431	3,700,000
Mass movement dry	1	2,000	2,000
Mass movement wet	4	21,717	12,000
Storm	64	1,201,805	300,000
Volcano	10	81,195	30,000
Grand Total	**292**	**31,460,088**	**3,700,000**

However, it would be foolish to assume that modern technologies along with professional agencies such as NOAA, USGS, and FEMA can buy invincibility. In fact, four disasters of this magnitude prove they are not unheard of in the United States, though three of them occurred early in the Twentieth Century during the early days of the modern, technological era. These disasters are the 1900 Galveston Hurricane, the 1906 San Francisco Earthquake, the 1926 Lake Okeechobee, Florida Hurricane, and the 2005 Hurricane Katrina. An important question, though one that is beyond the scope of the current dissertation, is whether Hurricane Katrina demonstrates the vulnerabilities of Twentieth century continue to exist in the early Twenty-first Century or whether this single event reflects a rare extreme in a modern era of reduced disaster impacts.

The U.S. Disaster Experience

Emergencies, such as severe storms or industrial accidents, are an everyday occurrence within the United States. Likewise, on a near daily basis, a community somewhere in the United States will see a small number of homes damaged or businesses disrupted due to floods or high winds. Few communities have not been impacted by such regularly occurring, low level natural hazard events. Disasters, which have broader and more complex affects, are less common, but also occur regularly. Many communities are likely to experience significant destruction from floods, high winds, earthquakes, heat waves, or other possible natural disasters. For 2005, the CRED dataset lists 16 events for the U.S., while FEMA responded to 48 declared disasters.

Considerably less common, major catastrophes are still an important aspect of the U.S. disaster experience. While infrequent, America has experienced a number of high fatality events since the beginning of the Twentieth Century. The worst disasters include the previously listed hurricanes and earthquake during the earlier part of the century, though more recent events, such as heat waves in 1980, 1998, and 1995 and recent hurricanes along the Gulf Coast, have produced deaths tolls in the hundreds.

In 1900, an unnamed hurricane made landfall near Galveston, Texas with 135 mph (217 km/hr) winds (Category 4) and a 15 ft (4.6 m) storm surge (Larson 1999). In sharp contrast to Hurricane Katrina, this storm caught the barrier island town of 42,000 largely by surprise and very few preparations had been undertaken. The storm destroyed 3,600 homes and caused 6,000 fatalities (CRED 2009).

In 1906, a major earthquake struck San Francisco, California destroying many structures in this city of approximately 400,000 at the time. Following the initial earthquake, numerous fires burned throughout the city contributing significantly to the extent of the disaster. CRED (2009) states 2,000 people perished due to this event.

In mid-September 1928, a major hurricane made landfall on the Florida coast near Palm Beach and then followed a track that took the storm up the Florida peninsula. Before turning northeast, the eye of the storm skirted Lake Okeechobee in south central Florida, causing a lake surge of 6 – 9 ft (1.8 – 2.7 m) (National Weather Service 2011). CRED (2009) states that 1,836 people died in Florida due to this hurricane, most of them due to the surge from Lake Okeechobee.

Two heat waves in the 1980s resulted in death tolls over 1,000. During the summer of 1980, high temperatures over 90 ˚F (32 ˚C) occurred daily in numerous cities throughout the southern and central regions of the U.S. resulting in 1,260 deaths (CRED 2009). Eight years later in 1988, the central and eastern regions of the US experienced more losses to drought and extreme heat. Deaths attribute to this disaster are estimated to be between 5,000 and 10,000 (National Climate Data Center 2011).

For means of comparison, the coordinated terrorist attacks on September 11, 2001 resulted in 2,974 known deaths while 24 people remain missing and are presumed dead. (Since this is not a natural disaster, this event is not listed by CRED). Thorough investigations have provided significant insight into the victims of this disaster. Of the known deaths, 2,603 occurred in or around the World Trade Center, 125 at the Pentagon, and 246 on the planes that crashed. In its final report on the World Trade Center disaster, the NIST provides a thorough analysis of the fatalities and the population at risk (Averill 2005).

One trend becomes apparent in the previous paragraphs. While two hurricanes caused fatality counts over 1,000 during the first 30 years of the Twentieth Century, no tropical system (prior to Katrina) had resulted in comparable loss of life since. Still, hurricanes have been a deadly part of U.S. disaster experience since the middle of the century. Between 1950 and 1975, four hurricanes resulted in over 100 deaths; they are: Diane (1950) with 184 deaths, Audrey (1957) with 390 deaths, Camille (1969) with 323 deaths, and Agnes (1972) with 122 deaths (CRED 2009).

Following Hurricane Agnes in 1972, no hurricanes or tropical systems caused over 100 deaths in the U.S. until hurricane Katrina in 2005. While some analysts attribute this trend to improvements in hurricane forecasting and evacuation procedures (Rappaport 2000), it is also possible that this trend simply reflects the fact that this period coincides with the phase of the North Atlantic Oscillation characterized by less frequent and intense Atlantic basin hurricanes (Pielke and Landsea 1999).

Between 1990 and Hurricane Katrina in 2005, two natural disasters in the United States resulted in over 100 deaths. In March 1993, a large blizzard delivered freezing temperatures and significant snowfall to much of the southeast. In parts of Tennessee, over 60” (152 cm) of snow fell, while the Florida panhandle experienced 2” (5 cm) of snow along with hurricane force winds. The 1993 blizzard resulted in 300 deaths throughout the United States. In July 1995, a weeklong heat wave gripped the Midwest cities of Chicago and Milwaukee. CRED (2009) lists 670 deaths, while Klinenberg (2002) cites 739 excess deaths in Chicago and the CDC (1996) notes 91 heat related deaths in Milwaukee.

So, while an initial look at disasters with over 1,000 deaths indicated that the Katrina disaster is a lone special case since the last half of the Twentieth Century, a more in depth look at the U.S. disaster experience found numerous cases of deadly disasters in the modern era. Perhaps, most indicative that Katrina represents the continuation of old trends, instead of the advent of a new era of reduced vulnerabilities in the U.S., is the 2004 and 2005 Atlantic hurricane seasons, a period that residents along the US Gulf Coast are likely to remember for the rest of their lives.

During these two record breaking hurricane seasons, 10 named storms impacted Gulf Coast states and FEMA responded to 20 different declared disasters along the Gulf Coast. Some observers have referred to this sustained onslaught of wind (Figure 1.1), rain, and high tides (Figure 1.2) as the 2004-05 Gulf Coast Hurricane Disaster (see Table 1.6). These 10 named storms (all but Tropical Storm Bonnie reached hurricane status) resulted in 1,876 known deaths across the five Gulf Coast states, an additional 3,348 deaths outside of the Gulf Coast region, and a total of $158 billion in damage (Franklin et al. 2006 and Beven et al. 2008). Naturally, Hurricane Katrina dominants these statistics, but other storms are noteworthy. Hurricane Charley, with $15 billion in damage, broke the previous record for costliest US hurricane set by Hurricane Andrew in 1992 (Beven et al. 2008). Hurricane Wilma, with $20 billion in damage, would have broken this record, if Hurricane Katrina had not caused $81 billion in damage two months earlier (Beven et al. 2008). Also of note, widespread rainfall flooding due to then Tropical Storm Jeanne claimed over 3,000 lives in poverty stricken and deforested Haiti, while Hurricane Ivan caused 92 deaths and Hurricane Dennis result in 54 (Franklin et al. 2006 and Beven et al. 2008). Figure 1.2 depicts the extent of hurricane winds during the 2004-05 hurricane season, while Figure 1.3 shows the peak surges observed during this period.

Table 1.6: The 2004-05 Gulf Coast Hurricane Disaster. This information was obtained from the NHC reports on the 2004 and 2005 hurricane seasons summaries (Franklin, et al. 2006 and Beven, et al. 2008). The figures reflect NHC criteria, and the source provide combined figures for Hurricane Charley and Tropical Strom Bonnie (both impacted similar areas consecutively).

Year	State	Storm	Deaths in Gulf Coast States	Deaths Outside US Gulf Coast States	Direct Damage (USD Billions)
2004	Florida	Hurricane Charley and Tropical Storm Bonnie	9	6	$15
2004	Florida	Hurricane Frances	6	3	$8.90
2004	Florida, Mississippi, Alabama, Louisiana	Hurricane Ivan	15	77	$14.20
2004	Florida	Hurricane Jeanne	3	3,000	
2005	Louisiana	Tropical Storm Cindy	0	1	$6.90
2005	Florida, Mississippi, Alabama	Hurricane Dennis	14	40	$0.32
2005	Florida, Mississippi, Alabama, Louisiana	Hurricane Katrina	1,831	2	$81
2005	Louisiana, Texas	Hurricane Rita	5	0	$11.30
2005	Florida	Hurricane Wilma	5	18	$20.60
		Total	**1,876**	**3,348**	**$158.22**

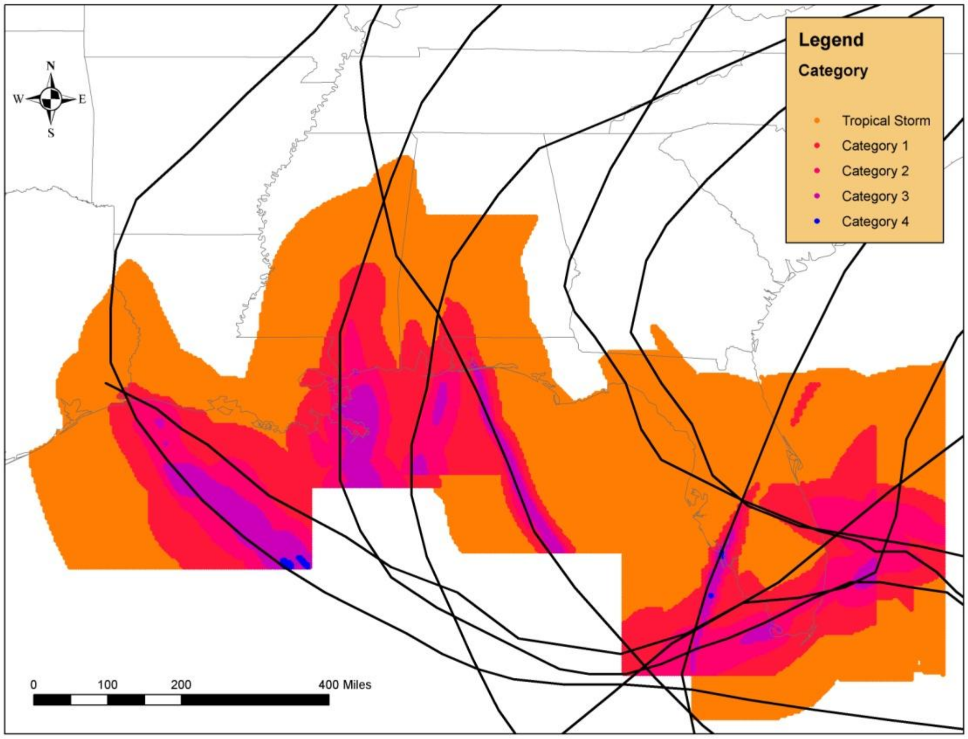


Figure 1.2: Select wind speeds observed during 2004-05 Hurricane Disaster. Map created by author using the H*Wind dataset provided by NOAA's Hurricane Research Division.

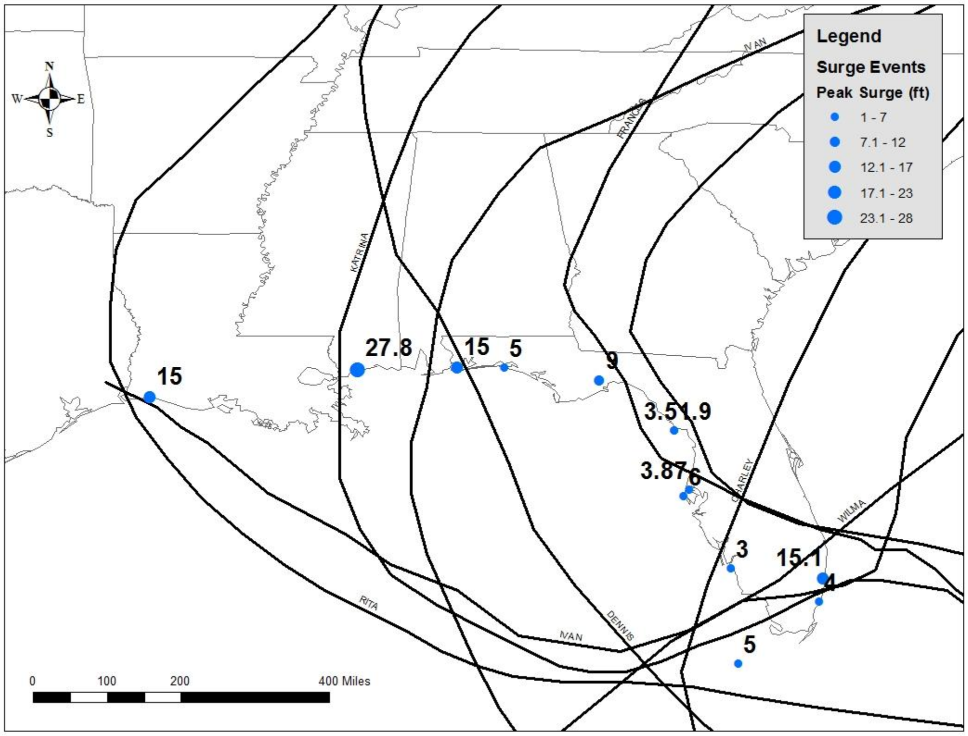


Figure 1.3: Select peak surges observed during 2004-05 Hurricane Disaster. Map created by author using data provided by Hal Needham, LSU Department of Geography.

The 2005 hurricane season produced other noteworthy storms. Hurricane Stan caused widespread flooding and mudslides throughout Central America and resulted in 1,000 – 2,000 deaths (Beven et al. 2008). While Hurricane Alpha, the first storm named with a Greek letter because the NHCs normal list of names had been exhausted, caused 26 deaths in Haiti and the Dominican Republic (Beven et al. 2008). Hurricane Gamma, the third storm named with a Greek letter, caused 37 deaths in Honduras and Belize (Beven et al. 2008). The 2005 season even extended into 2006; Hurricane Zeta formed December 30, 2005 and dissipated January 6, 2006 (Beven et al. 2008).

1.4 Research Questions, Objectives, and Expected Results

Originally, this dissertation research followed a limited scope of refining a direct flood fatality model, following the work of Jonkman and Asselman (2003) and Jonkman (2007). This research sought to use statistical analysis of data from different flood events to specify a dose-response relationship, an equation that expressed the flood fatality rate as a function of the flood depth and other characteristics. In extending this model, data on the flooding in metro New Orleans is used to infer a more refined dose-response relationship by examining multiple hazard characteristics of the flood event along with vulnerability characteristics of the exposed population. This model may be used to improve flood response planning, flood mitigation decision making, and flood emergency responses. During the Katrina disaster, the author applied a preliminary form of the model to estimate the number of flood fatalities for Louisiana state officials who had requested a fatality estimate. While initial estimates suffered from a lack of accurate flood data, later estimates provided near order-of-magnitude accuracy, thus validating the basic principles, form, and utility of the flood fatality model (see Table 1.7).

As previously noted, the Katrina disaster made it painfully clear that deaths during major flood disasters are not confined to just the flooded areas. As such, the scope of research has been expanded and the proposed dissertation will look at both the direct flood deaths and those deaths that resulted from circumstances related to the flood disaster. However, the original research goal, refining a direct flood fatality model, remains paramount.

Table 7: Revised Katrina flood fatality estimate based on a preliminary flood fatality model. Source: Estimate produced by author based on Boyd, Levitan, and van Heerden (2005).

Parish	Exposed Population	Estimated Fatalities (Min)	Estimated Fatalities (Max)
Jefferson	12,729	0	9
Orleans	78,166	1,507	3,145
St. Bernard	3,186	1	49
St. Tammany	4,263	3	30
Plaquemines	1,988	106	172
Total	**100,332**	**1,618**	**3,504**

Three important questions guide this research:

What factors determine and explain the loss of life due to Hurricane Katrina's impacts in Louisiana?
How can Jonkman's flood loss of life models be further developed and refined?
Can we extend the notion of a flood fatality model to include deaths related to the flood event but not directly caused by flood exposure?

The first question has been the subject of considerable debate and editorializing, usually involving unforgiving criticism of local, state, and federal preparedness and response efforts and/or accusations that certain elements of the New Orleans' improvised, minority population were "left to die" (Strolovitch, Warren, and Frymer 2006). While literature along these lines seems nearly endless, data based analysis of these questions is nearly nonexistent. This dissertation will, to the greatest extent possible, compile the relevant data and address this question through objective analysis based on the available data.

The second and third questions build on previous research in flood fatality modeling. One traditional approach has utilized limited historical data from isolated flood disasters to investigate the relationship between flood conditions (mainly flood depth) and flood deaths. This dissertation builds on this tradition in two key areas. First, for better or worse, Hurricane Katrina and the subsequent flood disaster provided the most accurate, precise, and comprehensive dataset for studying flood disasters and their impacts. Using this dataset, considerable refinement of the flood fatality model will be made. Secondly, the Katrina disaster also illustrated the need to look beyond the narrow confines of the flooded region when assessing loss-of-life from flood disasters. Toward implementing this lesson learned, this dissertation will expand flood fatality modeling to include loss-of-life indirectly resulting from the flood.

At this point, it needs to be noted that the focus of this dissertation is the loss-of-life associated with Katrina's impact in Louisiana. Hurricane Katrina also caused considerable loss-of-life in Mississippi along with deaths in other states. Rita resulted in one death in Louisiana along with over 100 in Texas. What basic data that is available on Katrina related deaths outside of Louisiana is presented and discussed. However, the in depth research and analysis is limited to Katrina related fatalities in Louisiana, for which the necessary data are available.

An additional caveat needs to be mentioned. Hurricane Katrina expanded the scope of research beyond the immediate flood zone, but did not replicate the considerable research developments in modeling direct flood deaths. When further specifying and refining the direct flood fatality model, I build on a body of research that has produced a number of complementary models for this specific flood outcome (McClelland and Bowles 2002, Graham 1999, Jonkman 2007). In contrast, modeling indirect flood fatalities delves into new territory. There is no pre-existing model to further develop. Given these different starting points, the end points will likewise differ. In regards to direct flood fatalities, the start point is an existing model (Jonkman 2007) and the end point is a more detailed and precise model. In contrast, the models for indirect flood fatalities starts from scratch and ends with only preliminary, order-of-magnitude type relationships drawn from the current dataset.

1.5 Objectives

This dissertation seeks to fulfill three important objectives. These objectives first require a couple of prerequisites. Specifically, these objectives require an authoritative historical record of this complex event, particularly in regards to the factors related to loss-of-life including the pre-storm evacuation and sheltering, the extent of hazard conditions, and the emergency response. Some aspects of this record are available in published reports, while others will be presented for the first time (for example interviews with persons involved in the response). As such, this dissertation will serve as a comprehensive, but unfortunately still incomplete, compilation of the published and unpublished data related to Katrina related loss-of-life in Louisiana and the factors needed to explain this loss of life.

Objective 1: Determine the circumstances of death for Katrina victims.

Hurricane Katrina and the levee failures resulted in the flooding of two parish coroner's offices, numerous hospital morgues, and an estimated 30 funeral homes in the New Orleans area. Thus, while creating an unprecedented demand for post-mortem investigations, the flood also decimated the local capabilities to complete such investigations. The solution implemented was a joint operation involving local, state, federal, private, and non-profit agencies to recover, examine, and identify the remains of the deceased victims. Fulfilling just these basic goals proved challenging, and no concerted effort was made to medically determine cause of death for the victims.

This dissertation takes off where Jonkman finished and will add to this literature by utilizing the impressive amount of data available from this disaster event. Using a variety of data sources, including medical examiner reports, field measurements from the location of death, and GIS analysis, victims have been categorized according to 3 categories of circumstances of death inferred from the data. The three categories consist of a) direct flood deaths, b) deaths linked to the emergency conditions in greater New Orleans, and c) deaths related to evacuation and displacement. For each category, there will be an associated set of causes of death. For example, drowning and trauma due to blunt impacts with flood debris are two possible causes of death for victims categorized as direct flood deaths.

Objective 2: Further refine and expand the flood fatality model presented by Jonkman (2007).

Flood fatality modeling is an emerging area of research within disaster science. Researchers in the U.S. (McClelland and Bowles 2002, Graham 1999, DeKay and McCelland 1993) have given extensive attention to the quantitative analysis of loss-of-life due to dam failure induced floods. In Japan, researchers have developed loss-of-life models based on typhoon induced coastal floods that have occurred in that country. Most recently, Jonkman (2007) furthered the Dutch tradition of flood fatality modeling, even including a preliminary analysis of Katrina related flood deaths in New Orleans, albeit one based on limited and less certain data. This dissertation will add to this literature by utilizing the impressive amount of data available regarding the Katrina catastrophe. Three major limitations of Jonkman's results will be overcome. One, the available data has been further processed, verified, and analyzed. Two, additional variables on the vulnerability characteristics of affected population will be included in the analysis. Three, the final statistical analysis will include more generalized dose-response functions.

Objective 3: Taking initial steps toward modeling indirect flood deaths.

When one thinks about flood deaths, one usually thinks about a person drowning in flood waters. Likewise, thoughts about hurricane deaths typically involve destructive winds and wind borne debris. Hurricane Katrina forced us to reconsider this narrow understanding of what constitutes a flood or hurricane death. As such, it is proposed that the concept of flood fatality model be expanded to include deaths indirectly associated with the flood waters. To its credit, Louisiana and the State Medical Examiner's Office gave significant attention to tracking deaths that could be indirectly linked with Hurricane Katrina, thus providing a dataset to begin exploring the possibilities of modeling indirect flood deaths.

In fulfilling these objectives, the author hopes to use the tragic event of 2005 to advance analytical tools that will help planners, responders, and engineers make decisions that will minimize the risk of similar events in the future. More specifically, this dissertation seeks to enable better emergency responses, mitigation plans, and flood defense policies. Most acutely, in terms of emergency responses to flood events, the analysis presented here will enable responders to better identify the areas of greatest risk for loss of life during flood events, thus allowing them to more effectively deploy response assets. Likewise, before the emergency arrives, this tool will enable planners to better assess flood risk and to develop more robust plans to reduce this risk. Finally, toward preventing large casualty flood disasters, this tool will help engineers and other professionals involved in designing flood reduction systems, such as levees or wetland restoration, to better identify the strategies that will have the greatest impact in reducing flood deaths.

Expected Results

The following results are expected:

A) The flood hazard characteristics are the most important determinants of the flood fatality rate, indicative of the important role of flood prevention in reducing loss-of-life due to floods.
B) For a given flood scenario, reducing the number of people exposed (through evacuation and sheltering) is the best strategy for protecting lives.
C) The negative health impacts extend far beyond the flood region, but exposure to flood waters constitutes the greatest flood risk.
D) Age is the dominant population characteristic associated with increased risk of death during Katrina; physical disability status is the second most important variable; gender, income, race are only marginally important, if at all. It is expected that this statement will apply each category of victim.

Significance

Geography focuses on the study of place and human interactions with place. In delineating a region on a map, one not only specifies a portion of the earth's surface, but also the geo-physical characteristics of the region. Additionally, drawing a region on a map specifies the population of humans that inhabit the area and utilize its resources. To a large extent, the science of geography centers on the need to understand how to best utilize those resources to meet human needs and desires. Many of the important questions in geography relate to how humans exploit their environment and how the environment constrains human development. Indeed, the renowned geographer Gilbert White (1945) noted that flood losses are merely rents collected by Mother Nature in return for human occupancy and exploitation of floodplains. Likewise, the causes, contributing factors, and the impacts of Hurricane Katrina and the 2005 flood of New Orleans provide an illustrative case study of the interaction between people and place, and this study bears significance on this general topic.

While floodplains provide many important benefits to the populations that settle them, flood deaths form an important constraint on human utilization of these productive ecosystems. As such, studying this class of disaster outcomes is important, not just because of the practical desire to prevent such deaths, because of the scholarly importance that this outcome bares on our understanding of the human-environment interaction. Within the very broad scope of this interaction, disasters represent extreme events characterized by acute losses. As just one type of disaster outcome, deaths are the most tragic and enduring outcomes of disasters. By quantitatively studying flood fatalities and the factors that contribute to these deaths, this study also advances our understanding of the human interaction with place.

In addition to the academic significance within geography, this dissertation will bear important relevance to a crucial problem facing humanity. The consensus of climate scientists accepts global warming and global sea level rise as facts, with the Intergovernment Panel on Climate Change estimating that global temperatures are rising by 0.6 to 0.8 °C per year and global sea levels are rising by 0.05 to 0.15 in. per year (1.3 to 3.8 mm/yr) (Intergovernment Panel on Climate Change 2007).

While the causes and future projections of climate change continue to be debated, some of the consequences are undeniable. Sea level rise alone will lead to more frequent and more intense floods, while changes in precipitation patterns may also increase flood damages. These disasters will only be made worse by increased overall population, increased settlement in flood prone areas, and land use impacts on runoff. Understanding the loss-of-life due to Hurricane Katrina will help manage the flood risks ahead.

The environmental change induced flood problems are particularly worrisome for southeast Louisiana. This region faces increased risk for a variety of reasons. A flood prone region before being settled by European colonizers, the arrival of Western civilization has drastically influenced the flood risk here. To a large extent, engineering and landscape modifications have conquered the river flooding problem. But levees around the Mississippi have starved the surrounding wetlands, a natural storm surge buffer for New Orleans, of the river sediments that sustain them. The resulting coastal land loss increased the storm surge exposure for the region, while an expanding City has created drainage problems. Hurricane Katrina brought considerable attention to this problem along with resources to long running efforts to restore the coast and increase flood protection.

However, it will take time to restore coastal wetlands and to build levees and floodwalls to standards, and the region continues to face increased storm surge exposure. Further, the rate of repopulation of New Orleans has exceeded most expectations and the City is far from forsaken (as many speculated in days immediately after Katrina). On average, southeast Louisiana experiences hurricane impacts every 7 years, and impacts of a category 3 or stronger every 25 years (Keim, Muller and Stone 2007). At the same time, the 2010 Census found vigorous repopulation in the affected area with 343,829 people living in Orleans Parish and 1,167,764 million in the metropolitan region (Plyer 2011). While no real data is currently available, past trends indicate that New Orleans continues to repopulate at a rate around 1,000 residents per month. While repairs and upgrades to the region's levee have been substantial, the system continues to have key weaknesses. At the same time, efforts at coastal restoration on the local level and climate change mitigation at the global level have yet to pick up steam. When taken together, these factors indicate something to be concerned about: it is very probable that a repopulated New Orleans will get another storm surge before its flood protection is restored and upgraded. Further, as Tidwell (2006) points out, after the next flood or hurricane ravages New Orleans, the nation that came to the victim's aid after Hurricane Katrina and the communities that housed the city's displaced residents may not have the resources to offer, as they may have been depleted by other climate change impacts.

1.6 Summary of This Dissertation

The next chapter, Chapter 2, presents a review of the relevant literature. In doing so, it traces the evolution of scholarly thought on the human-environment interaction and presents the human settlement and utilization of floodplains and other hazardous landscapes as a special class of this interaction. Beginning with early Greek notions of an uninhabitable Earth, this line of inquiry culminates with the emergence of risk analysis and disaster impact modeling, modern analytical tools that provide the means of rigorous assessments of the potential costs associated with settling floodplains.

The literature review is followed by an historical geography of the study region, which comprises Chapter 3. This historical geography spans over three centuries of European and American transformation to the southeast Louisiana landscape. A preliminary review of a National Hurricane Center database on hurricane impacts on Louisiana is analyzed to link levee construction along with Mississippi River with increase storm surge risk for New Orleans. Finally, this chapter culminates with the growing awareness and associated emergency management policies and practices that these changes have resulted in a densely populated landscape increasingly exposed to hurricane and storm surge hazards.

Chapter 4 tells the story of the Hurricane Katrina disaster in Louisiana. While this story has been told many times from many perspectives, this comprehensive assessment of the preparations and response to this complex disaster adopts a population level perspective. This helps to depict this story in totality, also quantifies many important facts and figures that have been lost in the contentious debate regarding this event. By compiling of figures scattered across numerous "After Action Reviews" and similar documents from response teams, these chapter weaves these disparate numbers into a unified story that has not yet been told in this manner. Moving beyond a static view of a single "At Risk" population exposed to a single hazard, this chapter describes a dynamic population exposed to numerous hazards.

Chapter 5 introduces the study regions and units of analysis along with the describing the physical hazards of this event and the underlying population of Louisiana. As a multi-hazard event, it is shown that a single study region is not sufficient to fully depict this event. To state it simply, the wind map, the rainfall map, the surge map, the levee failure flood maps, and the displaced population map allow cover different regions, necessitating a hierarchy of study regions. It is also in this chapter that the population of Louisiana possessed many of the attributes associated with disaster vulnerability.

Chapter 6 presents a descriptive summary of fatalities related to Hurricane Katrina's impacts on southeast Louisiana. First, the available data, both public and non-public, is described, followed by efforts to compile these data sources into a comprehensive Louisiana Katrina Victim Database. Using this database, the basic descriptive statistics of victims is presented and discussed, with important differences between this comprehensive dataset and previous analysis based on limited datasets. Further, this chapter also uses the available data to infer three categories of circumstances of death for the victims, and shows that these different circumstances bear an important role in interpreting the victim characteristics.

In Chapter 7, the information from Chapter 4 and 6 is used to estimate and map the fatality rate for direct flood deaths. This calculation requires three steps, that while conceptually basic, entails complicated tasks of bringing numerous disparate data sources into a single GIS-based framework. The first step is identifying the direct flood deaths among the general population, which is done by first mapping the victim recovery locations and then using two sets of attribute queries to eliminate those victims who were not exposed to flood waters. These deaths comprise outcome numerator, and the next step quantified the population denominator, defined as the population exposed to flood waters. This step required merging U.S. Census data from the 2000 Census Summary File 2 and the 2005 Gulf Coast American Community Survey along with parish level estimates of the effectiveness of pre-storm evacuations. These estimates are then cross-checked using other, independent measures such as traffic counts during the evacuation, rescue counts from search and rescue teams, emergency sheltering counts, and head counts from the post-storm emergency evacuation. The final step consists of counting the flood deaths and then dividing by the flood exposed population and is completed at the polder, neighborhood, and census blockgroup levels. Once the FFR is estimated, general trends are discussed.

A regression analysis of the FFR comprises Chapter 8. Using the dataset from the previous chapter as the dependent variable, numerous regression models are used to examine the factors that influence this measure of the disaster outcome. These regression models examine the flood hazard characteristics along with various population vulnerability characteristics. It was found that two flood hazard characteristics, the flood depth and the flow velocity, explain much of the observed variance in the observed FFR. Then, after examining how numerous population characteristics impact the model, it is found that age and race have a significant and meaningful impact on the model.

Chapter 9, the conclusion chapter, draws everything together and discusses the observed trends and statistics in the context of expanding our understanding of the human-environment interaction. Human settlement and utilization of floodplains has been an important aspect of this interaction, with flood events serving as important case studies in the nature's constraint on the productive use of floodplains. By analyzing the deaths due to this one flood disaster, this dissertation a perspective to this constraint this is grounded in rigorous analysis of the available data.

1.7 Conclusion

In southeast Louisiana, nearly 1,500 lives were lost when Hurricane Katrina's storm surge overwhelmed the region's poorly designed levee system. Described as an unprecedented flood catastrophe for modern America, a review of global and U.S. disaster experience shows that disasters with large death tolls are common globally and not unheard of in the U.S. Both for the benefit of the residents of southeast Louisiana and for everyone that lives with risk from natural hazards, it is important that lessons learned from the Katrina disaster are based on objective analysis of data and are not based on media hype, political spin, or elitist ideology. Toward this goal, this dissertation will compile the relevant data for understanding loss-of-life due to Katrina and provide an objective, data based investigation of the important factors that have contributed to Katrina's death toll.

Jonkman's (2007) dissertation on flood fatality modeling provides the launching point for this research. While the flood disaster in Louisiana provides a wealth of data for improving this model, this model also provides many useful concepts that help us interpret this data. The flood fatality rate is defined as the flood deaths divided by the flood exposed population. While the calculation is relatively straightforward, obtaining the data in the right format required a number of complex steps. Besides just data processing steps, it also required piecing together a complicated story of a dynamic population experiencing exposure to numerous hazards. As I pieced this story together, it became apparent that floodwaters were just one of many hazards and that flood deaths constituted less than half of the total deaths. Additionally, it was clear that the population denominator could not be described as a single, static "at-risk" population. Instead, it became clear the overall "at-risk" population, defined as the persons residing in or visiting the impacted area, consisted of numerous "exposed populations" defined in terms of hazard exposures specific to both place and time.

Chapter 2: Literature Review

2.1 Introduction

Hurricane Katrina and the flooding of Greater New Orleans consisted of a complex cascade of events which created a complicated set of circumstances resulting in a diverse set of impacts. For the author, the past five years have shown that understanding just one impact of this event, fatalities related to the storm's impacts in Louisiana, is a difficult task. How do we make sense of the complex sequence of human and natural events that lead to catastrophe and the high number of fatalities? Can the theories of hazards geography along with the tools of spatial analysis and disaster science provide a way to make sense of the complex processes and complicated outcomes? Is it possible to estimate the risk or forecast the impacts of this and similar events?

In their introductory textbook *Natural Hazards and Disasters*, Hyndman and Hyndman (2006) present a typical approach to explaining disasters – focusing on the physical hazard processes that disaster events. With chapter titles such as "Volcanoes: Material, Hazards, and Eruptive Mechanisms" and "Streams and Flood Processes: Rising Waters," this textbook provides a thorough explanation of the natural processes of changing landmasses, atmospheric masses, and water bodies that lead to events characterized by disastrous losses. While thorough in its explanation of these physical processes, disasters cannot be explained solely through physics. An approach to understanding Hurricane Katrina through just the physical processes of the storm and the sea level response would leave many questions unanswered.

In his essay *Poverty and Famines: An Essay on Entitlement and Deprivation*, Nobel prize winning economist Amartya Sen (1981) famously observed that famines do not occur in democracies, an illustration that natural hazards do not cause disasters alone. Famine's occur not just because of droughts, but also because of governments that are not held accountable to their people. To fully understand disasters, it is necessary to adopt a multi-disciplinary approach that sees the physical processes as they interact with human social processes. Two specialized fields of study, hazards geography and disaster science, provide the multi-disciplinary perspective needed to comprehend losses associated with Hurricane Katrina. Hazards geography, that is the study of environmental hazards and how they relate to human settlement and wellbeing, provides the intellectual foundations for understanding a millennium of human experience with hazards and disastrous losses. Disaster science seeks to apply the knowledge of hazard geography and other related fields to managing disasters and reduces losses due to them.

To be clear, hazards and disasters are distinct concepts. Hazards refer to physical processes with a potential to cause harmful impacts, while disasters refer to social events characterized by realized impacts. Hazards are continuously present in the environment, while disasters occur over a limited time span. For example, consider the difference between wind and a windstorm disaster. As a physical process within the atmosphere, wind exists continuously and continuously poses a potential to cause harm. However, a windstorm disaster, such as a tornado, occurs over a given time span during which a social group experiences a high degree of losses. Importantly, not every loss cause by a hazard is considered a disaster event. For example, if an isolated wind gust knocks a person off a ladder and causes an injury that event would be considered an accident. However, when a community experiences widespread and unacceptable losses to a wind event, such as a tornado, then we say that the wind hazard has caused a wind disaster.

Reviewing and classifying the broad based literature on hazards and disasters is a difficult task. Given the volume of published works, no review will be complete. Studying hazards and disasters draws upon a variety of disciplines that overlap in complex ways. As such, describing the literature in terms of hazard's geography and disaster science certainly obscures considerable areas of overlap. For example, spatial outcomes are inherent in the work of hazard's geographers (by training) and disaster scientists (by necessity).

Multidisciplinary fields of study, hazards geography and disaster science draw upon broad areas of research from many different topics, including social sciences, the physical sciences, and the mathematical theory of probability. The physical sciences have studied the hazard processes, thus facilitating prediction tools used to anticipate some disasters. Similarly, engineering knowledge on how the built environment responds to physical stress during extreme events has lead to models to calculate damage due to disasters. One concept that they have introduced is the notion of the vulnerability of a built structure. Social scientists who have studied disasters have applied the concept of vulnerability to describe the characteristic of populations that influence disaster impacts.

Drawing upon the tools of statistical modeling and probability-based risk analysis, hazard and disaster researchers have made considerable advances in the ability to anticipate the conditions and activities associated with high degrees of potential loss. Risk analysis provides a mathematical formulation that expresses potential disaster impacts through risk equations. In some cases, these tools can predict the anticipated losses for given (real and hypothetical) disaster scenarios. Such consequence models have found widespread application in hazard assessments and disaster planning. Flood fatality modeling is a class of consequence models that applies to the problem of estimating deaths resulting from real and potential flood disasters. Recently, Jonkman (2007), in his ground breaking dissertation, demonstrates how flood fatality models can help guide human adaptations to this environmental hazard.

2.2 Hazards Geography

Geography and The Study of The Human-Environment Interaction

As a key fundamental science, geography enjoys a long and respectable historic tradition. Like many sciences, the study of the earth as the home to humans has experienced many instances of "paradigm shift," that is a fundamental questioning and reformulation of the basic principles that provide the foundation of the field and its practioneers (Kuhn 1962). While the terminology and concepts have evolved over the years, many of the paradigms of geography have focused on how humans utilize the resources of the environment and how the environment responses to human use and exploitation. Previously this debate has been framed as one between environmental determinists, who seek to explain human activity through environmental processes, and the opposite view, termed human agency, which posited that human activity to drove environmental processes. Naturally, there is a broad area of middle ground, and more recently this line of inquiry has shifted adopted a perspective based on a human-environment interaction.

While many definitions of geography have been posited, they all center around a central theme of the field: the human-environment interaction. Human societies and the natural environment interact in a complex manner. This interaction includes humans as they exploit and modify the natural resources of the landscape, and the natural landscape as it facilitates and constrains human use and exploitation. Even pure physical geographers focus most of their study on the processes related to human activities. For example, the availability of climatological data and analysis correlates well with population density and economic activity, which is where these processes have the greatest human impacts. Likewise, the most important and intensely studied landscape features are the ones that provide resources of greatest value to humans. Many of the "paradigm shifts" in geography revolved around the best intellectual foundations for viewing the human-environment interaction. In 1922, Barrows provided a practical definition of geography that explicitly refers to this interaction. He defined geography as the study of the "relationships between man and the earth which result from his efforts to get a living" (Martin and James 1993, p. 345).

As described by Martin and James (1993), the Greek academic Eratosthenes was the first scholar to coin the term geography in 200 B.C. He also specified what can be viewed as the first paradigm in the human-environment interaction when he describes the "ekumene", the inhabitable Earth. This region stretched from the Atlantic Ocean to Bay of Bengal and from the deserts of Africa to glaciers of Northern Europe (Martin and James 1993). Beyond these borders lay the "non-ekumene," the non-inhabitable Earth. In this basic view of the human-environment interaction, there exist two dichotomous worlds, one where the environment fosters human habitation and another where the environment forbids human habitation.

With their direct experience limited to the Greek's Mediterranean centered sphere of influence and with legends of disastrous attempts to venture beyond their sphere, the Greek geographers imagined regions of the Earth's surface where the extreme heat, cold, water, and elevation precluded human habitation. At this extreme of the human-environment interaction, extreme physical hazards posed an overpowering constraint on human settlement and use of the vast expanse of unexplored Earth.

To the east, the ekumene ended at the insurmountable Himalayan Mountains. Little did the early Greek scholars know that beyond these mountains a thriving Chinese civilization inhabited a productive landscape along one of the world's greatest rivers. Nor could they imagine that by the Twentieth century, technology would allow humans to surmount the Himalayas, cross the Oceans, inhabit the South pole, explore the Ocean's bottom, build a space station, and plant a flag on the surface of the Moon. Indeed, while important for identifying the key role of physical hazards in constraining human habitation, the Greek notion of a non-ekumene seems woefully simple.

Later in the Fifth Century BC, Hippocrates also a Greek scholar, wrote *On Airs, Waters, and Places* which links human health to external environmental conditions such as winds, water, and seasons, laying the basic thoughts that would later form environmental determinism. While not necessarily precluding human habitation, Hippocrates' more nuanced paradigm implies that the physical characteristics of certain landscapes create hazards that constrain human land-use and that these constraints determine which civilization thrive and which ones falter. These constraints come in the form of death, disease, and lost productivity due to illness, but do not necessarily imply that a hazardous region is uninhabitable.

Modern geography emerged in the 1800s with the works of Humboldt and Ritter, both considered the fathers of modern geography (Martin and James 1993). With the Age of Exploration behind them and in the midst of the Age of Enlightenment, these two scholars applied reason and scientific method to compile and synthesize the newly acquired observations obtained through expanding exploration of the world. Western civilization's sphere had expanded much since the time of Eratosthenes, resulting in a wealth of newly acquired experience and knowledge from the region previously viewed as the "non-ekumene." Humboldt, largely an empiricist, focused on detailed observation of the natural world, particularly his early experiences in exploring South America (Martin and James 1993). Reflecting his theoretical interests, Ritter's *The Science of the Earth in Relation to Nature and the History of Mankind* explores how the physical environment influences human activity, thus adopting an environmental determinism view of the human-environment interaction (Martin and James 1993).

Just five years later in 1864, George Perkins Marsh presented the opposite view in *Man and Nature, or Physical Geography as Modified by Human Action*. Writing that "man has done much to mould the form of the earth's surface," Marsh creates what would be termed the Man-Land tradition in geography, an explicitly human agency paradigm (Martin and James 1993, Johnston and Sidaway 2004).

Building on this tradition in the 1930s, Carl Sauer studied the sequence of human settlements (Martin and James 1993, Johnston and Sidaway 2004). Focusing on the past processes of landscape change, as described by Johnston and Sidaway, Sauer observed that "investigations of the past are needed to comprehend regional patterns of the present" (2004, p. 56). These investigations of the past included the impacts that human's have had in changing the landscape. Sauer launched what would become known as the field of historical geography. Demonstrating Sauer's conclusion that the past enlightened understanding of the present, Colten (2005) examines the historical geography of New Orleans and reveals a series of human modifications to the landscape that lead to the unique circumstances underlying the Katrina disaster.

Edited by William Thomas, *Man's Role in Changing the Face of the Earth* (1956) contains a series of conference papers that explores Sauer's conception of historical geography on a global scale. Divided into three parts, this collection first describes the rise of humans as a major force of landscape change, in many respects outmuscling natural processes. For example, one chapter predicts that by the mid-1970s human activities and transportation systems will collectively move more materials than natural processes. Next, this volume describes the environmental changes that have resulted from human activities, such as changes to the water cycle and to the coast lines. The final group of papers examines limits of earth's resources, particularly in the context of growing populations and expanding consumption. While Sauer examined the local environmental impacts from human activities, the volume edited by Thomas explores this theme on a global scale. The works of both were crucial in paving that way toward our contemporary understanding of human impacts on the environment and environmental limitations in meeting our needs, wants, and desires.

Today, the study of the human-environment interaction forms a central theme of geographic research, with many important consequences. The next section describes hazards geography as a special class of this interaction where naturally occurring extremes interact with human behavior to create disastrous outcomes. Most scholar's fall somewhere in the middle, though many adherents to the extreme views remain. Later in this literature review, I will discuss how risk analysis provides a new level of comprehension of this age old question.

Hazards Geography as a Class of The Human-Environment Interaction

Hazard's geography is an applied and theoretical discipline of geography aimed at understanding conditions under which the human-environment interaction results in natural, technological, and human made disasters and other hazard related losses. In hazards geography, disasters losses represent an environmental constraint against human occupation and utilization of hazardous areas. While diverse in content, approaches, and methods, this discipline largely focuses on using geographic concepts and spatial methods to understand hazard exposure as it relates to human decisions regarding settlement and landscape modification. In this view, the mitigation, preparedness, response, and recovery cycle of emergency management is seen as an on going cycle of human adjustments to landscape constraints and landscape responses to these adjustments. Emergency managers describe a four step disaster cycle, and geographic research applies to each. Achieving the goal of reducing losses from disasters requires understanding the spatial dimensions of disaster risks and impacts along with the spatial trends in the factors underlying those risks.

In addition to the practical goal of reducing disaster losses, the study of hazards relates to one of the enduring questions of geography. Do environmental processes create insurmountable constraints on human activity or can we exploit natural resources without constraint? (Basically, the environmental determinism versus human agency question). Understanding the interaction of humans and the environment has been an important theme of geography since antiquity. Indeed, the modern notion of "landuse restrictions in hazardous locations" is reminiscent of the ancient Greek concept of the "non-ekumene," the major difference being in the modern view government regulations restrain human habitation.

The field of hazards geography is often traced to two influential works by Gilbert White. Published as his PhD dissertation in 1945, White in *Human Adjustments to Floods: A Geographical Approach to the Flood Problem in the United States* writes that "floods are 'acts of God', but flood losses are largely acts of man" (p.2). He describes flood losses as a rent that Mother Nature exerts on those who choose to occupy and utilize floodplains. He then provides a thorough accounting of flood reduction actions and policies undertaken within the United States. Structural adjustments, such as levees, flood walls, dams, and locks, modify the landscape in hopes of influencing the flow of water in a way that reduces flood risk. Complementing these approaches, non-structural measures include behavioral measures that include land use restrictions, elevation requirements, evacuation procedures, and emergency response plans.

What emerges is a two-sided view of human-environmental hazard interaction. While disastrous "Acts of God" constrain human activity within floodplains, human modification of the landscape influences the frequency and magnitude of flood events. White further elaborates this view in *Changes in Urban Occupance of Floodplains in the United States* (1958) which is considered the first work to inductively explore human behavior in response to environmental hazards (Martin and James 1993, Johnston and Sidaway 2004). White's empirical approach to understanding floods representing a great conceptual leap from the simple ekumene / non-ekumene view.

Martin and James (1993) describe the growth of the empirical studies on hazards that came in the decades that followed. In 1965 Burton and Kates published *Readings in Resource Management and Conservation.* Published in 1974, Mitchell's "Natural Hazards Research" provides one of many syntheses of the current state of hazards geography. In 1978, Burton, Kates and White provided a similar synthesis in *The Environment as Hazard*, while Whyte and Burton published *Environmental Risk Assessment* in 1980 (Martin and James 1993).

These inductive studies have lead to a vigorous debate on the role of land use restrictions in preventing disasters. After describing floods as a rent that Mother Nature collects from humans that inhabit floodplains, White goes on to describe levees and other structural control measures as a way for humans to reduce this rent. He writes "New Orleans citizens carrying on their business behind a levee withstanding a flood crest high above the streets, illustrat[ing] wise adjustments to flood hazard." (p. 1). However, others take the view that the structural approach is a wise adjustment. They argue that this approach only delays Mother Nature's rent collection. They say that Mother Nature will still eventually come demanding all back rent payments in full plus fees and interest. They argue that these structural adjustments merely replace low level short term risks with catastrophic long terms risks and advocate land use restrictions as the most viable strategy for reducing flood losses. Further, they argue that because levees encourage settlement in floodplains, they actually contribute to flood losses. Planning expert Raymond Burby (2006) argues that this pattern forms a "safe development paradox" (p. 171), while social scientist and critic Denis Miletti writes that flood losses are "primarily the consequence of narrow and shortsighted development patterns, cultural premises, and attitudes" (p.1) that underlie human attempts to modify floodplains (Mileti 1999). While the early works of White, Kates, and Burton provided well-rounded assessments of the pros and cons of inhabiting hazardous areas, Burby and Miletti's environmental determinist leaning analysis seems biased toward focusing myopically on the costs of hazards and giving only passing mention of the benefits.

The Social Science of Disaster Vulnerability

Social science is the field of science concerned with understanding and explaining group behavior and decision-making and has contributed considerably to the understanding of disaster impacts. Three review articles on disasters published in the *Annual Review of Sociology* between 1977 and 2007 show two views of the study of disasters within the social sciences. Quarantelli and Dynes (1977) describe the contributions that sociology has made to understanding disasters.

Kreps (1989, p. 310) presents the complementary viewpoint that “disaster studies provide rich data for addressing basic questions about social organizations.” Finally, as the title suggests “From the Margins to the Mainstream? Disaster Research at the Crossroads,” Tierney’s (2007) review summarizes both viewpoints and provides suggestions for an improved integration of disaster sociology and the social sciences in general.

Toward expanding the understanding of disasters impacts, the social scientists have adopted and applied a powerful and useful concept: the vulnerability of populations and individuals. First utilized in engineering, vulnerability initially referred to an engineered structure’s susceptibility to damage when exposed to a physical hazard. Through the sociological lens, vulnerability has come to refer to a characteristic of populations or individuals that describes susceptibility to adverse impacts when exposed to physical hazards. In this framework, the vulnerability of a population partially determines disaster outcomes and populations can reduce disaster impacts by reducing their vulnerability. For example, Kreps (1989) lists social units as one of the four core dimensions of disasters and writes that “patterns within the social order are both causes and consequences of environmental vulnerability.”

A vast and growing field, the sociology of disasters provides many definitions and applications of the concept of vulnerability. Through a large number of case studies, social scientists have identified a number of factors that are believed to make populations vulnerable to natural disasters. Such factors include poverty, lack of education, prevalence of female headed households, and the prevalence of mobile homes. However, critical reviews of this literature often point out that the field still lacks a basic, standardized definition of this key variable.

For example, the “Hazards” chapter of *Geography in America* (Montz 2004) provides various definitions of vulnerability:

- “People are vulnerable because of settlement patterns that have ignored hazards or because wealth and access to resources are unevenly distributed throughout a society.” (p. 483).
- “Vulnerability varies with differences in wealth, power, and control over resources.” (p. 484).
- “As cities grow in size, so too will hazardousness and vulnerability grow. The underlying conditions that promote growth of urban areas will, at the same time, serve to increase vulnerability, and this increase in vulnerability will not be equally spread throughout the population.” (p. 485).

Cutter (1996) described many of the conceptual foundations of current vulnerability theory. Her review of the emergent literature on the “hazards of place” presented disasters as a nexus of multiple processes: “vulnerability is conceived as both a biophysical risk as well as a social response, but within a specific areal or geographical domain” (Cutter 1996, p. 533). Consistent with her geographic perspective, Cutter notes the need to focus on “aspects of vulnerability that produce explicit spatial outcomes.”

Lindel and Prater (2003, p. 176) note that there is “no coherent model of the process by which hazard agents characteristics produce physical and social impacts.” Without specifying a model, they note seven components to such a model. The seven components are (1) Hazard agent characteristics, (2) Physical impacts of disaster (causalities and property damage), (3) Hazard mitigation practices, (4) Emergency preparedness practices, (5) Social impacts, (6) Community recovery resources, and (7) Extra-community assistance. In regards to hazard characteristics, they write that it is "difficult to characterize because a given hazard agent may initiate a number of different threats" (p. 176), but not three key measures: the impact intensity, the scope of impacts, and the probability of occurrence. They summarize:

> "The effects of the *hazard agent characteristics* on the disaster's *physical impacts* depend upon the affected community's *hazard mitigation practices* and its *emergency preparedness practices* because both of these can reduce the physical impacts of the hazard agent. The physical impacts, in turn, cause the disaster's *social impacts* but these can be reduced by *community recovery resources* and *extra-community assistance."* (p. 176)

In many ways, the U. N. Interagency Secretariat document *Living with Risk* (2002) provides a similar framework, though expressed through a simple risk-hazard-vulnerability equation. First this document defines **risk** as "the probability of harmful consequences, or expected loss (of lives, people injured, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human induced hazards and vulnerable/capable conditions" (p. 24). Here risk (R) is related to the hazard (H), the vulnerability (V) and the response capability (C):

$$R = H \times (V/C)$$

where **hazard** refers to "a potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation" (p.23), **vulnerability** implies "a set of conditions and processes resulting from physical, social, economical and environmental factors, which increase the susceptibility of a community to the impact of hazards" (p.23), and **capability** as "the manner in which people and organizations use existing resources to achieve various beneficial ends during unusual, abnormal, and adverse conditions of a disaster event or process" (p.24).

Referring back to concept model proposed by Lindell and Carter (2003), the above risk equation is equivalent if we view H as the Hazard agent characteristics, V/C as mitigation and preparedness, and R as a function of the physical and social impacts.

Rearranging this equation, we can express V as

$$V = R \times C/H.$$

In principle, R, C, H are all explicit spatial outcomes that can be readily measured. The key in this specification of vulnerability is to control for H and C and not just equate vulnerability to risk.

Risk, Hazard, Vulnerability, and Capability. This simple, four-variable conceptual model provides considerable insight for interpreting observations related to disaster outcomes. As described below, these concepts have been used heavily in policy decisions related to disasters, even mandated by FEMA. However, as the next sections also implies, the lack of standardized definitions of these terms leads to a somewhat arbitrary application of these concepts in the policy realm.

Vulnerability Indexes: Putting a Number on It

In the United States, interest in disaster vulnerability and vulnerability assessment methodologies has grown tremendously in recent years, primarily due to FEMA requirements that states conduct an approved Risk and Vulnerability Assessment (RVA) to receive federal disaster assistance. Two published methods, the Community Vulnerability Assessment (CVA) from the National Oceanographic and Atmospheric Administration (NOAA) and the *Handbook for Conducting a GIS-Based Hazards Assessment at the County Level* from the Hazards Research Lab (HRL) exemplify the typical approaches to vulnerability assessments and demonstrate some of the problems with the current approach.

Described as "a comprehensive and systematic framework to identify and prioritize hazards and to assess vulnerabilities of critical facilities, the economy, societal elements, and the environment," the CVA from NOAA's (2002, p. 164). Coastal Science Center is a guide designed to assist local emergency managers and hazard planners in producing their RVA (Flax, Jackson, and Stein 2002). The seven step process begins with an analysis of the location, frequency, and intensity of the physical hazards that affect a region, overlays population characteristics onto the hazard map, and finishes with a step that identifies mitigation opportunities. The seven steps of the process are: 1) Hazard identification, 2) Hazard analysis, 3) Critical facilities, 4) Societal vulnerability analysis, 5) Economic Analysis, 6) Environmental Analysis, and 7) Mitigation Opportunities.

A comparison of the tasks involved in steps 2 and 4 illustrate an important contrast. To complete step 2, the RVA specifies an approach centered on data depicting the study regions past experience with hazards and disasters. In contrast, step 4 amounts to simply compiling a generic set of Census attributes without consideration of the populations past experience with hazards and disasters. It advises that special considerations areas, including areas of high poverty, an elderly population, a prevalence of single-parent households, etc. be identified then overlaid with risk areas to get high-risk areas. Implicit in this process is the notion that the vulnerabilities listed in step 4 are correlated with disaster impacts, though no direct relationship is presented nor is there a technique to determining which apply to given study area and population.

In a very similar manner, the HRL *Handbook* also begins with the identification and mapping of hazards and their frequency (Cutter, Mitchell, and Scott 1997). The *Handbook* also follows this initial step by identifying vulnerable populations and calculating vulnerability scores based on a simple formula that includes 8 equally weighted Census population attributes. Next, the *Handbook* suggests integrating these two elements through a spatial overlay. Finally, the *Handbook* prescribes that mitigation planners establish the social and infrastructure context by mapping the special needs populations and the critical infrastructure.

Crucial to both methods is the assessment of a population's social vulnerability, which is defined as either the "social descriptors that are the most indicative of the population characteristics that may place people at greater risk" (Cutter, Mitchell, and Scott 1997, p.15) or the demographic characteristics that identify "special consideration areas where individual resources for loss prevention and disaster recovery tend to be minimal" (Flax, Jackson, and Stein 2002, p.166). However, despite the similarity to the two definitions of social vulnerability, the two groups disagree noticeably on how to measure it. The table below lists the indicators used for the two vulnerability assessments. The reader will note only a small amount of overlap, indicative of the confusion of current state of vulnerability assessment methodologies.

Moving beyond a simple list of social variables used to indicate a population's vulnerability, the HRL *Handbook* presents a method for calculating a vulnerability score for a location. In the first step of this calculation, the value of each indicator is standardized. Next, the individual scores are added to create an "overall social vulnerability score" (Cutter, Mitchell, and Scott 1997, p. 20). Clearly, this method implicitly assumes that each indicator has an equal impact on the population's disaster risk. However, is it safe to assume that a one unit change in the number of people over 65 and a one unit change in mean house value will produce identical changes in the impact of a natural disaster?

While these methods have certainly improved hazard assessments and disaster planning, these methods fall short of explicitly relating vulnerability to spatial outcomes associated with disaster losses. Instead, they rely on implicit links between the population characteristics of choice and vulnerability. For example, one of handbooks described above implicitly links the prevalence of public assistance with vulnerability, while the other implicitly links the number of mobile homes (see Table 2.1). Neither approach relies on a robust analysis that explicitly links vulnerability to explicit spatial outcomes. Both the list of variables and the weighting used to calculate the index are arbitrary.

Spatial Analysis and Vulnerability

The above section described steps to apply the concept of vulnerability in a planning context by using GIS based calculations of vulnerability indexes. However, they do not amount to measures of vulnerability that adhere to Cutter's (1996) requirement that they be calculated from explicit spatial outcomes. Recently researchers have moved beyond these initial steps and have begun to

Table 2.1: A Comparison of Two Sets of Indicators of Social Vulnerability.

Community Vulnerability Assessment (Flax, Jackson, and Stein 2002)	**Hazards Research Lab Handbook** (Cutter, Mitchell, and Scott 1997)
Poverty	Number of People under 18
Age	Number of People over 65
Minority Populations	Number of Females
No vehicles	Number of Non-Whites
Female Households	Number of Housing Units
Rental Households	Total Population
Public Assistance	Number of Mobile Homes
	Mean House Value

look at vulnerability through a framework of spatial analyzing disaster outcomes. In this regard the fields of mapping science and spatial analysis provide vary powerful tools, particularly in viewing patterns in disaster outcomes in relation to population attributes.

Morrow (1999) cites trends observed in recent disaster events that illustrate the vulnerability of certain groups, suggests steps for identifying and mapping community vulnerability. A number of researchers heeded this call. Cutter, Boruff, and Shirley (2003) used a factor analytic approach to create a social vulnerability index (SoVI) from a large set of demographic and socio-economic attributes (see Figure 2.1a). They then identified distinct spatial patterns in the SoVI with clusters of vulnerable populations identified in the metropolitan counties in the east, south Texas, and the Mississippi Delta region. While this analysis certainly represents a step forward from the arbitrary formulas described in the previous section, it still falls short of focusing on explicit spatial disaster outcomes.

Further advancing the spatial analysis of disaster vulnerability, Borden and Cutter (2008) assess spatial patterns in an important disaster outcome: disaster fatalities. These authors used disaster deaths recorded in the SHELDUS databases and age standardized population data to calculate standardized mortality ratios (SMRs) for counties in the United States (see Figure 2.1b). Upon looking at patterns in this direct measure of disaster outcomes, they found that the highest disaster deaths rate are found in the south and intermountain west. However, this analysis falls short of relating the observed trends to hazard agents or population vulnerabilities. In fact, it is interesting to note the lack of correspondence between regions identified in the SMR analysis and regions indentified in SoVI analysis.

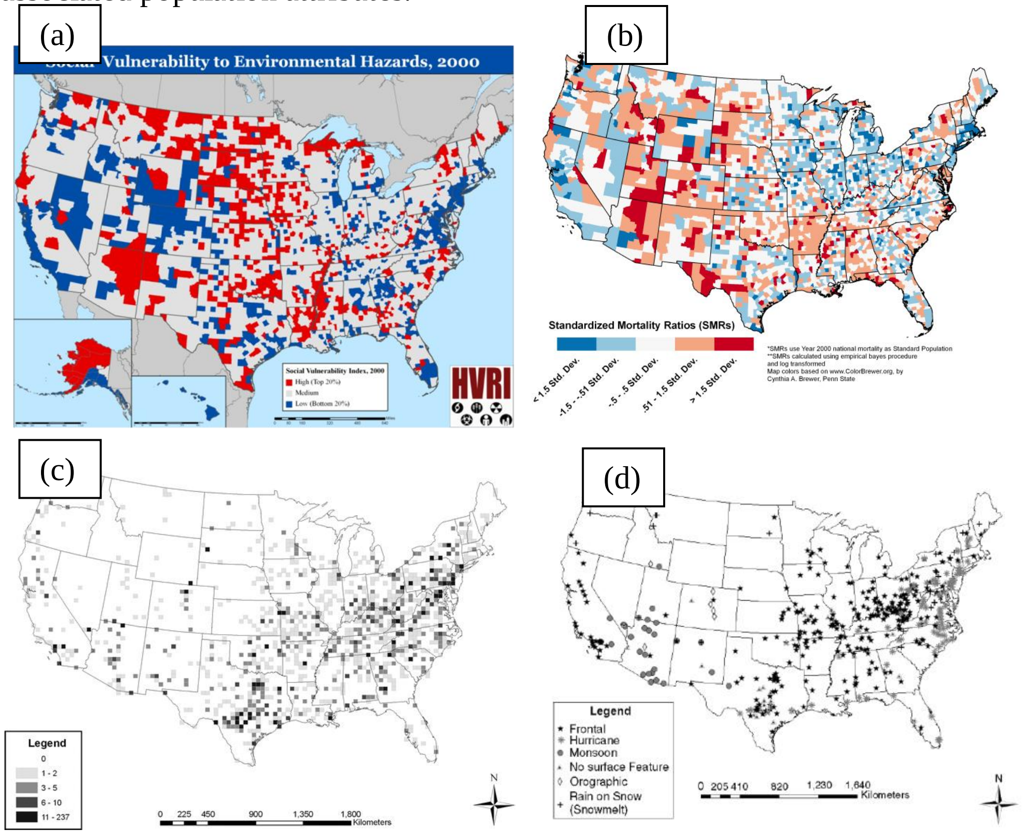
Ashley and Ashley (2008) created a spatial dataset on flood fatalities from the National Climate Data Center's "Storm Data" reports which they then mapped using a 40 km by 40 km grid (see Figure 2.1c). Upon inspecting this hazard outcome map, they identified regions of high flood fatalities along the Northeast Interstate 95 corridor, in the Ohio River Valley, and in south-central Texas. They also observe that flash floods account for the majority of the deaths, and note specific seasonal and demographic patterns in flood deaths.

Ashley and Ashley (2007) inspect the relationship between observed national level trends in flood fatalities and climate patterns. Using a manual classification scheme, they assess the synoptic and mesoscale environments associated with fatal flood events. They found that the most common weather patterns associated with fatal floods are frontal boundaries and tropical systems (see Figure 2.1d).

Limitations of the Field

Cutter's (1996) critique of the current state of vulnerability research describes the fuzziness of definitions and concepts along with the practical consequences of these ambiguities. She notes "a confused lexicon of meanings and approaches to understanding vulnerability to environmental hazards" (p.530). As demonstrated above, the typical approaches to studying vulnerability suffers from a limited definition that blurs cause and effect. Too often, authors define vulnerability in terms of factors that we expect to be related to vulnerability. While these factors certainly influence vulnerability, this variable must be defined, and more importantly measured, independently of these explanatory variables.

To be more specific, vulnerability must be considered as a population attribute that is distinct from other population attributes, such as mean income or mean educational attainment. Clearly, the value of the vulnerability attribute of a population relates values of other attributes of the population, but this relationship is currently unknown and will not be known without an independent definition and measurement of vulnerability. Just as we know that income affects educational attainment, we also know that both income and educational attainment affect disaster vulnerability. Yet, we define and measure income independently of how we define and measure educational attainment. Likewise, good science requires that we define and measure vulnerability independent of these or other population attributes. To truly understand how vulnerability relates to income, educational attainment and other population attributes, it is first necessary to measure this population attribute through a method independent of the hypothesized associated population attributes.



Figures 2.1a-d: Four views of the spatial distribution of disaster vulnerability and risk in the United States. (a) The SoVI, a vulnerability index calculated from demographic and socio-economic attributes (figure from http://webra.cas.sc.edu/hvri/products/sovi.aspx, based on Cutter, Boruff, and Shirley 2003), (b) The standardardized all hazard mortality ratio (Borden and Cutter 2008, Reprinted by permission from BioMed Central under open access license, copyright 2008), (c) Gridded U.S. flood fatalities (Ashley and Ashley (2008, reprinted by permission from John Wiley and Sons, copyright 2008), and (d) U.S. flood fatalities separated by weather type (Ashley and Ashley 2008b, reprinted by permission from the American Meteorological Society, Copyright 2008).

The highly influential study by Klineneberg (2002) entitled *Heat Wave: A Social Autopsy of Disaster in Chicago* illustrates these shortcomings. Full of broad based critiques of local leadership in Chicago, the news media, social isolation of poor senior citizens, and society's perceptions of extreme heat, this analysis lacks a basic key feature: a map showing observed temperatures throughout the impacted region. In the chapter titled "Race, Place, and Vulnerability: Urban Neighborhoods and the Ecology of Support" the book does contain three maps that appear to associate neighborhoods of high morality with a high prevalence of people over 65 living alone, high prevalence of violent crime, and high rates of poverty (Figures 23 – 25). Naturally, temperature is an important part of the narrative and this study does include a time series graph based on temperature measurements at one location. However, without any consideration of the spatial variation in temperature over the impacted region, the critical reader cannot tell if the observed patterns are explained by place based vulnerability or simply by differences in temperature. A quick glance at the Chicago weather map on any given day will show that temperatures vary noticeable throughout the city. As such, the author's conclusion that the "certain community area conditions" (p. 84) explain the observed mortality conditions essentially boils down the common approach that equates vulnerability to impacts, without controlling for the spatial variation in the underlying hazard.

An additional limitation of field results from a primitive methodology that attempts to derive general conclusions from isolated case studies. Quarantelli and Dynes (1977) noted instead of rigorous empirical data many of the field's most basic propositions rely on a small number on illustrative case studies. As an example, more than 95% of the findings for the much cited study from Mileti, Drabek, and Haas (1975) are based on data taken from a single set of events. Interestingly, the later reviews by Kreps (1989) and Tierney (2007) do not mention this limitation; rather, they tend to present observations from individual case studies as general trends.

A basic analysis of bibliographic citations in the "Hazards" chapter of *Geography in America at the Dawn of the 21st Century* (Montz and Cross 2004) further illustrates the shortcoming in current state of hazards geography and vulnerability theory. In assessing 25 citations from the "Theorizing Hazards and Risk" and "Changing Interpretations of Hazards" section of the chapter (they include a total of 90 citations) important gaps in literature were found.

Looking at the methods used in the cited articles, the majority of articles present single case studies. Only a quarter presented statistical analysis, most of which were restricted to physical geography and mapping sciences. None of the listed citations include a robust comparative analysis that explores human aspects of hazards and disasters. An overwhelming majority of these articles provided descriptive explanations, and only 20% represented efforts to test specific hypotheses regarding disasters. Finally, only ten articles appeared to explicitly focus on impacts, the majority of them being case studies. Only one presented a large-N comparative analysis focused on impacts, though it was largely an exercise in mapping sciences that did not examine specific hypotheses.

This gap in the hazards geography literature implies specific limitations on the current knowledge of disasters as they relate to the human-environment interaction. Without comprehensive, comparative studies that explore the human and natural interactions that lead to disaster impacts across a variety of hazard conditions and population attributes, many of the commonly held statements of the field lack a rigorous scientific validity. Generalizable observations from comparative analysis is largely absent and in this absence we do not know the conditions that explain exceptions to these statements.

2.3 Disaster Science

Disaster science is a new specialized field of the study that has only recently been recognized as a unique and independent field. For example, Louisiana State University's Disaster Science and Management program is among a number of recently initiated programs within the field.Generally speaking, it is an applied science aimed at developing practical results that effectively contribute to reduced disaster impacts. It draws upon hazards geography and in many respects is hard to distinguish from that field. One major distinction is that disaster science focuses largely on events, while hazard's geography adopts a more process oriented approach. A diverse field, disaster science includes the careful observation of specific disaster events, methods to estimate the frequency of hazardous extremes, and various attempts to model disaster impacts. Beyond the scope of the current review, topics such as developing information systems of disaster management and interoperable communication systems for disaster response fit under the broad umbrella of disaster science.

Single Event Case Studies

A number of sources provide detailed accounts of specific disaster events. Typically, these sources focus on a particular hazard type or on particular aspects of disaster research. For example, the National Hurricane Center publishes Tropical Storm Reports for every named storm and Hurricane Season Summaries for each hurricane season. These documents systematically document the key data related to tropical storms that impact the United States and its neighboring countries in the Caribbean and Central America. As another example, The Natural Hazards Center funds and publishes a large series of *Quick Response Reports*. These field oriented studies provide a non-systematic collection of basic data covering a variety of hazard types and disaster outcomes. Instead of a systematic focus on specific events or topics, these reports exploit opportunities for researchers to conduct field work in post-disaster environments and record "perishable" data. Also covering a variety of hazard types, the Morbidity and Mortality Weekly Report, a regular publication from the Centers for Disease Control, provides epidemiologic reporting and analysis of data on health outcomes due to various disaster events. These are just a small sample of disaster related publications that provide single event case studies. Generally speaking these sources are limited to factual descriptions of specific disaster events and do not attempt to derive general conclusions, though the *Quick Response Reports* do provide event specific analysis and interpretation.

A Few Large-N Comparative Studies

Mentioned previously, *Living with Risk: a Global Review of Disaster Reduction Initiatives* (U. N. Interagency Secretariat 2002) represents an attempt to move the field beyond just a collection of case studies without an overarching framework for analysis. After presenting a general framework for hazards analysis, $R = H \times V/C$, this study goes on to use this framework in a comparative study of different disaster reduction strategies. This comparison spans disaster types and magnitudes and it includes considerable variance in the cultural, political, social, and economic contexts. However, as a qualitative study, it does not employ direct measures of the variables specified, nor does it quantitatively assess the validity of the risk equation. Still, this research design contains many advantages over a single case study that does not account for variance in the physical hazard characteristics or the population vulnerability characteristics. Combining this conceptual framework with the tools of mapping sciences and spatial analysis will surely advance our understanding of disaster risks and impacts.

In what appears to be the first comparative study to utilize a statistically significant study design and dataset on disaster events, Davis and Seitz (1982, p. 547) explain "why disasters of same types sometimes differentially impact various countries." Their analysis explicitly links the number killed, a direct measure of disaster impact, to the political structure, social context, and economic conditions of the affected population. By comparing results across disaster types, this study design includes variance in the characteristics of the physical hazards. They employ the country as their unit of analysis and their sample consists of 748 disaster events listed in a database maintained by the US Office of Foreign Disaster Assistance. The statistical results indicate that government instability and government effectiveness explains much of the observed variance in the dependent variable. Naturally, their conclusions are limited by uncertainties and biases in the data and methodological limitations (many of which they acknowledge). Despite the limitations, these researchers provide an example of a large-N, comparative research design that explicitly models quantified variance in an observed disaster impact. However, there have been only limited efforts to expand on this line of analysis. The ISI Web of Knowledge online database of scholarly journals (accessed March14, 2011) only listed three citations of this work within the hazards or disasters literature (a 2010 article in *Progress In Human Geography*, a 2008 article in *Journal Of Conflict Resolution*, and a 1986 article in *Australian And New Zealand Journal Of Sociology).*

Two decades later, the current author, in his master's thesis titled *The Political Determinants Of The Impact Of Natural Disasters: A Cross-Country Comparison* (2003) utilizes a similar study design to examine the notion of political vulnerability to disaster. This study relies on a large N-statistical analysis using an international database (EM-DAT from CRED) on disasters joined with standardized datasets on economic, social, and political indicators. The dependent variable was the number of people killed divided by the number of people affected and a country level unit of analysis was utilized. It was found that level of democracy, regime durability, and political stability are statistically significant predictiors of the number of people killed in a disaster event.

Looking at Hurricane Katrina damage along the Mississippi Gulf Coast, Burton (2010) integrated the Social Vulnerability Index in a hurricane damage model. He notes the need to integrate two disparate lines of analysis: (i) vulnerability assessments based solely on demographic and socioeconomic attributes, and (ii) disaster impact models based just on the physical characteristics of the hazard agent. While limited to a single event, this seminal paper appears to achieve what no other author had achieved previously: a unified model that explicitly explains the observed spatial patterns in disaster outcomes with both the hazard characteristics and the population vulnerability attributes.

Disaster Databases

The previous section noted the small number of studies that extend beyond the confines of a single case study by employing comparative study designs. Comparative studies are necessary, because without them it is impossible to separate general trends applicable to a set of disaster events from the unique processes of a particular case. To reveal general trends on disaster outcomes, study designs must accommodate variance in the hazard conditions and in the population characteristics, and then link the observed variance in the explanatory variables to variance in the dependent variable, which typically amounts to some measure of disaster impact.

Naturally, comparative studies require comparative data on disaster events. While there are numerous sources of datasets that include a set of events, two are particularly noteworthy because of the systematic collection methods and inclusion of a wide variety of disasters. The Emergency Events Database (EM-DAT), maintained by the Centre for Research on the Epidemiology of Disasters (CRED), is a global database listing disasters, their location, and their impacts. According to the maintainers, it "contains essential core data on the occurrence and effects of over 18,000 mass disasters in the world from 1900 to present. The database is compiled from various sources, including UN agencies, non-governmental organisations, insurance companies, research institutes and press agencies." (http://www.emdat.be/) Both of these datasets are publically available and generally credible (though limitations are noted by the maintainers of both datasets).

Maintained by the Hazards & Vulnerability Research Institute at the University of South Carolina, SHELDUS (Spatial Hazard Events and Losses Database for the United States) is the national analog of EM-DAT. According to its maintainers "SHELDUS is a county-level hazard data set for the U.S. for 18 different natural hazard events types such thunderstorms, hurricanes, floods, wildfires, and tornados. For each event the database includes the beginning date, location (county and state), property losses, crop losses, injuries, and fatalities that affected each county." (http://webra.cas.sc.edu/hvri/products/sheldus.aspx)

Many authors have pointed out some of the limitations inherent in current disaster databases. Gall, Borden, and Cutter (2009) express these limitations particularly succinctly. In comparing these two databases along with Nathan (maintained by the reinsurer Munich Re) and Storm Events database (maintained by NOAA's National Climate Data Center), the authors identified what they describe as "six fallacies of natural hazards loss data" (p. 799):

1) Hazard Bias: Every hazard type is represented in loss estimates.
2) Temporal Bias: losses are comparable over time.
3) Threshold Bias: All losses regardless of size are counted.
4) Accounting Bias: All types of losses are included.
5) Geography Bias: Hazard losses are comparable across geographic units
6) Systemic Bias: Losses are the same regardless of source.

They conclude that hazard databases "suffer from a number of limitations, which in turn lead to misinterpretation hazard loss data" (p. 807) and recommend the standardization of data collection, documentation, accessibility, and dissemination. In conclusion, they advocate "clear guidelines and standard procedures… to estimate losses for all types of hazards" (p. 807).

While this laudable goal remains elusive, EM-DAT and SHELDUS both provide excellent potential for comparative research based on methodologically rigorous studies based on statistically significant samples.

Flood Frequencies and Impacts

As described in a later section, frequency and impacts are the two key dimensions to quantitatively assessing disaster risk. This sub-section provides an overview of some of the literature on these two dimensions of flood disasters. In the process, the reader will see the wide variety of disciplines involved in disaster science.

Floods are generally defined as the presence and accumulation of water in an otherwise dry location. They are the most common type of natural disaster, both globally and nationally (Greenough, et al. 2001, Few et al. 2004). In 2008, FEMA responded to a flood related Federal disaster declaration approximately once every ten days. Because they are the most common, they are also responsible for the greatest total losses of the different disaster types. Given the frequency and severity, they are also extensively studied.

A number of processes can lead to the accumulation of water in an otherwise dry location. There are four main flood types: a) riverine flooding, b) coastal flooding, c) dam break floods, and d) floods that result from poor drainage in urban / suburban areas. As such, flood conditions can vary along a wide variety of physical characteristics. Naturally, flood depth is an important physical characteristic of the flood, but the rate-of-rise, the flow velocity, the height of waves, the water temperature, and the duration of inundation all influence the severity of the flood disaster.

The climatological analysis of precipitation data and the hydrologic analysis of runoff / discharge data have provided measures of the frequency of the flood threat at a given location. Statistical analysis of precipitation in southeastern Louisiana (Keim and Muller 1992, Keim and Muller 1993, Faiers et. al 1994a, b) provides insight that will help us interpret future extreme rainfall events, such as the extreme rainfall observed during Tropical Storm Alison (which at the time of publication had not occurred). Similarly, Keim, Muller, and Stone's (2004) assessment of the variability seen in coastal storms and wave action in the North Atlantic basin clarifies recent observations, for example the near destruction of the Chandeleur Barrier Islands chain. However, these important contributions to physical geography are limited in their contribution to hazards geography, because they only assess the physical hazard and not disaster impacts or risks.

The most obvious and direct impact of floods is the inundation of communities and structures, which then create a drowning risk for persons exposed to flood waters. Persons exposed to cold temperature flood waters also face a hypothermia risk. In addition to inundation, floods cause structural damage when the waters are either fast moving, quickly rising, or have significant wave action. Damaged structures then become water borne debris, which can cause injuries and deaths. Also of concern, floods disrupt public services, stress health care facilities, and block the delivery of important supplies, once the waters recede, mold remains as an important environmental health concern.

Disasters have a number of public health impacts, and just classifying the nature of these impacts has been controversial. When compiling data on hurricane related fatalities, the National Hurricane Center employs two categories – direct and indirect. However, this classification is limited in a number of ways. For example, it does not distinguish wind and flood deaths; both are classified as direct. Likewise, the indirect category does not distinguish accidental deaths during rebuilding from medical emergency deaths due to power outages. These distinctions are important because preventing them requires different mitigation strategies.

Floods can lead to direct deaths due to drowning, trauma due to debris impact, heart attack / stroke, dehydration, hypothermia, and numerous other indirect causes (Jonkman and Asselman 2003, Diaz 2004b). Typically, drowning and trauma are the most common causes of flood deaths (Jonkman and Kelman 2005, Few et al. 2004, Kremer, et al. 2000, Shultz, et al. 2005). For storm surge floods, the risk of drowning and debris impact is greater than other flood types because of the increased depths and flow velocities. These factors explain why storm surge floods are among the most lethal.

Jonkman and Kelman (2005) discuss the current limitations in classifying flood deaths. They then propose a standardized classification, and apply this classification scheme in an assessment of 13 flood events listed in the CRED dataset. Their classification scheme is based on various possible circumstances that lead to flood deaths, and it describes both the hazard conditions along with the individual's situation and decisions. The notion of classifying disaster deaths according to the circumstances of death is used in an assessment of Katrina related fatalities presented in Chapter 6.

Other health impacts of floods result from their long term effects. Bennet (1970), comparing flooded communities to neighboring non-flooded communities, found 50% increase in mortality during the 12 months following the floods. Accidental injuries and deaths occur at higher rates than normal during the reconstruction period (Ohl et al 2000, Ogden, et al. 2001, Diaz 2004 b, Lopez, et al 2006). Flooded homes usually have long term problems with mold causing allergic reactions which can be very serious and even lethal for some people (Greenough, et al. 2001). Diseases that are endemic before the flood can present major problems to populations that are recovering from floods (Straif-Bourgeious, et al 2006, Toprani, et al 2006, Ahern, et al. 2005, Morgan et al. 2005, Diaz 2004b). Critical infrastructure such as health services and fire protection can be hindered or destroyed by floods, leading the health impacts when response times are reduced or important services are no longer available (Daley 2006, Norris, et al. 2006, Ogden, et al. 2001). In fact, the availability of adequate health care comprises one of the major problems facing New Orleans during the rebuilding process. Anxiety and depression can follow personal loss or simply being in an environment of destruction (Norris, et al. 2006, Meusel, et al. 2004, Ohl et al. 2000, Ahern, et al. 2005, Morgan et al. 2005, Chae, et al. 2005).

Public health officials often implement health surveillance systems in disaster affected regions. These surveillance systems systematically collect and monitor data from hospitals, clinics, doctor offices, and pharmacies to detect conditions early on and to enable a proactive medical response before many people are adversely impacted (Toprani, et al 2006, Lopez, et al 2006, Shultz, et al. 2005, Ogden, et al. 2001)

Windstorms constitute a broad class of weather related hazards, characterized by extreme winds along with lightening and precipitation. Windstorms include hurricanes, tornadoes, and severe thunderstorms. They can be characterized by multiple hazards, with lightening, flood, and landslides added to straight-line winds and tornadoes. In addition, to the well known hurricane season for coastal Louisiana, this region also experiences a mid-latitude cyclone season characterized by more frequent but with less severe thunderstorms (Yodis and Colten 2007).

If a windstorm forms over a water body and with strong winds directed toward the coastline, then the resulting storm surge can cause coastal flooding. Numerous coastal floods have caused disasters of historic proportions. Many of the most deadly and destructive disasters in the United States are due to storm surge (see Chapter 1). Likewise, other historic disasters have resulted from coastal flooding due to tsunami's. In the United States, an estimated 50 million people live in areas that put them at risk for coastal flooding (Diaz 2004).

While typically associated with tropical cyclones, other types of windstorms can cause a tidal surge to flood coastal areas. For example, the 1953 flood disaster in England and Holland resulted from a large winter storm that formed south of Iceland and moved over the English Channel (Jonkman 2007). This flood disaster killed over 2,000 people and prompted the Dutch to embark on an historic effort to modernize coastal flood defenses (Jonkman 2007). On a near annual basis, some portion of the Louisiana coastline experiences a moderate tidal surge due the onshore winds pushing water inland.

Storm surges can also cause negative health impacts through a number of other mechanisms. Hazardous materials, either released from industrial storage facilities or latent in the environment, can be released and mixed with the flood waters (Euripidou et al 2004, Showalter and Myers 1992, Pardue 2005). Injuries result from impacts with debris, being inside a building that gets torn apart by the surging water, and during rescue attempts (Ohl et al. 2000, Few et al. 2004).

Why are coastal floods more deadly and more destructive that other flood types? Generally speaking, different disaster types produce different impacts because of their different physical characteristics (U. N. Interagency Secretariat; International Strategy for Disaster Reduction 2002, Ahern, et al. 2005, Greenough, et al. 2001, Few et al. 2004). Water depth, rate of rise, flow velocity, and surface waves all influence the flood's consequences (Jonkman 2005; Jonkman et al 2003; others). The observation that rainfall is measured in inches (or millimeters) while storm surge is measured in feet (or meters) reflects the fact that storm surges result in flood depths that are an order-of-magnitude greater than rainfall floods. While rainfall floods can create water depths and flow velocities comparable to what is observed during storm surges, these conditions are usually confined to smaller areas with rainfall floods. During storm surges, hundreds of miles of coastlines are subject to water levels measuring many feet; Katrina is just one example. Additionally, surface waves play a major role in the consequences of coastal floods. Storm surges can bring the power of open water waves to the built environment with destructive consequences. Size of the area inundated also determines the flood's impact, though this affect is due more to the size of the population exposed to the flood as opposed to the direct forces of the flood.

Many have commented on trends in losses due to floods and hurricane. Rappaport (2000), in a study of the loss-of-life due to Atlantic hurricanes over a 30 year study period that corresponds to the previous era of low hurricane activity, found only six cases of direct storm surge deaths between 1970-99. However, three storms, Audrey, Camille, and Betsy, that occurred during the fifteen years prior to his study period resulted in nearly 600 fatalities. Before Katrina, the hurricane season of 2004 produced more storm surge deaths than the 30 year period of Rappaport. Seven people drowned in storm surges during 2004; two during Hurricane Frances (Beven 2005) and five during Hurricane Ivan (Steward 2005).

Disaster Impact Models

Limitations of the disaster data and vulnerability measures not withstanding, there has been considerable progress in developing quantitative models to estimate disaster losses from a given real or hypothetical disaster scenario. Progress in this direction has been largely driven by the insurance industry's use of economic loss models in the actuarial processes of determining profitable insurance policies.

To provide actionable intelligence for disaster response operations, FEMA has developed the HAZUS-MH tool as a robust GIS based tool for evaluating a variety of disaster losses for flood, hurricane winds, and earthquakes. "current scientific and engineering knowledge is coupled with the latest geographic information systems (GIS) technology to produce estimates of hazard-related damage before, or after, a disaster occurs."
(http://www.fema.gov/plan/prevent/hazus/index.shtm)

Flood Loss-of-Life Models

As a class of disaster impact models, flood loss-of-life models have expanded considerably in recent years. McClelland and Bowles (2002) and Jonkman (2007) both provide a thorough review of research on flood fatalities and flood fatality modeling. The current review lists the major contributions to the field, from the perspective of a spatial analyst.

In her seminal work on methods of assessing a community's vulnerability to natural hazards, Cutter (1996) notes the importance of analyzing the variables "that produce explicit spatial outcomes" (p.530). In the context of floods and flood deaths, approaches to estimating explicit spatial outcomes from what is known about the distribution of risk have improved over the years, though a number of uncertainties remain in this complex problem.

DeKay and McCelland (1993), motivated by dam failures and flash floods, propose two loss-of-life equations, one for highly lethal floods and another for low lethality floods. In both equations, the number of flood fatalities depends on the population at risk and evacuation time. Jonkman (2005) points out that, contrary to other results and to basic expectations, the number of fatalities depends non-linearly on the population at risk in the equations proposed by DeKay and McCelland.

Prefacing their article with the important statement that “this is not a model,” (p. 1) McClelland and Bowles (1999) present a comprehensive listing of realistic input variables inferred from a review of 38 flood events from the historical record. Central to their conceptual approach is dividing the population at risk (Par) into homogeneous subPar characterized by “predictable life loss distributions, with variance governed largely by chance” (p.2). These populations are termed homogenous base units (HBUs). For each HBU, many variables related to evacuation effectiveness determine the threatened population, while many variables related to the hazard exposure determine fatality rate. In comparison to previous approaches that focused exclusively on the flood hazard and evacuation logistics, this article begins to include the social distribution of risk in the flood fatality model framework.

As Jonkman (2007) describes, early flood fatality researchers in the Netherlands used the flood depth of a location to determine the local flood fatality rate. Later researchers added the rate of rise of the flood to the fatality rate equation, but do so in an ad-hoc manner that limits the domain of the two explanatory variables.

Looking at loss-of-life modeling within a general context of risk analysis, Jonkman and Lentz (2004) proposes three general steps in estimating loss-of-life:

1) Determine the physical hazard characteristics of the event,
2) Determine the number of people exposed to hazard,
3) Determine the mortality for the exposed population.

To complete step 3, they write that “dose response curves model the human resistance to a certain level of effects” (p.8), thus specifying the relationship between the physical hazard characteristics and fatality rate of the exposed population. They note that two approaches to developing dose response relationships; one approach depends on physical laws while the other approach utilizes the historical data to infer statistical relationships.

In this context, Jonkman’s method for estimating the mortality of a flood event centers on three dose response relationships. Flood depth plays the dominate role in these relationships, but flow velocity and rate of rise are also important variables. Implicitly, the level of building stock plays a limited role when Jonkman states that all buildings are destroyed when the conditions of the breach zone are met.

Jonkman (2007), concerned about potentially catastrophic flooding in Holland, presents a flood fatality model that includes the evacuation effectiveness and the physical characteristics of the flood hazard. In this model, the size of the total population and the effectiveness of the evacuation determine the size of the exposed population. The number of fatalities is expressed as a fraction of the exposed population, which Jonkman terms flood mortality (otherwise referred to as the flood fatality rate). Jonkman then uses data from the 1963 Dutch flood to statistically determine the dose-response relationship. Jonkman also completes this analysis using preliminary data from Hurricane Katrina.

2.4 Risk Analysis

The field of risk analysis provides a mathematical formulation of risk that both specifies a rigorous conceptual framework for consequence modeling and specifies important relationships inherent to understanding the human-environment interaction. In this field, risk is given a quantitative definition that allows us to equate probability times consequences to hazard, vulnerability, and capability. This expression of risk lets us derive quantitative definitions of vulnerability that utilize direct measures of spatial outcomes and controls for variance in the hazard.

Rooted in probability theory, risk analysis can be traced to intellectual foundations developed in the seventeenth century. Blaise Pascall was one of the more famous early mathematicians to study frequency and probability during this period. Initially, focused on combinatorial methods applied to discrete events, the proverbial series of coin tosses that lead to a series of heads and tails, probability methods were soon extended to continuous outcome variables, such as river discharge measured at the location over a span of time. While coin tosses are not generally considered risky activities, risk soon intertwined itself with probability when a gambling friend of Pascall began a correspondence on how the theory of probability applies to gambling (Singh 2004). [1]

Early thought on probability adhered to a frequentist approach that viewed probability as a objective measure of the frequency of an outcome over repeated events subject to random fluctuations. Later interpretations, called the Bayesian or Objectivist approach, view probability as a subjective measure of the state of knowledge about the potential outcome that can be improved upon through the accumulation of evidence.

Probability is crucial to understanding risk, and uncertainty is central to both. Both risk and probability entail some degree of uncertainty about the outcome of future events. While probability is value-neutral (in most cases there are no consequences associated with heads or tails), risk entails the possibility of loss associated with possible undesirable outcomes. Uncertainty is what leads to the probability of loss, and hence risk. Only when uncertainty is present, does probability and risk enter into the equation. In the absence of uncertainty, there is complete knowledge of the possible options and the rational human does not pursue the ones with loss. However, uncertainty is an inherent part of life, and this is largely a semantic point.

Often disaster scientists and hazard geographers discuss risk in an informal way leading to subjective judgments of decisions and behavior associated with greater risk. For example, there is a tendency to focus the risk analysis on whatever the last major disaster had been while ignoring other sources of risk. When risk is given a quantitative definition, it is usually simply the probability of an event times the consequences of the event. This approximation allows only limited analysis. For example, this specification of risk fails to distinguish high probability, low consequence events (for example a car accident) from low probability, high consequence events (for example an asteroid striking a major city).

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[1] In the fall of 2004, I took Professor Singh's Risk and Reliability course at LSU where he provided a draft version of text, which is where I obtained the referenced material.

Kaplan and Garrick, in their seminal article "On the Quantitative Definition of Risk" (1981), provide a robust definition of risk in terms of a set of triplets. To them risk entails "attempting to envision how the future will turn out if we undertake a certain course of action" (p. 12). Synthesizing common usage, they note two common conceptual notions of risk: (i) risk as uncertainty plus possible damage, and (ii) risk as hazard divided by safeguards. Going further, they note that a risk measure must answer three questions: (i) what are the possible events?, (ii) what is the probability of each of these events?, and (iii) what are the consequences of the events?

To specify a risk measure that answers these questions, they introduce a "set of triplets" (p. 12), that is a set of paired values of three variables, where each triplet represents a possible scenario, the probability of that scenario, and the consequences of that scenario. Mathematical, they define risk as

$$R = \{ <s_i, p_i, x_i>\}$$

where s_i = the i^{th} scenario, p_i = probability of the i^{th} scenario, and x_i = the consequences of the i^{th} scenario. The < > denote that s_i, p_i, and x_i form a paired triplet of numbers, while the $\{ \}$ imply the complete set of all possible pairs. More than just the probability and consequences of one event, risk is the set of triplets that describe all possible events. They observe that "a single number is not a big enough concept to communicate risk. It takes a whole curve." (p. 13). Since, many events (such as disasters) have multi-dimensional impacts (deaths, injuries, building damage), they note that x_i can be a vector to represent multiple classes of consequences.

From here, Kaplan and Garrick define "Risk Curves" in terms of the cumulative probability $P_i = p(x \leq x_i)$ plotted versus x_i. In essence the risk is the curve, and comparing the risk of a set of possible options boils down to comparing the curves associated with the events that could result from the options.

As the authors note this definition of risk does not lead to a linearly comparable number for identifying the least risk option from a set of options. As a result, this definition of risk does not readily lend itself communication with the public or participatory decision making. To meet this requirement, Kaplan and Garrick utilize the utility function of $U(x)$ (the utility function specifies the value given to outcome x) and "reduce the risk curve to a single number… through expected values" (p. 23) of U:

$$< U > = -\int_{-\infty}^{\infty} U(x) \frac{dP(x)}{dx}\, dx$$

In relation to the objectivists versus subjectivist debate, the state "frequency [is the] standard of reference" for "calibrating the entire probability scale." In a similar manner, Singh (2007) writes that "frequency is used to calibrate the probability scale [then we] use probability to express our state of confidence or knowledge" (Chap 2, p. 14) about events that are beyond the observational domain.

This definition of risk has been widely adopted and applied to a variety of problems. Focusing on their assessment of risk on casualties, Vrijling and Gleder (1997) in "Societal Risk and the Concept of Risk Aversion" describe how the risk curve (they term it the FN-Curve) plays a central role in Dutch risk-based regulations. Defining the FN-curve as the "exceedance curve with related pdf of the number of deaths," (p. 2). they derive two measures of social risk, which as just two familiar statistical moments of the FN-curve:

$E(N) = \text{Expected Number}$
$\Sigma(N) = \text{Standard Deviation}$

Singh (2007) applies this formulation of risk in the context of the performance engineering systems. Utilizing the set of triplets definition of risk, Singh defines hazard as a subset of Risk:

$H = \; = \{ <s_i, x_i> \}.$

Dropping the probability of the scenario from the set of triplets, a hazard consists of the set of scenarios with associate losses.

Following the logic of Singh, the set of triplets definition of risk can be reduced to illustrate other useful concepts. To start, the total risk is defined in terms of all possible scenarios:

$R_{Total} = \{ <s_i, p_i, x_i> \}$ where *i* is an element of the universe all possible events.

If considering a specific hazard type, we can restrict s_j to just the scenarios of that hazard type. Defining risk for the jth hazard (type of event):

$R_{hazard} = \{ <s_j, p_j, x_j> \}$ where *j* indicates all events of the j^{th} hazard type.

For the *kth* event, the risk is given by

$R_k = <s_k, p_k, x_k>$ where *k* represents the event of interest.

From here, we can describe s_k in terms of the set of hazard conditions, $(H_{1k}, H_{2k}, H_{3k}, \ldots)$ impacting a population whose vulnerability is defined by $(V_{1k}, V_{2k}, V_{3k}, \ldots)$. Since occurrence of the hazard conditions follows a probability function, we can write $p_k = p(H_{1k}, H_{2k}, H_{3k}, \ldots)$. Likewise, we can utilize a dose–response relationship to express x_k in terms of the hazard characteristics and population vulnerability, that is $x_k = f(H_{1k}, H_{2k}, H_{3k}, \ldots, V_{1k}, V_{2k}, V_{3k}, \ldots)$. From here, we get

$$R_k = < p_k(H_{1k}, H_{2k}, H_{3k}, \ldots), f(H_{1k}, H_{2k}, H_{3k}, \ldots, V_{1k}, V_{2k}, V_{3k}, \ldots) >$$

which expresses risk in terms of the hazard conditions and vulnerability characteristics. This logic will be further elaborated in the Chapters 6 and 9.

This formulation of risk provides insight into the key issues and debates discussed in this literature review. For example, the non-ekumene can be defined as any scenario where the

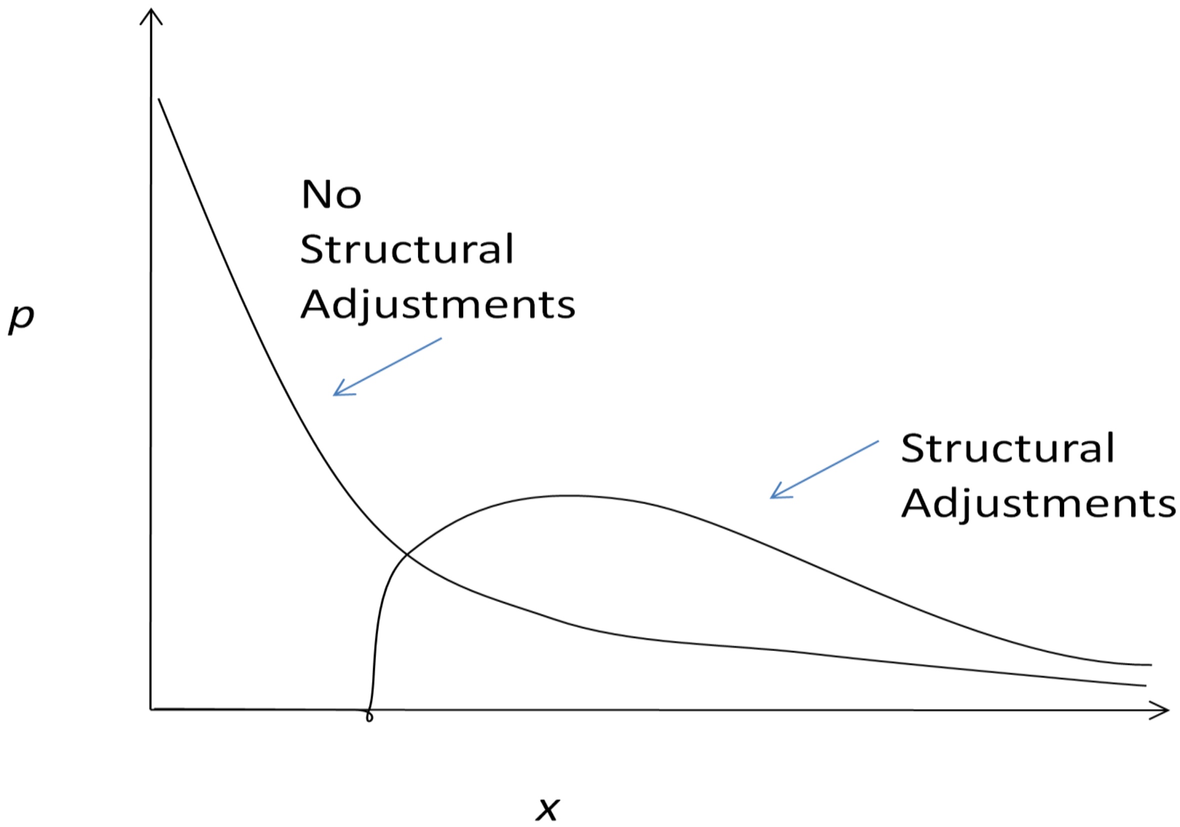


Figure 2.2: Hypothetical examination of how the implementation of structural flood controls impact the risk curve. In this example, the structural adjustments reduce the probability of low level floods (say anything below the design height of the levee), but then confining the flow of water increases the probability of more severe floods. (Figure by Author).

probability equals one that the consequences are greater than a level acceptable for human habitation. Likewise, structural approaches to reducing flood impacts can be assessed through their impact on the set of risk triplets, see Figure 2.2.

2.5 Predicting Catastrophe: Hazards Geography and Disaster Science in New Orleans

Lewis (1976), in what many consider the first geography of New Orleans, notes the lack of a native geographic specialist for the region. However, this observation is largely a semantic issue. Sherwood Gagliano, along with a host of other Louisiana “coastal scientists,” possess a broad geographic expertise of the region. Of particularly interest to these scientists was coastal Louisiana’s eroding landscape and flooding hazard. In fact, many historical geographers, climatologists, coastal scientists, spatial analysts, and others all contributed to planning for a Katrina like event.

As one example, Colten (2005) presents an historical geography of the region that examines growth of New Orleans and its relationship with its hazardous environment. He notes how past racism in the City has influenced the adaptation of hazard mitigation policies and concludes that the unequal provision of protection created population vulnerabilities. As an example, he describes how low lying, poor African-American neighborhoods were the last to receive sewage and drainage services and generally the worst affected by flooding through the early Twentieth Century. Published just months before Katrina, this book describes the current conditions that had created the potential for a flood catastrophe to strike New Orleans.

In the years preceding the disaster, two popular press articles summarized the science that predicted disaster for New Orleans. A series of articles in The Times-Picayune (McQuaid and Schleifstein 2002) along with articles in Scientific American (Fischetti 2001) and National Geographic (Bourne 2004) described how the loss of crucial wetlands combined with the bowl like topology of the city created the conditions for massive storm surge flooding. Citing Red Cross sources, McQuaid and Schleifstein (2002) go so far as to speculate that as many as 125,000 people could perish from storm surge induced flooding over much of New Orleans if evacuation procedures were not effective.

Other authors focused more specifically on analyzing the vulnerability of the population. After reviewing the hurricane and flood history for the New Orleans / Baton Rouge NWS forecast office's warning area, Jones, Lovette, and Trotter (2005) noted that the high percentage of African-Americans make the population there more vulnerable to severe hurricanes and floods. Boyd (2005) presented a storm surge vulnerability index that represented a first attempt at quantifying vulnerability based on explicit spatial outcomes. Utilizing the UNHCR risk equation, he specified a vulnerability index as $(V/C) = R/ H$, and then defined R in terms of the flood fatality rate and H in terms of the surge height. Utilizing historical data from Betsy, he estimated that $(V/C) \sim 10^{-5}$ deaths per exposed person per foot above sea level, and further posited that in the event of a 10 ft (3 m) storm surge and a 65% evacuation rate 400,000 people would be exposed and ~200 people would drown (Boyd 2005).

At the same time, modeling efforts looked at potential storm surge flooding scenarios and the implications of these scenarios. Computing and numerical modeling technology allowed considerable advances in storm surge prediction capabilities. Particularly, the ADCIRC model had been adopted for the Louisiana Gulf Coast and was providing both realtime and hypothetical storm surge models (van Heerden and Bryan 2006). Pedro (2006), in work that began before Katrina, used Census data along with storm surge simulations to examine the socioeconomic conditions in relation to the predicted flooding and to determine where a vulnerable population overlaps with potential flood exposure. Described in more detail in Chapter X, the Hurricane Pam exercise was a planning session based on a hypothetical storm that caused flooding throughout Southeast Louisiana. Though the science behind the predictions is not described, the exercise guide provides very specific estimates of the disaster impacts, including the number injured, rescued, sheltered, and deceased (Innovative Emergency Management 2004).

2.6 Summary of Katrina Related Literature

Without any doubt, Hurricane Katrina and the levee failures produced vast amounts of data related to this urban flood catastrophe. As just one example, John Pine's GIS Clearinghouse quickly amassed 1 TB of data on the disaster and it impacts (LSU CADGIS Research Laboratory

2005/06). Similarly, the many teams involved in the response complete Activity Reports or After Action Reviews which provide specific figures on impacted populations and response assets. Major government reports have been published by the House of Representatives, the Senate, and the White House. In addition, numerous Federal agencies, including the Department of Homeland Security and the Department of Health and Human Services, have produced reports on the event, as have Congressional Committees, the Congressional Research Services, and the General Accounting Office. The investigations of the levee failures spawned six different and independent reports on the sequence of flooding and the flood impacts.

A number of authors have provided initial assessments and analysis of Katrina related fatalities. Bourque et al (2006) reviewed the vital statistics from the St. Gabriel morgue available in December 2005. Having occurred just months into the recovery period, this source contains most, but not all, of the victims examined at St. Gabriel. They conclude the "vulnerable elderly are substantially overrepresented among the deceased, males are overrepresented among the identified dead, and African Americans are somewhat underrepresented" (p. 140). Campanella (2007) provided a more nuanced interpretation of the observed statistics based on the historical ethnic geography of the metropolitan area.

In 2005, the U.S. Army Corps of Engineers designated the Interagency Performance Evaluation Taskforce (IPET) as the official government technical investigation to "determine the facts concerning the performance of the [Hurricane Protection System] in New Orleans and Southeast Louisiana during Hurricane Katrina." During the nearly four year period following the event, the IPET team released a series of draft versions of the report and the final versions were released in June 2009. Volume VII of the IPET report looks at the consequences of the flooding, including health and safety consequences.

The IPET group looking at health and safety consequences developed a dataset from the published literature, including the SMEO reports, the above article by Bourque, et al., news media, and similar sources. After reviewing the published reports related to Hurricane Katrina related deaths in Louisiana, the IPET group concludes that the following causes of death were prevalent among the deceased victims: Lack of access to care, drowning, infection, suicide, homicide, and accident. While mentioning various individual cases that were uncovered, the authors do not attempt to quantify the prevalence of the outcomes.

Sharkey (2007) delves deeper into the connection between race, income, and age and the risk of dying during Katrina. As data sources, Sharkey utilizes a SMEO report of missing and deceased retrieved on May 30, 2006, a SMEO list of all individuals who remained missing as of May 2, 2006, and an unattributed dataset that includes the locations of deceased victims that were recovered prior to December 2, 2005. He also uses the 2000 Census for the baseline population. While he states that he found similar patterns for St. Bernard parish, he only presents and discusses results for Orleans parish. His analysis consists of a series of descriptive and bivariate statistical calculations along with qualitative mapping overlay and association. He finds that age is the dominant explanatory variable, and, that after controlling for age, that "African Americans were disproportionately likely to die in Katrina and… remain missing" (p. 483). After studying the spatial distribution of deceased victims, Sharkey found that "the neighborhoods with the highest numbers of deceased are overwhelmingly Black" (p. 484).

Stephens, et al. (2007) investigates the possibility of excess mortality during the recovery period, specifically the first six months of 2006. Since vital statistics from the state were not available at the time of the study, the authors construct their dataset from death notices in The Times-Picayune newspaper. They first compare the number of death notices counted during the first six months of 2002 and 2003, and find a significant correlation between this count and the official number of deaths from vital statistics for those periods. They then use the death notice count for 2002-03 as a baseline to determine the excess number of reported deaths for the first six months of 2006. They conclude that the number of deaths increased from 924 notices per month in 2002-03 to 1,317 notices per month in 2006, which indicates a total of 2,358 excess (and presumably storm related) deaths during the first six months of 2006.

Brunkard, et al. (2009) construct a dataset on Hurricane Katrina victims in Louisiana from the DMORT database , death certificates from Louisiana vital statistics, and death certificates from out-of-state coroners' offices. They then classify the deaths using the International Classification of Diseases-10 code X37, victim of cataclysmic storm, but note that "the majority of deaths had multiple hierarchical cause-of-death classifications; however, if trauma, injury, or drowning was listed as a contributing cause of death, these victims were categorized as drowning or injury victims" (p. 2). They conclude that 378 victims died due to drowning, and 246 people died due to trauma or injury. They also note that 70 hospital patients died in New Orleans hospitals, while another 57 non-patient storm victims were recovered from hospitals. They conclude that more than 70 people died in nursing facilities in Orleans, St Bernard, and Jefferson Parishes.

Consistent with Sharkey, they also find that "older adults were clearly the most affected" (p. 5) and that "stratified analyses evaluating the effect of race within age groups revealed that the dominant effect of age on overall storm mortality masked the differential effect of race in most age groups in Orleans Parish… Older black people in Orleans Parish, particularly men, were disproportionately represented relative to their underlying population distribution" (p. 7).

Jonkman, et al. (2009) used the data from Hurricane Katrina to further refine a flood fatality model that predicts the flood fatality rate (the number of flood deaths divided by the flood exposed population) based the flood hazard conditions. Flood deaths were determined by laying the geocoded SMEO recovery locations dataset from September 14, 2006, and the flood exposed population was determined from the Census population and an assumed 90% evacuation and sheltering rate. The independent variables consisted of the flood depth, the rate of rise, and the flow velocity from the SOBEK flood simulation tool. A non-linear, multivariate regression analysis assessed the relationship between the flood fatality rate and the flood hazard conditions. Results indicated that flood depth and flow velocity were important determinants of flood fatality rate.

2.7 Conclusion

Flood disasters prompt important questions: What factors contribute to flood losses? Can humans adequately accommodate for this constraint that nature places on the settlement and utilization of floodplains? Are costly structural adaptations (levees, flood walls, and flood gates) an effective means of overcoming this constraint? In many ways, these questions reflect the age old dichotomy of geography. Indeed, the basic dichotomy seen in flood control policies resembles the fundamental relationships of the man-land tradition of geography. On one side, the structural flood control approaches presume a human dominance over nature and that the control structures that we build will actually reduce flood risk. On the other hand, the land use management approach presumes that environmental constraints of human activity cannot be overcome and we can only reduce flood risk by restricting settlement within floodplains. Since much of the world's population and most of the world's economy resides on floodplains, this important issue demands a valid scientific analysis that critically examines the basic assumptions of the arguments on either side.

This literature review traces an evolution of thought on human's place and role on the face of the Earth. This review begins with the ancient notion of the ekumene versus the non-ekumene. From this simple view of the Earth, geographic thought evolved into a debate on human agency versus environmental determinism, and most recently the nature and value of the human-environment interaction. In the context of human habitation and utilization of floodplains, the debate becomes one of structural versus non-structural flood control measures.
The science of disasters lacks a general set of principles that relates impacts, the directly observable measure of the event, to the central conceptual variables of risk, hazard, and vulnerability. As such, researchers in this field are limited in their ability to rigorously test specific hypothesis on how disaster impacts relate to measurable aspects of hazards and vulnerabilities. Instead of universal relationships derived from rigorous empirical analysis, the commonly accepted knowledge of hazard research rests primarily on generalizations derived from isolated and limited case studies. Commonly accepted general statements on disaster risk and impacts have not been critically tested with robust, comparative studies that can exclude alternative explanations.

New to this ancient discussion, risk analysis brings a powerful framework for objectively assessing potential outcomes and consequences in an uncertain world. Conceptually, risk relates to the hazard characteristics of the physical process and the vulnerability characteristics of the affected population. Disasters result when a vulnerable population is exposed to a physical hazard that overwhelms the population capacity to respond. As such, much of hazard geography concerns the spatial dimensions of hazards and vulnerability. Like risk, direct measurement of the variables "hazard" and "vulnerability" remains problematic. Instead of direct measures, various indicators, or proxy measures, are used. For example, while the Richter scale provides a good indicator of the magnitude of an earthquake, the influence of other characteristics, such as the type of displacement and soil types, means that this scale is not a direct measure of degree of the physical hazard for the event. Likewise, income, education, and age are used as indicators in vulnerability indexes, but they do not provide direct measurement of the vulnerability of a population.

An emerging field, risk analysis considers a set of events, the probabilities of the events, the consequences of events, and seeks to identify the best strategy for minimizing the expected consequences from the set of possible events. However, in considering the probability of events, it explicitly accepts uncertainty. Risk is the central conceptual variable used in hazards analysis. Conceptually, this framework links observed impacts to hazards and vulnerability. Risk is a forward looking concept used to assess what might happen during future disaster events (thus immeasurable as a matter of principle). While definitions of risk vary, one simple and common definition equates risk to the probability of an event times the impact of the event. However, a more complete definition looks at all possible events to create a set of triplets that specify the possible scenarios, the outcome of those scenarios, and the probability of the scenario. From this set of triplet, specific measures can be calculated.

Consequences are an important element of risk analysis, and various models have been developed to estimate different classes of outcomes, including economic damage and deaths. One set of models provide tools to estimate deaths due to flood events. In these models, a dose response relationship expresses the flood fatality rate as a function of the flood characteristics. In other words, this function describes how a population responds when exposed to given dose of flood hazards. In the context of economic damages, Burton (2010) explores the possibility of merging consequence models based on just the hazard characteristics with measures of population vulnerability. While much work remains, these consequence models hold potential for fulfilling this difficult element of the risk triplet. In doing so, these models provide the tools needed to more rigorously address questions related to the ekumene versus the non-ekumene, environmental determinism versus human agency, and structural versus non-structural approaches to reducing flood losses.

Chapter 3: Historical Geography of the Study Region

All disasters occur within a context of an historical geography that leads to a vulnerable population residing in an area exposed to hazards. The famed historical geographer Sauer observed that processes of past landscape change are crucial to understanding the current landscape (Johnston and Sidaway 2004). This statement is particularly true in the context of major disasters. For example, *An Unnatural Metropolis: Wrestling New Orleans from Nature*, (Colten 2005) describes the conditions that set the stage for a Katrina-like disaster in New Orleans. Early-on this historical geography of New Orleans that spans rivers floods, epidemics, rainfall floods, hurricanes, and storm surges, states that "through and through, New Orleans's physical geography is interlaced with its local history (Colten's 2005, p. 2)." Colten then proceeds to describe a three century long story of landscape changes and other human responses to the various hazards inherent at the city's site, and how these conditions set the stage for a Katrina-like disaster.

3.1 Human Modifications to the Landscape

To fully understand a disaster, one must first appreciate the hazards of the landscape and vulnerabilities of the population that combined to create the conditions of the disaster. These statements are certainly true for the 2005 disaster in New Orleans. This chapter briefly summarizes the historical sequence that created the conditions for the Hurricane Katrina disaster. It starts at the very beginnings of the region that would become southeast Louisiana with a natural process of building a new landscape where the Mississippi River meets the Gulf of Mexico and forms a coastal delta plain, and finishes with the growing knowledge that human modifications to the landscape have resulted in a disappearing landform that left New Orleans's vulnerable population increasingly exposed to the hazards created storm surge flooding.

Nature Builds a Delta

As one of the world's major rivers, the Mississippi River and its deltaic plain provides an ecosystem of amazing natural beauty, bountiful natural resources, and perilous natural hazards. The Mississippi River winds 2,320 miles through the United States and, along with its tributaries and distributaries, constitutes a watershed that drains 42% of the area of the United States along with portions of Canada (Yodis and Colten 2007). Over time, precipitation eroded soils from the river's watershed, and delivered the eroded material down the valley and toward the Gulf-of-Mexico. The River and its valley are divided into two regions, the Upper Mississippi Valley and the Lower Mississippi Valley. Cairo, Illinois, where the Ohio River merges with the Mississippi, sits at the transition between the two regions. Below this region, sits a large alluvial valley, a geomorphic feature that shows the influences of tens of thousands of years of sedimentation and fluctuating sea levels. The lower most portion of the Lower Valley consists of the Mississippi River Deltaic Plain, a vast region of coastal wetlands and elevated natural ridges created by deposition during the last 7,000 years (Yodis and Colten 2007). New Orleans sits near the center of the deltaic plain, covering a section of a natural ridge and extending into reclaimed swamps beyond the ridge.

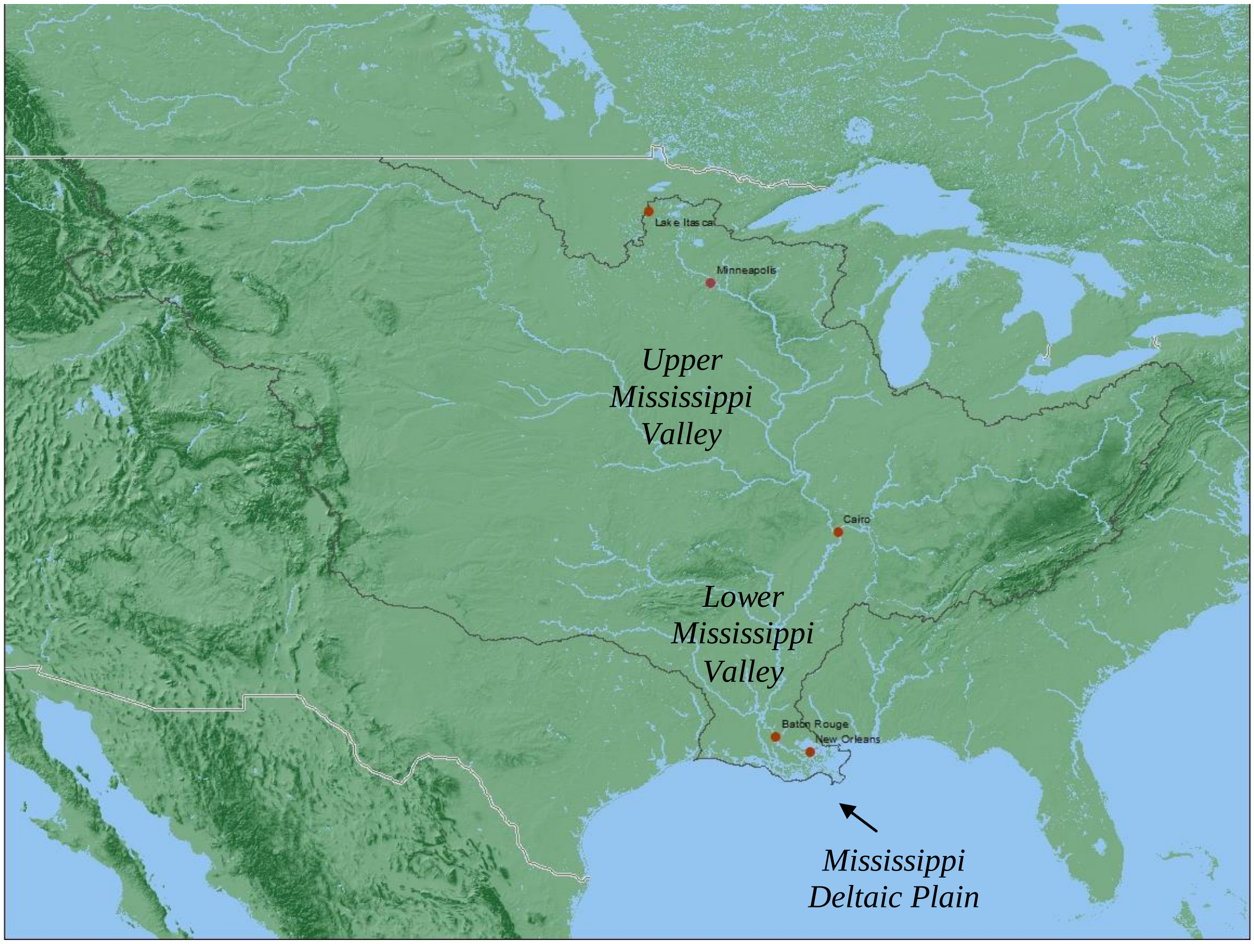


Figure 3.1: The Mississippi River Valley within the United States. (Map created by author using shapefile from University of Colorado's National Center for Atmospheric Research.)

Following the end of the Wisconsin Glacial advance over North America, some 10,000 years ago, a period of significant sea level rise began and lasted until 4,000 years ago (Nelson 2007). During this period, seas around the world rose nearly 135 m to roughly its current level. Sitting at the edge of the Gulf Coast Physiographic Plain, Cairo, Illinois, represents the edge of northern movement of the Gulf-of-Mexico during the period of sea level rise. As sea levels dropped and stabilized roughly 4,000 years ago, the Mississippi River and it watershed started to deposit sediment throughout its lower valley, resulting in the Mississippi alluvial valley and the Mississippi deltaic plain. The alluvial valley extends from Cairo, Illinois, to an area just north of Baton Rouge, Louisiana. Located downriver from the Mississippi's confluence with the Red River, a tributary, and the Atchafalaya River, a distributary, the Deltaic Plain comprises much of current southeast Louisiana. Where New Orleans now sits was part of the Gulf-of-Mexico some 4,000 years ago (Nelson 2007).

Possibly, the youngest naturally created and currently inhabitated land on the earth, the area that would later become New Orleans was built through an untamed natural process of sedimentation that began when Europe was still in the bronze age and the Phoenician civilization was taking shape along the eastern coast of the Mediterranean sea. For four thousand years, an annual flooding and sedimentation process began with the spring snow melt and rain through out the Mississippi's watershed. This precipitation caused eroded materials to enter the flow of the river toward the Gulf-of-Mexico. It also caused a surge of sediment rich high water to travel down the valley resulting in flow over the banks of the river throughout the delta. The result was widespread flooding of the delta by sediment rich water. Throughout the Alluvial Valley, the floods deposited a layer of alluvial soil over the existing land, while in the Deltaic Plain the sediment accumulated to create a vast new ecosystem of natural ridges, freshwater swamps, brackish wetlands, and coastal marshes. Naturally, tidal erosion was a major part of this process. During the periods between spring floods, the waves and tides from the Gulf-of-Mexico eroded some of the material deposited on the delta. However, for four thousand years sedimentation outweighed erosion and the Deltaic Plain grew as new land emerged.

The land that emerged reflected the interaction of freshwater, sediment, salt water, and Gulf currents throughout the land creation process. Along the banks of the river and its major distributaries, the heavier sediments accumulated and formed natural ridges of dry land that sat a few feet above the water level. Beyond the natural ridges, the many distributaries of the river, later termed "bayous" by the Native American cultures that would populate the area, fed fresh water into a vast array of wetlands and backswamps. Moving toward the coast, salt water mixed with fresh water resulting in distinct wetland habitats defined by salinity and full of tremendous biodiversity and bountiful seafood harvests (Yodis and Colten 2007).

At times, when the spring floods started to recede, the previous river channel would be blocked by built up sediment and a distributary would offer a shorter, steeper path to the Gulf-of-Mexico. By the time the flood receded completely, the Mississippi River had jumped course to the new route which now carried the bulk of the water and sediment. The old route became relegated to distributary status. This event started the creation of a new deltaic lobe, and as the new lobe grew it would often overlap the previous lobes. During the last five thousand years, the Mississippi River jumped course six times (Yodis and Colten 2007). The resulting overlapping delta lobes constitute the Mississippi River Deltaic Plain and most of southeast Louisiana. Interestingly, there is archaeological evidence that Native American cultures populated some of the ridges shortly after they emerged from the Gulf-of-Mexico (Yodis and Colten 2007, Kidder 2000).

Humans Settle and Modify the Landscape

Europeans arrived in Louisiana in the Seventeenth Century, and they brought with them a mindset of willfully and massively transforming the physical characteristics of the natural world to meet human goals and objectives. Prior to European settlement, human activity had modified the landscape, though in more passive and less substantial ways. Native American populations cleared swamp and forest land to create farmland. In northern Louisiana, they also constructed a 3-mile complex of earthen ridges and clay structures along the banks of Macon Bayou at a site now called Poverty Point. This distinct landscape feature exists today and was believed to be natural features of the Mississippi Alluvial Valley, until aerial photograph in the 1950s revealed a uniquely human configuration to the ridges. In the coastal zone, the Tchefuncte people extended the natural ridges being created through sedimentation by discarding their shellfish

Figure 3.2: An oak tree that had grown in a shell waste midden in the Barrataria Preserve south of New Orleans. After the tree had grown, the shells were mined in the early Twentieth Century exposing the trees root system. A few remnant shells remain and can be seen in the zoomed portion of the image on the left. Photo by author, description from National Park Service placard.

mollusks and other waste into waste middens (Kidder 2000). Naturally, these waste middens where located at the edge of settlement where the dry ridge gives way to wet swamp. As time passed, these features provided elevation above sea level for oak trees to grow, a distinct vegetation of the ecosystem that found a niche in the natural, or in this case man made, ridges that protected the trees from salt water (Kidder 2000, Figure 3.2). In sharp contrast to human modifications since the arrival of the Europeans, the Tchefuncte people appear to have been passive participants in the natural process of land creation that was going on around them.

French settlers, having established a presence in the North American interior, first started to settle the Gulf Coast in the late 1690s. Seeking natural resources and trading routes, they established bases and outposts along the coast. In 1718, French colonists formally decided to establish a town at the site of an outpost at a crescent shaped natural ridge along the northern edge of a bend in the Mississippi River roughly 90 miles upstream from the Gulf-of-Mexico (Morris 2000). In 1720, the colonial government used slaves to begin clearing land at the site, and in 1722 they moved the colonial capital here. In addition to river access, this location also provided access to Lake Pontchartrain via Bayou St. John. With its fertile alluvial soils, a defendable vantage point, and convenient access to the Gulf-of-Mexico, the French soon recognized the strategic importance of this location, and established the city as a center of trade.

The early French settlers begun building what would later be described as “the impossible, but inevitable city” (Lewis 1976, p. 19). In the harsh swamp environment and humid subtropical climate, the French saw a potential for abundant agriculture and profitable trade. They set about building along the natural ridge and clearing the surrounding land for agriculture. However, the one thousand or so early French settlers struggled to overcome the extreme conditions (Yodis and Colten 2007). Beginning in the 1720s, the French started to bring several thousands of slaves from West Africa to provide the labor force needed to transform the land, extract the natural resources, and build the colony. By the 1740s, African slaves, comprising roughly three-quarters of the colony's population, turned out to be a crucial factor in the survival of settlement (Yodis and Colten 2007).

While struggling to fulfill the economic potential of the settlement location, the French settlers, their slaves, and a small contingent of German settlers that arrived in 1720s suffered from the many natural hazards of the region. The diseases of the new climate killed many, while food shortages were prevalent until the German settlers successfully transformed the land and cultivated a set of the staple crops and fruits. Flood and windstorms were also a persistent threat. Early construction of the colony suffered regular setbacks as the spring floods caused considerable damage to what had been built. First designated a town 1718, New Orleans also suffered its first river floods during that year (Seed et al. 2006).

To better control the threat posed by the annual river floods, the early French settlers constructed a 3-ft levee along 1 mile of riverfront adjacent to New Orleans in 1722 (Morris 2000, Yodis and Colten 2007). Later construction extended the levee system to encircle the entire city. After floods in 1735 proved this levee insufficient to protect the settlement, the French colonial government ordered all rural landowners to construct a levee along their riverfront property (Yodis and Colten 2007). By 1763, artifical levees extended about 50 miles upstream from New Orleans and provided the city with some, but not complete, flood protection (Yodis and Colten 2007). Early-on during their settlement of Louisiana, the French began a process of human adjustments to the landscape that ultimately lead to severe alterations to the process of land creation throughout the Deltaic Plain.

Despite the early settler's best efforts to contain the mighty Mississippi, the settlement suffered regular inundation from the spring high water throughout the 18th century. During the colonial period, notable Mississippi River floods occurred in 1770, 1782, 1785, 1771, 1796, and 1799 (Seed et al. 2006).

At the end of the colonial period, Louisiana was largely a collection of clustered settlements and agricultural farmsteads that clung to the rivers and bayous that formed the deltaic plain. New Orleans formed the major population center with a diverse population that included Africans, French, Germans, Spanish, and Native Americans along with increasing numbers of Anglo pioneers entering from the newly independent United States of America. After nearly a century, the colony had developed an agriculture suited to the climate and soils of the region, resulting in fairly stable food supplies. Flood protection efforts had started to pay off as inundations became less frequent, though there were still common and remained as a major concern (Yodis and Colten 2007).

Origins of The Modern Mississippi Flood Reduction Infrastructure

The United States acquired the Louisiana territory 1803, and levee construction continued up and down the river under the American's authority. In 1861, as the U.S. Civil War was starting, Louisiana ceded from the Union and joined the Confederate States. Along the River and throughout the South, the war meant both neglect and destruction. In some instances, the Union forces willfully removed sections of levee to achieve strategic objectives. By 1865, the war had ended, and Louisiana was once again part of the United States. As a result of the Civil War, 4 million African slaves in the southern states, including 330,000 in Louisiana, gained their freedom and started a massive migration from the rural, plantation communities to the emerging urban, industrializing cities.

A major Mississippi River flood occurred again in 1874, causing widespread damage along with disruption of commerce. The impact on commerce further encouraged a growing trend of Federal involvement in the management of the Mississippi River system. In 1879, Congress established the Mississippi River Commission, and tasked this Federal executive organization with maintaining the river for navigation and preventing floods due to the spring high water. Emphasizing navigation over flood prevention, the Federal government, in 1885, implemented a "Levees Only" policy that closed off all outlets of the Mississippi except for the Atchafalaya (Pabis 2000, p. 64). According to this policy, the spring high water would be contained between the artificial levees along the banks of the river, and the resulting currents would scour the bottom of river, thus easing navigation. One of the unintended, though hypothesized at the time, consequences of this policy was an end to the land creation process for southeast Louisiana. By reducing the frequency of flooding, the artificial levees also blocked the annual deposition of sediment throughout the deltaic plain. Sedimentation no longer outweighed erosion and the loss of Louisiana's coastal wetlands began.

Storm Surges Before "Levee's Only"

Throughout the history of southeast Louisiana, hurricanes often devastated coastal areas, but the vast wetlands created by the Mississippi River along with the elevation of the natural ridge largely protected New Orleans from storm surge inundation. Just as the river rose in the spring, the Gulf grew anxious in the summer. Indeed, just four years after construction of the settlement begun, "The Great Hurricane of 1722" passed over the region destroying most of what had been built (Roth 1998). Both hazards have always been a constant of the physical environment of southeast Louisiana. However, it appears, that, compared to the significant role of Mississippi River floods, hurricanes were much less of a factor in the historical geography of New Orleans prior to the 20th Century.

A National Hurricane Center compilation of hurricanes that impacted Louisiana lists 105 events between 1722 and 1998 (Roth 1998). Much of this and the next section rely on the storm descriptions provided by this source. Of these, 67 caused some sort of noticeable impact on New Orleans, though the impacts varied from mild to severe. During this 276 year period, hurricanes caused flooding in or around New Orleans 39 times, but only 6 had a significant impact on the urban areas (Roth 1998). Levee failures around New Orleans occurred twice, during 1901 and 1965 (these events are described in the next section).

In the history of Louisiana, two hurricanes from the Nineteenth Century are noteworthy: the Racer's Storm of 1837 and the Isle Dernieres Hurricane of 1856. The Racer's Storm of 1837 struck along the Cameron coast, but still pushed an 8 ft storm surge into Lake Pontchartrain flooding some of the lower portions of New Orleans. At this point in time, urban settlement was just starting to extend past the natural levee in the lowlying backswamps. The Isle Dernieres Hurricane of 1856 struck a resort barrier island located southwest of New Orleans. The tidal surge from this storm flooded the island to depths of 5 ft. and caused 200 deaths. As a result of this devastation, the resort on the island was abandoned. This storm caused 11" inches of rain in New Orleans, the Roth (1998) does not note any storm surge flooding.

A quick analysis of the Roth database shows that storm surges rarely threatened New Orleans prior to 1885. This database includes 29 events before 1885 that had some sort of recorded impact on New Orleans. Of these, only 14 events resulted in noteworthy damage in New Orleans. Much of this damage consisted of crop damage due to wind and rainfall and/or storm surge damage to settlements along the shores of Lake Pontchartrain (which at that time were separated from the urban areas of the city). Among these events, storm surge flooding of coastal settlements was common, occurring 22 times, and somewhat common along the shores of Lake Pontchartrain, occurring 9 times (Roth 1998). However, storm surge related flooding of the central settlement was rare, occurring only twice during this 163 year period. The trend during this period seems to be that the combination of robust coastal wetlands and elevation along the natural ridge protected the urban settlement from storm surge inundation.

Major Hurricanes After "Levees Only"

In contrast to the previous period, an analysis of the Roth database suggests that storm surges threatened New Orleans more often following the implementation of "Levees Only." In the period between 1885 and 1998, Roth (1998) lists 27 events that affected New Orleans, 13 of which resulted in significant damage for New Orleans. Along the coastal areas, Roth notes 34 incidences of storm surge flooding, while four events resulted in storm surge flooding of urbanized areas.

In 1888, a storm considered the most "severest and most extensive" since the Racer's storm of 1837 caused extensive damage throughout southeast Louisiana. Surge damage extended along the coastline from the Atchafalaya Basin to the Northshore of Lake Pontchartrain. According to Roth, almost the entire city was inundated. However, this was flooding most likely due to the 14" of rain over the city that week (Roth 1998).

Perhaps the most deadly hurricane in the history of the region, an unnamed hurricane in 1893 took the lives 2,000 people along coastal Louisiana (Roth 1998). Making landfall in early October, this hurricane pushed a 16 ft surge across the Chandeluer Islands and 15 ft of water into the coastal bays that are south and east of New Orleans (Roth 1998). Close to 800 deaths occurred in Cheniere Caminanda, near Grand Isle, and another 250 at Grand Lake (Roth 1998). Closer to New Orleans, 200 storm survivors sought refuge from floodwaters in the Port Pontchartrain (also known as Milneburg) lighthouse. This event is the first mention of storm surge posing a peril to the lives of New Orleans area residents in the compilation by Roth.

A storm in 1901, which raised river levels along New Orleans by 7 ft, caused the first incidence of storm surge induced levee breaks listed in the Roth chronology. Ten deaths and $1 million in damages are attributed to this storm (Roth 1998). During a major storm in 1915, newly built 10 foot high levees along the Lakefront were tested (Roth 1998). They held, but barely, prompting the city to heighten the Lakefront levees.

In 1947, an unnamed Hurricane pushed a 15 ft storm surge into Bay St. Louis (east of New Orleans along the Mississippi Gulf Coast) and powered 112 mph wind gusts in New Orleans (Roth 1998). Just east of New Orleans, along the shores of Lake Borgne, the surge peaked at 11.5 ft at the Ostrica Lock and 11.2 ft at Shell Beach (both in St. Bernard parish). West of New Orleans, the newly built Moistant Airport (now known as the Louis Armstrong International Airport) was covered with 2 ft of water, while lower parts of Jefferson parish flooded under 6 ft of water (Roth 1998). In the city itself, widespread flooding resulted in $100 million in damages. Overall this storm killed 51 people, 12 of whom died in Louisiana (Roth 1998).

Making landfall in Southwest Louisiana, Hurricane Audrey in 1957 is an important aspect of Louisiana's hurricane history because the storm killed over 400 people (Roth 1998). Other than Katrina, this is the only U.S. hurricane in modern times to kill over 200 people. The first to be tracked using satellites, the landfall of this hurricane was preceded by early warnings and official calls for evacuation, though many people doubted the credibility of this new technology and chose not to evacuate.

Hurricane Betsy made landfall in early September 1965. It created a 15 ft surge in Plaquemines, a 10 ft surge in St Bernard, and 6.2 ft surge in Orleans parish (USACE 1965). Just as Hurricane Katrina did in 2005, Hurricane Betsy caused levees along the Inner Harbor Navigational Canal to fail, flooding most of St. Bernard parish and the Lower Ninth Ward. Sections of Gentilly adjacent to the Inner Harbor Navigational Canal also flooded due to overtopping. The surge flooded 14,000 homes and resulted in 58 deaths in Orleans parish. Of the 14,000 flooded homes, nearly half were in the Lower Ninth Ward (USACE 1965). Occurring right after the construction of the Mississippi River-Gulf Outlet, the widespread flooding from Betsy contributed to public suspicions that the artifical navigational shortcut from the Gulf to New Orleans also served as a storm surge shortcut.

Mississippi River Management and Storm Surge Flooding

Administered by the Mississippi River Commission, the Federal government implemented the levee's only policy in 1885, thus setting into place a historical path of river management that is viewed of having starved the deltaic plain of its sediment and increased the risk to storm surge flooding in New Orleans (van Heerden 2006, Colten 2005). The above review of Louisiana's hurricane history, based on Roth's "Louisiana Hurricane History" (1998), supports this conclusion.

During the period from 1722 to 1885, this chronology lists 22 incidences of storm surge inundation of the southeast Louisiana coastal areas and 2 incidences of the storm surge flooding New Orleans. During the period from 1885 to 1998, there were 34 incidences of storm surge inundation of the coast and 4 incidences of surge reaching New Orleans. So during the post "Levee's Only" period, New Orleans suffered surge inundation for every 8.5 incidences of the surge reaching the coast, while during the previous period New Orleans suffered surge inundation every 11 incidences of coastal surge flooding.

To a large extent, the occurrence of hurricane landfalls and storm surge inundations along the coast reflect climate conditions that are largely independent of river management. However, whether or not a surge that inundates the coast pushes inland to New Orleans reflects the capacity of the coastal wetlands to absorb storm surges which is influenced by the Mississippi River management. As such, the observation that surges that inundate the coast are more likely to inundate the city is consistent with the proposition that the "Levee's Only" led to increased risk of storm surge flooding for New Orleans.

Naturally, the above simple analysis, based on just one source, does not fully capture New Orleans's evolving storm surge risk. The conclusions that surges striking the Louisiana coast were more likely to cause New Orleans flooding after the implementation of the "Levee's Only" policy is consistent with the widely accepted knowledge that the coastal wetlands i) reduce the height and energy of storm surges, and ii) these wetlands along the Louisiana coast have disappeared at an alarming rate since the implementation of the "Levee's Only" policy.

The Expansion of The Urban Settlement and New Orleans at the Turn of The Century

The settlement history of New Orleans is another important factor in understanding the impacts that hurricanes have had on the city over the years. After all, settlement decisions and patterns are what led to vulnerable populations living in hazardous areas. The original settlement was located atop the natural ridge along the riverfront, and the early expansion of the city extended along this ridge. As population grew beyond the constraints of the main ridge along the Mississippi River, later settlement expanded along other ridges. Relicts of previous river and distributary channels, these ridges stretched through the back swamp toward Lake Pontchartrain north of the city. Along the lake shore, fishing camps and resort villages sprouted up. In 1831, the U.S.'s second railroad was constructed along the present day Elysian Fields Avenue connecting the main settlement with Milneburg, a port and resort development along the Lakeshore (Barcza et al. 2011). Located along the fuzzy boundary between the wetlands and the lake, buildings in Milneburg and other lakefront resort communities were built on piles that elevated the structure a few feet above of the fluctuating water level below.

Sustained urban growth in this impossible environment resulted in extraordinary localized modifications to the landscape. The threat of epidemic disease was a constant until the early 1900s when drainage technologies allowed waste to be removed from the settlement (Colten 2005). Utilization of the Wood Screw Pump, beginning in 1913, became a major factor in landscape change (Colten 2005). This technology along with the digging of drainage canals and building of levees allowed low lying backswamps to be levied and drained, and then paved and settled. The expansion of the urban settlement toward the lake meant that the boundary between land and water had to be made more definitive. The shore of Lake Pontchartrain was laid in a cement floodwall in the 1930s, as part of the New Orleans Levee Board ambitious response to the 1915 hurricane to protect the lowlying land (Colten 2005).

Throughout the city's growth, race and wealth have been important factors in settlement patterns. Originally built largely by African slaves, the African-American population of the city grew as part of post civil war urban migration. The newly freed slaves mixed with freed men of color who lived down river of the original settlement and long held property, wealth, and political influence (Colten 2005). Politically free but economically constrained, the former slaves settled in the undesirable land at the edge of the natural ridge. This section of town, a second crescent between modern day Claiborne and Broad Streets remains poor, heavily African-American, dilapidated, and crime ridden. The Twentieth Century expansion of urban settlement provided an opportunity for blacks to purchase property in the suburbs. Pontchartrain Park became the first subdivision constructed by blacks for blacks. In the 1970s, the Eastover subdivision in New Orleans East became one the few gated and predominately African-American subdivisions in American. However, despite these and other gains made by blacks, the city remained highly segregated.

Perhaps most representative of ongoing racism in Louisiana, David Duke rose as a popular political figure in late 1980s. A former Ku Klux Klan Grand Wizard, Duke espoused white nationalist and segregationist policies throughout his political career. In 1989, he was elected to represent District 89, which included suburban parts of Jefferson Parish, in the Louisiana House of Representatives. In 1991, he ran for Louisiana governor, and received over 650,000 votes or 38% of the total voters (Tyler 1994). While his opponent, Edwin Edwards won more votes, Duke claimed success after winning the majority of the white vote (Tyler 1994). Of note Edwards, who was considered the lesser of two evils in the 1991 election, went to jail on corruption charges in 2001.

Having been in a slow economic decline for over a century and a population decline since the 1960s, a number of processes compounded to bring misery to New Orleans in 1980s. The oil bust of the late seventies along with the national recession of the early eighties both impacted the city, and economic conditions were severe throughout much of this decade. Corporate flight, the process of corporations relocating high paying executive positions along with middle income support positions, added to the severity of the city's economic conditions. Modernization at the city's port brought automation and containerization which resulted in significant job losses to what had traditionally been a major, stable employer. Adding to the misery, the crack epidemic of the 1980s brought further social disruption while corruption within the police department and political system continued.

In 2002, Ray Nagin was elected the mayor of New Orleans, succeeding Marc Morial. Running as an outsider, Nagin pledged to cleanup corruption and restore public services. Of note, several associates of Morial, a political insider whose father had been mayor previously, have been convicted on corruption charges, though Morial was never charged himself. During the years that followed, Nagin made modest success in cleaning up and restoring hope, though the underlying problems of poverty and racism remained fundamental and seemingly intractable. Sally Forman, who served as Nagin's Communication Director and later wrote *Eye of the Storm: Inside City Hall During Katrina*, described the current state of affairs as having "left government officials the complicated task of tirelessly offering hope to a citizenry that was, in many respects, hopeless" (Forman 2007, p. 9).

The Hurricane Protection System

When Hurricane Betsy struck in 1965, New Orleans was set to become the nation's first modern major urban disaster. The urban settlement extended well away from the natural ridge and filled most of the area between the river and the Lake. The area of town known as Gentilly stretched from City Park east to the Industrial Canal and from the Gentilly Ridge to the Lakeshore. Down river from central New Orleans and across the Industrial Canal, the Lower Ninth Ward (part of Orleans Parish) and Chalmette (part of St. Bernard Parish) experienced extensive development that pushed the urbanized area into reclaimed swampland. Gentilly, Lower Ninth Ward, most of St. Bernard Parish, and parts of sparsely developed New Orleans East all flooded as the surge overtopped and toppled levees.

In response to the damages caused by Hurricane Betsy, Congress quickly authorized the Corps of Engineers to construct hurricane protection levees around Lake Pontchartrain and its vicinity. Different from river levees which are built along the stable natural ridge to prevent flooding from long duration, slowly rising river events, these levees were built along the unstable low lying areas and designed to minimize flooding from short duration, high energy tidal events. Delayed by disagreements and court battles over the design and impact of the structures, construction of this levee system was slow and only 90% complete when Katrina struck forty years later (van Heerden, et al, 2007).

3.2 Geography in Context

In a groundbreaking study, Costanza, et. al (1997) assessed "the value of ecosystem services and natural capital." Looking across a range of services and capitals, the authors estimated the total global value and total value per area for 11 different ecosystem types. They found that wetlands and coastal ecosystems were the two most valuable ecosystem types, both in terms of total value and value per area. Further subdividing wetlands and coastal ecosystems, they found that coastal marsh / mangrove (wetland) and estuary (coastal) ecosystems are highly valuable per acre. Interestingly, Costanza's map of ecosystem value (Figure 3.3) appears to show a great deal of spatial association with the population density (Figure 3.4), particularly in the eastern hemisphere. Understanding the value of the coastal marsh and estuary ecosystems around New Orleans helps explain the inevitability of this impossible city.

Major River Deltas and Major Cities

Indeed, the Mississippi River Delta is one of the world's major river deltas where perilous geography is juxtaposed with economic significance. A review of the world's major river's shows they are often associated with important world cities. A list of the world's ten largest rivers, measured in terms of annual discharge, was obtained from the Water Encyclopedia Website (http://www.waterencyclopedia.com/Re-St/Rivers-Major-World.html). While possessing the third largest drainage basin, the Mississippi River ranks number seven on this list, which is based on annual discharge volume. A review of this list shows that nearly all have major cities, and some have some of the world's most populated and prosperous cities, within or adjacent to their deltas.

The Mississippi River watershed, the world's third largest drainage basin, is surpassed in size only by the drainage basins that feed the Amazon and Congo Rivers. Adjacent to the estuaries of the Amazon delta region and sitting about 60 miles (95 km) from the open Atlantic, the Brazilian

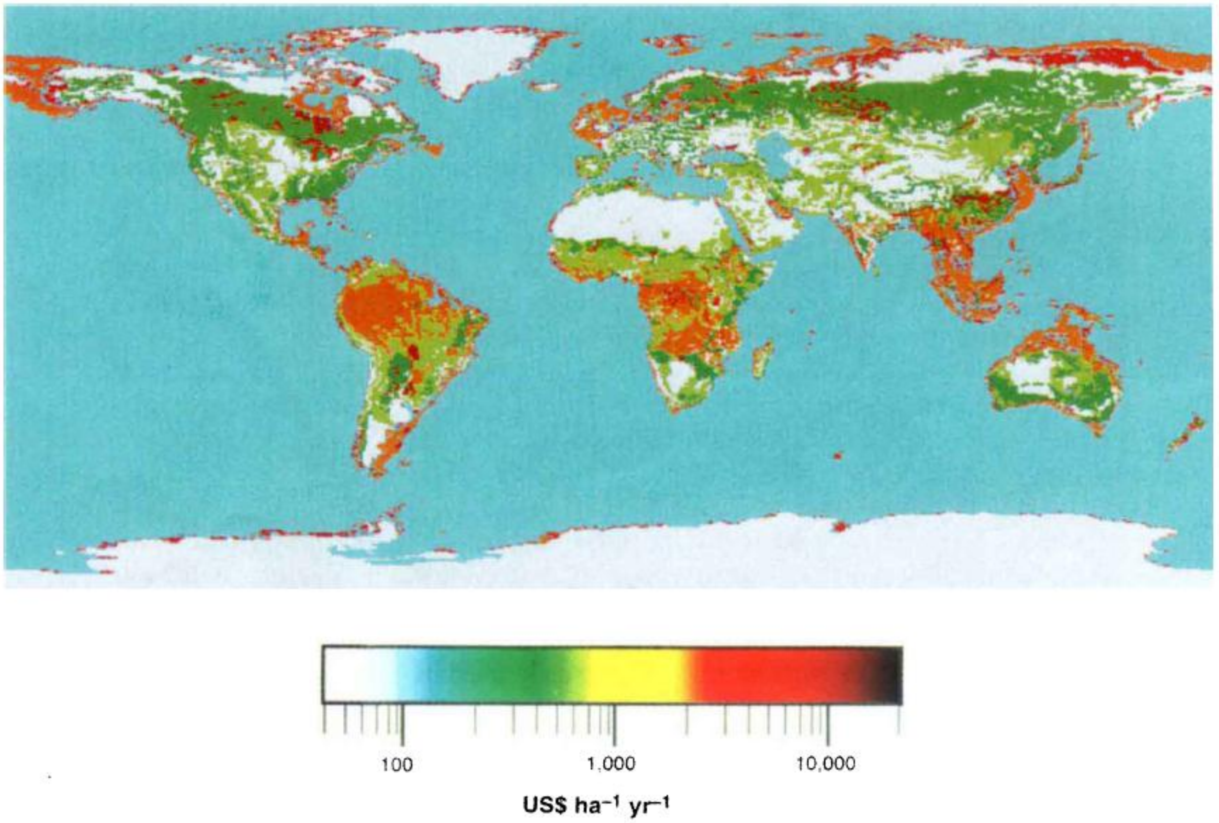


Figure 3.3: Global map of ecosystem services. [Reprinted by permission from Macmillan Publishers Ltd: Nature (Constanza, et al. 1997), copyright 1997].

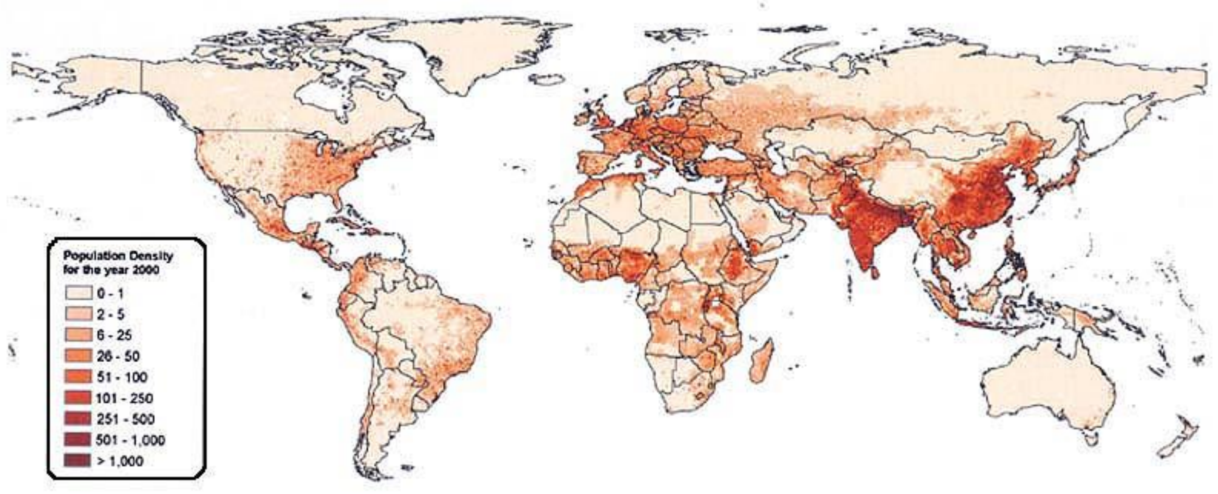


Figure 3.4: Global Population Density. (UNFAO, http://www.fao.org/docrep/009/a0310e/A0310E07.jpg)

metropolis of Belem is the home of 2 million people (Wold-gazetteer.com 2010) and one of Brazil's busiest ports. Also about 60 miles (95 km) from the Atlantic Ocean, but on the opposite shore, sits the city of Bomo near the mouth of the Congo river. This port city, along with neighboring Matadi, is home to a half million people (Wold-gazetteer.com 2010) and a major source of export income in the poverty stricken country.

The Yangtze, while not necessarily the longest or largest basin, is perhaps the world's most important river. Running through China and emptying into the East China Sea off the Pacific Ocean, this major world river plays an important role in sustaining the lives and livelihoods of 1 billion Chinese people along with numerous export markets that depend on this crucial link with the Chinese manufacturing base. Shanghai, located in heart of Yangtze delta and along the shores of the East China Sea, is the heart of one of the world's most populated and productive regions. Home to nearly 80 million people, the Yangtze delta region industry produces nearly $2 trillion annually (Brooks 2010).

Throughout the world, major cities are found near or inside the major river deltas. Located near the confluence of the Ganges and Buriganga Rivers and 80 miles (130 km) from the northern shores of the Indian Ocean, Dhoka, Bangladesh was home to 10 million residents in 2001 (Wold-gazetteer.com) and the largest city in this densely populated country where the growing textile export industry. Located 300 miles (483 km) from the mouth of the Yenisei in North Russia, the port town of Dudinka, Russia, is an export hub for non-ferrous metals, coal and ore. In Venezuela, the town of Tucupita sits along the Orinoco River and at the edge of the river's huge mangrove swamp delta. The city of Buenos Aires, largest in Argentina and second largest in South America, sits near the mouth of the Parana River. Home to 13 million people (Wold-gazetteer.com 2010), the city is considered among the wealthiest cities in South America.

In a review of the world's ten largest rivers, only one river does not have a major city located on or near its delta. The Lena River, in isolated northern Russia, is ninth in terms of annual discharge. A frozen tundra for most of the year, this uninhabited delta is a clear exception to the trend.

A similar review of the world's largest metropolitan areas (Demographia 2003) reveals a geographical context in which a major harbor near an oceanic water body supports large, urban populations (Google Maps 2011). Tokyo-Yokohama, Japan, the world's largest city is situated where three rivers converge into Tokyo bay. Located along the U.S. Atlantic coast, New York City, the second largest city, is located on a large natural harbor where the Hudson River drains into the Atlantic. The third largest city, Seoul-Inchon , South Korea, sits along the Han River just 15 miles from the Yellow Sea. Sao Paul, Brazil, the fifth largest city, sits just 30 miles from the Atlantic Ocean. The sixth largest city, Mumbai (Bombay) lies on the east coast of India where the Ulhas River has built large mangrove swamps at the edge of the Indian Ocean. A huge port complex along the banks of Osaka Bay allows the seventh largest metropolitan population in the Osaka-Kobe-Kyoto urban conglomerate to be among the most productive cities in the world. Los Angeles, the eighth largest city, sits on the US Pacific Coast, while Manila, Phillipines, the ninth largest city, sits along a harbor connected to the South China Sea. The tenth largest city, Cairo, Egypt, straddles the Nile river at the head of its delta just 110 miles (176 km) from the Mediterranean sea. Of the world's ten largest metropolitan areas, only Mexico City does not exist near a coastline. Mexico City, the fourth largest, was built in the large Mexico Valley on the banks of Lake Texcoco.

One major factor provides a unifying theme to the above described cases: the global movement of good via navigable waterways. Every major city sits adjacent to a major harbor, and all but one of the world's major deltas includes a harbor.

Viewing the context of New Orleans' location as part of globalized system of trade that endows port cities with the attributes that sustain growing population and wealth, it is clear that New Orleans is one of many "impossible but inevitable" cities (Lewis 1976, p. 19).Undoubtedly many aspects of New Orleans' perilous settlement history have been experienced in Buenos Aires, Dhaka, Shanghai, Bomo, and Belem. While the human adjustments to the hazards of these locations varied greatly, many of these locations followed a path of structural adjustments to the landscape and waterbodies to expand the urbanized area, improve drainage, reduce floods, and foster navigation. In Shanghai and Buenos Aires, this historical path has led to enormous wealth. Throughout these locations, this historical path has also lead to significant risks. While many are currently economically vibrant, these cities face many pressures from rapid population growth, deterioration of the ecosystem, and the threat of rising seas.

New Orleans: One of Many "Impossible, But Inevitable" Cities

As part of a set of unique ecosystems that are vital to the global economy but stressed by human infringement and vulnerable to climate change, New Orleans remained an "impossible, but inevitable city" throughout the Twentieth Century (Lewis 1976, p. 19). However, as time passed, technology progressed, and human modifications to landscape continued, the impossible seemed to become more possible. If they had been around to observe this historical path of settlement, the Greek geographers might have described the growth of New Orleans as the transformation of the non-ekumene (the uninhabitable earth) into the ekumene (the inhabitable earth) (Mathewson 2006). Epidemics had not occurred since 1905 and high waters in the river had not threatened the city since 1927.

At the same time, growing world population, increasing trade, and expanded globalization made the city more inevitable. As a navigational system, the Mississippi and its distributaries form a major backbone of global trade. It connects some of the world's largest grain producers with some of the world's hungriest populations, and it also connects some the world's wealthiest consumers with producers from around the world. Indeed the lives and livelihoods of large segments of the global population made New Orleans even more inevitable.

Throughout the Twentieth Century, human modifications to the landscape continued to make the city seem less impossible. With levees and spillways, the river seemed tamed (at least from the perspective of New Orleans). Drainage canals and pump stations made the infamous heavy rainfall events manageable, if not necessarily preventable. With the Lake Pontchartrain and Vicinity Hurricane Protection Project, the Corps of Engineers promised protection for any storm up to a Category 3 (Colten 2005, van Heerden 2006). Under this context, the settlement continuously expanded into reclaimed swamp and marsh toward the tidal water bodies.

Particularly after World War II, the urbanized area expanded significantly in every direction. To the north of the central settlement along the riverfront, developers built the neighborhoods of Gentilly and Lakeview. To the west of Lakeview, the suburbs of Metairie and Kenner (in Jefferson Parish) also expanded toward the Lakefront. To the east of Gentilly and across the Industrial Canal, New Orleans East grew into a suburban area, ringed by levees and floodwalls, and home to nearly 85,000 people in 2005 (U.S. Census 2005). Up river from the central city, LaPlace, a suburban town with a heavy manufacturing and petrochemical base, was built on top of the deposits of a previous crevasse splay from the Mississippi River and then expanded onto the Maurepas Swamp (Davis 2000). Across the Mississippi River, an area known as the Westbank (though technically south of the central city), also followed the general trend of suburban expansion into the reclaimed swamplands from the early settlement built along the natural ridge. Following the dominate housing trend in the country during this period, most of the new, suburban homes were slab on grade construction that provided little elevation above the ground, but better cooling and lowered energy costs during the long, hot summers. (The traditional approach of using elevation above ground to encourage ventilation became a liability that lowered the energy efficiency of modern air condition systems, which are most efficient with a large concrete slab attached to ground to act a temperature regulating thermal mass.)

Two other recent demographic trends are noteworthy in this settlement history. Following desegregation, black political leadership ascended in New Orleans, triggering an exodus of whites from the city and into the suburbs (Yodis and Colten 2007). As part of a national trend of "White Flight" that took capital and investment out of the central urban areas, New Orleans was one of many cities that was mostly African-American and mostly poor at the end of the 20th Century. Additionally, New Orleans was not immune to the outmigration Louisiana experienced over recent years. A reflection of the stagnant economy, the period between 1965 and 2005, saw a significant drop in the metropolitan population.

In 2005, this "impossible, but inevitable" metropolitan area was home to over 1 million residents. The New Orleans-Metairie-Kenner, La. Metropolitan Statistical Area, a designation of the U.S. Census, consisted of the seven urbanized parishes around New Orleans. In 2005, the Census estimated the population of this metropolis to be 1,190,615 (U.S. Census 2005). The employed civilian population 16 years and over included 547,842, workers across 492,912 households (U.S. Census 2005). With a mean household income of $55,326 (U.S. Census 2005), total annual GDP for this seven parish region is estimated to be $27 billion. In additional to income, the oil and gas industry associated with the region contributed many billions of dollars in royalty income to the federal treasury every year. While the actual amount of royalty income varied every year with market conditions, the estimated revenue for this source is $4 to $6 billion per year with the cumulative total estimated at nearly $150 billion in Federal royalties generated from the Louisiana coast (Walsh 2006).

The 2005 American Community Survey describes a diverse economy with nearly 20% of the workforce employed in construction, extraction, production, or transportation related occupations. (U.S. Census 2005). The ports of New Orleans and South Louisiana (located upper river of New Orleans but partially within the metropolitan statistical area) account for 23 percent of total U.S. exports and provide $36 billion annually in trade services (Schnepf and Chite 2005).

Numerous grain elevators along the river facilitate the shipment of U.S. produced corn, soybeans, wheat and rice to global markets. .

According to a Congressional Research Service report (Schnepf and Chite 2005), the Port of New Orleans annually handles 2 billion bushels of grain. According to the United Nations, global food needs consume about 6.8 billion bushels of coarse grains annually (Food and Agriculture Organization of the United Nations 2009) indicating that nearly 30 percent of grain eaten by the world’s population passes through the Port of New Orleans. Despite the economic importance of the region, poverty was still prevalent: 17 percent for the metropolitan region and 25 percent for Orleans parish (U.S. Census 2005).

3.3 Fearing the ‘Big One’

In the early 1970s, Sherwood Gagliano lead a team of geologists at Louisiana State University that published a study documenting for the first time the extent and likely consequences of coastal landloss in Louisiana (Gagliano, Kwon, and van Beek 1970). Published 70 years after the federal engineers implemented the “Levee’s Only” policy, this study documented the deterioration of the deltaic plain by comparing maps of the shoreline and wetlands over the decades. It also heralded an era of growing consciousness among the Louisiana population about the coastal landloss issue and a growing awareness of the emerging conditions for catastrophe among the emergency preparedness community in southeast Louisiana. During this era, numerous predecessors to Hurricane Katrina impacted the New Orleans region, resulting in continuous assessments and improvements of emergency preparedness plans.

Hurricane Betsy impacted the region in 1965, just a few years before Gagliano’s study, and just after the completion of the Mississippi River-Gulf Outlet. Authorized by the U.S. Congress in 1956, this artificial navigational canal epitomizes the nature and degree of human modifications on the Mississippi Delta landscape along with the consequences in terms of storm surge flooding. The construction of the canal directly removed the dirt and vegetation along a path that was 600 ft (183 m) wide and 76 miles (122 km) long (see Figure 3.5). A section of the 8 – 10 ft (2.4 – 3.0 m) high natural ridge along Bayou LaLutre had to be physically removed for the canal (see Figure 3.6). Built as a navigation shortcut between the Gulf-of-Mexico and the Port of New Orleans, this canal also provided a shortcut for salt water to intrude inland. The salt water intrusion into the wetlands south and east of New Orleans caused considerable landloss. By 2005, a former cypress swamp to the east of central New Orleans had become largely open water with some marsh grass and the ghostly stumps that remained of the hardwoods that thrived before the salt water intrusion. In what could be considered an ominous stage in the coastal landloss saga, winds and currents associated with Hurricane Katrina removed most of these stumps.

When Betsy came along, New Orleans was considered inland, high ground and a safe evacuation destination. Previous experience demonstrated that most of New Orleans was largely sheltered from the devastation that hurricanes brought to the coastline. Naturally, areas outside the area levees were considered dangerous. Residents of outlying, coastal parishes were advised to evacuate to New Orleans, and New Orleans officials suggested that residents of low-lying areas near Lake Pontchartrain consider evacuating to higher ground close to the river. As Betsy bore down on the region, the many hotels in downtown New Orleans were filled with evacuees, while a shelter in the Municipal Auditorium (along the northern edge of the original settlement and just a few blocks from the river) was also utilized U.S. Army Corps of Engineers (1965)

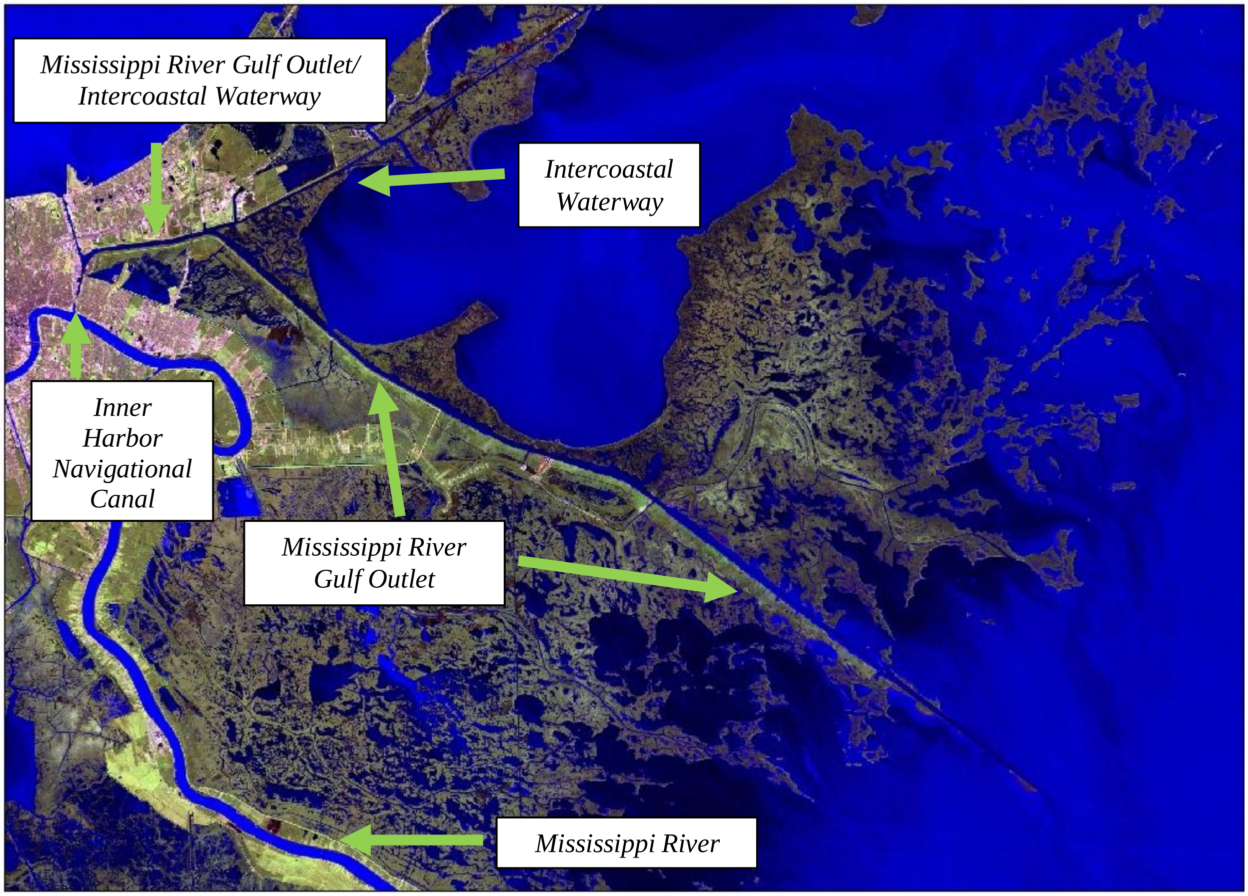


Figure 3.5: The Mississippi River Gulf Outlet. (Source: 2002 Landsat 7 Imagery from the 2007 Louisiana GIS DVD).

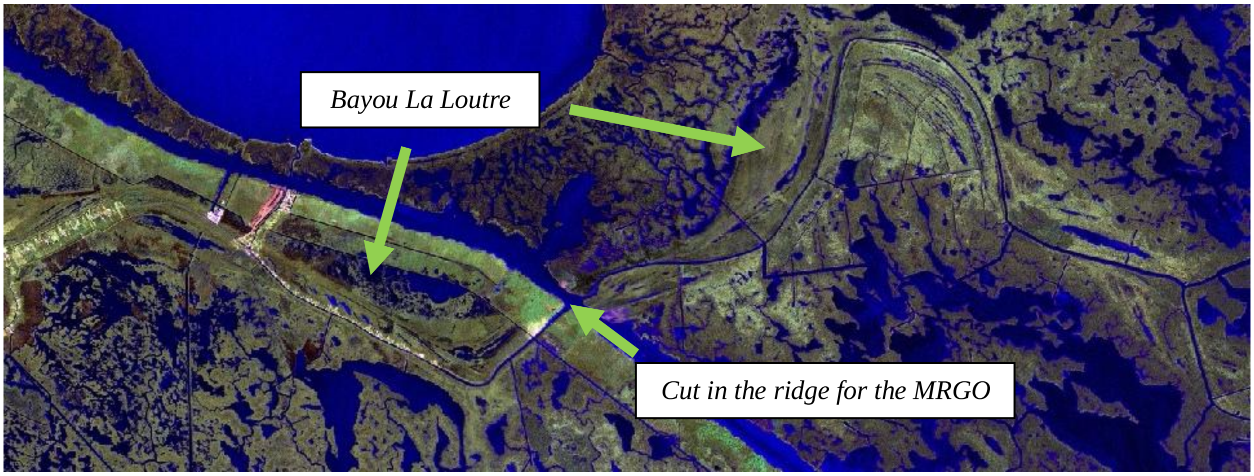


Figure 3.6: Bayou La Loutre and the cut in the ridge for the MRGO. (Source: 2002 Landsat 7 Imagery from the 2007 Louisiana GIS DVD).

Following the trend that appears to follow the "Levee's Only" policy, Hurricane Betsy's storm surge pushed further into New Orleans than any known storm preceding it. For the first time, large urbanized sections of greater New Orleans flooded due to storm surge. In Orleans parish, the areas of Gentilly, the Ninth Ward, and New Orleans East flooded. Levee breaches along the Inner Harbor Navigational Canal, possibly caused by barges that broke lose from their moorings, flooded the Lower Ninth Ward, Arabi, and Chalmette. In their "Report on Hurricane Betsy" the New Orleans Sewerage &Water Board engineer Modianos described a first hand account of these breaches:

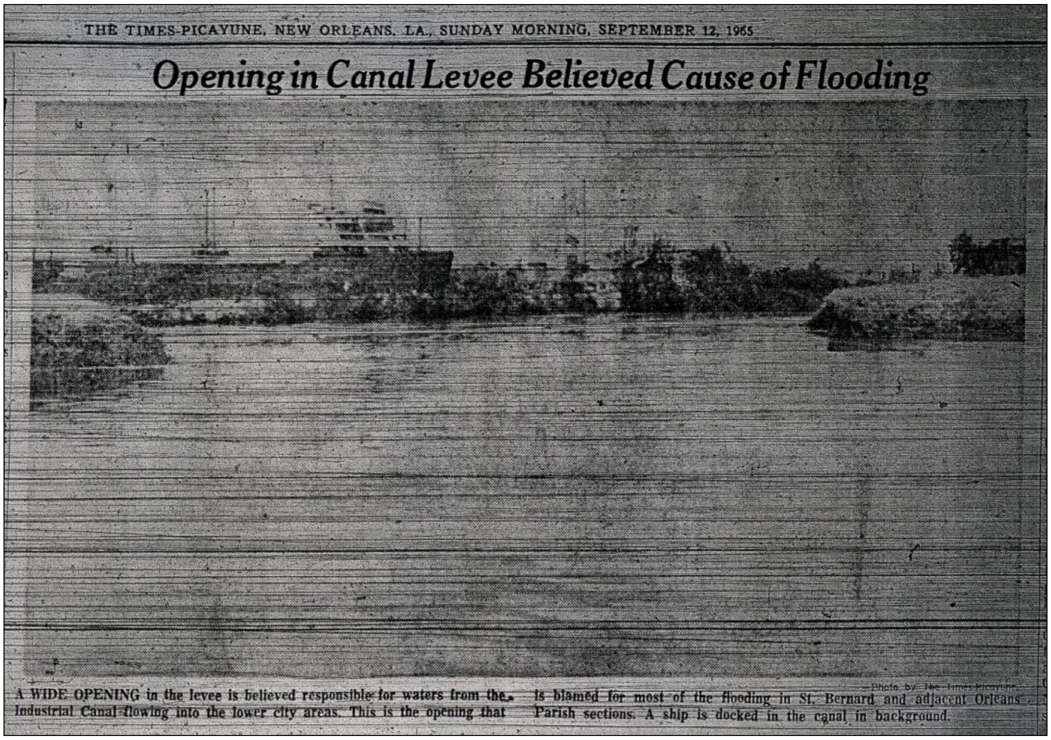
> "Finally, we reached the Seeber bridge at Caliborne Ave. and we decided to ascend the bridge to get a bird's eye view of the levees. This revealed that levees on the west [of the INHC] had been overtopped at numerous places, but that the flow from the canal over the levees was not light to moderate at the overtopped and scoured areas. Just north of the Seeber bridge, a barge was beached on top of the levee.
>
> "There was no sign of complete levee failure on the west side. However, we could see four massive levee breaks on the east side, which we still conveying large quantities of water into the east side sytem. This water was obviously flowing back to the west side through the siphon, as well as continuing to flood the eastern area." (New Orleans Sewerage &Water Board 1965, p 23).

(At the time, a siphon ran under the INHC to connect pump station #5 on the western side to the Bayou Bienvenue Outfall canal on the west side).

Toward the coast, nearly all of Plaquemines parish flooded, while most of St. Bernard parish also flooded. The assumption that New Orleans provided safe refuge was proven to no longer be true, and 12,000 residents had to be rescued from the flooded homes and neighborhoods (U.S. Army Corps of Engineers 1965). Eighty-one deaths in Louisiana are attributed to Hurricane Betsy (U.S. Army Corps of Engineers 1965)., including 38 drownings, two heart attacks in the Municipal Auditorium shelter, one heart attack in a flooded home in New Orleans, and one suicide in a flooded home in New Orleans (Times-Picayune Reports 1965).

Figures 3.8 and 3.9 provide some evidence that the MRGO acted as a deadly storm surge funnel. Figure 3.8 shows that flooding in Orleans and St. Bernard Parishes impacted the areas immediately adjacent to the MRGO. Likewise, Figure 3.9 shows that deaths due the flooding in Orleans are concentrated in areas of New Orleans located in the immediate vicinity of where the MRGO/GIWW meets with the INHC.

Tables 3.1- 3.3 along with Figure 3.10 summarize a list of Betsy victims compiled from *The Times-Picayune.* While the Corps report lists 81 victims in Louisiana, *The Times-Picayune* lists only 58 known victims (along with 16 unknown victims who are not included in the tables). While not representative of every victim, the tables still reveal some interesting trends. Most of the deaths occurred in Orleans Parish, though a number of other parishes experienced loss-of-life. Most victims died of drowning, though there are numerous other causes. The histogram of age of victims shows a relatively even distribution, with some indication of deaths more common amongst the young and old and less common amongst middle ages. The clearest trend relates to the race of victims: of 39 victims for which the race is known, 38 were African-American and only 1 was white.



THE TIMES-PICAYUNE, NEW ORLEANS, LA., SUNDAY MORNING, SEPTEMBER 12, 1965

Opening in Canal Levee Believed Cause of Flooding

—Photo by The Times-Picayune.

A WIDE OPENING in the levee is believed responsible for waters from the Industrial Canal flowing into the lower city areas. This is the opening that is blamed for most of the flooding in St. Bernard and adjacent Orleans Parish sections. A ship is docked in the canal in background.

Figure 3.7: Levee breach along the INHC documented after Hurricane Betsy (Photo by the Times-Picayune, Copyright 1965 by The Times-Picayune).

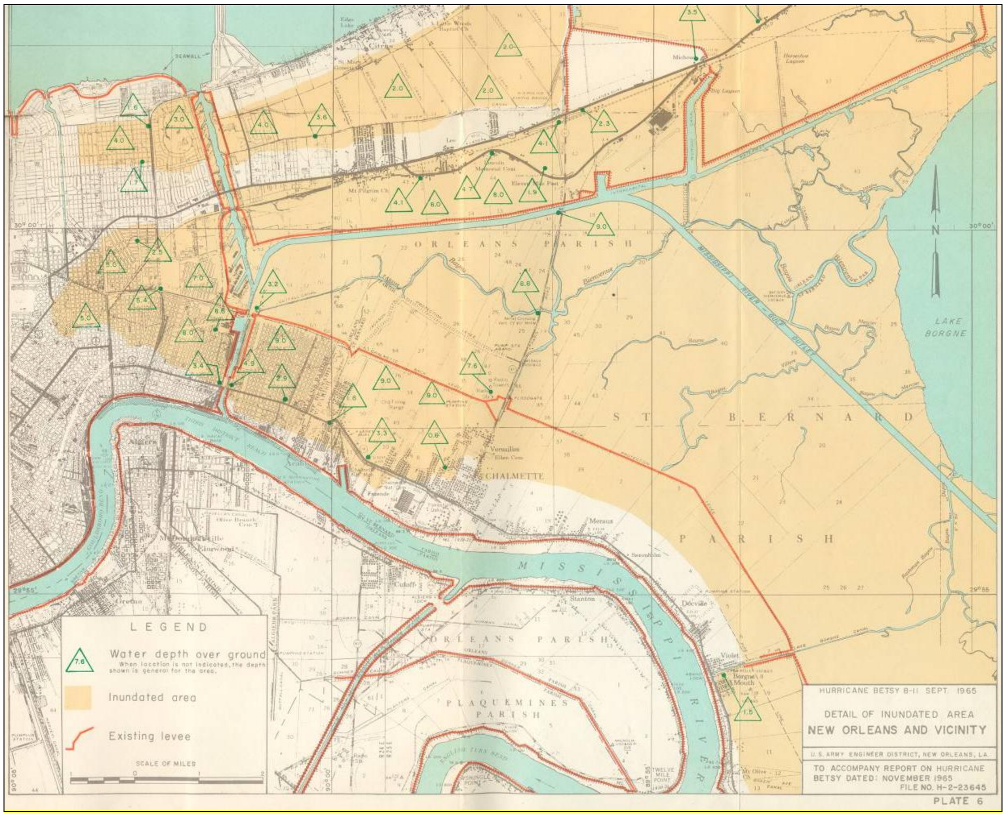


Figure 3.8: Army Corps of Engineers map of flooding in New Orleans during Hurricane Betsy. (US Army Corps of Engineers 1965)

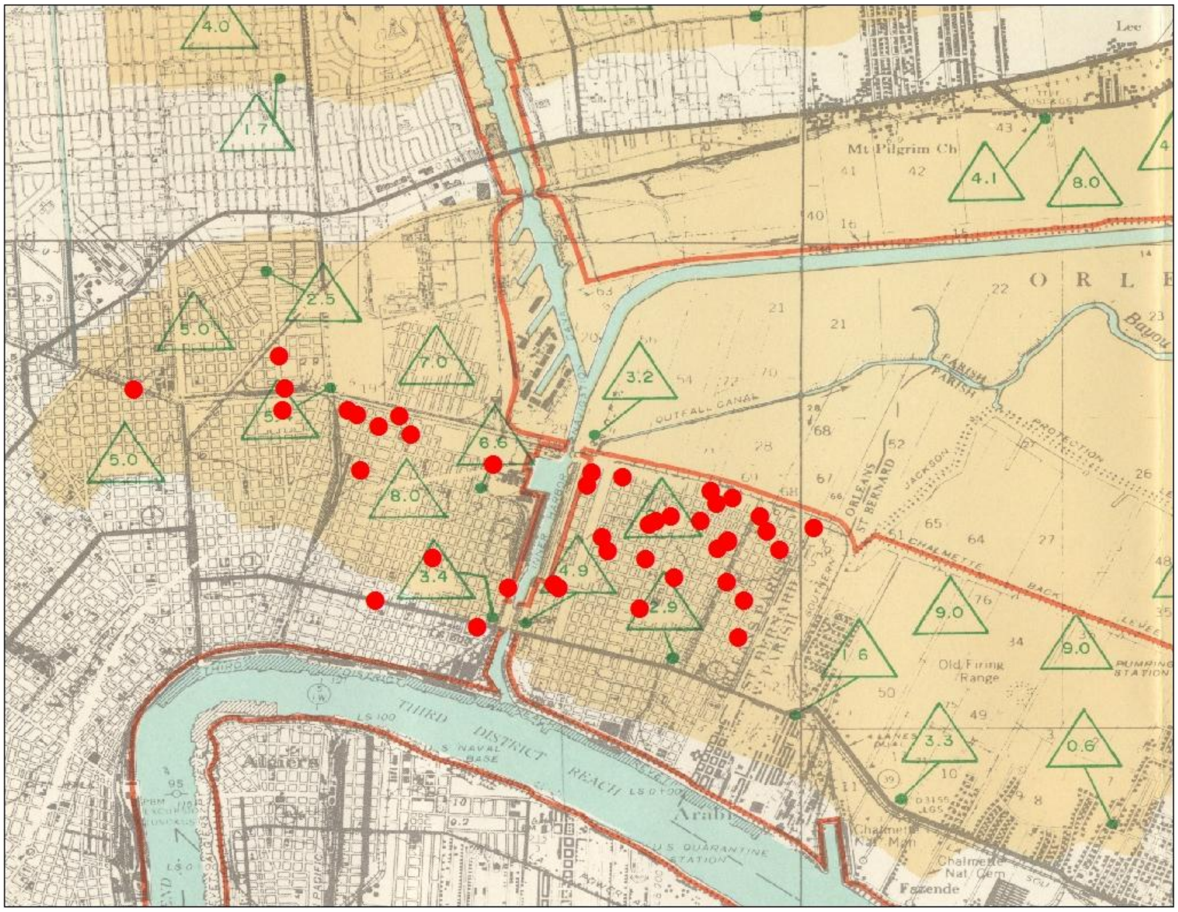


Figure 3.9: Geocoded drowning cases recorded by the Orleans parish coroner laid over the flood map. (US Army Corps of Engineers 1965 and Times-Picayune Reports 1965).

Table 3.1: Betsy Fatalities by Parish (Times-Picayune Reports 1965).

Parish	**Total Fatalities**
Ascension	2
East Baton Rouge	3
Jefferson	3
Orleans	37
Plaquemines	6
Richland	2
St James	3
St Landry	1
St Tammany	1
Grand Total	**58**

Table 3.2: Betsy victims by cause of death (Times-Picayune Reports 1965).

Cause of Death	**Total Fatalities**
Accident	1
Church Collapse	3
Drowning	37
Drowning (Traffic Accident)	1
Drowning (Ship)	2
Electrocution during recovery work	1
House Collapse	2
Stroke or Heart Attack	3
Suicide	1
Traffic Accident	6
Grand Total	**57**

Table 3.3: Betsy victim by race. (Times-Picayune Reports 1965).

Race	**Total**
African-American	38
White	1
Grand Total	**39**

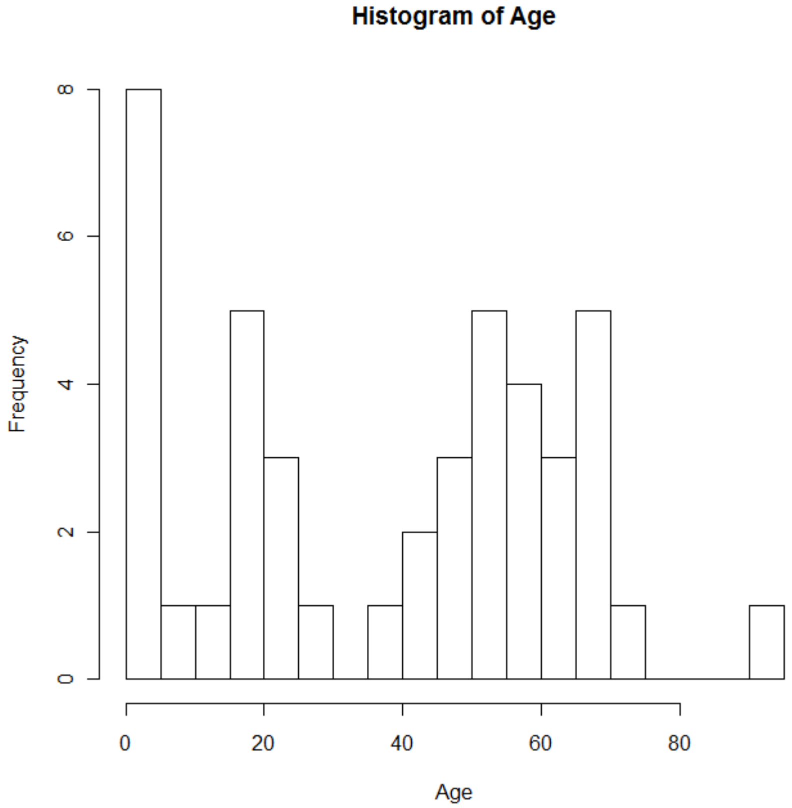


Figure 3.10: Histogram of Age of Betsy Victims (Times-Picayune Reports 1965).

As described above, the damages of Hurricane Betsy prompted Congress to authorize the Corps of Engineers to construct hurricane protection levees, floodwalls, and floodgates for the New Orleans region (van Heerden 2006).

Just a few years after Betsy, in 1969, Hurricane Camille crossed over Plaquemines Parish and then made landfall near Bay St. Louis, Mississippi. Damage in Louisiana was limited to the coastline, and 9 deaths occurred in Plaquemines Parish (U.S. Army Corps of Engineers 1970). However, Camille caused considerable damage along with 172 deaths along the Mississippi coast (Hearn 2004). Undoubtedly, the death and damage in nearby Mississippi did not go unnoticed to Louisiana residents or civil defense personal.

In 1979 through a Presidential executive order created the Federal Emergency Management Agency (FEMA) and tasked this new agency to merge the many separate disaster-related responsibilities of various other government agencies. Created in response to a request from the National Governor's Association, the new agency institutionalized a growing trend toward federal involvement in disaster response and planning.

In 1985, Juan followed an erratic path that first had it make landfall in southwest Louisiana as a Category 1 hurricane, only to loop back around over the Gulf of Mexico, and then cross over southeast Louisiana as a tropical storm. While only a tropical storm, Juan still caused a significant storm surge in southeast Louisiana. Along the coast, Cocodrie and Grand Isle were both flooded, while levee overtopping caused some flooding in the inland towns of Lockport, Myrtle Grove, Marrero, and Westwego (Roth 1998). The last two towns, located on the West Bank, are considered part of metropolitan New Orleans.

Hurricane Andrew first passed over Florida on August 24, 1992, and then made a second landfall in Louisiana, near the mouth of Atchafalaya, on August 26. This storm caused death and destruction in both states. In Louisiana, an estimated 1.5 million people evacuated the at risk areas before landfall (Roth 1998). With the storm making landfall where it did, the storm surge was largely confined to the sparsely populated Atchafalaya basin, and a major disaster was avoided. Seven people in Louisiana lost their lives due to Hurricane Andrew (Roth 1998). Most importantly, Andrew set a precedent for mass evacuation when a major hurricane threatens the region.

In 1994, U.S. Army Corps of Engineers published a study that estimated that a 44 – 50 hr clearance time would be required to completely evacuate New Orleans. The study authors assume that 403,000 vehicles would be involved (USACE 1994).

In early September 1998, Frances developed in the central Gulf of Mexico and then slowly moved northward. Southwest Texas and most of Louisiana experienced strong rains and wind driven coastal tides. Most of the Louisiana coastline suffered moderate storm surge flooding, while isolated incidences of rainfall flooding occurred throughout southern Louisiana and parts of Texas. In Houston and in New Orleans, sections of Interstate 10 were closed by flooding (Roth 1990).

Just a few weeks after Frances, in late September 1998, Hurricane George terrorized the West Indies before taking aim for New Orleans. The threat posed by this storm persuaded the Mayor of New Orleans to order the first ever official voluntary evacuation of New Orleans (Louwagie 1999). It is estimated that half of the regional population complied (Wolshon et al. 2001, Urbina et al. 2002). The Superdome, which was provided as a shelter-of-last resort, was highly vandalized. As Georges moved on land, a 9 ft storm surge inundated Plaquemines parish and 7 ft storm surge in Lake Pontchartrain flooded some of the unprotected land and homes near the lake. The levees held, and widespread urban flooding was avoided. Having killed 600 people in the Caribbean Islands, Georges resulted in 2 deaths in Louisiana (Pasch 2001).

The evacuation for Hurricane Georges exposed a major shortcoming of the region's hurricane preparedness plan: gridlock. With limited transportation infrastructure, the lack of a comprehensive traffic management plan for evacuating the region's population meant that those who did comply with the voluntary evacuation order spent many hours trapped on the interstates and highways. Many naturally wondered if they were safer staying at home. For the new Orleans region, the major impact of Georges was the development of a proactive evacuation traffic management plan that relied heavily on contraflow, that is reversing the flow of traffic along inbound lanes to increase the outbound capacity. According to Wolshon (2009) "the first proactive evacuation roadway management plan for Louisiana was developed in 2000 through an effort led primarily by the Louisiana State Police (LSP 2000). This plan (heretofore referred to as the "Ivan Plan") introduced freeway contraflow to Louisiana for the first time."

Whereas Georges prompted further resources dedicated to evacuation planning, that year also coincided with the release of *Coast 2050: Toward a Sustainable Coastal Louisiana* (Louisiana Coastal Wetlands Conservation and Restoration Task Force and Wetlands Conservation and Restoration Authority 1998). This comprehensive coastal restoration plan proposed broad-based strategies to "sustain a coastal ecosystem that supports and protects the environment, economy and culture of southern Louisiana, and that contributes greatly to the economy and well-being of the nation" (p. 2). However, the solutions were not cheap, and implementing the entire plan would have cost an estimated $14 billion, most of which the Federal government would have to cover. The state's struggle to get Federal financial support for the Coast 2050 lasted years. In 2004, President Bush approved a plan to provide $1.9 billion to fund limited restoration projects, beginning in 2006 (Walsh 2004).

In 2001, Tropical Storm Allison, caused significant flooding from Houston, Texas to Slidell, Louisiana [about 30 miles (48 km) east of New Orleans]. While winds never topped 60 mph (97 km/hr) and no significant tidal surge was observed, extreme rainfall ensued as this large storm sat over Houston, before slowly moving east over the Louisiana coast. Parts of Houston received 36 incehs (91 cm) of rain, and nine hospitals within the Texas Medical Center there closed due to flooding. South of New Orleans, 30 inches (76 cm) of rain fell on Thibodaux, La. All told, Allison caused 50 deaths and over $6 billion in direct damage (Risk Management Solutions 2001).

In 2002, Louisiana State University built and started using a supercomputer, dubbed Supermike, for studies that required complex simulations of the physical processes of coastal erosion and storm surge flooding. Built with a state allocation of $2.8 million, this supercomputer ranked second fastest among supercomputers at academic institutions. Though utilized for a variety of high performance computing applications, the main impetus for the state investment was to provide capabilities for real time predictions of storm surge flooding. Complementing this investment, the Louisiana Board of Regents provided $3 million for the LSU Hurricane Center to study the potential health impacts of a major hurricane impacting New Orleans. While broadbased in its approach, the study primarily focused on adopting the Advanced Circulation (ADCIRC) hydrodynamic simulation model to predict storm surge flooding along Louisiana's complex coast.

Two relatively weak storms occurred back-to-back in 2002, and both resulted in considerably more storm surge damage than was expected based on the storms' windspeeds. In late September, Tropical Storm Isodore, having quickly crossed the Gulf-of-Mexico from the Yucatan Peninsula, pushed an 8 ft storm surge ashore, while just two weeks later Hurricane Lili, which reached Category 4 while over the Gulf-of-Mexico but made landfall near Vermillion Bay as a category 1, pushed a 12 foot surge ashore (Pasch 2004). An estimated 360,000 people evacuated before Lili. Levee failures occurred in Montegut and Franklin, though neither storm resulted in flood related deaths (Roth 1998).

In June 2004, Federal, state, and local emergency response professionals meet in Baton Rouge to respond to the fictious Hurricane Pam. Described as the first comprehensive, scenario-based planning exercise to involve officials from all levels of government, this exercise started with an in depth description of widespread levee overtopping and flooding, and then tasked the participants to develop realistic plans across a variety of response activities. The scenario revolved around a slow moving category 3 storm following a track similar to Hurricane Betsy. Based on this track and intensity, the ADCIRC simulation showed that the storm surge would overtop many levees and inundate nearly all of southeast Louisiana. The exercise planners predicted that 64 percent of the population would not evacuate necessitating 22,000 rescue missions, 100,000 people in shelters, 180,000 injuries, 204,000 illnesses and 61,000 deaths (Innovative Emergency Management 2004).

As part of the deadly and destructive 2004 hurricane season, Hurricane Ivan made landfall near Gulf Shores, Alabama. Before curving east at the last minute, Ivan threatened New Orleans with a direct hit from a Category 4 Hurricane. Much of southeast Louisiana was placed under evacuation orders, the state instituted contraflow along the major highways leaving New Orleans. An estimated 60% of metro New Orleans residents evacuated, or approximately 600,000 people. (National Weather Service-New Orleans 2004). Again, the Superdome was provided as a shelter-of-last resort and, again, it was highly vandalized. Weather was calm in New Orleans, while damage was extensive along the coastline near the Alabama-Florida State line. Of particular note, damage to the I-10 bridge over Pensacoula Bay was severe, with large sections collapsing into the bay.

The 60 percent compliance with evacuation orders was largely considered a sign of improved evacuation planning and public risk education. However, the high compliance complicated a previous problem, gridlock, this time turning the interstate into a parking lot. Considerable and careful traffic management still did not eliminate a few key bottlenecks along the evacuation highways. The public expressed widespread disapproval and called for better evacuation management. Governor Kathleen Blanco responded to this public sentiment by forming the Southeast Louisiana Hurricane Task Force, and tasked them to improve the flow of evacuation traffic out of the region. They were instructed to have ready by the start of the 2005 hurricane season a regional, phased contraflow plan finalized, to have maps describing this published and available to the public, and to have the contraflow highway crossovers paved.

Early in the 2005 hurricane season, Cindy quickly developed in the central Gulf-of-Mexico and made landfall near the Louisiana-Mississippi state line. A weak Category 1 at landfall, it was originally thought to be only a tropical storm. Damage was relatively mild, though nearly 278,000 homes around southeast Louisiana lost electrical power during the event (Stewart 2006).

Just a few weeks after Cindy, Hurricane Dennis entered the Gulf-of-Mexico, strengthened, and at one time was predicted to strike New Orleans. At the time, some neighborhoods in New Orleans were still without electricity from Cindy. Before the predictions moved the storm’s path east of the city, Jefferson Parish President Arron Broussard, citing the timing of the storm’s predicted arrival, called for a mandatory evacuation of Jefferson parish without following the regional plan or consulting with other government leaders. State and local officials chided Broussard for breaking from the regional evacuation plan, while residents shunned him for prematurely ordering them to evacuate.

Indeed, it appears that well before August 2005, the story of Hurricane Katrina had already been told, though in parts spread over different events and in varying degrees. The helicopters and boats that canvassed the Lower Ninth Ward, Arabi, and Chalmette after Betsy set a precedent for modern search & rescue and proved that the urban areas of metropolitan New Orleans were no longer safe from the threat of hurricanes. Andrew, Georges, and Ivan all set important evacuation precedents, while Georges and Ivan both demonstrated the difficulties of managing the Superdome as a shelter-of-last resort. Juan demonstrated that levees could be over topped by storm surge, and Isidore showed that levees can fail with just a tropical storm. Both Isidore and Lili showed that the storm surge could be larger than expected based on the storm’s category, a reflection of the disappearing coast. Frances flooded the major interstate running through New Orleans, and Alison crippled a huge, state-of-art medical center. Denis showed the difficulty that leaders face when timing evacuation orders under uncertain predictions. Cindy exposed the vulnerability of the city’s electrical system to hurricane damage. Camille remained as a solemn reminder that storm surges pose a significant risk to lives of those that experience them. All of these themes would return in late August 2005.

During this period, heavy rainfalls and localized street flooding (Keim and Muller 1992) tested the population’s and government’s response to extreme weather and flooding, while major industrial accidents regularly tested emergency response systems for hazmat incidents.

The drainage system, while one of the world’s most complex, was often times overwhelmed by heavy precipitation. It was common for a neighborhood to experience street level flooding, and it seemed like every spring some unlucky driver would get their car stuck in one of the low dips under railroad lines that quickly flooded during heavy rains. In May 1995, a two-day rainstorm soaked the region with 20 inches of rain (Scallon 2005). Sections of Interstate 10 were closed, 56,000 homes and businesses flooded, and six storm related deaths were reported. A similar two-day rainstorm in May 1978 dropped over 9 inches of rain throughout the region, causing 71,500 homes to flood and seven deaths (Colten 2005).

An important part of Louisiana's modern hazards geography and emergency response system, this chapter would not be complete without a least a cursory discussion of chemical and industrial accidents in southeast Louisiana. Called the "Industrial Corridor" by some and "Cancer Alley" by others, the 93 mile stretch of the Mississippi river between Baton Rouge and New Orleans is home to over 100 large petrochemical industrial facilities (Yodis and Colten 2007), including six large refineries (Louisiana Bucket Brigrade 2009). The six refineries alone were the source of 1,056 accidents with unauthorized chemical releases during 2005 – 08 (Louisiana Bucket Brigrade 2009). These incidents, along with accidents at the other facilities or during the transportation of hazardous substances to and from these facilities, meant that emergencies responders were quite experienced in responding to these incidents. Among the most notable incidents, a 1988 explosion at the Shell Oil refinery in Norco, La resulted in six deaths and 42 injuries (Schneider 1991).

3.4 Conclusion

Residing on a young and dynamic deltaic floodplain along the Gulf Coast and near the tropics, extreme weather and floods have been ingrained in the culture of southeast Louisiana since the first colonial outpost was flooded by the river, then destroyed by the wind. Throughout the 300 year history of western influence and governance, numerous flood events prompted massive human modifications to the landscape. Because of these modifications the risk of the Mississippi flooding New Orleans has been considerably reduced, while the persistent heavy rains became manageable. With the promise of Category 3 protection from the Corps of Engineers, the urbanized settlement expanded from the natural ridge into reclaimed swamplands and, like most American cities, experienced considerable suburbanization during the post-WW II period.

Over the last half century, growing awareness of coastal erosion and subsidence motivated emergency planning focused on protecting the population during hurricane events. Coastal landloss was first cataloged in 1968. This event, along with Betsy in 1965, signaled that the urban areas of metropolitan New Orleans were no longer safe from storm surge flooding. Twenty-eight years after Gagliano's study (1970) Georges caused the first official evacuation order for New Orleans. In 2004, the first contraflow evacuation plan was tested with Ivan. By the start of hurricane season 2005, the Southeast Louisiana Hurricane Task Force completed an intensive, regional planning effort, paved a dozen or so crossovers for contraflow, printed 1 million maps, and worked with the local media to further public awareness of the hurricane threat and evacuation procedures (Wolshon, Catarella-Michel, Lambert 2006). Similarly, the Hurricane Pam exercise produced a detailed response plan for the inevitable "Big One" hitting New Orleans.

Chapter 4: The Hurricane Katrina Disaster in Louisiana

4.1 Introduction

In many ways, the catastrophic Hurricane Katrina disaster can be characterized as a complex interaction of events, each of which could be labeled as a disaster by itself. It was a massive windstorm that left all but three counties in Mississippi and all of southeast Louisiana without power. The windstorm left many transportation routes blocked by debris and destroyed multiple communication systems. It also produced an unprecedented storm surge that stretched from Port Fouchon, Louisiana to Pensacola, Florida, affecting over 350 miles (562 km) of coastline, not including the shores of various bays and lakes along this section of coastline. Numerous unprotected coastal communities suffered the direct effects of surge and waves. In southeast Louisiana, Hurricane Katrina flooded five separate ringed levee systems, three of which are urban and two of which are rural. Additional storm surge flooding occurred in areas, such as Slidell, Louisiana and Grand Isle, Louisiana, outside of the levee protection system. The surge overtopped levees in Plaquemines Parish, flooding polders on both sides of the Mississippi River, while three polders in Orleans, St. Bernard, and Jefferson Parishes flooded due to levee failures, overtopping and rainfall. Hurricane Katrina also resulted in an acute public health crisis in New Orleans, as tens of thousands of flooded persons first required rescue from dangerous floodwaters, and then required emergency assistance, including food, water, shelter, and medical attention. This population also suffered from extreme heat in the days that followed the passage of Hurricane Katrina with daytime high temperatures above 90°F (32 °C) and the normal coping mechanisms (air conditioning, fans, and refrigerated fluids) not available. Finally, conditions of extended displacement and long term damage to public safety infrastructure posed a final set of hazards to victims and responders. While the destruction was massive all along Katrina’s path and while the displacement crisis affected most of America, the metropolitan New Orleans area, with its large population, catastrophic flooding, and enduring disruption of public safety infrastructure, suffered the greatest loss of life.

This chapter provides a chronological overview of Hurricane Katrina as it impacted southeast Louisiana. It starts with tracking and warnings for the storm which leads to theonset of hazard conditions. The chapter then describes the different physical hazards that impacted different sub-populations which set the stage for a chaotic aftermath and widespread emergency response. This recounting finishes with the final evacuation of New Orleans and an overview of general impact. The chapter introduces some of the basic facts, factors, trends, and processes relevant to the analysis of loss of life in chapters that follow. The remaining chapters crunch the numbers related to this event. This chapter introduces these numbers in the context of the story of Hurricane Katrina’s impacts in southeast Louisiana.

In *Waters Dark and Deep*, journalist Katie Thomas (2006) tells the story of one family’s relocation from New Orleans as a result of the hurricane and flooding. In this ordeal, the family firsts gets separated when some evacuate before the storm, but others cannot get it together quickly enough to get out in time. After the flood traps those that remained in an apartment building surrounded, a second separation occurs when a rescue helicopter takes all the kids and one adult, but never returns for the remaining adults. The kids and one adult wind up at the I-10 / Cloverleaf intersection west of New Orleans, a dry open area where 7,000 people gathered after rescue and before final evacuation. Eventually, another rescue helicopter returns and transports the remaining adults to the Lakefront Airport, another collection point located about 8 miles east of the Cloverleaf. Eventually, the kids are reunited with their parents in Baton Rouge and they later reunite with the rest of the family at a shelter in San Antonio, Texas.

In the context of this chapter, one can view this family and their story as analogous to tracer particles in a fluid flow. Tracer particles are used by physicists that study fluid dynamics. They allow scientists to visualize, record, and trace the flow of fluid particles. Examples include using thousands of rubber duckies to study ocean currents and using smoke to study turbulence from a bird flapping its wings. In this case, this family's story, told in detail by Thomas (2006), traces the flow of nearly 1 million people out of greater New Orleans in the face of perceived and realized threats. This chapter tells this story from a population movement perspective. Whereas Thomas (2006) puts names and faces on the story, this chapter puts numbers on the story. In doing so, it sets the foundation for a dynamic, risk based assessment of the disaster's outcomes.

4.2 Tracking Hurricane Katrina

Hurricane Katrina formed as a tropical depression in the Caribbean Sea toward the southern end of the Bahamas island chain and about 350 miles southeast of Miami, Florida. Shortly after the storm reached tropical depression status (sustained winds of 35 mph or greater), the National Hurricane Center (NHC) released "Hurricane Katrina Advisory #1" on Tuesday, August 23, 2005 at 4 p.m. CDT (the local time for southeast Louisiana and used hereafter unless stated otherwise). This advisory predicted that the storm would pass near Miami by that Thursday afternoon and then move west into the Central Gulf of Mexico.

By 10 a.m. the next morning, Katrina had reached tropical storm strength with sustained winds of 39 mph or greater. On the afternoon of Thursday, August 25, 2005, Katrina made landfall near Miami, Florida, as a Category 1 (sustained windspeeds of 74 mph or greater) hurricane resulting in fourteen fatalities (Centers for Disease Control and Prevention 2006b). The storm weakened slightly as it crossed the Florida peninsula and entered the Gulf of Mexico on August 26 as a tropical storm. It quickly regained hurricane status, though it was not initially predicted to impact the New Orleans area.

At 10 p.m. on Thursday, August 25, as the hurricane was crossing Florida, the NHC released Advisory #10 which predicted a second U.S. landfall along the Florida Gulf Coast near Apalachicola as a likely Category 2 and some 300 miles (482 km) east of New Orleans. With Advisory #10, only a small portion of southeast Louisiana, basically the lower river delta region in Plaquemines parish, was barely within the cone of uncertainty in the predicted trajectory. This predicted path from the NHC reflected the consensus among the various weather models that they use to predict the path of hurricanes. While most models predicted that the storm would quickly turn to the northeast and head toward Apalachicola, Florida, one model, reflected in the westward edge of the cone of uncertainty, predicted the storm would take a slight jog in a westerly direction before turning to the north and passing close to New Orleans. Over the next few hours, imagery from the GOES satellite would show the eye taking the slight jog predicted by the lone model that brought the storm closer to New Orleans. That night, Katrina started to take aim for southeast Louisiana.

Shortly after the storm entered the Gulf of Mexico, the NHC Advisory #11, released at 4 a.m. on Friday, August 26, still predicted that the storm would turn north and make landfall along the Florida coast. However, as the westerly movement had been noted by the forecasters, the landfall location and the cone of uncertainty shifted to the west. southeast Louisiana was still along the edge of the cone of uncertainty, though Advisory #11 did show a greater portion of the region, including parts of Metropolitan New Orleans, within the region possibly impacted by Katrina. As the day would progress, it became more obvious that the overnight jog to the west had a greater influence over the storms trajectory (and the fate of New Orleans) than forecasters realized that morning.

While Advisories #12 and #13 showed little change in the predicted path, with Advisory #14, released at 4 p.m. that Friday, the NHC predicted that Katrina would make landfall near the Mississippi-Alabama state line, a shift west of about 150 miles. While the predicted landfall location for the eye of the hurricane was still 100 miles east of New Orleans, all of the southeast Louisiana was under the cone of uncertainty with Advisory #14.

By 10 p.m. on that Friday night, with the release of Advisory #15, the predicted path showed a direct hit for southeast Louisiana.   The eye of the storm passing over lower Plaquemines Parish on Monday morning, then passing just east of downtown New Orleans before making a final landfall near the Louisiana-Mississippi state line. Whereas on Friday morning, New Orleans was barely within the cone of uncertainty, by Friday night the storm was predicted to pass about 30 miles east of New Orleans. In the twelve hours that passed between Advisory #13 and Advisory #15, the predicted path had moved 230 miles to the west (see Figure 4.1). Notably, the predicted path of the storm would change little before it made final landfall.

Naturally, as the predicted path moved west, the storm itself was moving west. Importantly, this path took the storm directly over the Loop Current, a warm water current within the Gulf of Mexico. Even as the storm turned toward the north toward the Louisiana-Mississippi coasts, it continued to track over the Loop Current.

As a physical system, hurricanes are efficient heat engines that convert the heat energy of the oceanic waterbodies into the kinetic energy of hurricane winds. While other factors can mitigate the storm’s intensity, greater amounts of heat energy cause stronger hurricane winds. Hurricane Katrina, and more generally the 2005 hurricane season, demonstrated this relationship well. Chapter 1 listed some of the hurricane records that were broken in 2005, a season that coincided with a period of higher than normal water temperatures throughout the Atlantic Ocean and particularly along the Loop Current in the Gulf-of-Mexico (see Figure 4.2).

As it passed over the loop current, Hurricane Katrina strengthened from Category 1 to Category 5 in just three days.   By mid-day on Saturday, August 27, maximum wind speeds had reached 173 mph. New Orleans faced a Category 5 hurricane pointing directly at the city.

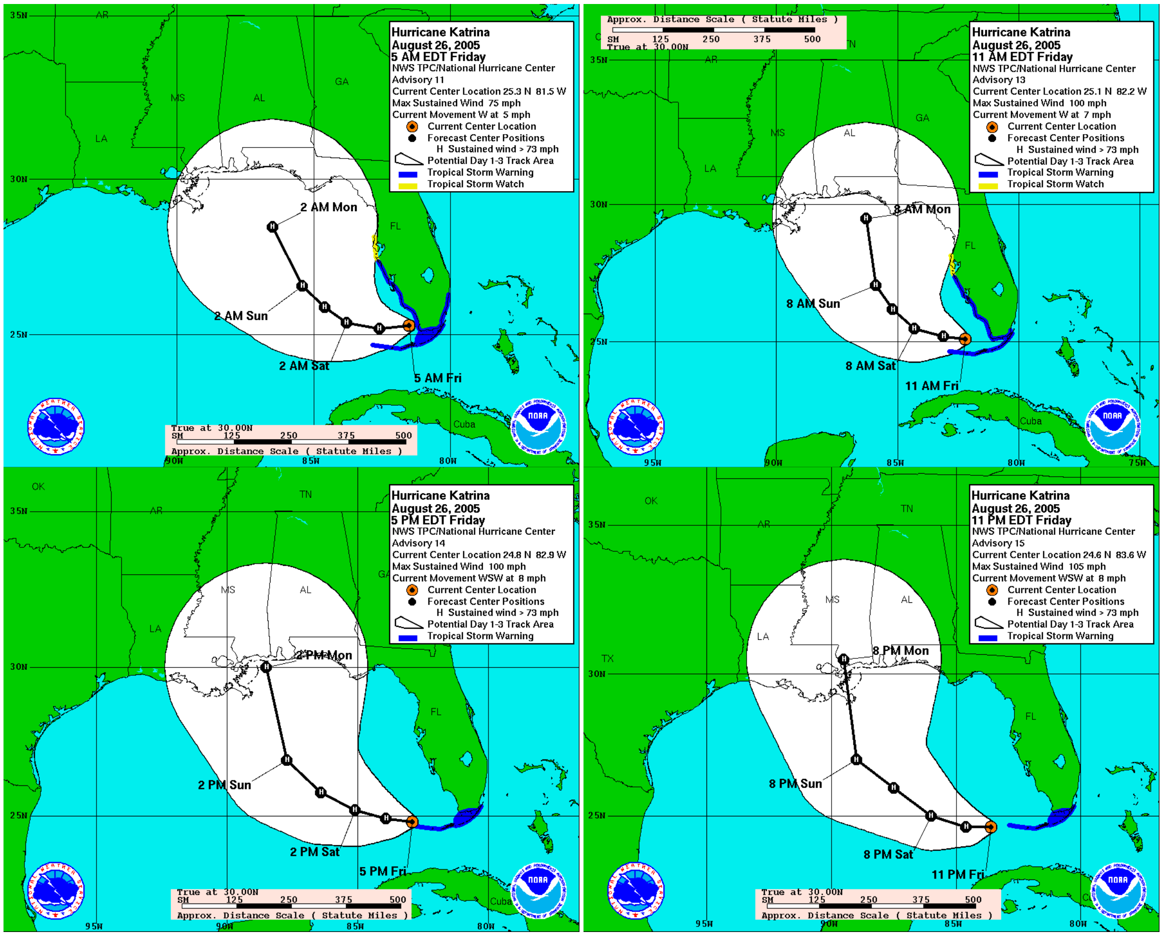


Figure 4.1: Katrina Advisories from Friday, August 26, 2005.
Source: National Hurricane Center,
http://www.nhc.noaa.gov/archive/2005/KATRINA_graphics.shtml

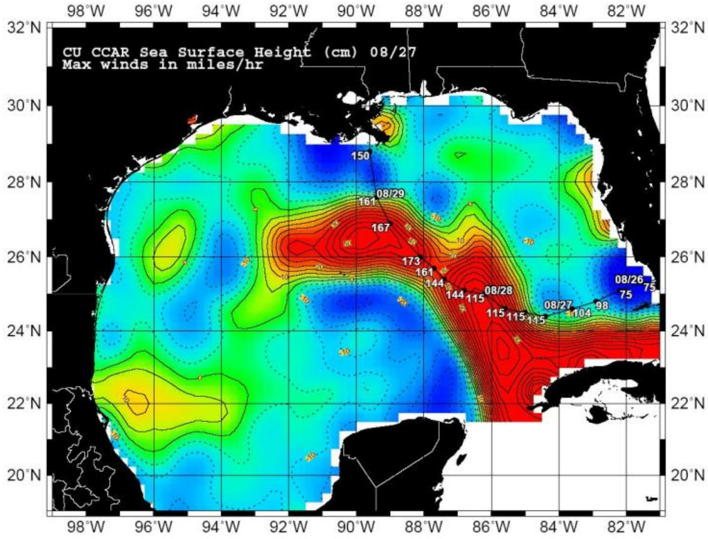


Figure 4.2: Hurricane Katrina’s trajectory passes over the warm waters of the loop current.
Source: Colorado Center for Astrodynamics Research.

Through Saturday evening and night and into Sunday morning, Katrina continued to strengthen as it moved over the warm waters of the loop current. With Advisory #22 at 7 a.m. on Sunday, August 28, Hurricane Katrina had reached Category 5 status with sustained wind speeds of 160 mph. By the 10 a.m. Advisory #23, sustained wind speeds had reached 175 mph and wind gusts had topped 210 mph. It was predicted that by 7 a.m., Monday, August 29, the eye of Katrina would cross lower Plaquemines parish with Category 5 winds and then move north, passing about 20 miles east of downtown New Orleans, before making final landfall between Slidell, Louisiana and Bay St. Louis, Mississippi.

During that Sunday evening and night, the storm left the loop current and then weakened considerably before making a second landfall near Buras, Louisiana. Currently, the NHC officially designates it a category 3 hurricane when making landfall in Louisiana, though there is significant evidence to suggest it was only a category 2 on land.

Since 1967, the National Hurricane Center, a division of the National Weather Service of the National Oceanic and Atmospheric Administration has tracked and forecast tropical systems in the Atlantic basin. Over the years, considerable advancements in atmospheric science, satellite monitoring, and the power of supercomputers that run weather models have greatly increased the precision and accuracy of these forecasts. While forecast errors were still prevalent, as evidenced by the initial, inaccurate prediction that Katrina would make a second landfall along Florida's Gulf Coast, forecast accuracy of the trajectory of the eye of the hurricane had improved considerably, as evidenced by the accurate prediction of Katrina's landfall some 56 hours before landfall. However, significant uncertainty remained in the intensity forecast, as evidenced by the prediction that it would make landfall as a Category 4 just a few hours before it actually made landfall as a Category 3.

Storm surge intensity, largely a function of the hurricane's intensity, also eluded precise and reliable forecasts. The NHC used the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model, a desktop application, to produce forecast maps which provided an indication of areas at risk from possible storm surge inundation during the event, but nothing near an accurate prediction of expected storm surge inundation. Independent of the NHC, various institutions had begun to use supercomputers to run the ADvacned CIRCulation (ADCIRC) model as a forecast tool. By 2005, the LSU Hurricane Center used the supercomputers at LSU to run the ADCIRC model and provided an experimental forecast product that depicted storm surge heights along the Louisiana coast. Previous experiences with ADCIRC had shown that the model could produce accurate storm surge predictions given accurate storm track and intensity forecasts, and the state emergency management professionals had begun to utilize the "experimental" forecast product. The ADCIRC model also required accurate datasets on the underlying bathymetry, topology, and built environment. Both recent events and the event itself can cause changes in these landscape characteristics, resulting in a major uncertainty in storm surge prediction. Basically, the storm surge prediction depended on accurately predicting where the storm would push the mass of water inland, particularly in relation to landscape features such as barrier islands, natural ridges, and levees. But, these features became part of the dynamic interaction of the wind driven tides and the coastal landscape, leading to sometime unpredictable outcomes.

The NHC first predicted storm surge flooding along the Gulf Coast at 10 p.m. on Saturday night with Public Advisory #19, which stated:

> "COASTAL STORM SURGE FLOODING OF 15 TO 20 FEET ABOVE NORMAL TIDE LEVELS...LOCALLY AS HIGH AS 25 FEET ALONG WITH LARGE AND DANGEROUS BATTERING WAVES...CAN BE EXPECTED NEAR AND TO THE EAST OF WHERE THE CENTER MAKES LANDFALL."

By Public Advisory #23, released 10 a.m. Sunday morning, the prediction had changed to "18 TO 22 FEET ABOVE NORMAL TIDE LEVELS" and "LOCALLY AS HIGH AS 28 FEET"

Coastal scientists at LSU began running ADCIRC for Hurricane Katrina on Saturday morning and, by 10 p.m. on Sunday, August 28, they had predicted that the storm surge would overtop some of the levees around New Orleans. (See Figure 4.4). This simulation was based on NHC Advisory #18, which had been released approximately 6 hours before the release of the ADCIRC prediction. The resultant storm surge map showed surge levels around 17 feet (5 m) overtopping the south levee in St. Bernard parish and flooding a number of small towns in southern St. Bernard. For Plaquemines, the surge was predicted to overtop levees on both sides of the Mississippi, flooding all of the east bank and most of the west bank south of Belle Chase. Within New Orleans, surge levels nearing 17 feet (5 m) in the Mississippi River Gulf Outlet (MRGO), Gulf Intercoastal Waterway (GIWW), and the Inner Harbor Navigational Canal (IHNC) overtopped levees along these canals flooding most of the Lower Ninth ward and adjacent Arabi, parts of the Upper Ninth Ward, and parts of New Orleans East. Surge levels of 10 – 12 feet (3 – 3.7 m) were predicted for the south shore of Lake Pontchartrain, and surge heights within the three drainage canals in central New Orleans were not predicted to overtop levees. Along the Mississippi Coast, the surge was predicted to reach 21 feet (6.4 m), though a later ADCIRC simulation completed just hours before landfall predicted 24 feet (7.6 m). Of course, ADCIRC could not model the surges interactions with landscape features, such a levees, along with possible landscape changes due to that interaction, such as levee erosion.

In many ways, the storm surge can be viewed as a feedback loop that returns some of the lost heat energy back to the water body in the form of kinetic energy. The interaction of the hurricane's surface winds with the water surface, results in the surface layer of water being pushed in the direction of the prevailing winds. When the storm is over water, the atmospheric forcing causes a dome of water that stretches along the length of the storm usually as far as the tropical storm force winds. As the storm makes landfall, the impermeable land surface causes the dome to bunch up. As it bunches up, surface winds continue to push water inland, thus resulting in surface water heights significantly above sea level and an extended zone of coastal flooding. In the hours before landfall, Katrina left the Loop Current and weakened in terms of wind speed. However, as part of the delayed feedback, the storm surge did not weaken immediately and continued to possess significant energy and momentum as the storm winds continued to push Gulf waters toward the coastline.

The tides along the Louisiana and Mississippi coastline had started to rise above normal as early as mid-day on Saturday, August 27. By 7 p.m. Sunday, as Katrina was about 130 miles south of the mouth of the Mississippi River, the NOAA tidal gauge at Southwest pass started to rise

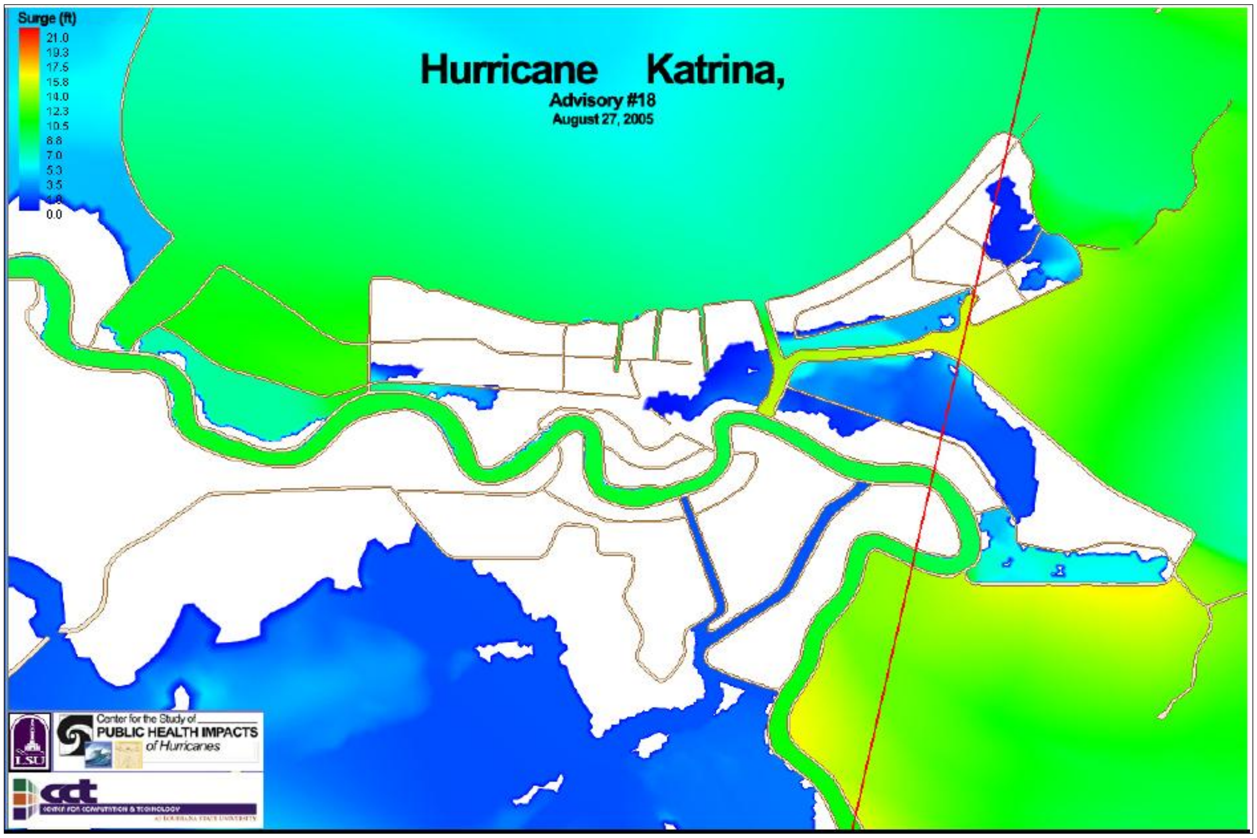


Figure 4.4: ADCIRC prediction based on NHC Advisory #18 and completed on 10 p.m. August, 28. Source: LSU Center for the Study of the Public Health Impacts of Hurricanes.

significantly until it peaked 12 hours later. Other tidal gauges along the Gulf Coast showed a similar pattern of notable rise on Sunday evening and peaking by Monday morning. The water levels also took about 12 hours to recede to normal tides

In addition to straight line winds and storm surge, hurricanes also pose a risk for heavy rainfall and tornados. The NHC Public Advisory #23, contained the first predictions regarding these hazards:

> “RAINFALL TOTALS OF 5 TO 10 INCHES...WITH ISOLATED MAXIMUM AMOUNTS OF15 INCHES...ARE POSSIBLE ALONG THE PATH OF KATRINA ACROSS THE GULF COAST AND THE TENNESSEE VALLEY. RAINFALL TOTALS OF 4 TO 8 INCHES ARE POSSIBLE ACROSS THE OHIO VALLEY INTO THE EASTERN GREAT LAKES REGION TUESDAY AND WEDNESDAY.
>
> ISOLATED TORNADOES WILL BE POSSIBLE BEGINNING THIS EVENING OVER SOUTHERN PORTIONS OF LOUISIANA...MISSISSIPPI...AND ALABAMA...AND OVER THE FLORIDA PANHANDLE.”

4.3 Preparations

The Warning Phase

The first official warnings that southeast Louisiana should prepare for a likely hurricane impact came from the NHC at 4 p.m. on Saturday, August 27 with Public Advisory #18, which stated:

> "AT 4 PM CDT...2100Z...THE HURRICANE WATCH IS EXTENDED WESTWARD TO INTRACOASTAL CITY LOUISIANA AND EASTWARD TO THE FLORIDA-ALABAMA BORDER. A HURRICANE WATCH IS NOW IN EFFECT ALONG THE NORTHERN GULF COAST FROM INTRACOASTAL CITY TO THE ALABAMA-FLORIDA BORDER.
>
> A HURRICANE WARNING WILL LIKELY BE REQUIRED FOR PORTIONS OF THE NORTHERN GULF COAST LATER TONIGHT OR SUNDAY. INTERESTS IN THIS AREA SHOULD MONITOR THE PROGRESS OF KATRINA."

A part of the NHC's standardized hazard assessment and warning vocabulary, a hurricane watch implies "hurricane conditions (sustained winds of 74 mph or higher) are possible within the specified coastal area" " while a hurricane warning means "hurricane conditions (sustained winds of 74 mph or higher) are expected somewhere within the specified coastal area" (National Hurricane Center 2010).

By 10 p.m. the NHC released Public Advisory #19, which upgraded the Hurricane Watch along the Louisiana, Mississippi, and Alabama's coasts to a Hurricane Warning. In addition to the 15 – 20 ft storm surge predictions included in Public Advisory #19 (see previous section), this advisory also included the following advice:

> "PREPARATIONS TO PROTECT LIFE AND PROPERTY SHOULD BE RUSHED TO COMPLETION."

By 10 a.m. on Sunday, with Public Advisory #23, the NHC increased the urgency of its advisories:

> "KATRINA IS A POTENTIALLY CATASTROPHIC CATEGORY FIVE HURRICANE ON THE SAFFIR-SIMPSON SCALE. SOME FLUCTUATIONS IN STRENGTH ARE LIKELY DURING THE NEXT 24 HOURS."

With the Public Advisory #23, the NHC also made specific warning of flooding in New Orleans and along the Gulf Coast:

> "SOME LEVEES IN THE GREATER NEW ORLEANS AREA COULD BE OVERTOPPED. SIGNIFICANT STORM SURGE FLOODING WILL OCCUR ELSEWHERE ALONG THE CENTRAL AND NORTHEASTERN GULF OF MEXICO COAST."

In addition to the statements from the NHC, the New Orleans / Baton Rouge Forecast Office of the National Weather Service released a strongly worded Urgent Weather Message at 10:11 a.m. on Sunday morning:

> "...DEVASTATING DAMAGE EXPECTED...
>
> .HURRICANE KATRINA...A MOST POWERFUL HURRICANE WITH UNPRECEDENTED
> STRENGTH...RIVALING THE INTENSITY OF HURRICANE CAMILLE OF 1969.
>
> MOST OF THE AREA WILL BE UNINHABITABLE FOR WEEKS...PERHAPS LONGER. AT LEAST ONE HALF OF WELL CONSTRUCTED HOMES WILL HAVE ROOF AND WALL FAILURE."

This message also warned of deadly air-borne debris: "PERSONS...PETS...AND LIVESTOCK EXPOSED TO THE WINDS WILL FACE CERTAIN DEATH IF STRUCK."

It also noted that widespread damage to public health infrastructure, including "POWER OUTAGES WILL LAST FOR WEEKS" and "WATER SHORTAGES WILL MAKE HUMAN SUFFERING INCREDIBLE BY MODERN STANDARDS." The risks to livestock was also noted: "LIVESTOCK LEFT EXPOSED TO THE WINDS WILL BE KILLED."

The Urgent Weather Message also stated:

> "ONSET OF TROPICAL STORM FORCE WINDS WILL BE AROUND 3 PM AND PERSISTFOR 24 TO 28 HOURS. HURRICANE FORCE WINDS WILL ONSET AROUND DAYBREAK MONDAY AND PERSIST FOR 12 TO 15 HOURS."

It also gave this final advice: "ONCE TROPICAL STORM AND HURRICANE FORCE WINDS ONSET...DO NOT VENTURE OUTSIDE!"

In other words, evacuation procedures for the coastal residents must be completed by 3 p.m. Sunday, while residents of the metro areas have until a few hours later that afternoon.

Evacuation and Sheltering

With advisory #19, released Saturday night at 10 p.m., 12 southeast Louisiana parishes adjacent to tidal waterbodies, and hence prone to storm surge, where placed under a hurricane warning (see Figure 4.5). Approximately 1.6 million lived in these parishes in 2005. However, for many of these parishes only limited evacuations were necessary. For example, in St. Tammany parish, on Lake Pontchartrain's Northshore, only residents near the lakeshore (south of Interstate-12), in low-lying areas adjacent to rivers, or in mobile homes were ordered to evacuate. However, for six of these parishes, storm surge flooding threatened the entire parish and no one within these parishes was not at risk. These six parishes are: Orleans, Jefferson, Terrebonne, Lafourche, St. Bernard and Plaquemines with an estimated 1.1 million residents at the time, all of whom would be under evacuation orders.

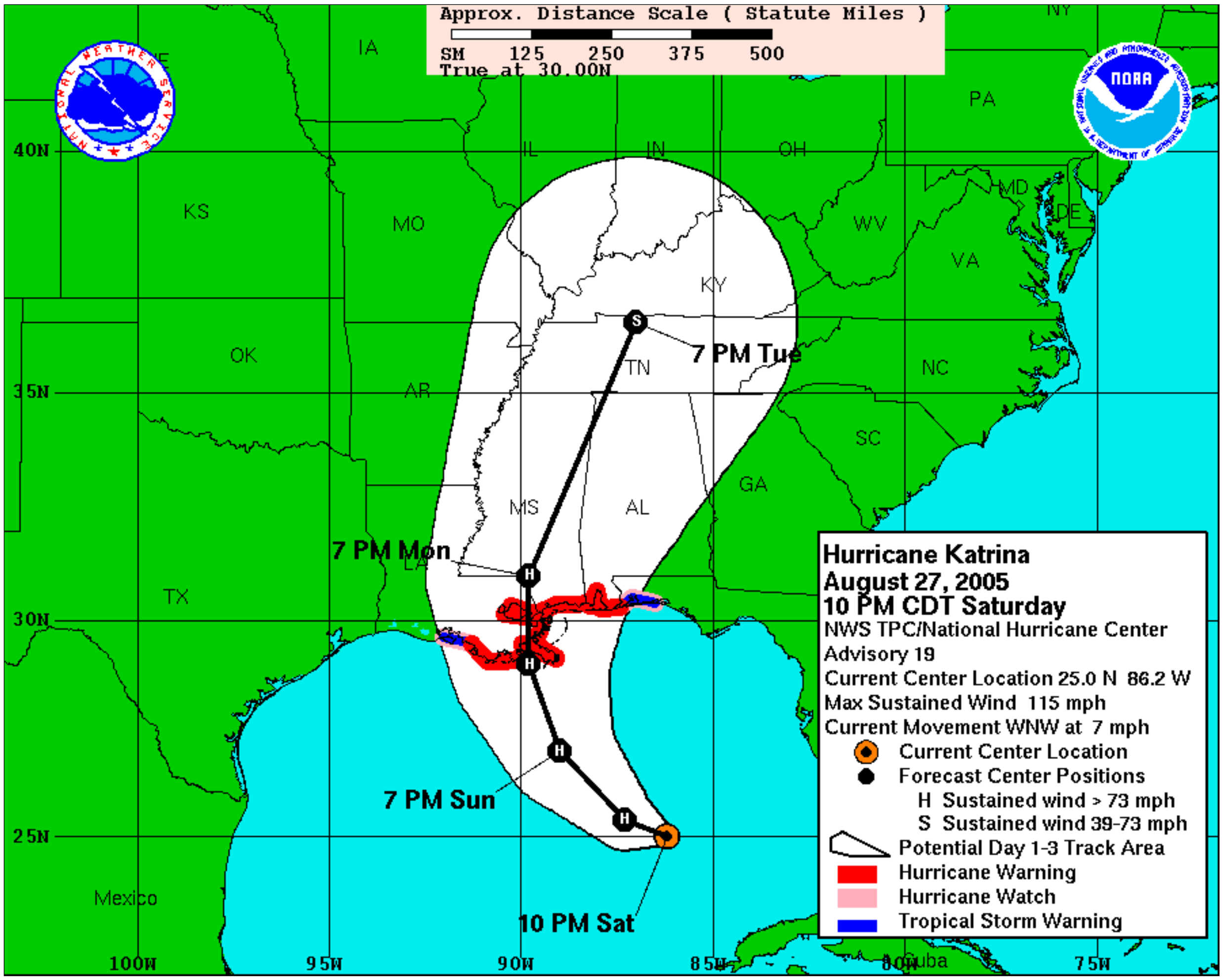


Figure 4.5: NHC advisory showing southeast Louisiana under Hurricane Warning. Source: NWS TPC/National Hurricane Center.

As Friday progressed, most of this population went about their day believing that Katrina would go to Florida and not be a threat to the region. The political leadership and emergency management personnel followed the basic practice of monitoring any storm that enters the Gulf of Mexico regardless of its predicted landfall. At 12:25 p.m. the State's Emergency Operations Center started to prepare for possible activation for Hurricane Katrina and at 5 p.m. the Southeast Louisiana Hurricane Task Force held its first conference call to discuss the possibility of initiating the evacuation plan the next morning (Louisiana State Police 2005). By Friday night, the predictions had changed drastically, and Katrina was now expected to be a direct threat to New Orleans and southeast Louisiana. Surely, some members of the general population, such as those that watch the 10 p.m. newscasts on Friday night, were aware of this change, but it is also true that many people throughout the region went to bed Friday night thinking that Katrina was going to Florida. In contrast to the ambivalence of the general population, Friday night brought a major sense of urgency for the region's leaders and emergency managers.

With the Friday night Advisory #15, it was clear that state and local officials would have to activate the evacuation plan for southeast Louisiana. The regional, phased plan would have to be implemented, even though the timing of Advisory #15 implied certain time constraints. This plan, developed by Southeast Louisiana Hurricane Taskforce, assumed an accurate warning was available early enough to provide a 50 hour evacuation period before tropical storm conditions reached the coastline. According to Phase 1 of the plan, coastal residents south of the Intracoastal Waterway would start evacuating 50 hours before the onset of tropical storm conditions. During Phase 2, which would start 40 hours before landfall, residents south of New Orleans (but north of the Intracoastal Waterway) would evacuate. These two phases gave residents south of metro New Orleans time to get through the populated, urban core before Phase 3 when residents of urban areas behind hurricane protection levees would start evacuating 30 hours before landfall (Louisiana Department of Transportation and Development and Louisiana State Police 2005).

That was the plan - at least on paper. However, it was well understood by the emergency management professionals that complex atmospheric dynamics and the limits of hurricane prediction technology could result is less time than the hoped-for 50 hours. Such was the case with Hurricane Katrina. Tropical storm conditions were expected by Sunday afternoon and 50 hours prior to that time would have been Friday 3 p.m. At this time, Katrina was expected to make landfall near the Mississippi-Alabama state line and was not expected to noticeably affect Louisiana. If officials attempted to call on the public to evacuate at that time, they would have likely been met with public skepticism. Calling for an evacuation at this time would have achieved nothing but further undermining public confidence in hurricane evacuation guidance. When Advisory #15 predicted a path much closer to New Orleans, the available time for evacuations was already less than 45 hours. In addition, just about everyone was in bed for the night, and attempts to initiate the plan in the middle of the night would have resulted in a confused and panicked public along with gridlock the next morning. That Friday evening, Governor Blanco declared a “State of Emergency” for Louisiana and mobilized 2,000 National Guard members (Louisiana National Guard 2005). But, it was decided to wait until the next morning before initiating Phase 1 of the evacuation plan.

Local leaders first called on their citizens to evacuate around 9 a.m. on Saturday morning, just 30 hours prior to the expected Sunday afternoon arrival of tropical storm conditions along the coast. Phase 1 of the evacuation plan was initiated with the first evacuation orders for the outlying coastal areas, including portions of Plaquemines, Jefferson, and St. Bernard parishes. Somewhat jumping the gun, more inland St. Charles and St. Tammany parishes released evacuation calls for their residents, even though the plan called from them to wait until Phase 2 and Phase 3 respectfully. Likewise, Mayor Nagin urged a voluntary evacuation for Orleans parish. He specifically urged persons with special needs to begin evacuating immediately, but requested that the general population wait until the next morning to evacuate so that the coastal residents had time to clear the city. Nagin also announced that the Superdome would be available as a special needs shelter for those members of the special needs population who did not have the ability to evacuate and that the Regional Transit Authority (RTA) buses would pick-up citizens at ten specified stops and provide transportation to the Superdome free of charge. Behind the scenes, Nagin ordered his legal staff to draft a mandatory evacuation order to be put into effect the next morning (Forman 2007). Later that Saturday morning, Governor Blanco requested a Federal Emergency Declaration for Louisiana, which President Bush granted a few hours later.

At 4 p.m. on Saturday, Governor Blanco and Mayor Nagin held a joint news conference in New Orleans during which they updated the public on the predicted threat posed by Katrina and they urged all citizens of metro New Orleans to prepare to evacuate. Nagin stated that he would stick with the regional evacuation plan, though he noted the compressed time span currently available. He again urged that those with special needs to evacuate immediately, but requested that the general population wait until the next morning. Also, throughout the afternoon officials from the various local parishes, state police spokespersons, state emergency management personnel, and numerous media personalities provided continuous updates on the storm and the preparations.

Also at 4 p.m., state police and transportation officials initiated the contraflow evacuation procedures (Louisiana State Police 2005, Wolshon and Ardle 2006). Interstate lanes coming into the city were closed to incoming traffic so that outgoing evacuation traffic could be diverted into these lanes. Throughout that Saturday morning, traffic counters had shown a noticeable rise in the volume of outgoing traffic. There were some delays during the hour immediately before the start of contraflow, but traffic volume quickly increased after the start of contraflow. That Saturday night, outbound traffic volume along I-10 westbound at LaPlace, Louisiana, peaked at just under 2,500 vehicles per hour (vph) around 7 p.m. then dropped slightly and hovered around 1,700 vph throughout the night (Boyd et al. 2009). Similar values are observed along I-10 in the eastbound direction (Wolshon and Ardle 2006). For comparison, the normal Thursday and Friday afternoon rush hour at the LaPlace traffic counter peaked with about 1,600 vph.

Also on Saturday, New Orleans Health Director Dr. Stevens, during a meeting of Nagin and key city administrative staff, mentioned preliminary plans being developed by the Health Department to use rail, ferries, and barges as part of a multi-modal evacuation for those with mobility limitations. During the meeting, it was decided that the incomplete plans were not ready to be implemented and that it would be safer route to stick with the tested plan of using the Superdome as a special needs shelter and refuge of last resort (Forman 2007).

By Sunday morning the front page of The Times-Picayune, the local newspaper, showed the LSU ADCIRC predictions showing levee overtopping and flooding of the greater New Orleans area. At 7 a.m., the NHC announced that Katrina had reached Category 5 status. At 9:30 a.m., Mayor Nagin announced the first ever mandatory evacuation order for New Orleans, but noted that hospitals, hotels, nursing home patients and personnel, and members of the media were excluded (Committee on Homeland Security and Governmental Affairs 2006). Neighboring St. Bernard parish had issued a voluntary evacuation, while Jefferson parish issued a mandatory evacuation for coastal residents and voluntary evacuation for residents within the levees protecting metro New Orleans. Like Orleans parish, Plaquemines parish had issued a mandatory evacuation for the entire parish.

By 1:30 p.m., the storm surge started to flood the low lying highways used to evacuate the coastal areas (Louisiana State Police 2005). Later that day, communities outside the levee system, including Venetian Isles, a subdivision of elevated homes built atop coastal marshland within Orleans parish, started to flood.

By 5 a.m. Sunday, the traffic volume outbound from New Orleans had begun increasing, and by 8 a.m. an estimated 2,500 vehicles per hour (vph) were crossing over the I-10 counter near

LaPlace. Similar volumes were observed in eastbound direction of I-10, while additional secondary roads and highways showed considerable outbound traffic volume throughout the day. After about 7 hours of hovering around 2,500 vph, the outbound traffic at LaPlace started to decrease around 3 p.m. By 5 p.m., as tropical storm winds started to bear down on New Orleans, contraflow was terminated and highway workers swept the contraflow routes to retrieve their traffic control assets before the onset of hazard conditions.

The outer rain bands reached New Orleans around 3 p.m. that Sunday. At the time, a large line of many hundreds of people waiting to get inside the Superdome stretched around the facility. Earlier that day Nagin announced that the Superdome would open as a Refuge-of-Last-Resort for members of the general population unable to leave the city. Again, Nagin followed the plan in timing this announcement. The plan sought to encourage as many people to safely evacuate before the storm; announcing a general population shelter too early would encourage people to simply go there instead of evacuating. Likewise, not opening a general population shelter when it was known that many within the general population could not evacuate would have left these people to fend for themselves. Nagin warned that everyone entering the Superdome would be searched for drugs and weapons, which meant a slow intake process for the Superdome.   By 5 p.m. some 2,500 people were registered entering the Superdome, with many thousands still waiting to enter. A Louisiana National Guard (LANG) team had arrived earlier that day with 9,792 MREs (Meals Ready to Eat) and 13,440 liter bottles of water (Louisiana National Guard 2005).

Tropical storm winds reached the coast by about 1 p.m. CDT (1800 UTC) on August 28 and New Orleans by 11 p.m. CDT (0300 UTC) (Hurricane Research Division 2006). A few hours later, Katrina's surge and waves started to crash over the I-10 Bridge to the east of New Orleans and the last few cars attempting to evacuate over that bridge had to be diverted to the nearby Highway 90 bridge.

By the time storm conditions reached New Orleans, 430,000 evacuation vehicles were counted with traffic counters along the primary roads (Louisiana Department of Transportation and Development 2005, Wolshon 2006; Wolshon and McArdle 2011). In addition, Wolshon and McArdle (2011, p. 20) note that "tens of thousands more vehicles utilized the score of highways that were not monitored." Based on these traffic counts and the assumption of 2.5 persons per vehicle, it is estimated that around 1.1 million people evacuated during the 43 hrs between the release of Advisory #15 and the onset of hazard conditions in New Orleans. This overall figure is consistent with the figures provided by parish officials, see Table 1. Only 40 hours elapsed between the release of Advisory #15 and flooding of the coastal evacuation routes (see Table 4.1). Referring to figures above, this corresponds to about 90 percent of the 1.2 – 1.3 million people most at risk in southeast Louisiana.

As Katrina started to bear down on New Orleans that Sunday night, there were an estimated 10,000-12,000 general population shelterees at the Superdome[1] (Louisiana National Guard 2005, Duncan 2006). Many of them had gotten there via RTA buses, though the New Orleans Fire

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[1] An initial report in The Times-Picayune blog that 26,000 people sheltered at the Superdome before the storm does not appear to be accurate.

Department (NOFD) canvassed neighborhoods that ADCIRC predicted would flood and transported holdouts to the Superdome, while the New Orleans Police Department (NOPD) patrolled the entire city and provided transportation to the Superdome to anyone who requested it. In the Superdome, nearly 1,000 personnel from the LANG, the NOPD, and the Superdome security force provided an initial sense of security. In addition to the Superdome, adjacent parishes also provided storm refuges. Two schools in St. Bernard sheltered about 800 citizens total. In Jefferson, four shelters were provided. While there are no population counts from these shelters, the parish emergency manager implies during congressional testimony that as many as 60,000 people may have been in these shelters[2] (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006). Plaquemines Parish officials did not open any shelters.

Table 4.1: Summary of evacuation efforts for Orleans, Jefferson, St. Bernard, and Plaquemines Parishes. Sources: Population data from Census (2005), Evacuation figures from Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina (2006), except for Orleans parish which is from (Russell 2005). Shelter counts from Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina (2006) and Louisiana National Guard (2005).

Parish	**Evacuation Calls**	**Evacuation Effectiveness**	**Number Evacuated**	**Sheltered**	**Non-Evacuate & Non-Sheltered**
Orleans	Mandatory Evacuation called Sunday morning	80%	358,484	11,000	67,692
Jefferson	Voluntary for most of Parish, Mandatory for coastal areas	75%	336,476	56,000	56,079
St Bernard	Voluntary	92%	59,438	800	4,369
Plaquemines	Mandatory	97%	25,954	0	803
		Totals	780,353	67,800	128,942

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[2] In his testimony, the Emergency Director of Jefferson parish did provide specific sheltering figures. He stated that roughly 70 - 80 percent percent evacuated and that he estimated that half of those who did not evacuate went to the parish refuges (Committee on Homeland Security and Governmental Affairs 2006).

Table 4.2: Available time for evacuations (Louisiana Department of Transportation and Development 2005, Louisiana National Guard 2005, Knabb 2005).

Event	**Time**	**Hours Since Adv. #15 Friday, 10 p.m.**	**Hours Since Adv. #12 Friday, 10 a.m.**
La Hwy #1 floods due to surge	Sun, 1 p.m.	39.5	51.5
People entering Superdome get rain	Sun., 3 p.m.	42	54
Evacuation ends due to high winds	Sun., 5 p.m.	45	57
Eye makes landfall along Louisiana Coast	Mon., 6 a.m.	56	68

Indicative of what likely progressed in other surrounding parishes where the storm surge risk did not cover the entire pariah, St. Tammany ramped up shelter capacity throughout the day Sunday. At noon that day, two shelters were opened in St. Tammany parish. By 2 p.m. that day, one of those shelters was full and it was announced that a third shelter would open up at 3 p.m. A 2:30 announcement stated that the second of the original two shelters had filled up and that two more were opening up. At 3:30, parish officials announced the final two shelter openings. In all, six shelters had been opened by 5 p.m (St. Tammany Parish Government 2010).

In addition to the general population preparations, health related facilities implemented their various preparedness plans. Pharmacies, clinics, private practices, specialist centers, etc. canceled services, secured the facility, updated emergency contact lists, and encouraged employees to evacuate. Hospitals and nursing homes, with extremely vulnerable persons under their care, faced more difficult decisions. Evacuating frail patients was certainly a risky option, but so was not evacuating. In general, the practice was for hospitals to remain open and for nursing homes to evacuate only as a last resort.

The Superdome was originally opened as a special needs shelter, and approximately 200 persons with medical needs had arrived there by Sunday morning. Naturally, many more arrived throughout the day on Sunday. During the day, state and local health officials coordinated the evacuation of 500 special needs patients from the Superdome using local EMS vehicles, private ambulances, and RTA paratransit buses (Kosak 2006). However, this was only half of the special needs population that had arrived at the Superdome. Following their first trip bringing patients to hospitals and shelters in Baton Rouge, a caravan of 20 ambulances planned to return to the Superdome for a second evacuation. However, by Sunday afternoon, Katrina’s hazards were bearing down on New Orleans and the second planned pre-storm special needs evacuation had to be canceled (Cataldie 2006). The additional 500 special needs patients, including approximately 50 people in critical condition, were stuck in the Superdome until post-evacuations were possible. In addition to the state and local health workers, one Disaster Medical Assistance Team (DMAT) arrived at the Superdome before landfall.

To prepare for the storm, hospitals cancelled elective surgeries and discharged what patients they could. They called up staff for storm duty, checked their supplies, and prepared to hunker down. One general hospital did evacuate from the New Orleans area. However, they did not reach their destination before the storm arrived, and the patients rode out the storm while in transit (Gray 2006). Ironically, the actual hospital was sufficiently west of the storm's path to avoid major damage. One other hospital, aware that a safe patient evacuation was not possible during the time window available, began planning for a possible post-hurricane evacuation. Nursing homes discharged residents who could evacuate with family, then faced the complex choice of evacuating the facility or hunkering down. Nineteen nursing homes evacuated before the storm, while thirty-four did not (Donchess 2006).

While hospitals and nursing homes tended for their own, local and state health departments began setting up special needs shelters for those amongst the general, non-institutionalized population that would require medical attention during the passage of the hurricane. In Orleans parish, the Health Department provided medical and evacuation assistance for the special needs shelter in the Superdome. Similarly, local health departments throughout the region instituted plans to provide special needs residents. DHH both provided assistance to the locally run special needs shelters and DHH opened 7 additional special needs shelters throughout the state (Louisiana Department of Health and Hospitals 2005).

In general, special needs persons did not receive transportation assistance out of the region. Local governments largely used their transportation assets to move special needs persons to refuges within the parish. However, a few exceptions are noteworthy. In Orleans parish, city owned paratransit buses and state chartered ambulances were used to evacuate 500 patients from the special needs shelter in the Superdome to a special needs shelter in Baton Rouge. In Plaquemines Parish, a proactive emergency preparedness plan allowed immobile residents to register for evacuation assistance and most of the parishes immobile residents were evacuated by the parish. In areas under mandatory evacuation, DHH maintained an adolescent care home, a residence for persons with developmental disorders, and a mental health hospital. All of these facilities were evacuated completely by DHH before Katrina. In St. Bernard, administrators of an inpatient, chronic care facility for elderly residents moved their residents to the relative safety of Memorial Hospital in Orleans parish. Despite these special needs evacuation efforts, an additional 400 patients remained in the special needs shelter in the Superdome (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006), some 3,000 patients sat in hospitals (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006), and many hundreds, perhaps thousands, more special needs residents remained in their homes, businesses, and churches throughout the soon-to-be flooded region.

Outside of the evacuation zone, nearly 40,000 people found shelter state run shelters, administered by the Department of Social Services (Louisiana Department of Social Services 2005). An additional untold number of evacuated residents were scattered in shelters setup by private organizations, and many homes took in family, friends, family's friends, friend's families, and countless pets.

Also during the preparatory phase, many preventive flood fighting steps were undertaken. Numerous levee and drainage work crews completed tasks such as closing floodgates, clearing drainage basins, and pumping down the water levees in drainage canals. In Jefferson parish, large sandbags were placed across Hwy-90 to plug a levee low point were the highways crossed it. In Orleans and St. Bernard Parishes, pump station operators prepared to hunker down in pump stations. In Jefferson Parish, officials activated the "Doomsday Plan" which emphasized the safety of pump station operators and called for them to evacuate before a Category 3 or stronger storm. Since many of these preparedness steps impacted roads and highways, many of these flood fighting steps required careful coordination with the evacuation process.

In addition to the evacuation and flood fighting steps, local leaders and emergency management officials began preparing for the post-storm response by pre-positioning response teams and assets and activating rescue and medical teams. Throughout the metro region, essential city crews manned their stations and hunkered down. This includes levee and drainage personal, emergency medical services, and police and fire departments. The LANG and Louisiana Department of Wildlife and Fisheries (LADWF) prepositioned at Jackson Barracks (located between the Lower Ninth Ward and Arabi) and prepared for post-storm rescues. Additionally, LANG units throughout the state activated for storm response and prepared to move supplies in immediately after the storm's passage. Likewise, the entire LADWF Enforcement Unit, the state's designated search and rescue team, mobilized for post-storm search and rescue operations. State officials also requested activation of the Strategic National Stockpile, a large cache of emergency medical supplies maintained by Centers for Disease Control, and Disaster Medical Assistant Teams (DMATs). In response, FEMA mobilized 18 DMATs for deployment across the Gulf Coast (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006).

Despite the robust planning and comprehensive set of preparedness measures undertaken before Katrina's impact on southeast Louisiana, a number of shortcomings in the pre-storm preparedness would set the stage for catastrophe. Probably the most notable, the 10 percent that did not evacuate and shelter reflected shortcomings in public risk communication, public transportation assistance along with individual stubbornness and risk denial. However, even in this regard it is important to note that former FEMA administrator, Michael Brown, who had described the evacuation of southeast Louisiana "dysfunctional" during Congressional testimony, later stated that he would consider 80 percent successful (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006b). Congressional investigators only found a few examples of a more effective evacuation (Democratic Staff of the House Committee on Science 2005).

Based on the data available, it is estimated that between 47,000 and 83,000 of the nearly 127,000 people in Orleans parish without access to personal transportation were able to evacuate. There is no hard data on the number of carless persons who did evacuate, though the available data does provide for some basic inferences. At the very least, approximately 80,000 remained in Orleans Parish, so at least 47,000 (of the 127,000 carless persons) were able to evacuate. However, a survey of evacuees at the Houston Reliant Center (*The Washington Post*, Kaiser Family Foundation, and Harvard University 2005) indicates that 55 percent of non-evacuated did not have access to transportation, which yields the high end estimate of 83,000 carless persons that did evacuate.

Another major shortcoming of the preparations involves the incomplete evacuation of hospitals, nursing homes, and prisons. As the storm bore down on New Orleans, some 3,000 patients were scattered through 25 hospitals, an estimated 3,400[3] elderly residents were scattered across 36 nursing homes, and one prison, the Orleans Parish Prison, held some 6,400 inmates apprehended in Orleans Parish plus 374 inmates transferred from St. Bernard parish (Inglese and Gallagher 2008).

While numerous municipal and state work crews and response teams pre-deployed to crucial locations throughout the region, many of these crews and teams did not have adequate supplies or communication systems. As just one example, the special needs shelter at the Superdome did not have enough oxygen for the number of patients that arrived there. But, again even this shortcoming must be viewed with a holistic vein of fairness and pragmatism. Previous experience with running the special needs shelter during hurricanes had taught health officials to have enough supplies for about 50 patients that arrive at the Superdome (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006). When 20 times that number arrived before Katrina, half of them were evacuated before the storm. Further, health officials at the Superdome had sufficient stocks of all other supplies for the 500 patients that at the special needs shelter to make it through the hurricane's passage and the first few days afterwords. Oxygen was the only supply that ran low after the Superdome clinic operated for days without external assistance (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006).

4.4 Hazards: Wind, Rain, Storm Surge, and Levee Breaches

Wind and Rain

The eye of Hurricane Katrina made landfall near Buras, Louisiana around 6 a.m. on August 29, with windspeeds in the Category 3 range. In the ensuing hours, the storm tracked nearly due north, passing about 20 miles east of New Orleans around 10 a.m. Shortly thereafter, the storm made final landfall near the Louisiana-Mississippi state line. This massive windstorm tore roofs off of houses, generated destructive wind borne debris, and spawned 44 confirmed tornados. As previously mentioned, the windstorms strength and extent is best illustrated by the large region left with power, including most of Mississippi, all of southeast Louisiana, and parts of southern Alabama were left without power. After the worst had passed southeast Louisiana, Katrina continued to pound Mississippi with wind and rain throughout the day, and then caused inland flooding through the Tennessee River Valley.

Officially, the National Hurricane Center has designated Katrina as a Category 3 hurricane when it made first landfall along the Gulf Coast (Knabb, et al. 2006, Beven et al. 2008). However, the

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[3] No precise figures on the non-evacuated nursing home population are available. Donchess (2006) stated that approximately 5,500 residents were evacuated before and after the storm, and that 63 percent (36 out of 57) were evacuated after the storm.

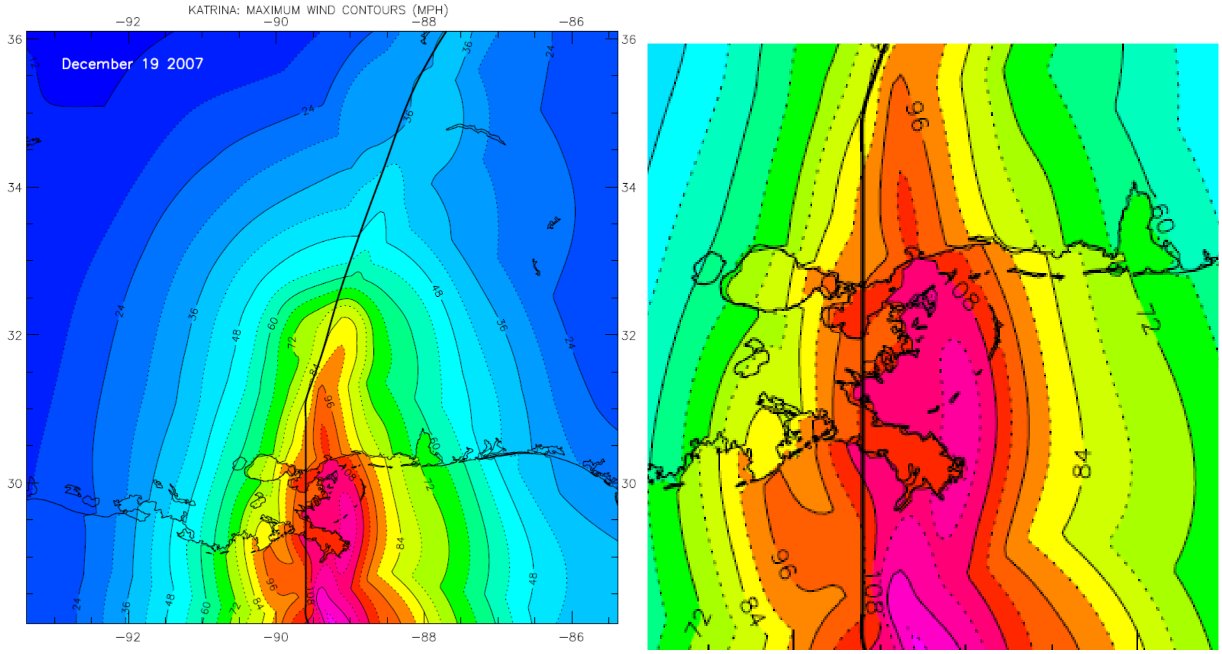

Figure 4.6: Maximum sustained wind swaths based on an analysis of surface wind measurements completed by NOAA's Hurricane Research Division. Note the 108 mph (174 km/hr) contour lines the Louisiana coast.

initial NHC designation is not final and there are precedents for a hurricanes designated category at landfall being revised once the volume of data generated by these events is fully analyzed. For this particular event, two NHC reports (Knabb, et al. 2006, Beven et al. 2008) do not cite any ground based wind measurements above 110 mph (178 km/hr) threshold for category 3 strength (the strongest reported overland windspeed was 87 mph (141 km/hr) recorded at Grand Isle, Louisiana). Further, as shown in Figure 4.6 below the H*Wind analysis from NOAA's Hurricane Research Division (a government office independent of the NHC and National Weather Service) shows overland winds around 105 mph (169 km/hr). Finally, when asked by the author if they observed any evidence of Category 3 windspeeds on the ground, the Louisiana State Climatologist and a world renowned LSU wind engineer (both who conducted early ground based surveys) sated that they had not found any such evidence (Keim and Levitan 2006).

According to the windspeed analysis by the Hurricane Research Division, tropical storm force winds reached New Orleans by 4 p.m. on Sunday. Hurricane force winds started to impact downtown New Orleans by 7 a.m. the next Monday and lasted for approximately 3 hours. Naturally, observed maximum windspeeds varied throughout New Orleans, with the strongest winds closer to the path of the eye. The NHC's "Tropical Cyclone Report: Hurricane Katrina" lists official and unofficial wind measurements. The strongest wind measures in the city were seen at the New Orleans Lakefront Airport, which sits along Lake Pontchartrain near the INHC. Here sustained winds were measured at 60 kt (30 m/s), with gusts reaching 75 kt (39 m/s). Unofficial measurements include gusts of 104 kt (54 m/s) and 107 kt (55 m/s), both estimated at the NASA Michoud facility in New Orleans East and an 105 kt (54 m/s) gust measured at Slidell Memorial Hospital (Knabb, et al. 2006).

It also states (p. 7):

> "The estimated Buras landfall intensity of 110 kt, just beneath the threshold of Category 4…. Overall, it appears likely that most of the city of New Orleans experienced sustained surface winds of Category 1 or Category 2 strength. It is important to note, however, that winds in a hurricane generally increase from the ground upward to a few hundred meters in altitude, and the sustained winds experienced on upper floors of high-rise buildings were likely stronger than the winds at the same location near the ground."

Rainfall in southeast Louisiana due to Hurricane Katrina was moderate, but not intense. The National Hurricane Center estimates that 10-12 inches of rain fell over the region, with 11.63 inches measured at a National Weather Service office in Slidell. This amount of rainfall was about half of the amount that fell during the May 1995 flood (Scallon 2005), but is similar to a 1978 rainstorm that dropped 9 inches on New Orleans and caused 5 deaths (Colten 2005). (Naturally, a May rainstorm is a much different than an August hurricane).

The National Hurricane Center attributes 43 tornadoes to Hurricane Katrina, but none of them occurred in Louisiana.

Storm Surge

Hurricane Katrina's storm surge was massive, unprecedented, and very destructive and deadly. As the storm made final landfall along the Gulf Coast, its storm surge stretched from LaPlace, Louisiana to Pensacola, Florida. Nearly 350 miles (563 km) of coastline was inundated. The entire Mississippi Gulf Coast experienced surge levels of at least 17 ft (5 m), with a surge of over 24 ft (7 m) inundating a 20 mile (32 km) swath of the Mississippi coast. A peak surge height of nearly 28 ft (9 m) was measured near Bay St. Louis in Mississippi. On top of the surge, 10 ft (3 m) waves crashed inland. Nearly 45,000 homes flooded due to the direct impacts of the storm surge that inundated the entire Mississippi coast (Department of Homeland Security 2006). Parts of Mobile, Al, located 150 miles (240 km) east of New Orleans, also flooded.

In southeast Louisiana, the storm surge along with inadequate design and construction resulted in overtopping and breaching of levees around New Orleans (van Heerden and Bryan 2006; van Heerden et al. 2007; Interagency Performance Evaluation Taskforce 2007; Seed, et al. 2006). While flood waters due to overtopping and rainfall would have caused damage to neighborhoods in New Orleans, most of the floodwaters and the ensuing tragedy resulted from numerous breaches in the levee system. The next few paragraphs summarize the sequence of a rising tide, multiple levee failures, and a catastrophic flood in New Orleans.

Early Sunday afternoon, the storm surge had started to flood outlying, coastal areas of southeast Louisiana, and the surge continued to rise and push inland through the night. By 6 a.m. Monday, most of Plaquemines parish was under water as the 20 ft (6 m) storm surge that first overtopped the east bank hurricane levee, then the east bank river levee, and finally the west bank river levee. At about the same time, the earthen levee along the banks of the MRGO started to erode away allowing the storm surge to inundate the wetlands located between the MRGO levee and the 40 Arpent levee, which is located along the northern edge of the urban areas of St. Bernard parish. The ghostly remains of the once thriving wetlands there provided little resistance as the surge waters started to threaten the populated areas just across the 40 Arpent levee.

An ADCIRC hindcast of Katrina's storm surge is shown in Figure 4.7, while Figure 4.8 shows simulated hydrographs. These are based on the observed meteorological characteristics of the storm, but assumes that all levees performed up to their design criteria. Limited flooded due to the surge overtopping levees can be seen, but the flooding depicted in this image fails to describe the full extent of flooding that was observed.

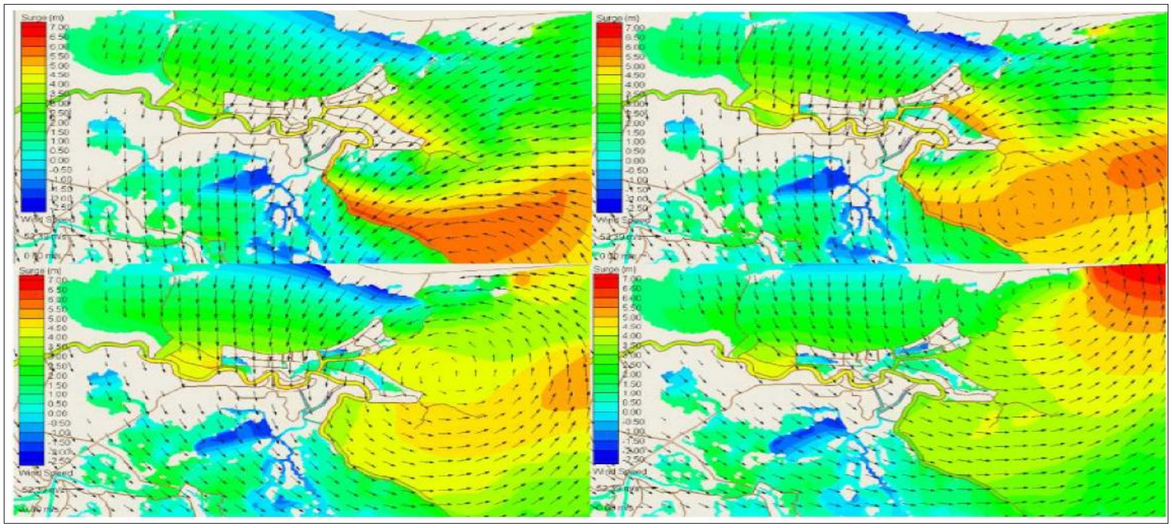

Figure 4.7: A series of screen shots from ADCIRC shows the surge's progression at hour-long intervals starting at 8:00 CDT on the day of landfall. The surge height is given in meters and the arrows indicate wind direction (van Heerden, et al. 2007).

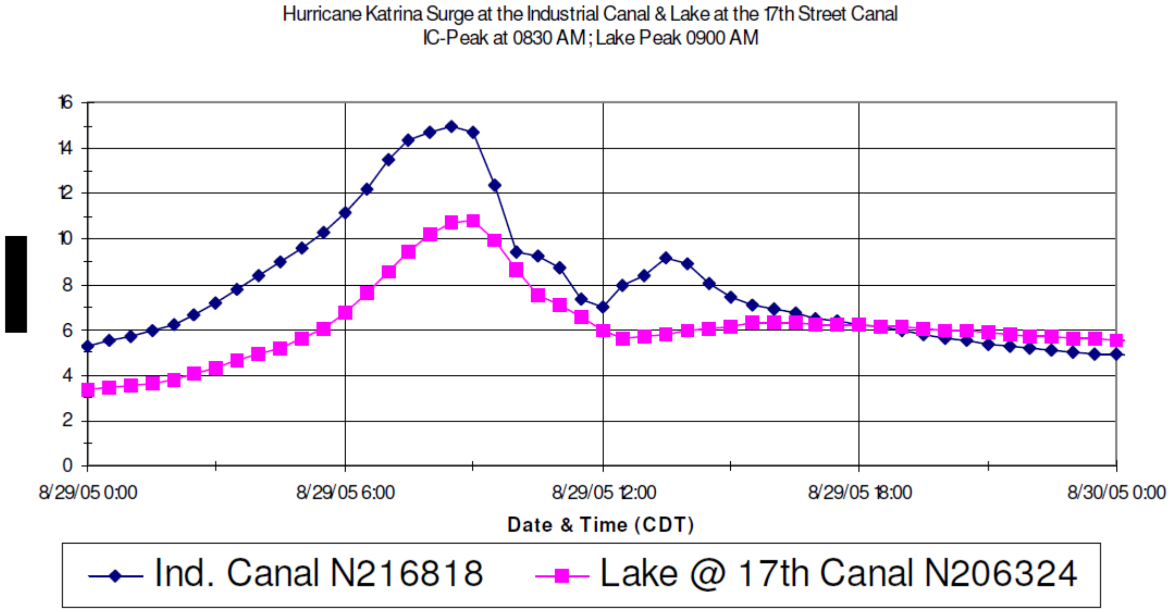
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Figure 4.8: Storm surge hydrographs generated from ADCIRC for the IHNC near the Lower Ninth and in Lake Pontchartrain at the 17th Street Canal (van Heerden, et al. 2007).

Levee Failures

Figure 4.9 depicts the locations of levee failures and degradation. The first flooding of urban areas in New Orleans occurred almost two hours before the storm's landfall on Monday morning. Between 4:30 and 5:00 a.m., rising water entered the GIWW / MRGO, where the funnel effect concentrates the surge into a high velocity flow directed straight toward New Orleans (van Heerden and Bryan 2006, van Heerden et al. 2007). The water overtopped floodwalls along the canal and flowed into the Gentilly section of the Orleans Metro polder to the west, and into the New Orleans East polder on the North side of the Canal.

By 6:30, the surge had overtopped the hurricane levee on the south edge of New Orleans East, flooding the entire area. At about the same time, eye-witnesses in the Lakeview neighborhood noticed a crack starting to form in the floodwalls along the 17th Street canal. By 6:50, the MRGO funnel effect was in full force, pushing fast moving water over the levees along both sides of the IHNC (van Heerden and Bryan 2006, van Heerden et al. 2007).

At 7:30, the floodwall west of the IHNC failed and the storm surge funnel pushed the surge water through this breach, flooding parts of the Upper Ninth Ward, Bywater, and Treme. Fifteen minutes later, two massive sections of floodwall collapsed on the other side of the IHNC (van

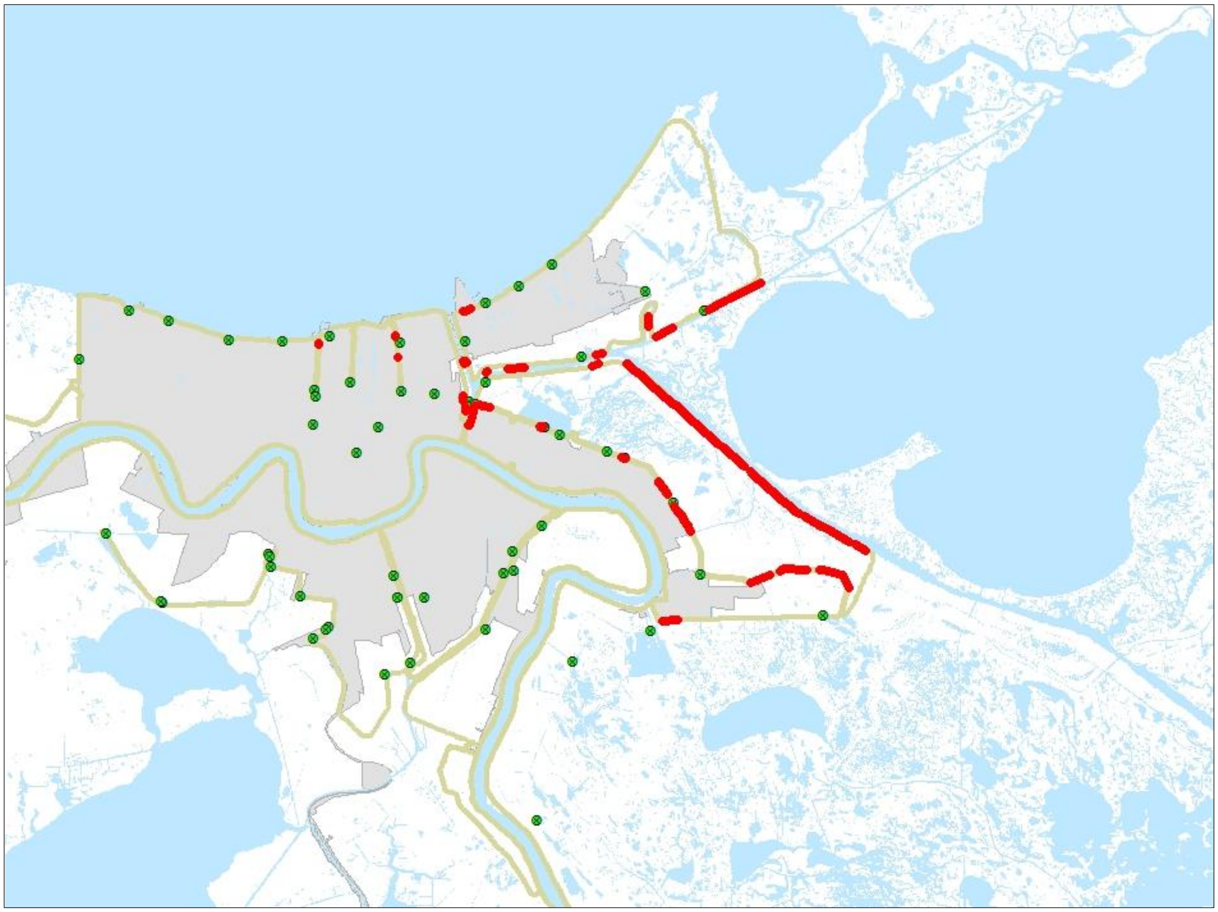

Figure 4.9: Levees, Levee breaches and degradation, pump stations, and urban areas of Greater New Orleans (van Heerden, et al 2007, Guidry and Gisclair 2007).

Heerden and Bryan 2006, van Heerden et al. 2007). Destructive flood waters started to flow into the Lower Ninth Ward, leveling every building for ten square blocks. The neighboring community of Arabi, in St. Bernard Parish, also flooded from these waters.

By 8:30, the rising surge in the wetlands in north St. Bernard parish started to overtop the 40 Arpent levee, flooding the remaining portions of St. Bernard parish. At about the same time, the surge in Lake Pontchartrain overtopped a lower section of floodwall in New Orleans East along Lake Pontchartrain, adding to the severe flood conditions there (van Heerden and Bryan 2006, van Heerden et al. 2007).

By 9:00 that morning, the water levels had reached 10 ft along the southern shore of Lake Pontchartrain and in the three canals in central New Orleans that drain into the Lake. At the lower end of the Orleans Avenue Canal, the surge had been flowing over the top of an incomplete section of floodwall, flooding the New Orleans City Park. Along the London Avenue Canal, two sections of floodwall started to lean over, allowing water to flow through the cracks and erode the floodwall's earthen base (van Heerden and Bryan 2006, van Heerden et al. 2007).

Around 9:30 the first of three floodwall failures in the central New Orleans drainage canals occurred along the London Avenue Canal near Mirabeau Ave. Fifteen minutes later, the floodwall along the 17th Street Canal collapsed, and at the 10:30 a second section floodwall failed along the London Avenue Canal. These failures allowed a storm swollen Lake Pontchartrain to gravity drain into New Orleans (van Heerden and Bryan 2006, van Heerden et al. 2007).

As these floodwall failures occurred, the hurricane made its final landfall just east of Slidell, Louisiana. The storm surge reached nearly 15 ft (4.5 m) along the northern shore of Lake Pontchartrain and in the Rigolets. It pushed nearly 20 miles (32 km) up the Pearl River basin. In St. Tammany parish, 80 percent of Slidell along with portions of Pearl River, Lacombe, Mandeville, and Madisonville all flooded. Additionally, moderate flooding of the northern sections of Jefferson parish located along Lake Pontchartrain, occurred due to rainfall and backflow through unmanned pump stations. Finally, throughout the region, Katrina's rainfall caused rivers, creeks, and ditches to swell and poorly drained areas to fill with water (see Figure 4.10).

As the day progressed, Hurricane Katrina continued to move north and weaken. As the rain and wind driven tide died down, floodwaters started to drain back toward the Gulf of Mexico. However, flood waters in central New Orleans continued to rise. Though the wind had stopped pushing water inland, Lake Pontchartrain remained swollen as surge water took time to drain back out into the Gulf of Mexico, during which time rain swollen rivers and streams drained into the lake. During this period, flood waters continued to flow into Central New Orleans through the three breaches along the drainage canals and the one breach on the east bank of the IHNC. By 2 p.m., Wednesday, two days after the breaches occurred, the water level in Lake Pontchartrain, at 4.6 ft, equalized with the floodwaters in central New Orleans. The floodwaters in New Orleans stopped rising and the city went “tidal,” meaning that floodwaters in the city fluctuated with the tidal cycle of the Lake.

In the other two urbanized polders of New Orleans, flooding followed a difference sequence. For the St. Bernard / Lower Ninth Ward polder levee breaches occurred early during the event, as the tidal surge was rising. This factor, along with the high volume of water pushed by the funnel effect, meant that water levels inside the levied neighborhoods equalized with the tidal water levees outside the levee system during the event. These waters reached a peak of about 15 ft (4.6 m) above sea level as Katrina passed, but started to drain back out through the breaches once the surge receded (van Heerden, et al. 2007). In New Orleans East, no breaches occurred and flooding resulted from rainfall and levee overtopping. Compared to the other polders, the elevation of the water surface was much lower, one foot below sea level. These flood waters could only be removed by the pump stations, a process that took a few days.

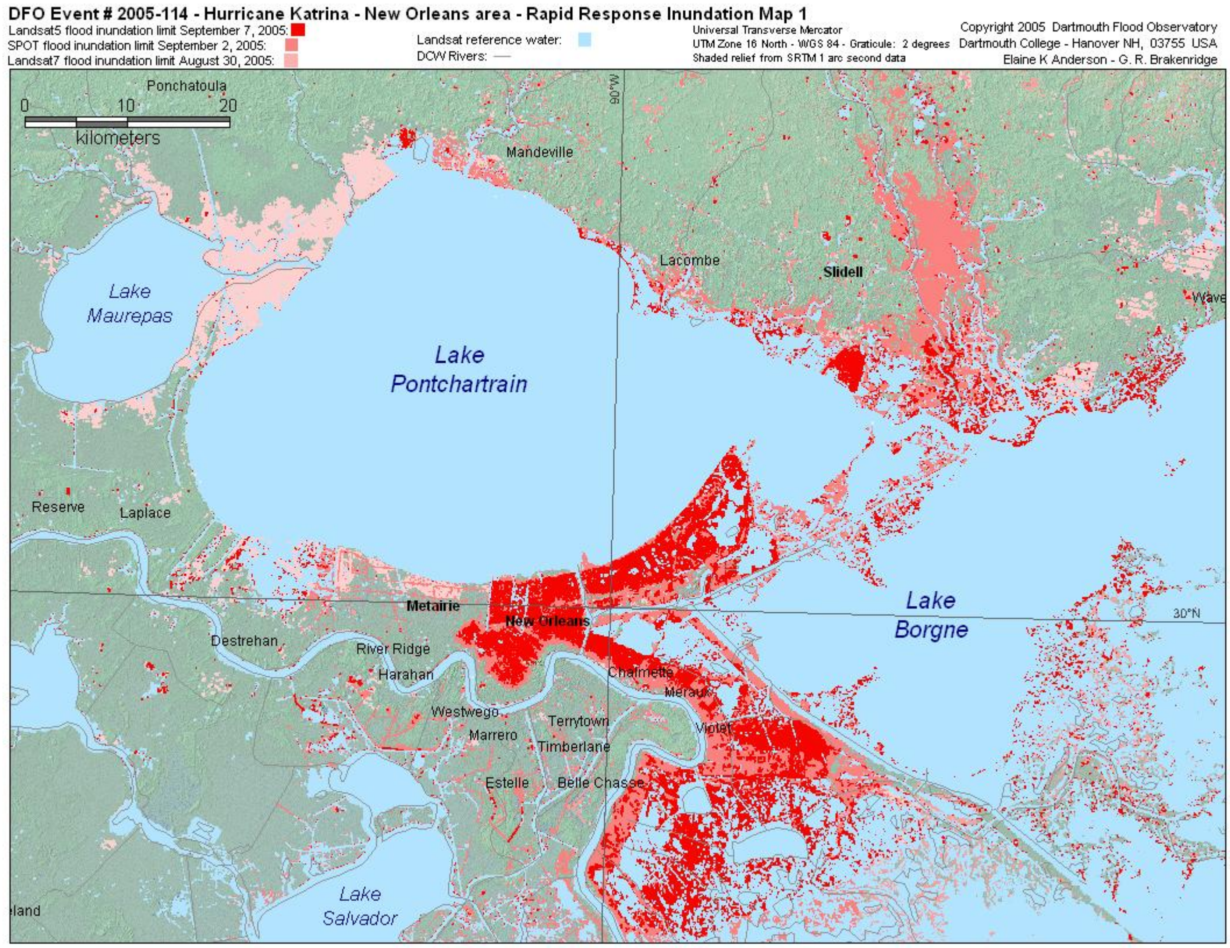

Figure 4.10: The Dartmouth Flood Observatory map, which is based on satellite imagery and remote sensing algorithms, shows the full extent of flooding in southeast Louisiana. In addition to heavy flooding in the urban areas of Orleans and St. Bernard parishes, flooding extended downriver from the city, around most of Lake Pontchartrain’s shoreline and throughout the Pearl River basin. (Dartmouth Flood Observatory 2005, Copyright 2005 by Dartmouth Flood Observatory used with permission under Creative Commons Attribution 3.0 Unported License).

In the end, many portions of greater New Orleans flooded, including approximately 80 percent of Orleans Parish, where water reached more than 15 ft (4.6 m) deep in some locations (see also Figure 4.11). All of St Bernard parish also flooded. Approximately two-thirds of Plaquemines Parish flooded, with surge waters first overtopping levees and then causing numerous structural failures (van Heerden, et al. 2007). A significant portion of the urban areas in Jefferson parish flooded due to rainfall and surge backflow through the pumping system. Much of southern St. Tammany Parish, including 80 percent of Slidell, also flooded. Throughout the region, isolated rainfall flooding entered homes and blocked roads.

Over the duration of the event, five distinct processes lead to floodwaters in Greater New Orleans. They are: direct storm surge in unprotected areas, rainfall, levee overtopping, levee failure, and pump backflow. Considerable debate revolves around the relative contribution of each process to the overall flood damage, particularly for parts of Orleans, St. Bernard, and Plaquemines parishes were levee failures were an important factor. The federally commissioned Interagency Performance Evaluation Team (IPET) claims that 65 percent of floodwaters within the levied areas of Orleans and St. Bernard Parish resulted from levee failures (Interagency Performance Evaluation Taskforce 2007), while the state commissioned Team Louisiana concluded that the actual number is 80 – 85 percent (van Heerden, et al. 2007).

4.5 Emergency Response

Flood Fighting

Once the storm had passed, a large portion of southeast Louisiana remained flooded with waters that would not all drain back to sea. While the incoming surge quickly overtopped the landbridge in eastern New Orleans [a natural ridge of land between Lakes Pontchartrain and Lake Borgne at about 3 feet (1 m) elevation], the receding high water was confined by this landscape feature and drainage could only occur though the two passes. In the days that followed, floodwaters continued to rise and spread across parts of metro New Orleans. Numerous flood fighting efforts were made. Locally, pump stations in Orleans and St. Bernard parishes (that were designed to fight a heavy rainfall and not a tidal surge) were used to pump floodwaters back into Lake Pontchartrain even though many of them suffered damage due to the storm. The levee workers from Orleans and Jefferson along with LADOTD began repairing the breach in 17th St Canal levee. They used the assets at their disposal, a fleet of dump trucks and reserves of rocks, to fill in the breach. After a few days the Corps coerced their way into being the boss at the job site. They brought with them impressive capabilities, including Blawkhawk helicopters and a supply of 3,000 pound sandbags. But, a reflection of their failure to anticipate and plan for possible structure failures in a Federally engineered and constructed floodwall[4], they forgot to bring the gurneys used to lift the sandbags with the Blackhawks. Soon after the Corps took over, progress in sealing the breaches slowed (van Heerden and Bryan 2006).

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[4] In an August 5, 2005 email, Harley Winer, chief of the coastal engineering section of the USACE's New Orleans District wrote "I don't think an engineered levee would fail during a storm" in response to a question from the author regarding whether hurricane response plans for New Orleans should include contingencies for possibility of "a major section of levee failing during a storm event" as had occurred during Betsy.

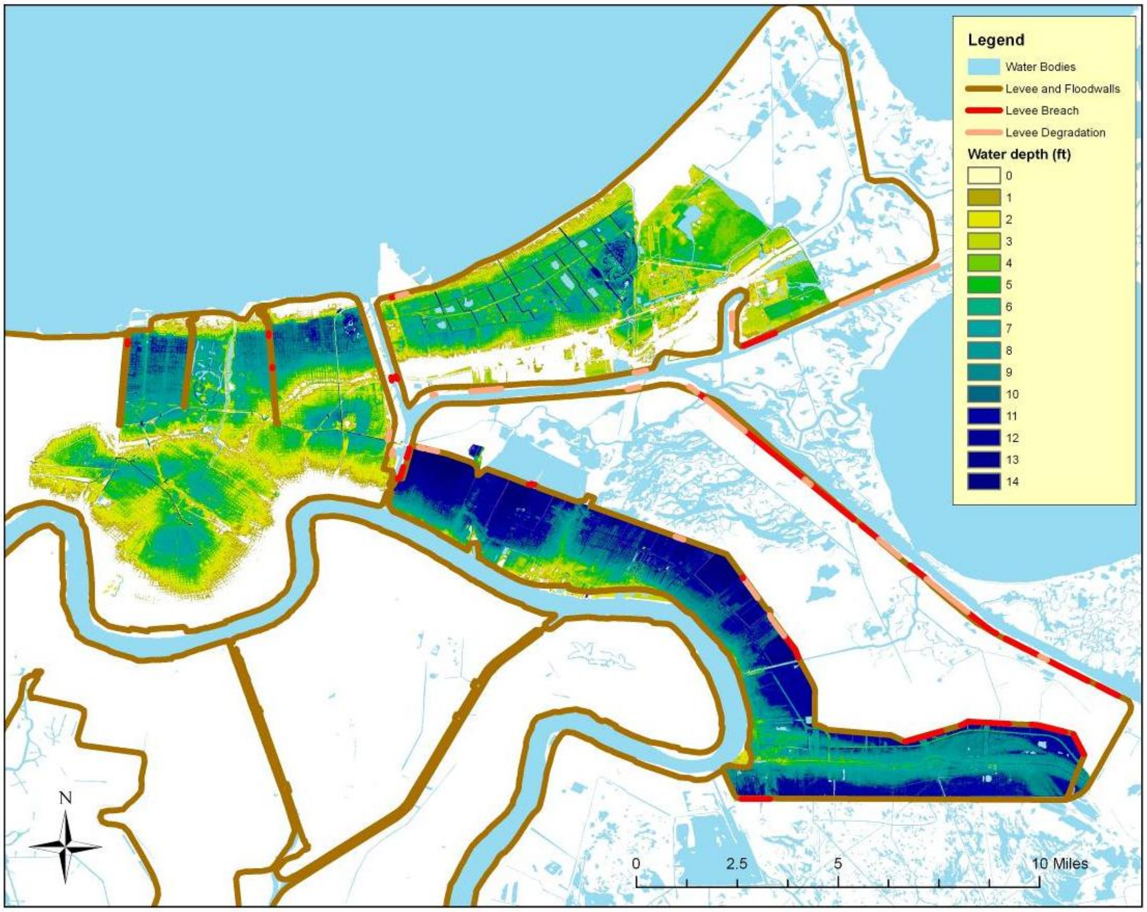

Figure 4.11: Levees, levee breaches, and flood depths for Orleans and St. Bernard parish. Note that the figure does not depict flooding in Jefferson, Plaquemines, or St. Tammany parishes. Sources: Flood Depths from Cunningham, et al. (2006) and Levees and levee breaches from van Heerden, et al. 2007).

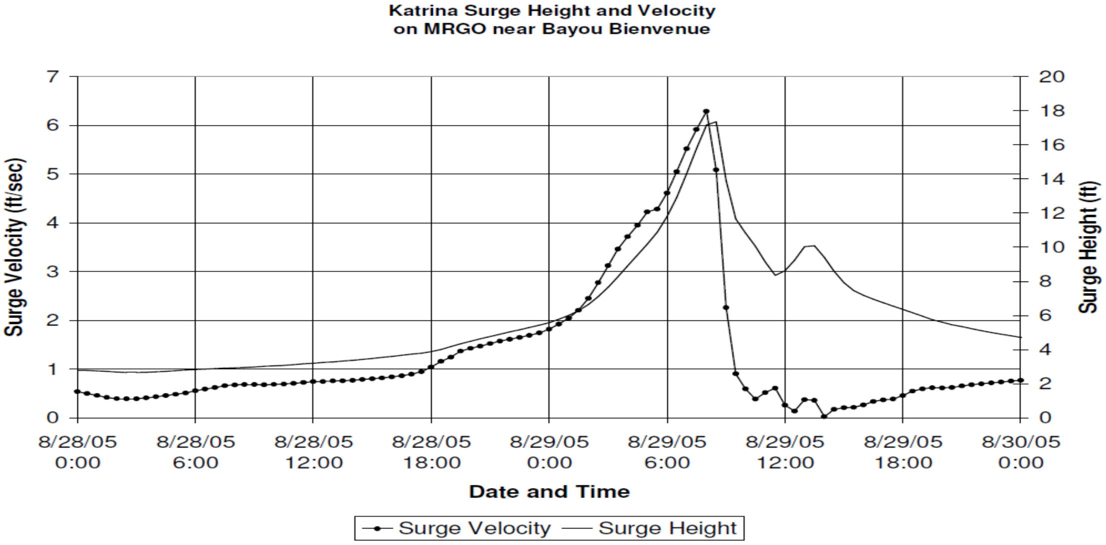

Figure 4.12: ADCIRC derived hydrograph with flow velocity for MRGO near Bayou Bienvenue (van Heerden, et al. 2007).

In the meantime, fatigued pump station operators struggled with stressed and damaged pump stations, and key pump stations started to fail. On Thursday morning, Nagin announced in an interview on a local radio station that, despite widespread efforts to get assistance, Pump Station #6 had failed and, in Nagin's words "water started flowing again into the city , and it started getting to the level that probably killed more people" (Forman 2007, p.134). When describing the consequences of Pump Station #6 failing Marcia St. Martin, the director of the agency that operated the pump stations, said "we will have no pumping capacity at all. That means within 15 – 20 hours the city if going to be even with Lake Ponchartrain" (Forman 2007, p. 93). Also that day, Nagin spoke with President Bush requesting assistance patching the breech in the 17th Street Canal levee, to which Bush reportedly promised to take care of the problem (Forman 2007).

Dewatering the city essentially required two tasks: 1) restoring pumping capacity , and 2) sealing the breaches so that the pumped water does not flow back into the city. Efforts to seal the breaches largely involved giant sandbags dropped by the helicopter or dump trucks of rock and fill. In some cases, emergency sheetpiling was driven into the ground. To get the water out, temporary pumps were brought in from around the world to augment pump stations. Dewatering operations, which were complicated by Hurricane Rita, took a total of 43 days.

Search and Rescue

This unprecedented urban flood disaster necessitated an unprecedented urban search and rescue (S&R) mission involving numerous local, state, and federal agencies along with private corporations and civilian volunteers. Individuals in peril had to be rescued from roofs and attics. Patients, staff, and family members had to be evacuated as hospitals and nursing homes became victims of both the flood and the wide spread emergency. The Louisiana Office of Homeland Security and Emergency Preparedness (OHSEP) estimates the number of people rescued at over 62,000 in addition to nearly 12,000 people from hospitals and nursing homes. Rescue operations involved over 100 helicopters and 600 boats (Louisiana Office of Homeland Security and Emergency Preparedness 2006).

The earliest rescues in flooded urban areas occurred in the Lower Ninth Ward by the LANG and LADWF soon after the winds subsided. The search and rescue operations continued for the next ten days. During this period the United States Coast Guard (USCG) performed or assisted in over 22,000 rescues of flooded residents plus 11,000 rescues from health care facilities (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, Committee on Homeland Security and Governmental Affairs 2006). The Louisiana DWF performed 22,000 rescues (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, Committee on Homeland Security and Governmental Affairs 2006, LaCaze 2005, LaCaze 2005b).

The LADWF Enforcement Division is the state agency tasked to lead search and rescue operations and their operations in response to Hurricane Katrina are described in a series of activity reports (LaCaze 2005, LaCaze 2005b). Figure 4.13 shows the timeline of rescues by the state teams. With a State of Emergency declared in Louisiana on the Friday before landfall, they began over the weekend mobilizing personnel, boats and other equipment from all over the state.

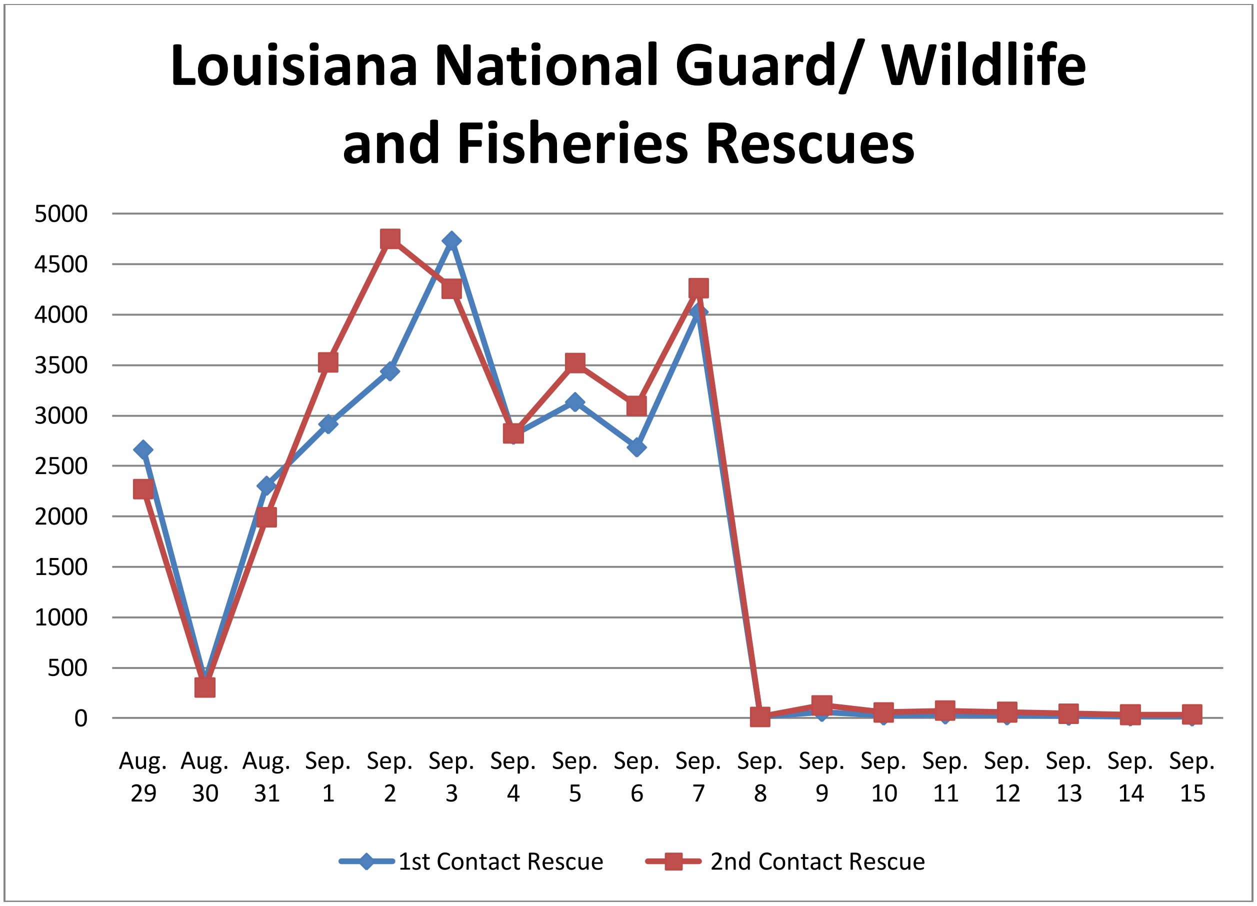

Figure 4.13: Timeline of rescues by Louisiana Department of Wildlife and Fisheries and National Guard (Louisiana National Guard 2005).

By the time that Katrina's hazards had arrived, LADWF had prepositioned with LANG at Jackson Barracks, a LANG facility that sits between the Lower Ninth Ward and St. Bernard parish. Though they encountered problems when the barracks flooded (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006), soon after the storm subsided they were still able to begin rescuing people from flooded houses in the Lower Ninth Ward, depositing them at two bridges that cross the INHC. At the same time, other LADWF rescue teams deployed from a staging area in Baton Rouge. Eventually, LADWF teams were engaged in continuous rescue operations, using interstate on ramps as launching points and "Lily Pads." As crowds grew at the lily pads, the expected ground transportation did not arrive. Thousands of people spent the night on the interstate or on bridges with only minimal supplies. In addition to the LADWF operations, the LADHH set up three SARBOO's (Search and Rescue Base of Operations) including one the at I-10 / I-610 merger near West End.

Sheltering and Relief

In the days immediately following the onset of the flood, response efforts focused on protecting life. On the ground, this first meant moving people from the immediate flood hazard and bringing them to the closest high ground, bridge, or elevated highway. A number of spontaneous drop-off points emerged were rescuees congregated but found limited relief. They were dry, so the flood hazard was no longer a threat. Limited and random supplies of food and water were available, but no shelter from heat. Some S&R teams were equipped and trained to provide basic first aid, but none were able to meet the overwhelming medical needs that presented themselves. These locations were only a temporary fix that did not address the additional crucial needs for sustained shelter, food, water, and medical care.

As search and rescue operations continued, the number of people at these locations continued to grow, with little relief coming, see Figure 4.14. Additionally, frustration grew as promised ground transportation to bring people to shelters and relief stations did not materialize (LaCaze 2005). Eventually, buses, vans, boats, and helicopters transported rescuees to the next stop on their journey of survival: one of the five post-storm emergency shelters / evacuation hubs.

By Wednesday the Superdome had reached capacity, and flood rescuees mixed with pre-storm shelterees. Three additional emergency shelters / evacuation hubs emerged: The Convention Center in downtown New Orleans, the Louis Armstrong Airport about 10 miles west of downtown, and the I-10 / Causeway Cloverleaf intersection about 5 miles west of downtown. While the Airport had an official designation and emergency response presence, the Convention Center was an ad-hoc gathering of people and had no response other than a few officers from NOPD. The airport was also used as a field hospital and medical evacuation hub with between 3,000 and 8,000 patients being treated (Miller 2005). The Cloverleaf can best be described as

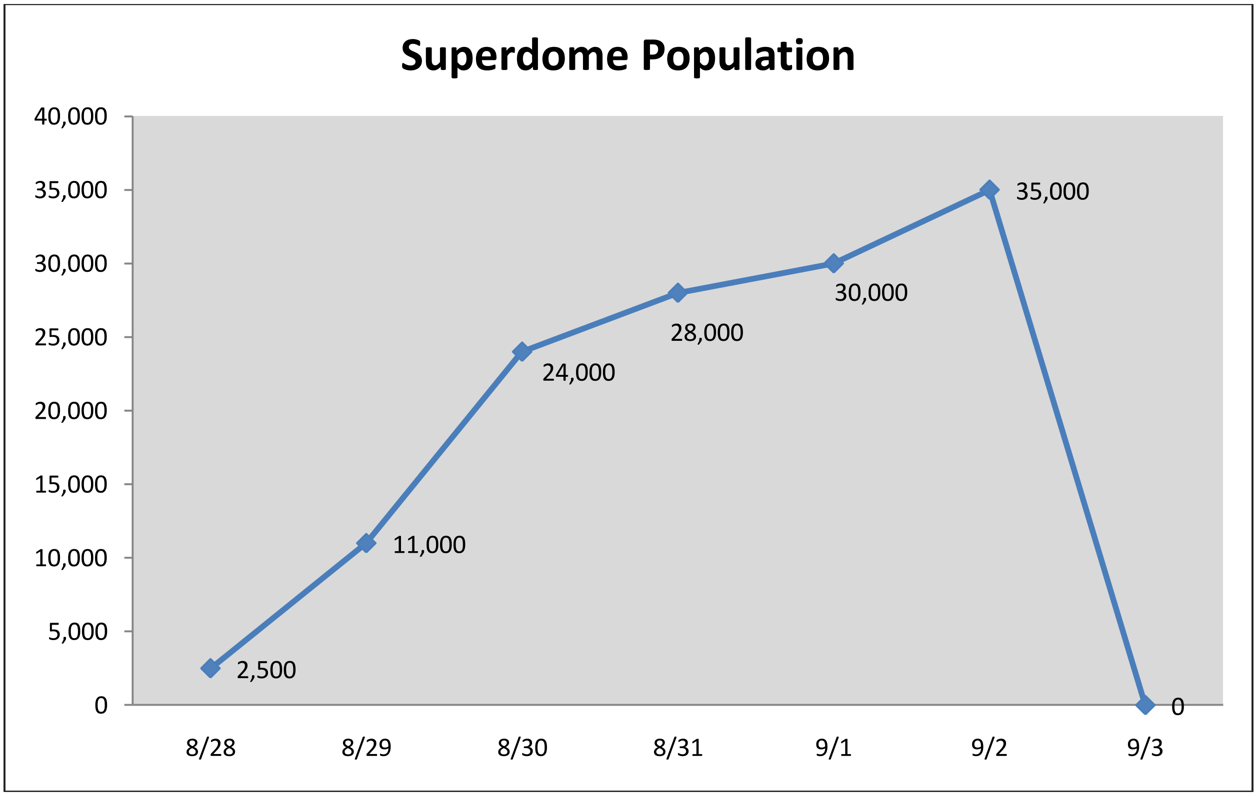

Figure 4.14: Timeline of Superdome population (Louisiana National Guard 2005).

functioning as a relief valve for the pressure created by all the desperate people trapped in New Orleans. Though not official, this location was on the state's radar, and limited relief assets were sent their including ambulances, a field medical clinic, truckloads of MRE's and water, and a LANG unit. The sheltered population at these locations continued to grow in the days that followed the hurricane. In total, an estimated 94,000 people would be evacuated from these three locations and the Superdome.

As conditions in the Superdome deteriorated, the special needs clinic run by state and local health officials relocated to the neighboring New Orleans Arena. They continued to provide services, mostly chronic disease management, to the patients that arrived before landfall, but they also received people with a variety of ailments from the growing crowd in the Superdome. Search and Rescue dropped off a variety of injuries and other ailments. State health workers setup an aid station at I-10 / I-610 split in western Orleans Parish to serve flood rescues, and the few ambulances that were available were used to evacuate the most severe cases to Baton Rouge. The single DMAT initially deployed to the Superdome quickly became overwhelmed, and soon retreated.

Final Evacuation

As the catastrophe in New Orleans continued to grow in the days following landfall, it became evident that a complete evacuation of the city was required to minimize exposure to numerous widespread and persistent hazards. Given the estimated 100,000 destitute people gathered at various locations around the city, it was clear that massive outside assistance would be required. At 1:30 am Wednesday, the first task order requesting buses from the Federal government was completed and the first round of buses arrived later that day (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006).

Hours later, the first bus arrived at the Cloverleaf and by that afternoon this collection point had been cleared. On Thursday morning the evacuation of the Superdome began, and on Friday buses arrived at the Convention Center (Committee on Homeland Security and Governmental Affairs 2006). By Sunday, most of the City was cleared out, a process that took five days to complete. Complementing the ground transportation, commercial airlines were used to evacuate 13,000 people from the airport (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006).

In this final step of the evacuation, people were taken to emergency shelters and transitional housing around the country.

Once on an evacuation bus, people were taken to shelters throughout Louisiana, and then throughout the United State. Within Louisiana, three Temporary Medical Operations and Staging Areas (TMOSA's) were set-up to triage evacuees with medical needs. The TMOSA set-up on the Louisiana State University campus in Baton Rouge consisted of 800 beds and has been described as the largest acute care field hospital ever created in the United States (Committee on Homeland Security and Governmental Affairs 2006, Guidry 2006). At this location, over 40,000 evacuees were triaged and 6,000 people received basic medical treatment. The second TMOSA's, setup on Nichols State University in Thibodaux triaged nearly 20,000 evacuees

Table 4.3: The final evacuation (Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina 2006, Louisiana National Guard 2005, Louisiana Department of Transportation and Development 2005, Federal Emergency Management Agency 2006).

Location	**Shelter Opened**	**Evacuation Starts**	**Evacuation Ends**	**Number Evacuated**
Superdome	Aug. 28, 12 pm	Sept. 1, 10 am	Sept. 3, 2:00 pm	40,000
Convention Center	Aug. 30	Sept. 3, 10 am	Sept. 3, 6 pm	19,000
I-10 Cloverleaf	Aug. 30	Aug 31, Afternoon	Aug 31, Night	7,000
Armstrong Airport	Sept. 1	Sept 2	Sept 9	26,000
Algiers Ferry				7,000
			Total Evacuated	99,000

(Guidry 2006). For tens of thousands of evacuees, the TMOSA's represented an important transition from an acute emergency to a transitional phase.

Break Down of Public Health and Safety Systems and Infrastructure

In the aftermath of Hurricane Katrina and the levee failures, the sheer number of destitute people caught in the flood zone, the refuges, and the hospitals of heavily impacted New Orleans and surrounding areas created a large magnitude public health emergency. However, the cascading impacts of this complex disaster created additional stresses on basic public safety infrastructure and systems that ultimately lead to the breakdown of these systems.

Fires and spills quickly emerged as a cascading effect of the flood. As homes and neighborhoods flooded, garages and workshops also flooded, leading to numerous small point sources of toxic compounds mixing with floodwaters (Torres 2005, Pardue 2005). At the same time, numerous major industrial facilities that flooded or suffered wind damage released additional hazardous materials into the mix. Most notably, a flood damaged kinked pipe at a refinery in Chalmette caused oil to spill into floodwaters, affecting over 2,000 homes.

The cascading impacts of this disaster also wore down the psyche of that population that remained in New Orleans, with looting and lawlessness emerging by Wednesday. In the Superdome, the sheltered population grew as rescuees arrived, but buses did not. On Wednesday, FEMA stopped distributing MRE's, reportedly in response to displays of frustration in the distribution line (Duncan 2006). This event initiated a rapid descent there, with chaos prevailing throughout the Superdome just a few hours later. As the same time, 21,000 people gathered at the Convention Center, with only limited security provided by a handful of police officers (Peristein and Lee 2005).

Outside these shelters, social descent also quick took hold. Reportedly, the Mayor and his command center came under attack by a mob (Forman 2007), while both a Sewerage and Water Board facility (Forman 2007) and the NOPD's 1st District station both received shots fired (Peristein and Lee 2005). Looting was widespread, but most rampant on Canal Street, the Garden District Walmart, and the Oakwood mall on the Westbank.

Across the Mississippi River and outside the flood zone, events of the Westbank demonstrate the expansion of the breakdown beyond the spatial extent of the flooding. Looters here set the Oakwood mall on fire (Brown 2005). On September 5, an Algiers resident allegedly shot at a Coast Guard Rescue helicopter with a handgun from his apartment and was then overheard by Federal ATF agents as telling his friend "they won't be back now" (Filosa 2005, Hamilton 2005, Purpura 2006). The Jefferson Parish Sheriff reported four separate shootouts involving either law enforcement or relief workers (Brown 2005). Citing this violence, law enforcement officers in Jefferson Parish enforced a blockade on the bridge crossing the river from downtown New Orleans, and forced residents fleeing the Eastbank on foot to return (Anderson 2005, Forman 2007). On September 1, two white Algiers residents who had formed a neighborhood militia shot an African-American resident (Thompson, ProPublica, and MrCarthy 2010).

These conditions created overwhelming stresses on all of the major systems entrusted with maintaining public health and safety. As an institution, the NOPD felt these stresses mostly acutely, and eventually cracked. While it seems that the majority of individual police officers performed professionally even under the most extreme conditions that this disaster caused, a large portion either abandoned their posts or are implicated in property and/or violent crimes. The currently available evidence suggests that a number of officers committed civil rights violations against citizens that remained in New Orleans.

Out of a force of approximately 1,500 officers, it was initially reported that approximately 500 had abandoned the force. Upon investigation, it was determined that approximately half of those who had not reported for duty where either assisting residents while unable to communicate with command or were themselves trapped by floodwaters. Still nearly 250 officers have been investigated for abandonment, looting, or other allegations, while nearly 140 of these were either fired or resigned while under investigation (Peristein and Lee 2005). In addition, seven separate police shooting incident, many of which are currently under investigation by FBI, left four people dead and seven injured (Peristein and Lee 2005, Thompson, McCarthy and Maggi 2009).

Two police shootings occurred on Thursday, September 1, four days after Katrina hit. In the Garden District, at the corner of Race and Religious Streets, police detained two men who they said were shooting at police. While reporters stated that they witnessed that the men had been shot and appeared dead, police have stated that the men were released unarmed. However, no police report on this incident was every filed (Russell 2009). That same day, on an elevated section of Interstate 10 near the Superdome, two police officers shot a man who they said brandished a gun on them. The victim survived, no gun was found, and charges against him were dropped (Thompson, McCarthy and Maggi 2009).

On September 2, Danny Glover was shot by police outside of an Algiers shopping mall. A second civilian in a car found the wounded Glover and offered him assistance. They then drove to a makeshift headquarters for the SWAT team, where the driver was detained and beaten while the car with body was driven to Mississippi River batture (a strip on land on the riverside of the levee) where it was set on fire (Thompson, McCarthy and Maggi 2009).

The next day, on September 3, NOPD officers shot and killed Danny Brumfield in front of the Convention Center. The officers involved stated that he was attacking their patrol car with a pair of scissors, while his family states that he was trying to wave them down for help (Thompson, McCarthy and Maggi 2009). Later that day, in the Fouberg Marigny, near the end of the French Quarter, police shot and killed Mathew McDonald, stating the he failed to comply with orders that he drop a bag believed to be containing a gun. No gun was found on the victim, and his family was later told by police officers that he was killed by an unknown civilian (Thompson, McCarthy and Maggi 2009).

On September 4, two civilians were killed by police and four others shot on the Danzinger Bridge. In this incident, police responded to a call that snipers on the bridge had been shooting at a rescue helicopter and opened fire on fleeing civilians that were crossing the bridge to find supplies and refuge (Thompson, McCarthy and Maggi 2009).

Initially, it was reported that 2 police officers committed suicide (Peristein and Lee 2005). In one of these cases, published and credible eyewitness accounts attest the officer in fact took his own life (Forman 2007). However, the second reported officer suicide is currently being re-examined by the NOPD with assistance from the FBI and may provide a shocking indication of the degree of breakdown that occurred within the NOPD. Recent reports have suggested that the second officer that died of close range gunshot wounds while on duty may have been executed by fellow officers involved in one of the fatal civilian shootings (Paulson 2010, Maggi 2010). The original police report was written by a Sergeant who has been implicated in the coverup of the Danzinger bridge shooting (Paulson 2010, Maggi 2010). The current NOPD police chief has described the initial report on this death as “It's garbage. Useless to us. That's why we're recreating the investigation from the very start” (Paulson 2010b). The officer’s wife maintains that her husband did not kill himself, and the police chief has noted irregularities on the suicide note (Paulson 2010, Maggi 2010).

4.6 Summary of General Impacts

In 2005, Louisiana had a population of just over 4 million. Approximately 1.2 million people resided within the New Orleans-Metairie-Kenner Metropolitan Statistical Area, which consisted of the 7 parishes most heavily impacted by Katrina. While every neighborhood and community in southeast Louisiana experienced major damage from Hurricane Katrina, there was considerable variance in the magnitude and type of damage. North of Lake Pontchartrain, damaged consisted primarily of wind damage, with some flooding occurring along the rivers and the lakeshore. An estimated 15,000 homes along Lake Pontchartrain or adjacent to the Pearl River experienced direct surge effects and suffered major flood damage Department of Homeland Security (2006). Power, phone, and cable were temporarily out everywhere, but most of the basic infrastructure escaped significant damage and the needed repairs went quick. South of Lake Pontchartrain, wind damage was everywhere and flooding was widespread. Many homes were rendered uninhabitable, most by water but some by wind. Electrical, natural gas, communications, water, and sewerage systems were inoperable throughout. No one returned to a community that was absent damage and disruption. While a few returned to homes and neighborhoods that could be made habitable within a few days or weeks, many people faced uncertainty and extended displacement from homes and neighborhoods that suffered considerable damage.

Once Katrina had passed, nearly 900,000 people were left without power in southeast Louisiana (Federal Emergency Management Agency 2006). FEMA determined that every parish within the State of Louisiana was eligible for some type of assistance, either public or individual. Of these parishes, 23 had been declared eligible for both public and individual assistance. According to an assessment completed by the Department of Homeland Security (2006), over 500,000 homes suffered some sort of damage, affecting over 1.6 million residents or nearly 40 percent of the state's population. Of the damaged homes, approximately 106,000 were classified as severely damaged or destroyed. Of these, nearly 102,000 were severely damaged or destroyed by flood waters.

While the human suffering was certainly greatest where the flood conditions were worse, it is also true the area suffered from a regional emergency that extended well beyond the flooded areas. Power and communications were wiped out for much of southeast Louisiana. Down trees and power lines blocked roads throughout the region, making delivery of essential commodities difficult. Many hospitals in these areas were closed, while those that remained open suffered from a surge of patients and a lack of staff. Businesses, both family-owned and corporate, were shut down. Many essential public services, including water and sewerage, were unavailable. Numerous fires raged throughout the region, while firefighters were overwhelmed by immediate live or death tasks of rescuing flood victims. Throughout Louisiana, evacuees strained the host community services and businesses.

The next chapters provide a much more thorough assessment of the population in Louisiana impacted by Hurricane Katrina.

4.7 Conclusion

When interpreting the outcomes of disasters, health scientists often present the incidences of outcomes relative to an underlying "At Risk" population. Typically, analysts employ a static view of the population. For example they might employ Census numbers to estimate how many people lived within a flood zone. The typical analysis also considers exposure to only a single hazard.

In regards to hurricane and flood disaster that impacted southeast Louisiana, the notion of a static "At-risk" population does not fully capture this story. This disaster event is a dynamic story of population movements in the face of numerous real and perceived threats. Over the course of nearly two weeks, nearly 1 million people endured one or more of the following: evacuation / displacement, extreme winds, flood exposure, overcrowded and undersupplied emergency shelters, hot days trapped in an attic, nights sleeping at a Lily Pad with only minimal supplies, toxic pollution, disruption of medical services, lawlessness, and other aspects of the widespread regional emergency.

Waters Dark and Deep: One New Orleans Family's Rescue Amid the Devastation of Hurricane Katrina (Thomas 2006) describes these distinct stages of population movement and hazard exposure for one family. Some members of the family evacuate before the storm, while others were unable to muster the wherewithal to get out in time. The family members that stayed soon find themselves trapped in an apartment building surrounded by floodwaters. The family is further separated when the first search and rescue helicopter takes the kids and one adult to the I-10 Cloverleaf, while a second helicopter takes the other adults to the Lakefront Airport. Following their emergency, assisted evacuation from New Orleans a partial reunion occurred in Baton Rouge, and then a second reunion occurred in San Antonio. Like so many other aspects of the Hurricane Katrina, this family's story also got obscured in the "Fog of War" when national media outlets reported that, instead of being separated by search and rescue teams, the kids had been abandoned by their family.

This complex sequence of population movements and hazard exposures coupled with the confused early reporting created the need for a systematic, data-based approach to assessing this dynamic "At Risk" population. Utilizing numerous Census data, traffic counts, evacuation and sheltering figures, and numerous after-action reports this chapter told the story at a population level. Tracing the sequence of warnings, evacuation calls, and then evacuation observations, it was estimated that over 1 million people evacuated. While these people avoided the wind and flood hazards, they still endured risks associated with their evacuation and displacement. Once the evacuation completed and Katrina's hazard conditions took hold, approximately 130,000 people remained in the four hardest hit parishes of southeast Louisiana. Of these, approximately 65,000 would suffer flood exposure;100,000 would endure overcrowded and unsanitary conditions at one of five emergency shelters / collections points; 2,500 patients sat in hospitals without power or supplies; approximately 3,400 residents sat in nursing homes, hundreds spent a hot day trapped in their attics, tens of thousands spent a night on an elevated expressway, a bridge, or some other Lily Pad with only minimal supplies, and untold thousands suffered from a widespread regional emergency characterized by the breakdown of basic public health and safety infrastructure and systems.

Chapter 5: Study Areas, Background Population, and Extent of Hazards

While the previous chapters provided the necessary background for understanding the context of Hurricane Katrina and 2005 flooding of New Orleans, this chapter sets the stage for the analysis of fatalities associated with the disaster. This chapter begins the analysis with delineating the study areas, describing the background population, and quantitatively assessing the numerous hazards to which this population was exposed. In short, this chapter presents the background GIS layers needed for analysis and interpretation of fatalities due to Hurricane Katrina and the levees failures in Louisiana. This chapter can also be described as presenting the first three steps of risk-based disaster research: 1) specify the study area, 2) determine the “at risk” population, and 3) assess the hazard exposure.

5.1 Study Areas and Units of Analysis

Defining the study region and the spatial units of analysis are important first steps in geographic research, though a step that is complicated when studying an event such as Hurricane Katrina. This multi-hazard event affected numerous distinct populations at a variety of spatial scales. The large windstorm made landfall along two separate U.S. coastlines and impacted numerous coastal and inland states. Significant inland impacts occurred hundreds of miles inland from the area of Gulf Coast landfall. Both between and within the affected states, the hazards and impacts of the storm varied considerably. Within Greater New Orleans, a major natural disaster was accompanied by a catastrophic engineering failure that resulted in a regional public health emergency and displacement disaster. Even if the focus is narrowed to include just the health outcomes associated with Katrina’s impacts in Louisiana, a narrow study region confined to just Louisiana would exclude the impacts experienced by Louisiana residents who evacuated out of state. Because, these out-of-state health outcomes are an important part of the Katrina disaster, it is important to adopt a broad study area that includes these outcomes. On the other hand, when modeling the direct flood deaths, many of whose location of death is precisely known, it is important to utilize a study area that accounts for the neighborhood level variance in the flood conditions. To best address these needs and to provide multiple perspectives on the issue of health outcomes associated with Katrina’s impacts on Louisiana, a hierarchy of study areas are described below and utilized through the remaining analysis. Basically, the microscope is systematically fine-tuned to explore greater detail at finer scales.

Technically, the United States is the first study area in the hierarchy. This study area is necessary to include Louisiana residents that evacuated out of state before or after the hurricane and to depict Hurricane Katrina’s physical hazards in their totality. However, this step in the analysis is a cursory look largely confined to general trends related to evacuation and displacement related health outcomes amongst the Louisiana population affected by Katrina. Beyond the national view, the primary study areas that are utilized in the analysis are: 1) Louisiana, 2) southeast Louisiana, 3) Metro New Orleans, and 4) Orleans and St. Bernard parishes. This sequence of study areas systematically views outcomes of interest across many scales. The next section presents the natural, human, and built landscape features of these study areas, while the subsequent sections present the rationale for choosing these study areas.

Louisiana

Louisiana (see Figure 5.1, 5.2, 5.3, and 5.4) is a state of about 4 million people that is considered part of the Deep South Cultural region of the United States (Birdsall and Florin 1981). The state is entirely within the Gulf Coast Physiographic Plain, a landscape feature that shows the effects of previous periods of higher sea levels (Yodis and Colten 2007). As such, the state is largely flat and low lying. As described in Chapter 2, the Mississippi River dominants the state's landscape, with the coastal zone a direct result of sedimentation from the river.

In 2005, the population of Louisiana was 4,068,028 (Census 2005), a 9 percent drop from the 2000 population of 4,468,976 (Census 2002). About half of this population lives within the coastal zone. Two population and economic centers, Metro New Orleans and Lake Charles, are located within the Mississippi Deltaic Plain and others are located along the periphery of the Deltaic and Chenier Plains, see Figure 5.3. Gagliano (1972) describes an economic circle that encompasses the coastal plains and adjacent terraces. Outmigration had long been the trend for Louisiana, some of the reasons for which are illustrated in the next section. Throughout much of Louisiana, levees are an important feature of the landscape (see Figure 5.4).

Figure 5.1: True-color Landsat Satellite Image of Louisiana (Guidry and Gisclair 2007).

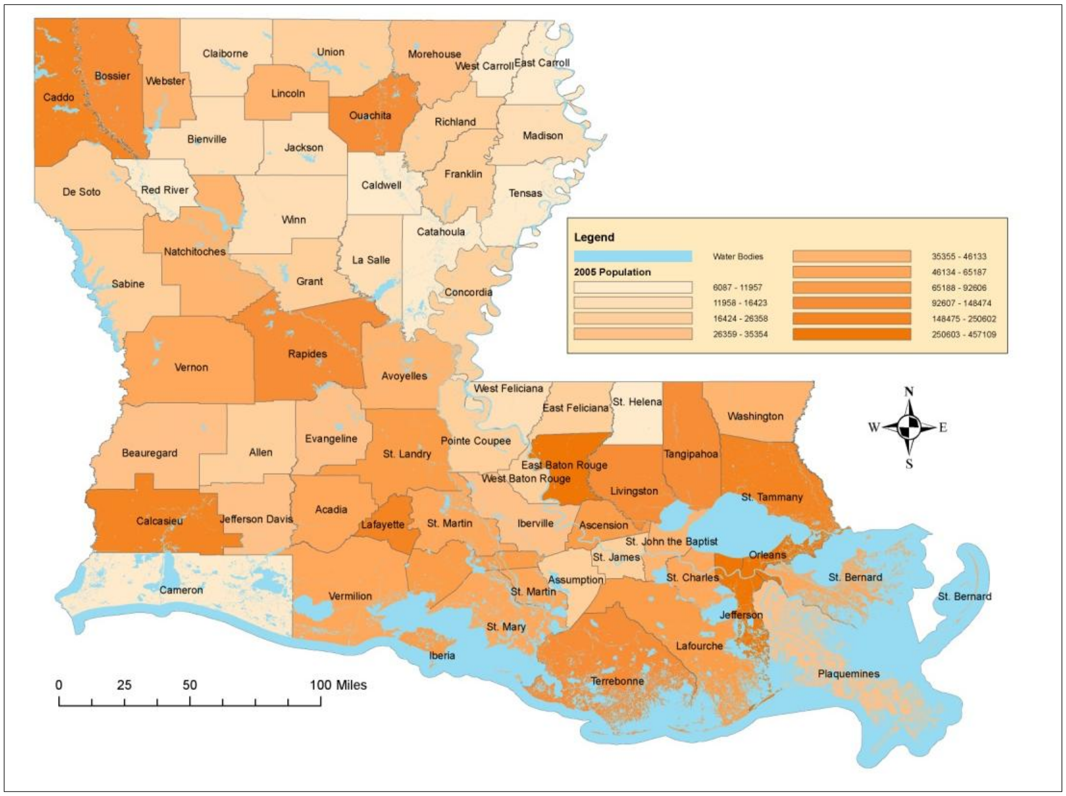

Figure 5.2: Parish boundaries and water features for Louisiana (Guidry and Gisclair 2007).

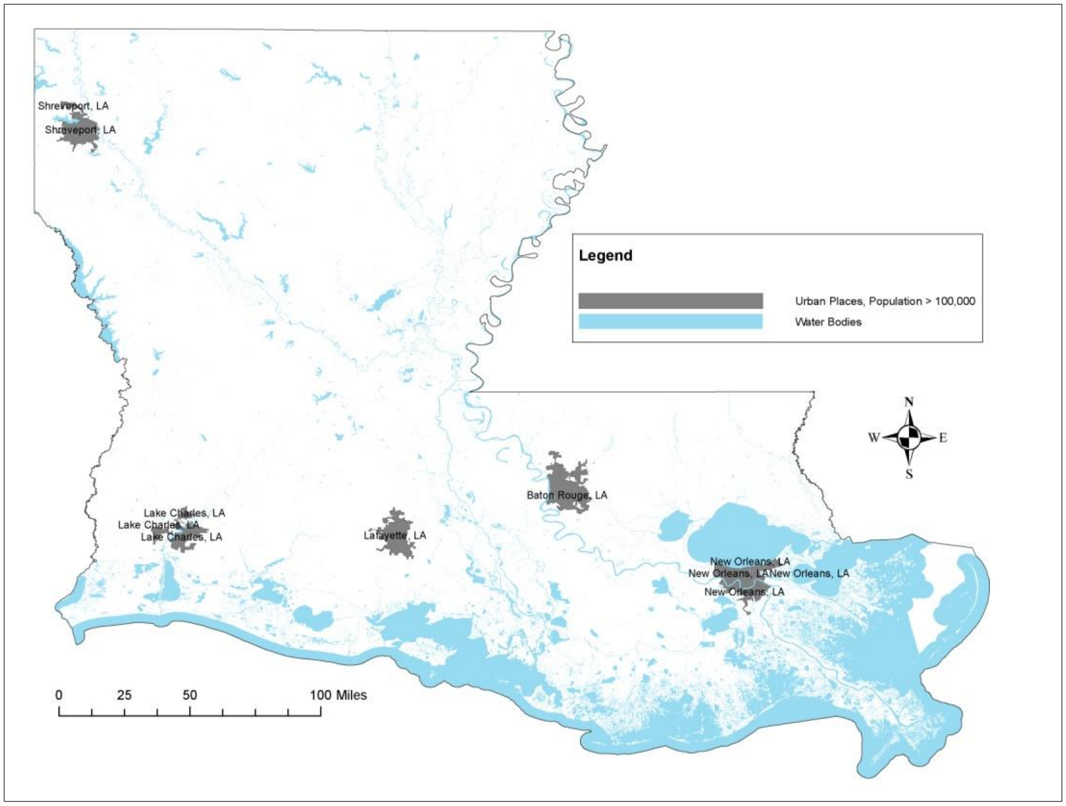

Figure 5.3: Major Urbanized areas and waterbodies of Louisiana (Guidry and Gisclair 2007).

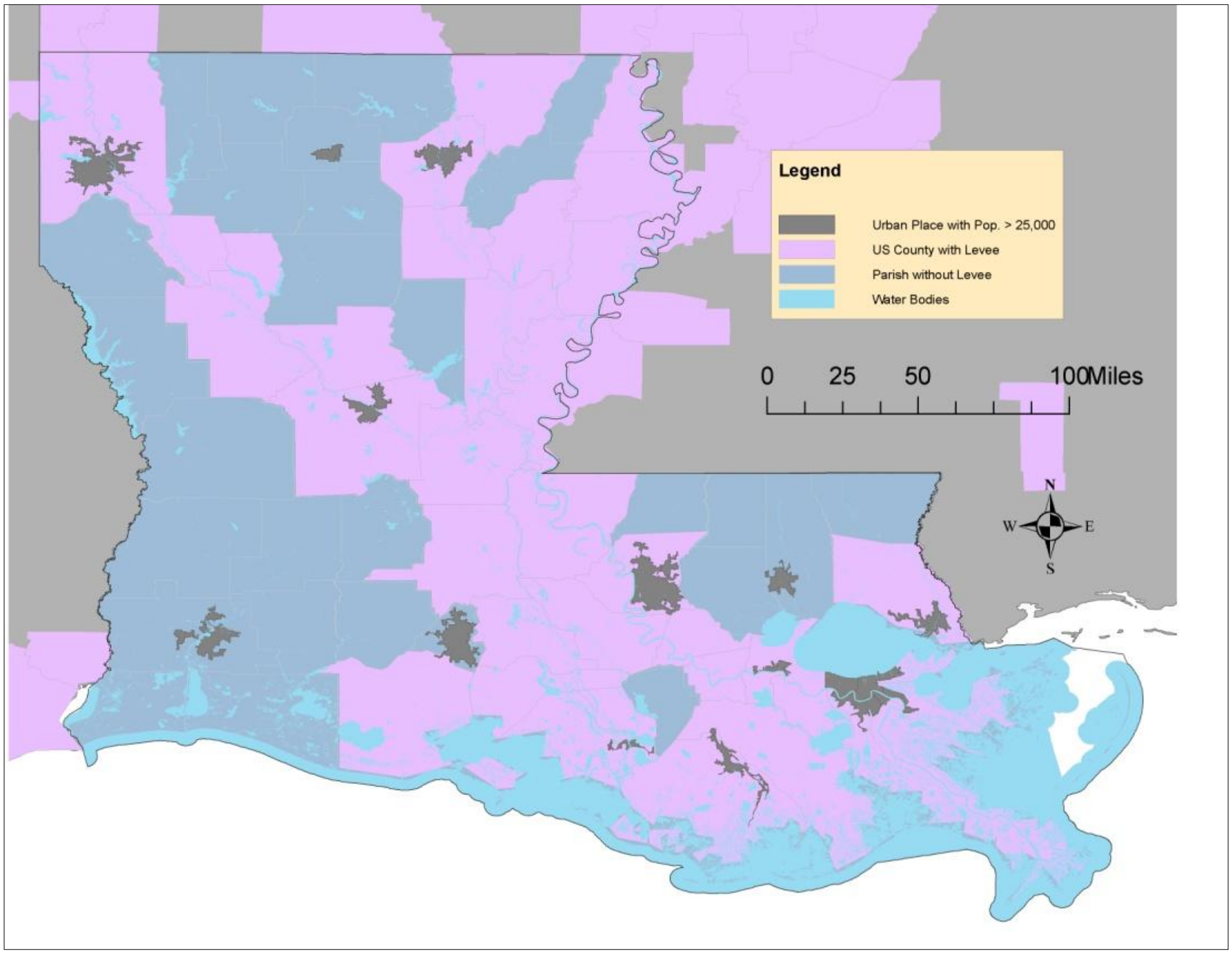

Figure 5.4: Louisiana parishes with levees (Boyd 2009).

Southeast Louisiana

Reflecting the influence of French and Spanish Catholicism, Louisiana is divided into 64 parishes which are functionally equivalent to counties. From these 64 parishes, the southeast Louisiana region is designated as a 13-parish region chosen because of location adjacent to the key water bodies of the region, including the Mississippi and Pearl Rivers; Lakes Pontchartrain, Borgne, Maurepas, des Allemandes, and Salvador; the Barataria and Terrebonne Bays, and the Gulf of Mexico. The parishes are: Jefferson, Lafourche, Livingston, Orleans, Plaquemines, St. Bernard, St. Charles, St. James, St. John the Baptist, St. Tammany, Tangipahoa, Terrebonne, and Washington. These parishes are susceptible to storm surge related flooding when hurricanes make landfall along the southeast Louisiana coastline, though not all of these parishes suffered flooding during Katrina. This area roughly correlates with Yodis and Colten's (2002) Circum-Pontchartrain region. In 2005, the area encompassed a total population of 1,798,457, about 45 percent of the state's population (see Figure 5.5).

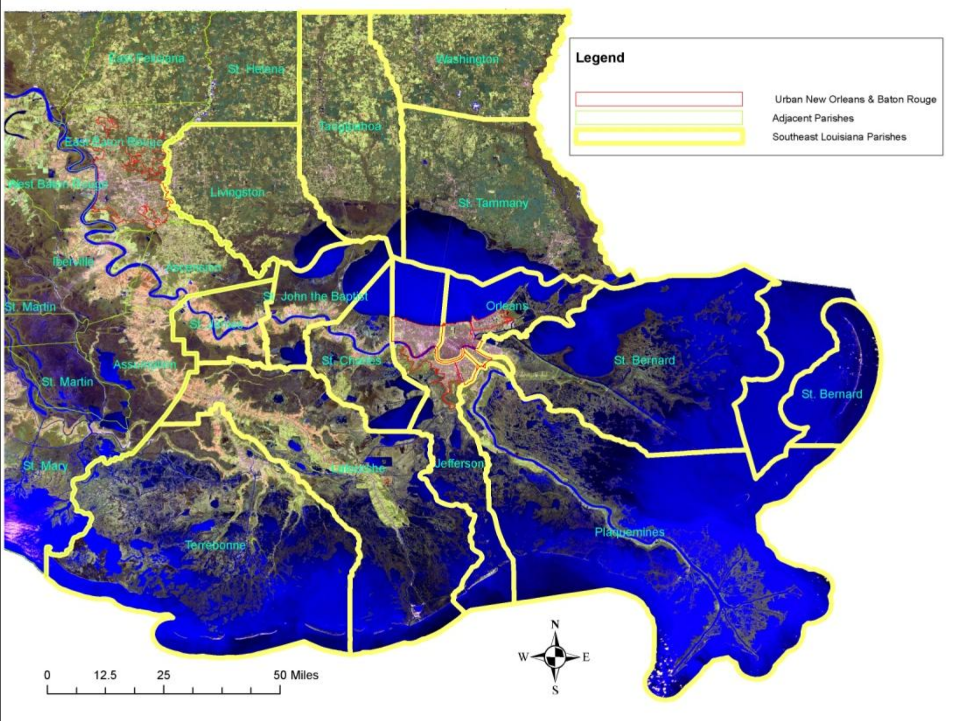

Figure 5.5: The 13-parish southeast Louisiana Region. Traditionally the entire area shown in the map comprises the functional-cultural region of southeast Louisiana, which extends to Baton Rouge. The delineation used here includes a more restrictive set of parishes selected based on proximity to tidal waterbodies or, in the case of Washington Parish, in the far Northeast, proximity to the trajectory of Hurricane Katrina (Guidry and Giscliar 2007).

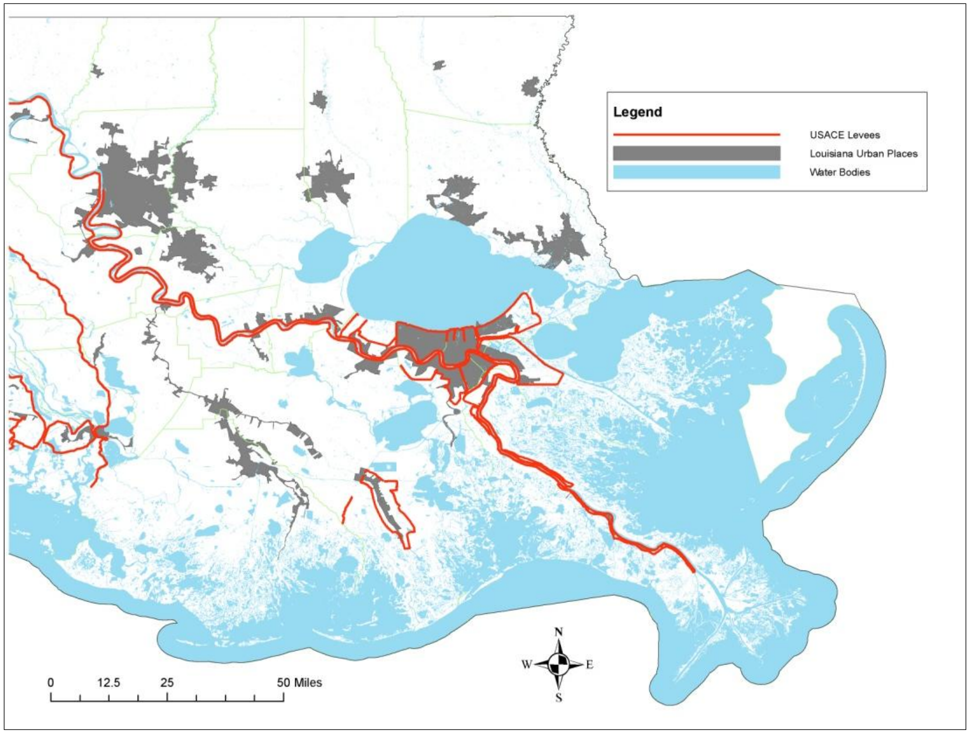

Figure 5.6: Urban areas, Federal levees, and waterbodies in southeast Louisiana (Guidry and Gisclair 2007).

Metro New Orleans

Within southeast Louisiana lies the New Orleans-Metairie-Kenner, Louisiana Metropolitan Statistical Area (hereafter referred to as Metro New Orleans, see Figures 5.7, 5.8, 5.9), an official designation of the U.S. Census that includes Orleans, Jefferson, St. Bernard, Plaquemines, St. Tammany, St. Charles, and St. John the Baptist parishes. Being adjacent to New Orleans or immediately up the Mississippi River, these 7 parishes from a region based on daily economic interactions. This seven parish region had a 2005 population of 1,190,615 (Census 2005).

Within this region, exists what can be described as the Metro New Orleans Central Urban Area, see Figure 5.9. This study area consists of the central continuous urban conglomerate that includes portions of Orleans, Jefferson, and St. Bernard parishes along with peripherial places within Plaquemines and St. Charles parishes. This entire region is distinct because it constitutes a continuous urban conglomerate that is completely within the U.S. Army Corps of Engineers major flood protection levees. While Metro New Orleans is an official designation of the U.S Census with relevant data compiled and available, the central urban area makes a better study region because of the concentration of disaster impacts across this urban area.

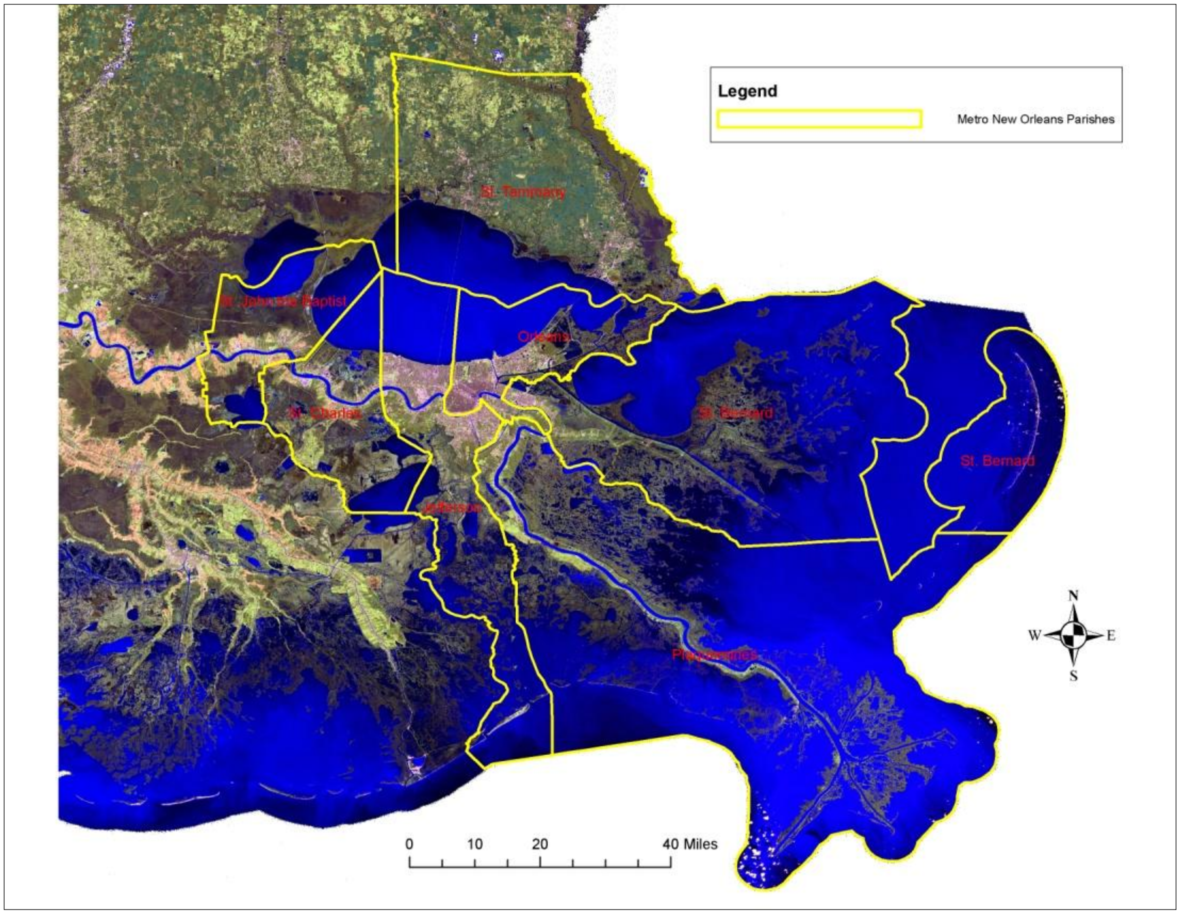

Figure 5.7: The 7 parishes that make up the New Orleans-Metairie-Kenner, Louisiana Metropolitan Statistical Area, the Census's official designation of what constitutes Metro New Orleans (Guidry and Gisclair 2007).

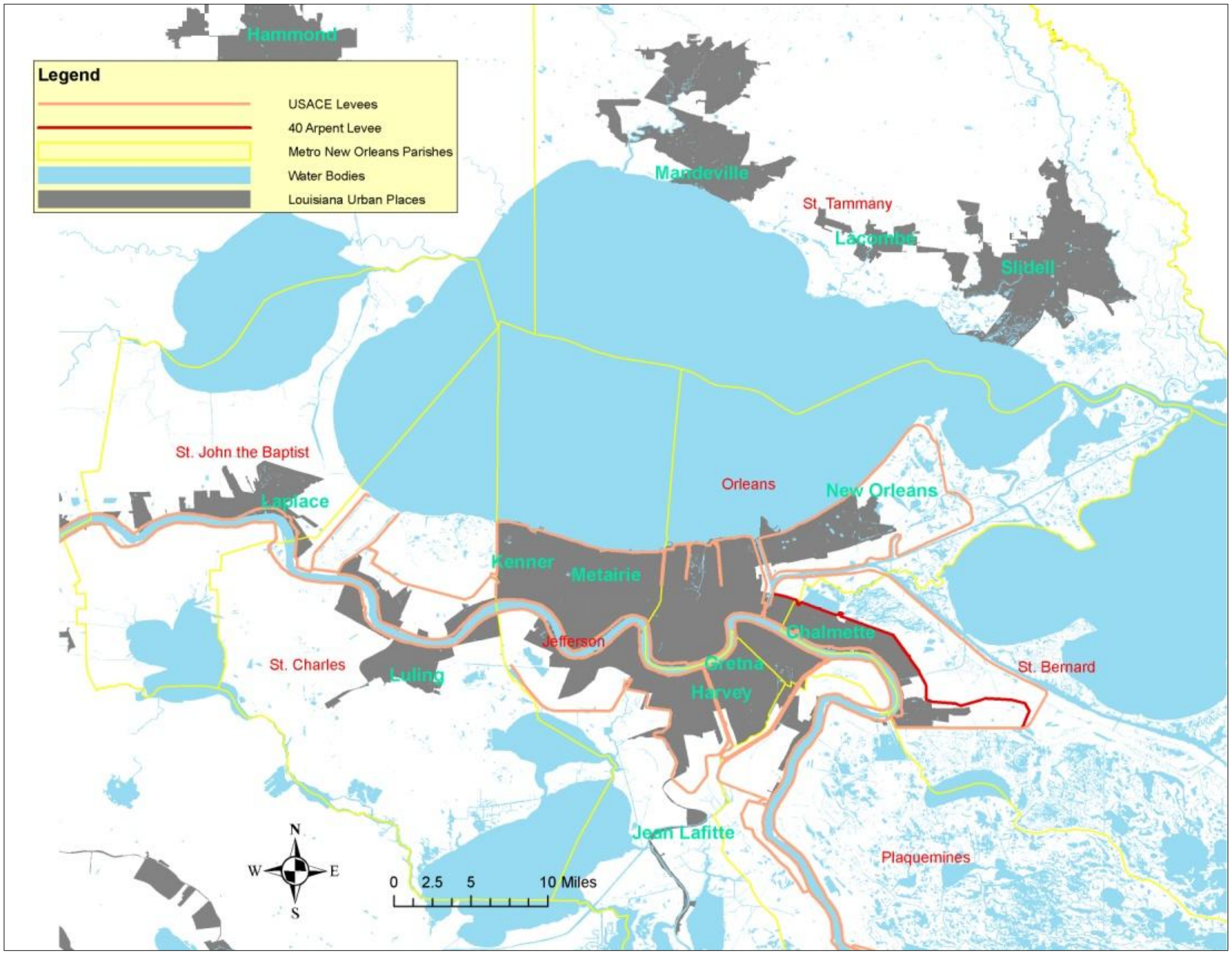

Figure 5.8: The urban areas within Metro New Orleans. Census determined urban areas are shown in grey. The central Feature consists of New Orleans and urban parts of Jefferson and St. Bernard parishes. Peripheral urban places extend along with river and across Lake Pontchartrain. While Hurricane Katrina caused numerous hazards across a large region of the United States, the worst impacts were experienced in the urban areas shown above and along the Mississippi Gulf Coast. Also shown are Federal levees which surround nearly all of the urban areas except for those on the north of Lake Pontchartrain (Guidry and Gisclair 2007, van Heerden 2007).

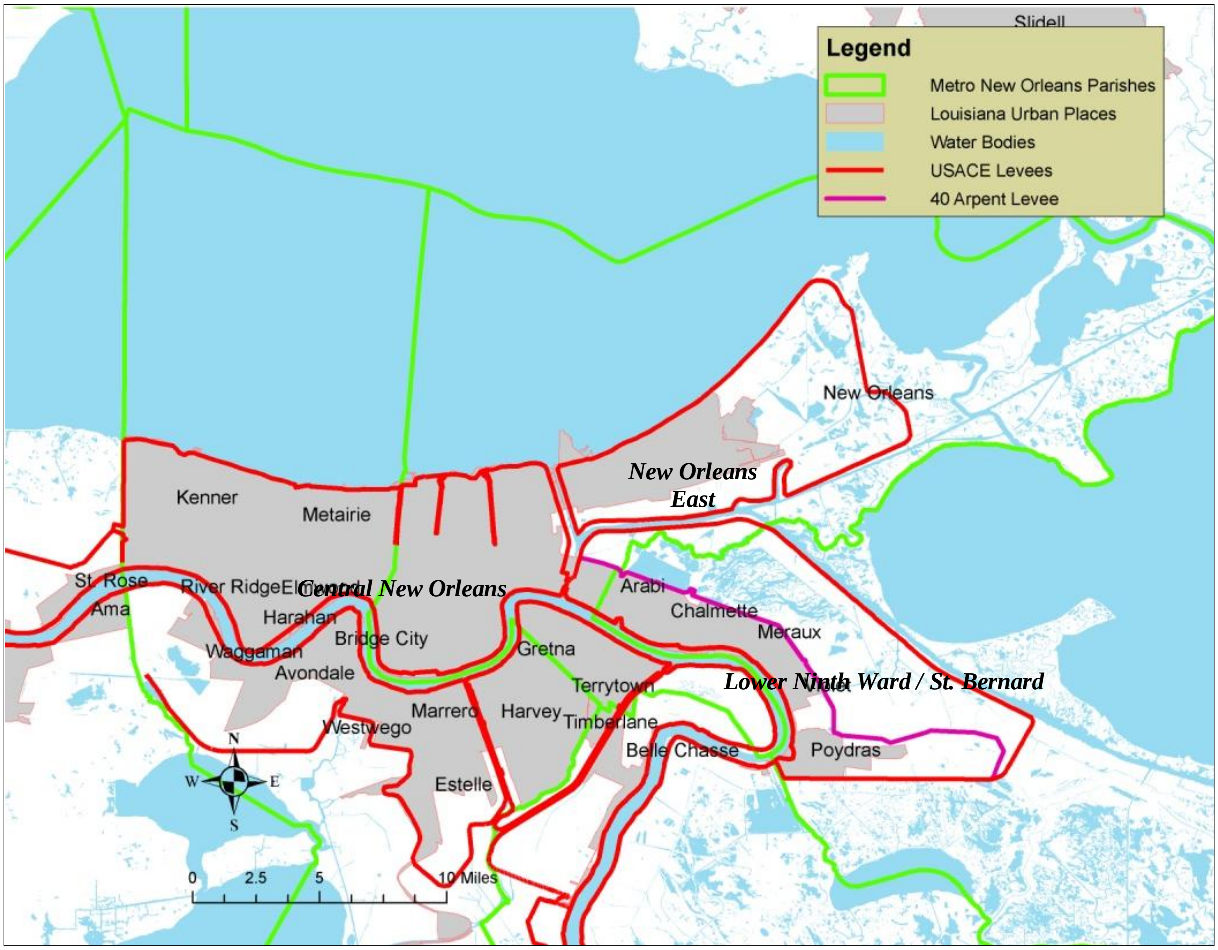

Figure 5.9: The central urban area with Metro New Orleans. This is region that suffered from the urban catastrophe during Hurricane Katrina. The entire region suffered wind impacts, while storm sure and levee breach flooding impacted most of the eastern half of the map. Distressed hospitals, nursing homes, and shelters were scattered across the entire region, as were incidences of violence and lawlessness. Flood Control Levees are shown in red. The names of the three flooded polders are given in italics while the names of Census designated places are in normal font (Guidry and Gisclair 2007).

Flooded Polders within Orleans and St. Bernard Parishes

Finally, within Metro New Orleans, two parishes are noteworthy for the widespread destruction and death brought upon by catastrophic engineering failures during Hurricane Katrina. They are Orleans and St. Bernard parishes, with a combined 2005 population of 522,296. This mostly urbanized area possessed the combination of population density and widespread flooding during Hurricane Katrina. Of note, Plaquemines Parish to the south experienced considerable flooding, but this largely rural parish was almost completely evacuated before the storm and did not suffer heavy loss-of-life. Likewise, urbanized portions of Jefferson Parish to the West of New Orleans and suburban portions of lower St. Tammany Parish both possessed high population densities, but escaped the worst flooding. As such, the main data processing and statistical analysis in Chapter 8 and 9 that focuses on direct flood deaths is confined to these two parishes.

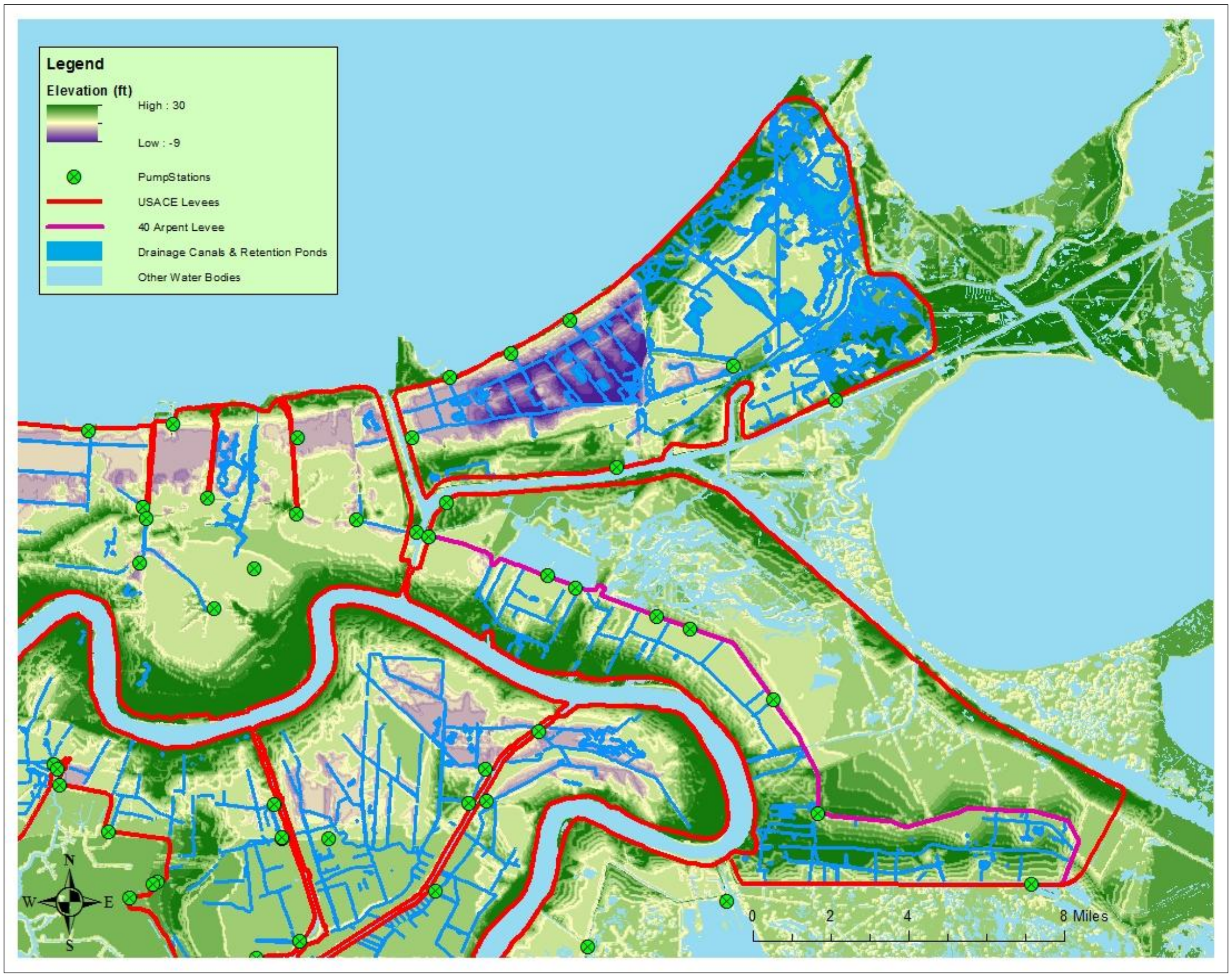

Figure 5.10: Elevation, levees, pump stations and drainage canals for Metro New Orleans that suffered flooding during Hurricane Katrina (Guidry and Gisclair 2007, van Heerden 2007).

5.2 Units of Analysis

The study regions are divided into different spatial units of analysis. Two basic categories are available: jurisdictional and hydrological. Jurisdictional refer to units based on human associations, and basin refer to units on hydrological flow. Just as networks of human association can be divided and sub-divided, for example parish, city, neighborhood, census tract, it is also true that the major river basins of Louisiana can be divided into levels of sub-basins. Figure 5.11, 5.12, and 5.13 show the major drainage basins of southeast Louisiana while Figure 5.14 and 5.15 show the sub-basins within Metro New Orleans. Figure 5.14 and 5.15 show various organizational units.

The question is which unit of analysis will prove the most useful in the analysis. That is, which units best resemble McClelland and Bowles's (1999) Homogenous Base Units (HBU's), which they define as spatial units with "predictable life loss distributions, with variance governed largely by chance" (p.2). In terms of loss-of-life, it is known that this distribution is determined by flood hazard characteristics of the unit along with the vulnerability characteristics of the impacted population. As a potential unit, basins and sub-basins are defined based on hydrological characteristics which create relative homogeneity across the flood hazards. On the other hand, parishes, zip codes, and other jurisdictional units are defined in terms of human characteristics which includes the all important population denominator. During the course of this research, I examined the data using various spatial units that were available. For the statistical analysis in Chapter 8 and 9, I chose a hybrid unit that consisted of neighborhoods in Orleans Parish and modified zip codes for St. Bernard Parish (see Figure 5.16).

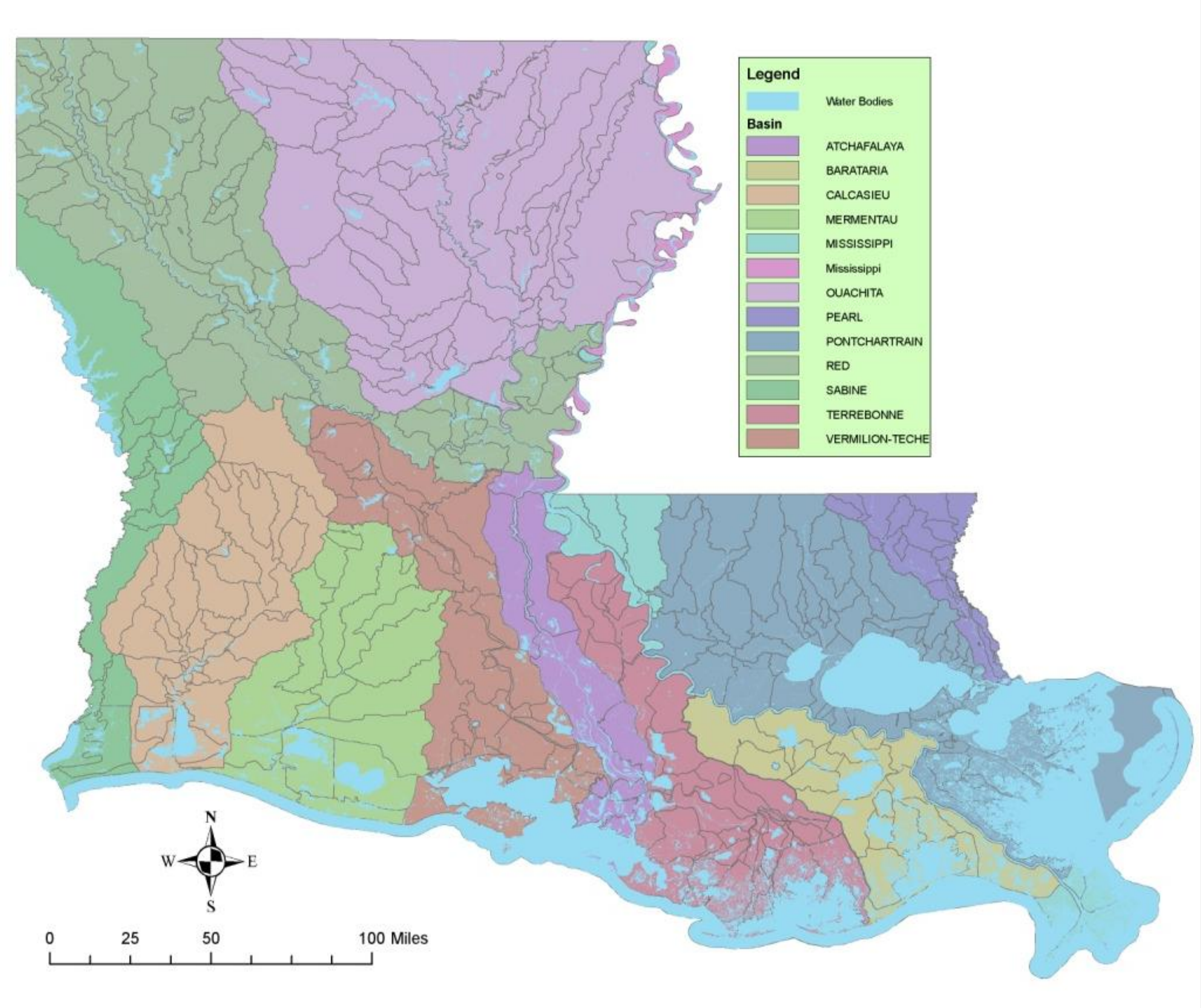

Figure 5.11: Major drainage basins of Louisiana (Guidry and Gisclair 2007).

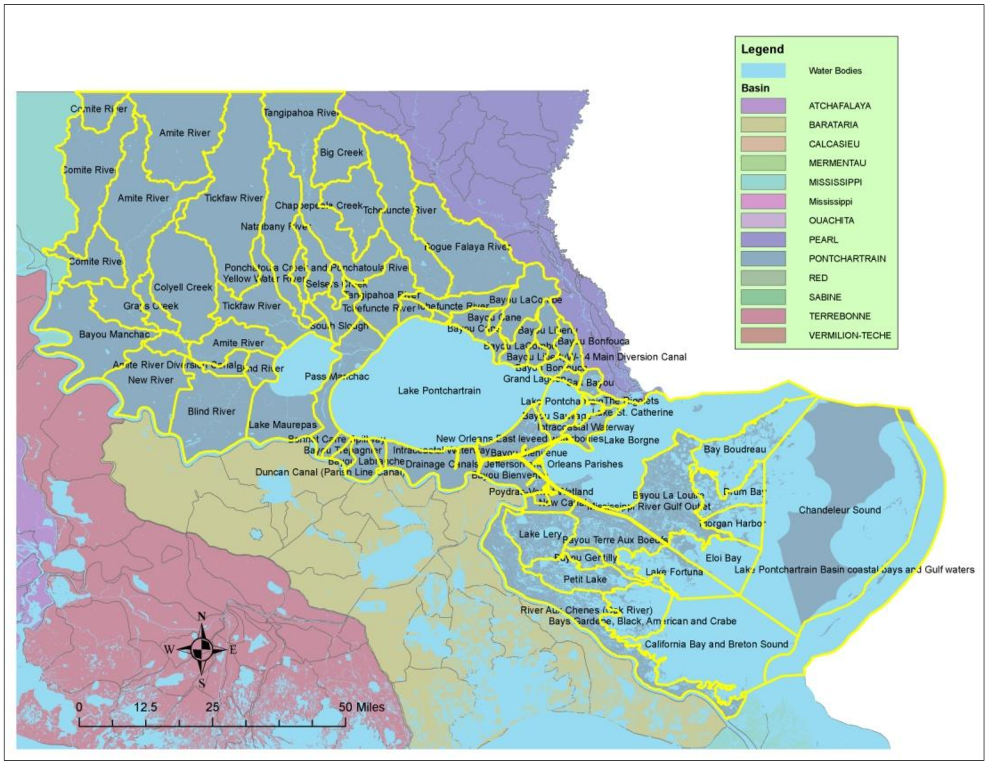

Figure 5.12: Sub-basins of the Pontchartrain Basin which is centered around Lake Pontchartrain (Guidry and Gisclair 2007).

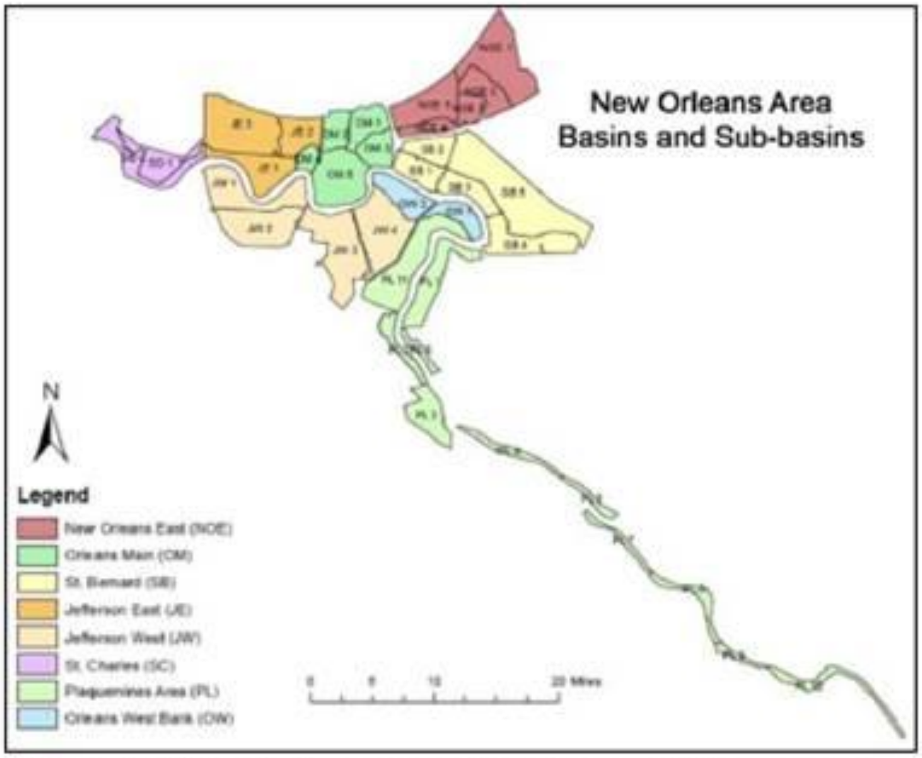

Figure 5.13: Drainage basins and sub-basins of Metro New Orleans (Interagency Performance Evaluation Taskforce 2007).

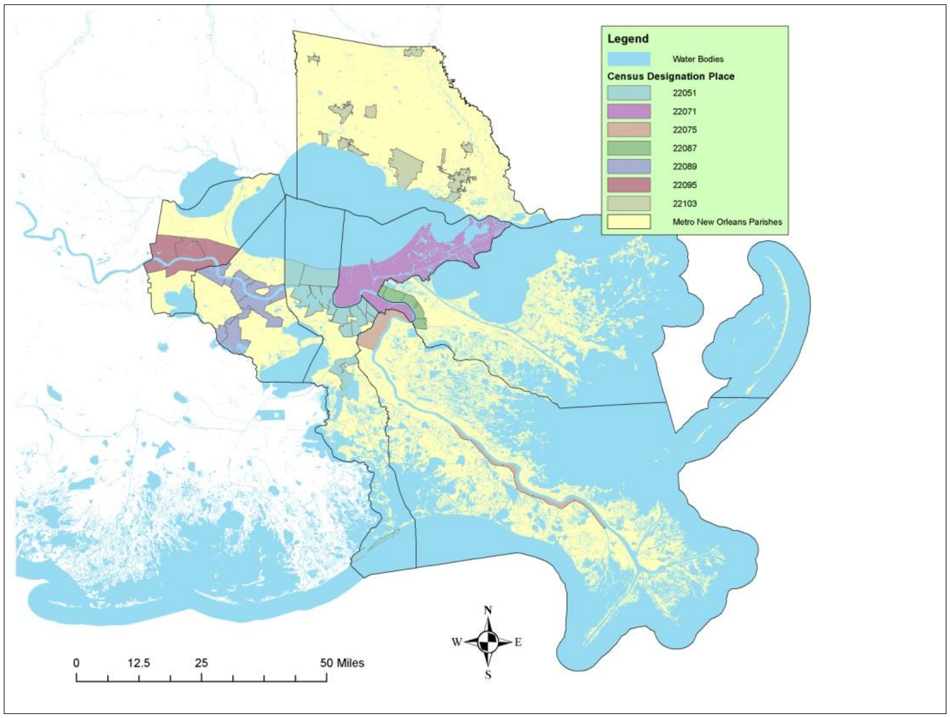

Figure 5.14: Southeast Louisiana and U.S. Census designated Places. Note that the Places layer does not provide complete coverage of rural areas (Guidry and Gisclair 2007).

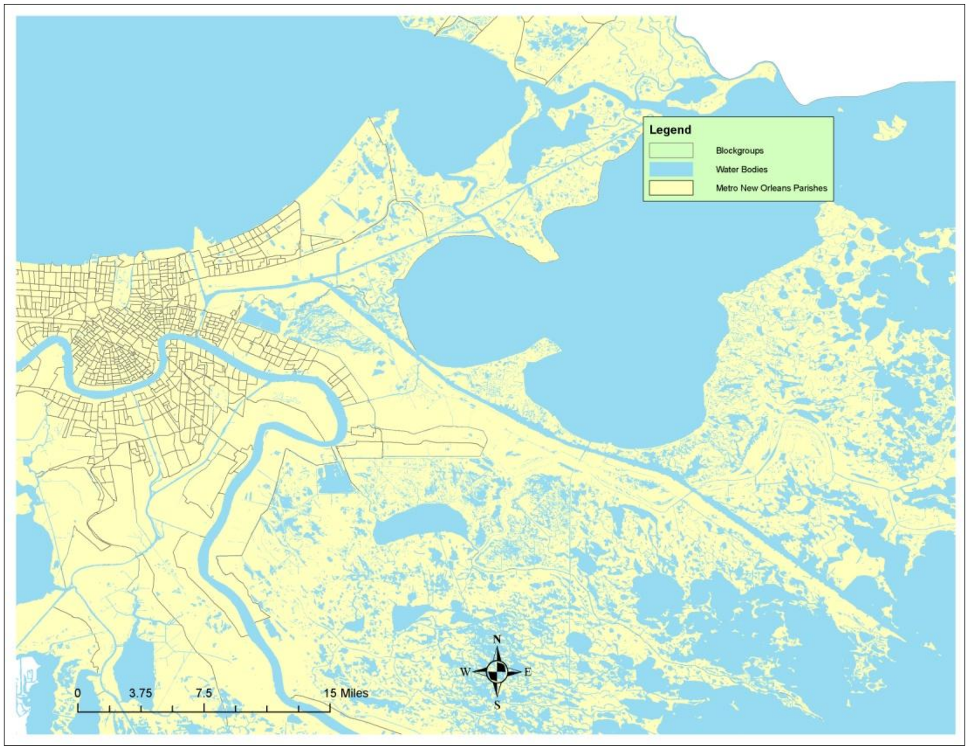

Figure 5.15: Census blockgroups for Orleans along St Bernard parishes along with portions of Plaquemines, Jefferson, and St. Tammany parishes. Unlike the places layers shown above, this Census layer provides complete coverage of all areas within the study region. However, given the small size of each blockgroup, this unit led to the small population problem when assessing flood fatalities (Guidry and Gisclair 2007).

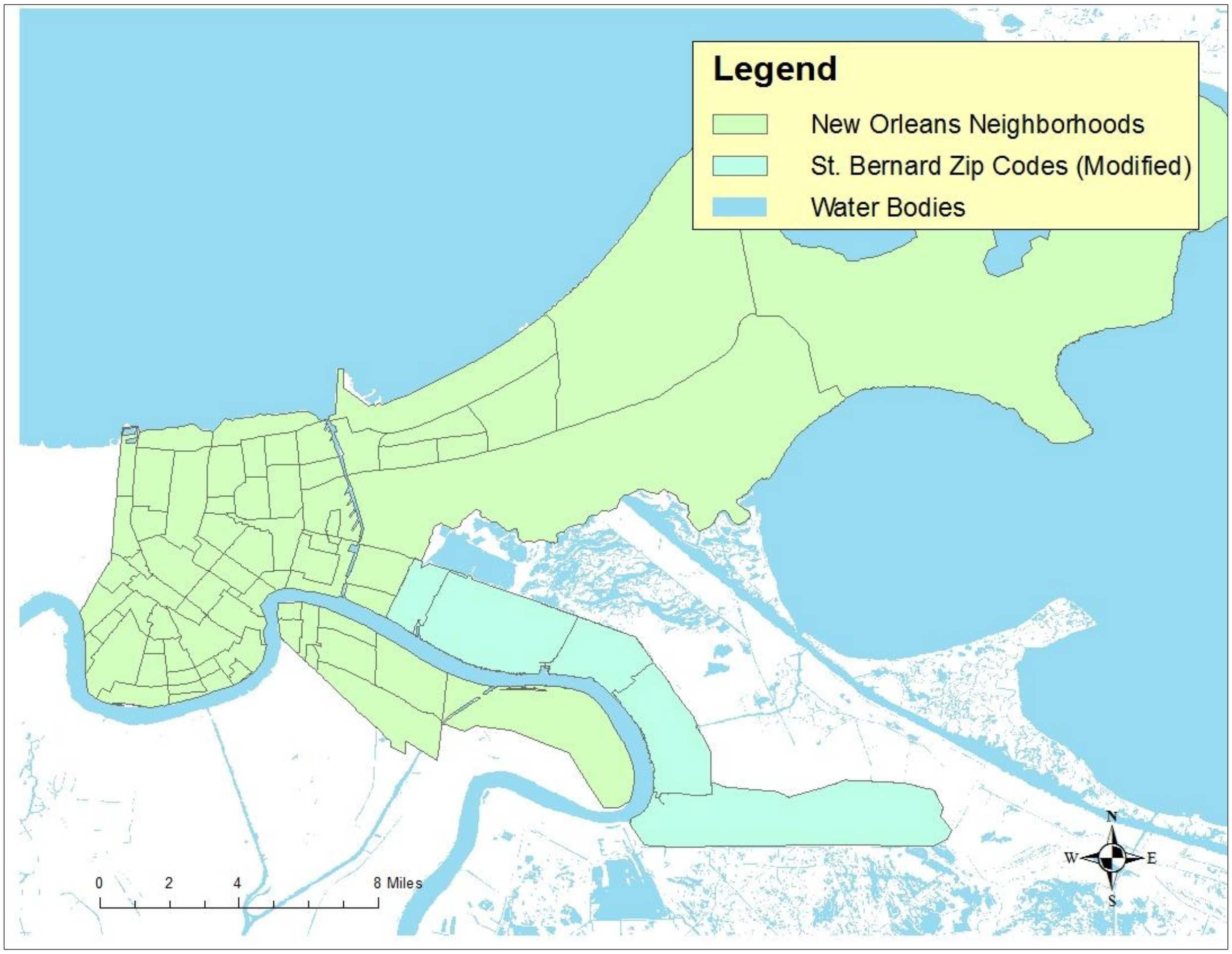

Figure 5.16: New Orleans Neighborhoods (Greater New Orleans Community Data Center 2006) and modified St. Bernard Zip codes (Guidry and Gisclair 2007) used in the flood fatality analysis in Chapters 7 and 8.

5.2 Background Population

As described in Chapter 3, Louisiana's population in 2005 reflected various waves of migration, though outmigration has been the most recent trend. While 4,468,976 people were counted in Louisiana during the 2000 Census, the 2005 Gulf Coast American Community Survey estimated the population to be 4,068,028. Metro New Orleans had seen a similar decline during that period, and had dropped to 1,190,615 in 2005.

Table 5.1: Outmigration from Louisiana and Metro New Orleans (Census 2002 and Census 2005).

	2000	2005	Percent Change
Louisiana	4,468,976	4,068,028	-8.97%
Metro New Orleans	1,316,510	1,190,615	-9.56%

Population Vulnerability Characteristics for The Study Areas.

What made Louisiana's population, and particularly the Metro New Orleans population vulnerable to disaster?

Sociologists and other researchers who have studied disasters have identified population vulnerability as an important variable influencing the outcome of a disaster event. Speaking in very general terms, a more vulnerable population experiences more severe impacts when exposed to hazards. Further research along these lines has identified certain population characteristics that influence a population's vulnerability. Age, income, disability status, education levels, and access to personal transportation are all characteristics believed to be associated with the severity of disaster events. This section briefly describes some of the vulnerability characteristics of the Louisiana population impacted by Hurricane Katrina. A later chapter, examines the relationship between population vulnerability and the disaster outcome of interest. In this section, it will be shown that the Louisiana population impacted by Hurricane Katrina possessed many of the characteristics associated with high levels of disaster vulnerability.

By 2005, the basic demographics of Louisiana had been affected by the outmigration, with the loss of young people reflected in the age distribution for the state (see Table 5.2).

In addition to the out migration, race was an important demographic characteristic of Louisiana. With over 1.4 million people identified as black or African-American alone in the 2000 Census, the percentage of the population in this group was nearly three times the national percentage, see Table 5.3.

Also, it is worth noting that Louisiana's African-American population is concentrated along or near the rivers (see Figures 5.17 and 5.18), and Louisiana's racial geography fits the national trend of African-Americans concentrating in the South and particularly along the Lower Mississippi River's former "plantation country." While plantations have lost their status as a center of economic and social organization, the lingering effects of this system left a major impact of the nation's modern day human geography. Within Metro New Orleans, the population showed levels of segregation between predominantly white suburban parishes and predominantly African-American Orleans Parish. Within Orleans Parish, some areas demonstrated segregation, though most blockgroups were integrated. Table 5.4 gives the racial breakdown of the four most heavily impacted parishes of Metro New Orleans.

Table 5.2: Age distribution of Louisiana compared to the nation (Census 2002).

Age Group	Percent for Louisiana	Percent for Nation
under 18	28.89%	27.30%
over 65	11.59%	12.40%

Table 5.3: Racial breakdown of Louisiana population compared to the national population (Census 2002).

Race	**Louisiana Total**	**Louisiana Percent (%)**	**Nation Percent (%)**
Total	4,468,976		
White alone	2,855,964	63.9	75.1
Black or African American alone	1,444,566	32.3	12.3
American Indian and Alaska Native alone	25,833	0.6	0.9
Asian alone	55,492	1.2	3.6
Native Hawaiian and Other Pacific Islander alone	1,379	0.0	0.1
Some other race alone	31,803	0.7	5.5
Two or more races	53,939	1.2	2.4

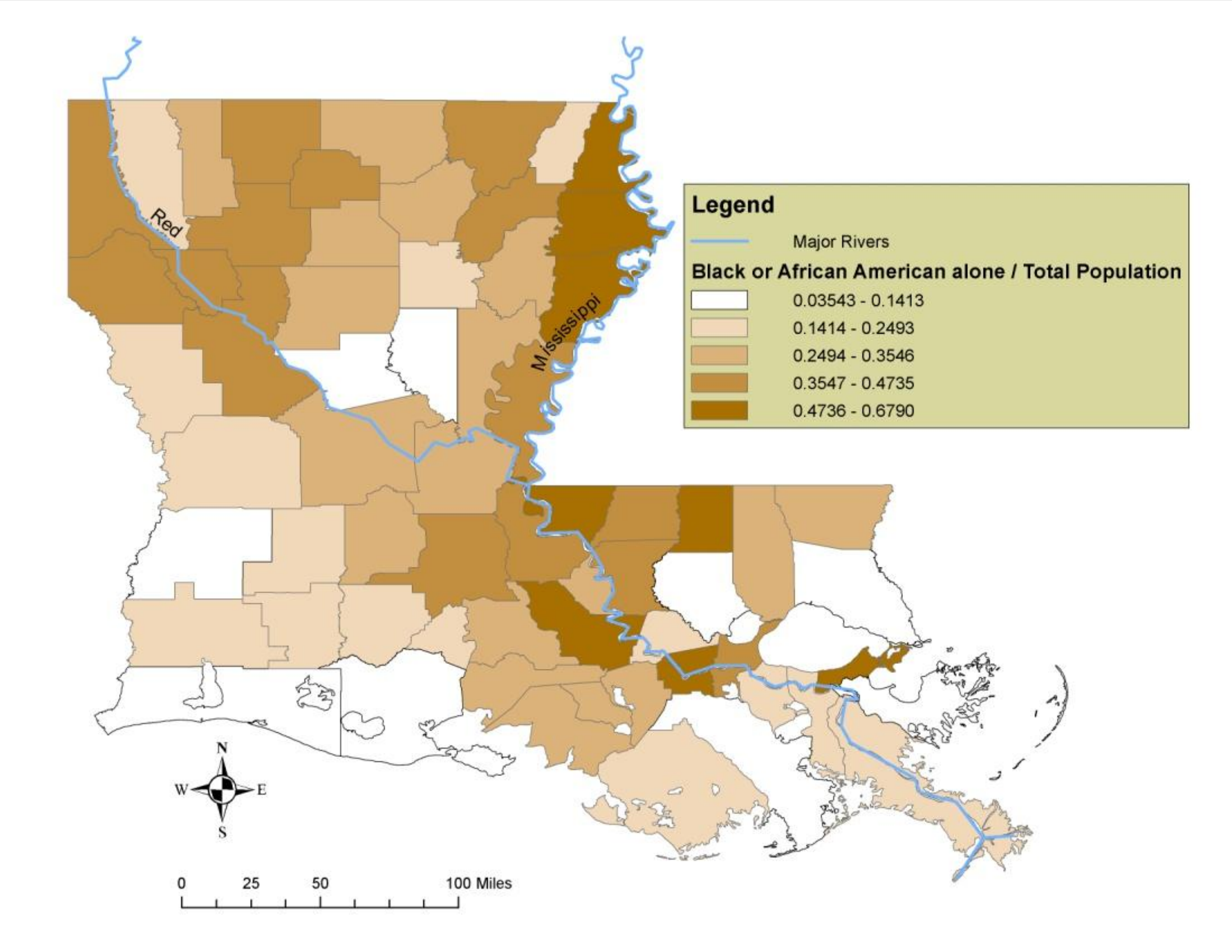

Figure 5.17: Percent of population identified as black or African-American alone for Louisiana parishes (Census 2002).

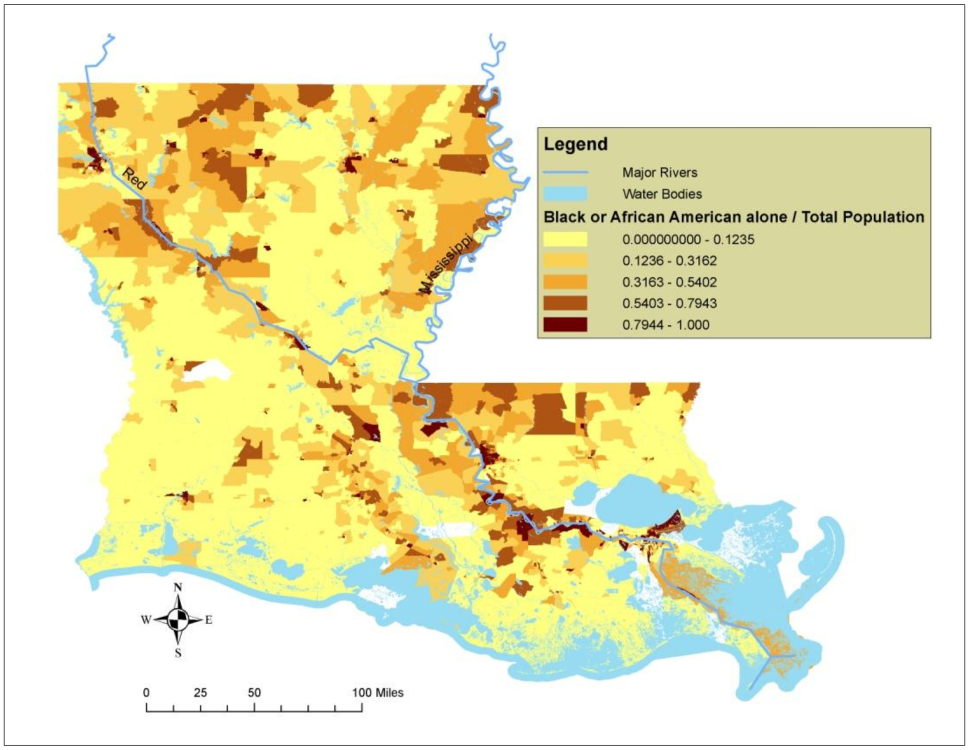

Figure 5.18: Percent population identified as black or African-American alone for Louisiana blockgroups. The near linear clustering in the south-central portion of the map corresponds to Bayou Teche (Census 2002).

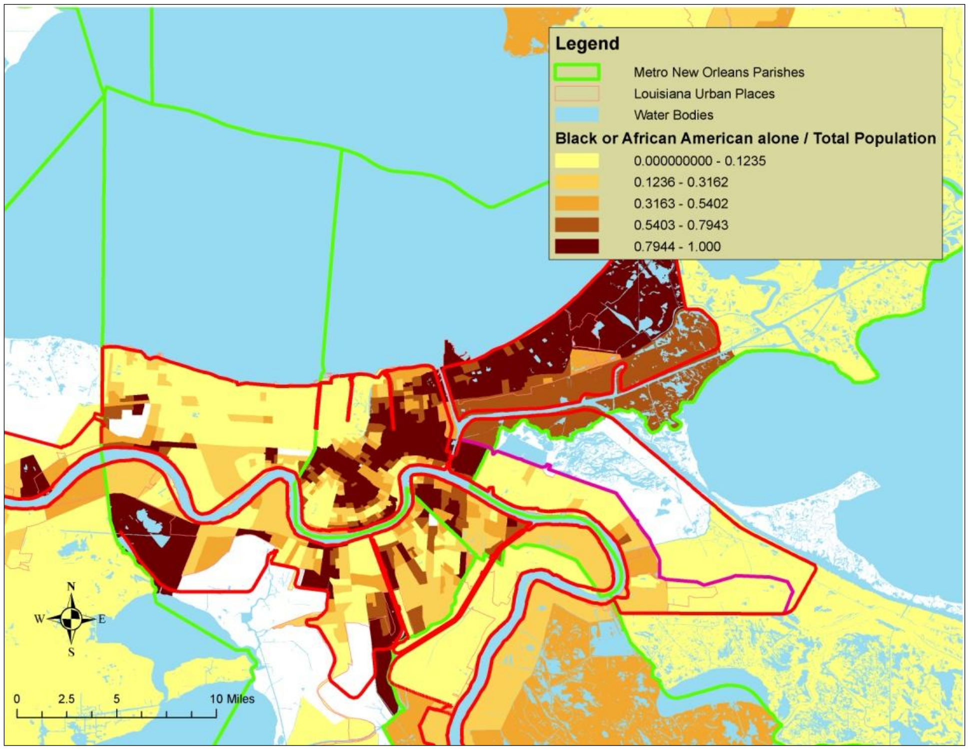

Figure 5.19: Percent black for Census blockgroups with the central urban area of Metro New Orleans (Census 2002).

Table 5.4: Racial distribution of background population for the heavily flooded parishes of Orleans, St. Bernard, and Plaquemines (Census 2002).

	Total	**White**	**Black**	**Native American**	**Asian**	**Pacific**	**Other**	**Two or More**
Jefferson	455,466	317,948	104,025	1,865	13,790	161	9,507	8,170
Orleans	484,674	136,241	325,216	1,495	10,503	112	4,376	6,731
St. Bernard	67,229	59,421	4,615	378	1,079	0	578	1,158
Plaquemines	26,757	18,707	6,115	543	637	0	167	588
Total	1,034,126	532,317	439,971	4,281	26,009	273	14,628	16,647
Heavily Flooded	578,660	214,369	335,946	2,416	12,219	112	5,121	8,477
Percent of Total		51	43	0	3	0	1	2
Percent of Heavily Flooded		37	58	0	2	0	1	1

In terms of economic characteristics, poverty was the dominant theme. According to the 2000 Census, 19.6 percent of the Louisiana population lived below the poverty line, compared to 12.4 percent nationwide (Census 2002). Not surprising, comparing Figure 5.19 above (percent black) with Figure 5.20 below (poverty) suggests a racial component to poverty, with poverty rates being higher in parishes with more African-Americans. Fitting this trend, poverty within the central urban area of Metro New Orleans was more prevalent in Orleans Parish, particularly in the central core, where many former slaves migrated to after the end of the civil war.

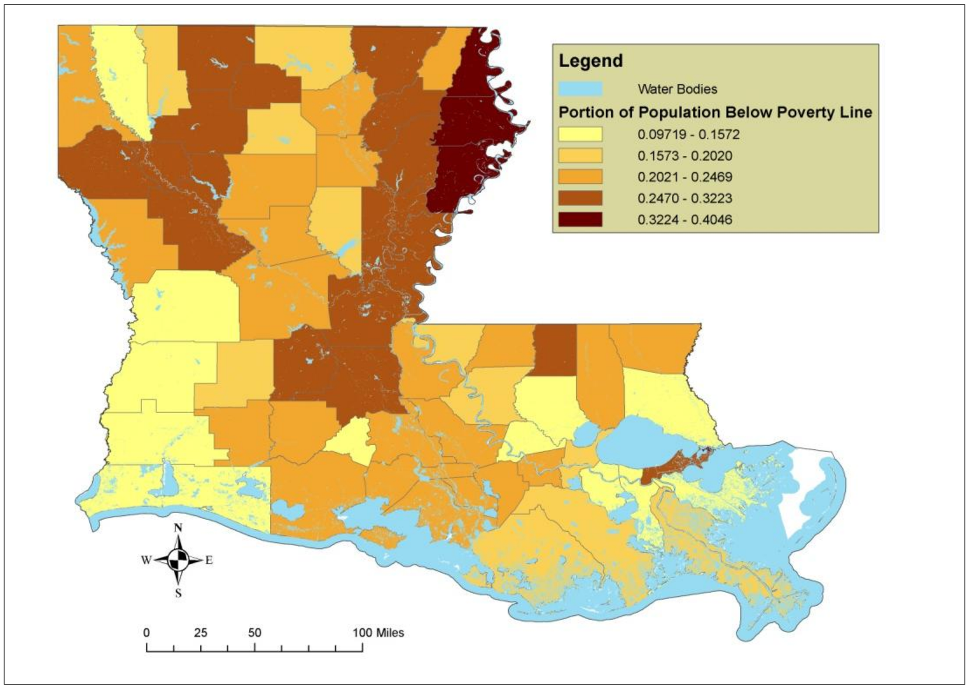

Figure 5.20: Poverty rate for Louisiana parishes (Census 2002).

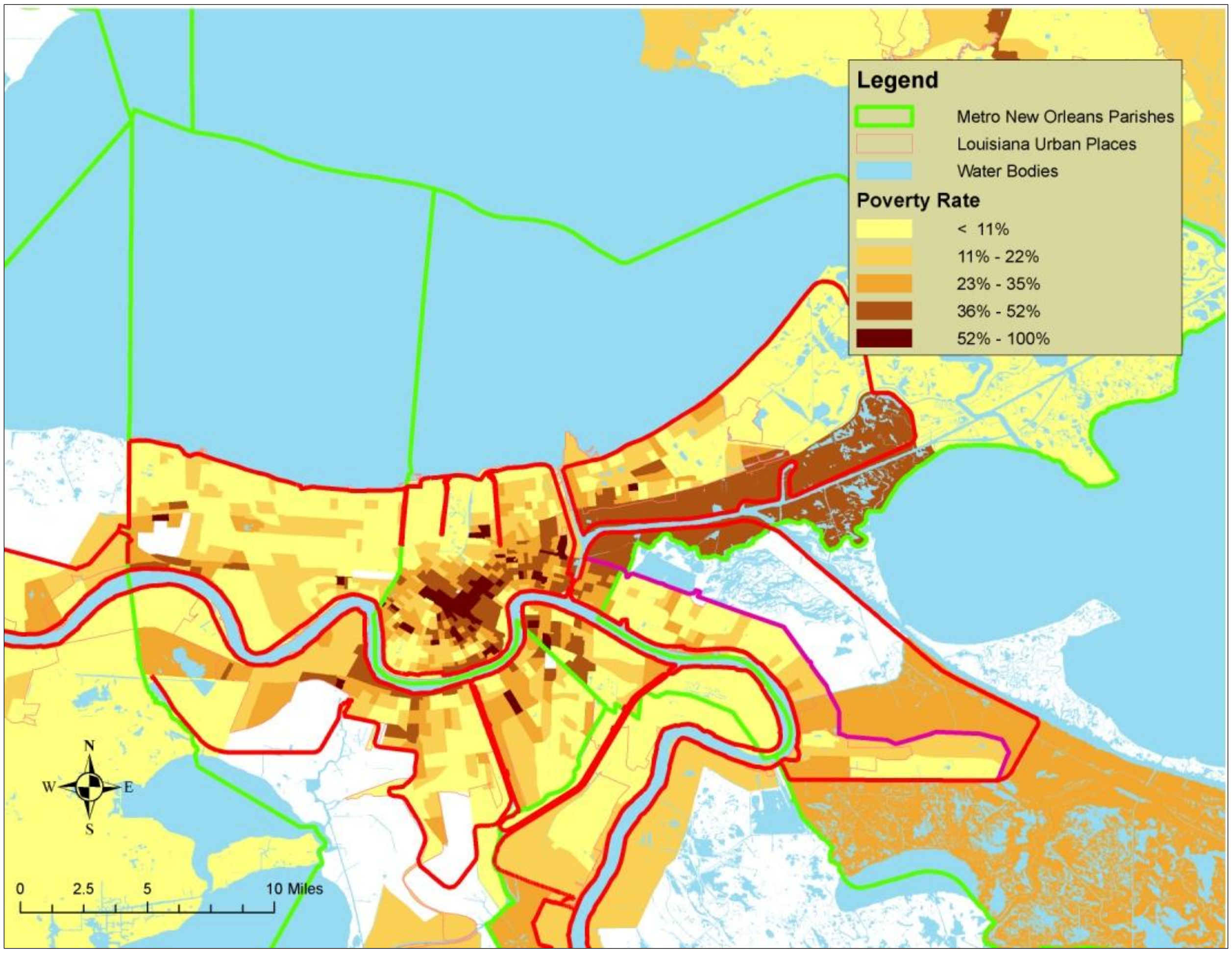

Figure 5.21: Poverty rate for Central Urban New Orleans blockgroups (Census 2002).

Related to the pervasive poverty in Louisiana were a number of other social ills, including poor educational attainment (see Table 5.5). For Louisiana, the percentage of population that graduated high school was 75 percent, compared to 80 percent nationally. Of the parishes that make-up Metro New Orleans parishes, none were above the national percentage, while three were below the state percentage. While this trend likely reflects both a general lack of access to quality education in Louisiana along with the outmigration of educated professionals, it is also directly related to ongoing racial discrimination that exists in the state. Over 50 years after Brown v. Board of Education of Topeka, some parishes in Louisiana, included Jefferson Parish, have continually failed to desegregate their public school systems.

Also associated with poverty, vehicle access was another factor that influenced the population's disaster vulnerability, particularly in regard to evacuation before a hurricane. Statewide, more Louisiana households had access to a vehicle (11 percent) than the national rate (10 percent), but Figure 5.22 below shows that for a number of parishes, the percentage was much larger than the national rate. In southeast Louisiana, Orleans Parish stands out with 27 percent of households lacking access to a personal vehicle. Not surprising, comparing Figure 5.23 below (carless household for New Orleans blockgroups) to Figure 5.21 above (poverty for New Orleans

Table 5.5: Comparing Louisiana and Metro New Orleans Parishes to the United States in regards to measures of educational attainment. For each of three measures, the left column gives the percentage for Louisiana as a whole and for the parishes within Metro New Orleans, while the right column gives that number minus the percentage for the United States as a whole, which is given in the bottom row (Census 2002).

Location	Percent Graduated High School	Location Minus United States	Percent with Bachelor's Degree	Location Minus United States	Percent with Master's Degree or Higher	Location Minus United States
Louisiana	75%	-5%	19%	-5%	6%	-3%
Jefferson	79%	-1%	21%	-3%	7%	-2%
Orleans	75%	-5%	26%	2%	11%	2%
Plaquemines	69%	-11%	11%	-13%	2%	-7%
St. Bernard	73%	-7%	9%	-15%	3%	-6%
St. Charles	80%	0%	18%	-6%	5%	-4%
St. John the Baptist	77%	-3%	13%	-11%	4%	-5%
St. Tammany	84%	4%	28%	4%	9%	0%
United States	80%		24%		9%	

blockgroups) suggests a strong correlation between these two population attributes. Table 5.6 compares vehicle access between the United State, Louisiana, and Orleans Parish.

Likely, also associated with the greater prevalence of poverty, the population of Louisiana and particularly the population of heavily flooded Orleans and St. Bernard parishes had a large prevalence of people who possessed some sort of physical, mental, sensory, self-care, mobility, or employment disability. Within the United States as a whole, 19.3 percent of the population reported some type of disability, while in Louisiana that number was 21.8 percent. In Orleans Parish, some 102,122 persons, 23.2 percent of the population, reported one or more disabilities. St. Bernard had a similar percentage. Plaquemines Parish is the only parish heavily impacted by flooding where the percentage was lower than the national average, see Table 5.7.

Table 5.6: Households without access of vehicles (Census 2002).

	Percentage of All Households without a vehicle	Percentage of Owner Occupied Households without a vehicle	Percentage of Renter Occupied Households without a vehicle
United States	10.3	4.5	21.5
Louisiana	11.9	6.0	24.2
Orleans Parish	27.3	11.8	40.8

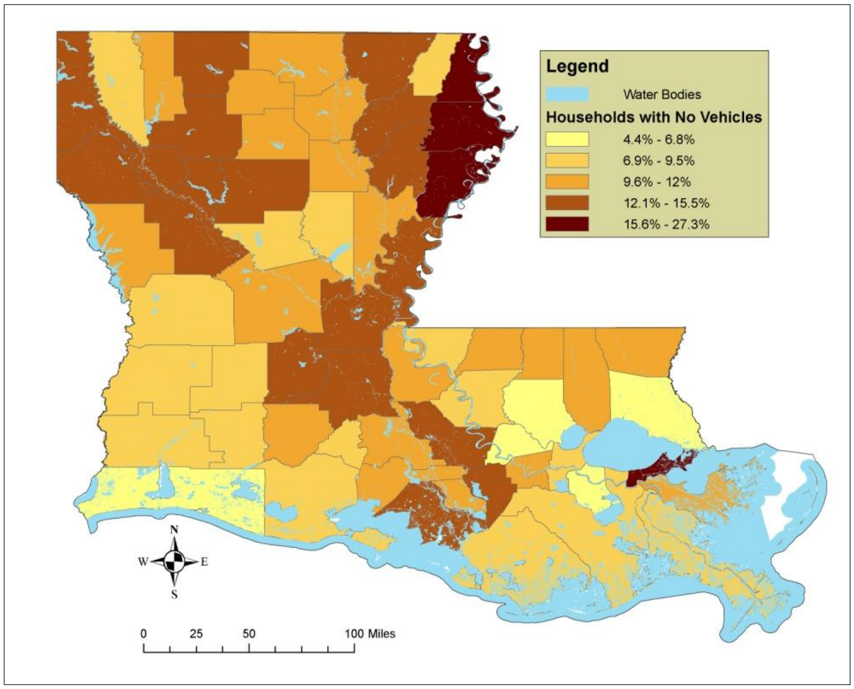

Figure 5.22: Percent households without access to personal vehicle at the parish level (Census 2002).

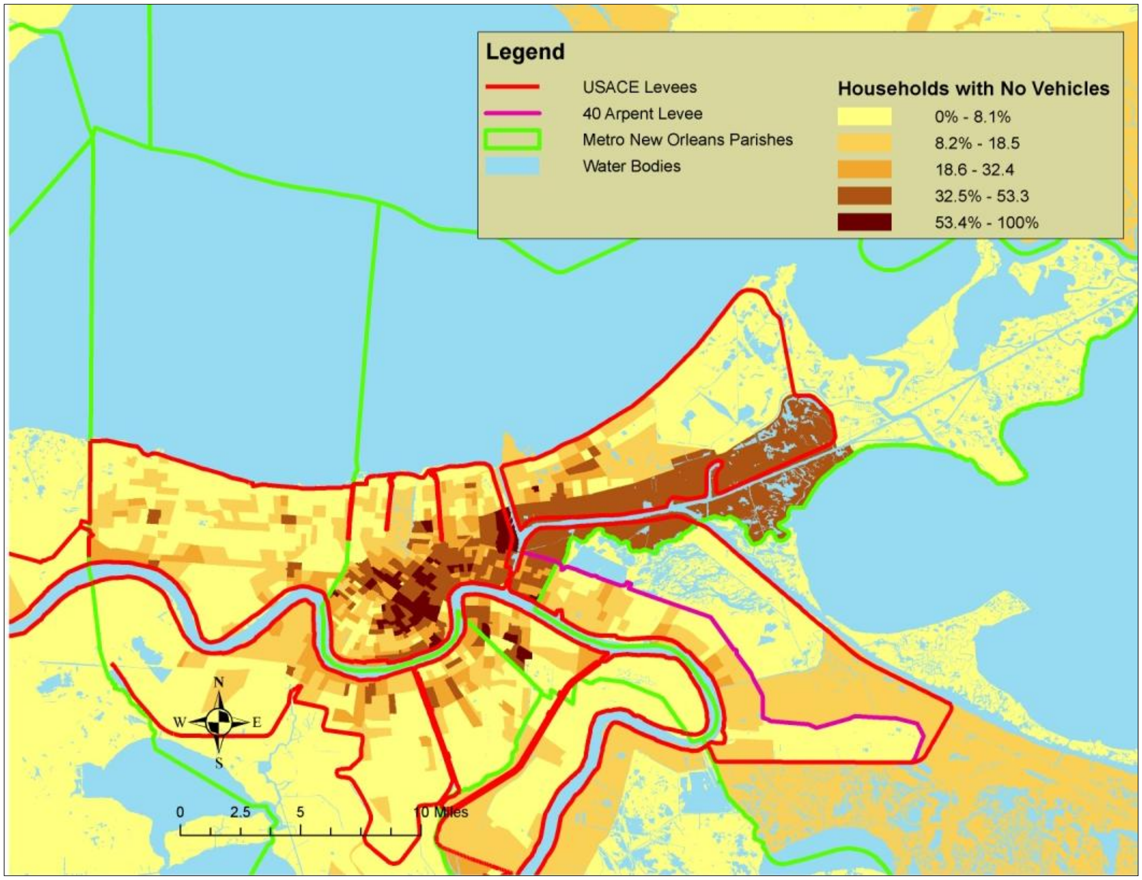

Figure 5.23: Percent households within the central urban are of New Orleans without access to personal vehicle at blockgroup level (Census 2002).

Table 5.7: Percentage of the population reported a disability for the United States, Louisiana, and the four heaviest impacted parishes (Census 2002).

	Number of Disabled	Percent of Population (%)
U.S.		19.3
Louisiana		21.8
Orleans Parish	102,122	23.2
St. Bernard Parish	14,518	23.4
Jefferson Parish	88,532	21.0
Plaquemines Parish	4,553	19.1

5.3 Hazards

This section presents the physical hazards associated with Hurricane Katrina. These hazards include hazards directly related to the physical system -- wind, rain, and storm surge – along with levee breaches and environmental contamination that indirectly resulted from the physical system. In addition, the period of high temperatures that followed the passage of the storm is described as an additional hazard that contributed to the disaster impacts. To best present these hazards, first a national level description of the hurricane is provided, followed by systematically reducing the scale to a focused examination on flood consequences within Orleans and St. Bernard parishes.

National Level Hazards

At one time, the windstorm that comprised Hurricane Katrina nearly filled the entire Gulf of Mexico. As it crossed the Louisiana-Mississippi coastline, Katrina's eye was as large as Lake Pontchartrain.

Figure 5.24 below shows the trajectory of Hurricane Katrina's eye along with a grid of interpolated surface windspeeds. While Katrina had reached category 5 status at one time, the windstorm had lost considerable strength, but not size, before making landfall. The figure shows that tropical storm force or greater winds stretched from Baton Rouge, Louisiana. to Pensacola, Florida., affecting all of southeast Louisiana, most of Mississippi, and a large portion of Southwest Alabama. Measuring from the southern tip of Plaquemines Parish, Hurricane force winds extended 225 miles (362 km) inland, as a far north as Jackson, Mississippi's latitude.

After its final landfall along the Gulf Coast, the storm continued northward and became a major rainfall event for much of the eastern part of the country. Figure 5.25 shows all official rainfall measurements over 2" (5 cm); measurements over 5" (12.7 cm) are labeled. As can be seen, a large swath of heavy rainfall stretched from Louisiana-Mississippi north through Kentucky then northeast over Ohio and New York State. In addition to the coastal states of Louisiana, Mississippi, Alabama, and Florida, five other states received localized rainfall over 5” (12.7 cm). Figure 5.26 shows all rainfall measurements near the central Gulf Coast over 0.1” (0.25 cm). According to this dataset, rainfall in the New Orleans area ranged from just under 1” (2.5 cm) to over 5” (12.7 cm).

Hurricane Katrina’s storm surge created unprecedented flooding along the entire central Gulf Coast. Flooding stretched from west of New Orleans to east of Mobile, see Figure 5.5.27. Measuring the distance along the Gulf of Mexico coastline, over 250 miles (402 km) of the coast experienced surge. If the shores of Lake Pontchartrain and Maurepas are added, then nearly 500 miles (805 km) of coastline where impacted by the storm surge. Adding other bays along this section of the Gulf Coast, 800 miles (1287 km) experienced higher than normal tides. However, these measures must be viewed with caution, since this stretch of coastline consists of very porous coastal marsh and wetlands. Counting every bay and peninsula, then over 4,000 miles (6437 km) of shoreline in Louisiana were impacted by Katrina’s surge.

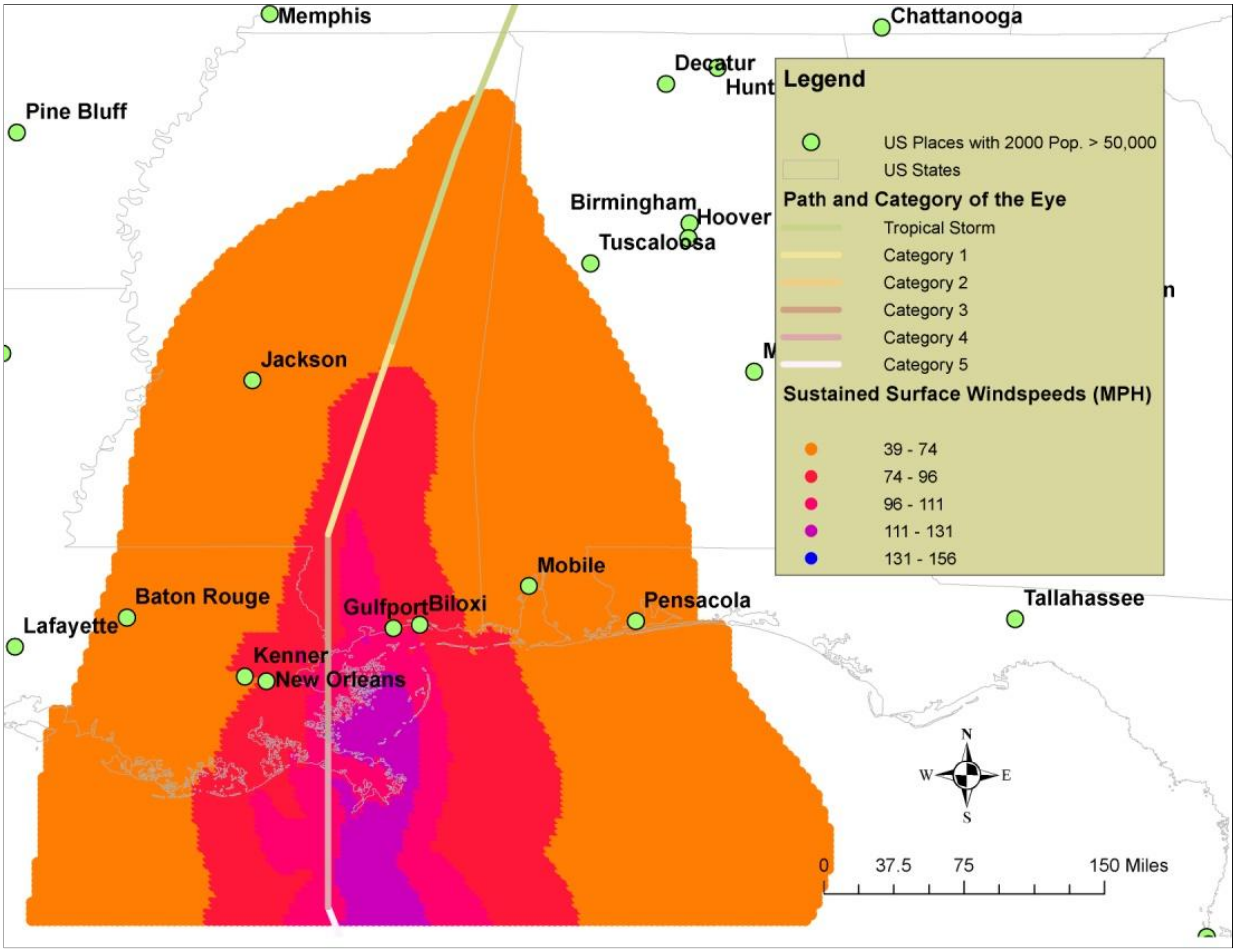

Figure 5.24: Hurricane Katrina windspeeds along the Central Gulf Coast region. (Hurricane Research Division 2006).

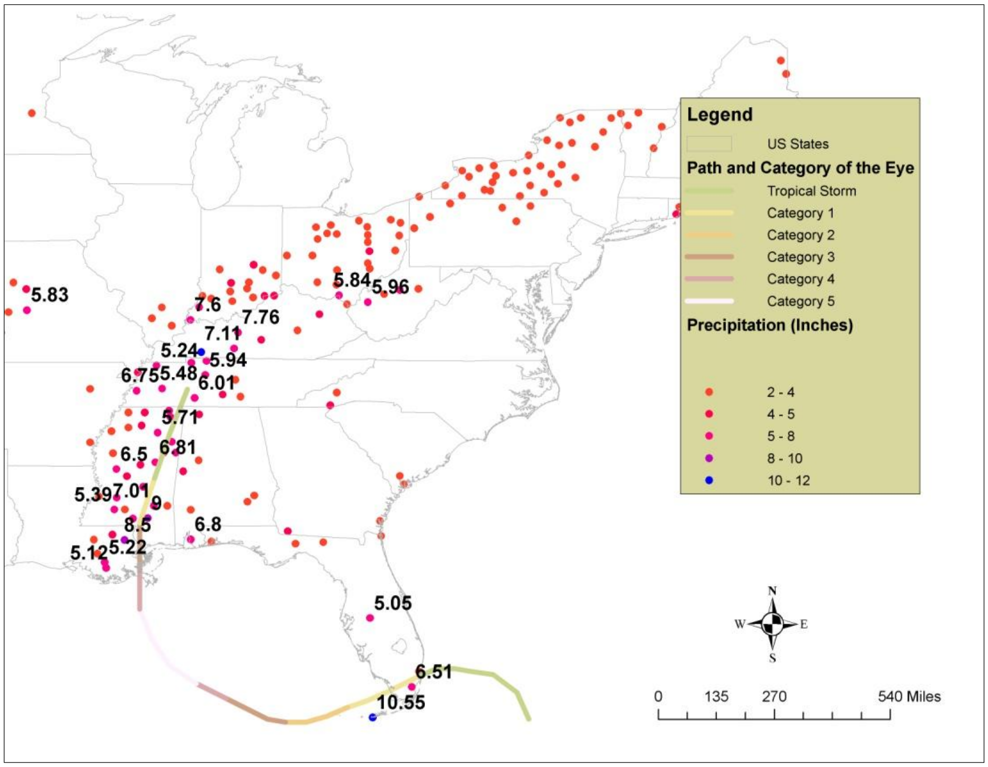

Figure 5.25: Official NWS rainfall measurements over 2” (5 cm) related to Hurricane Katrina. Measurements over 5” (12.7 cm) are labeled (Roth 2005).

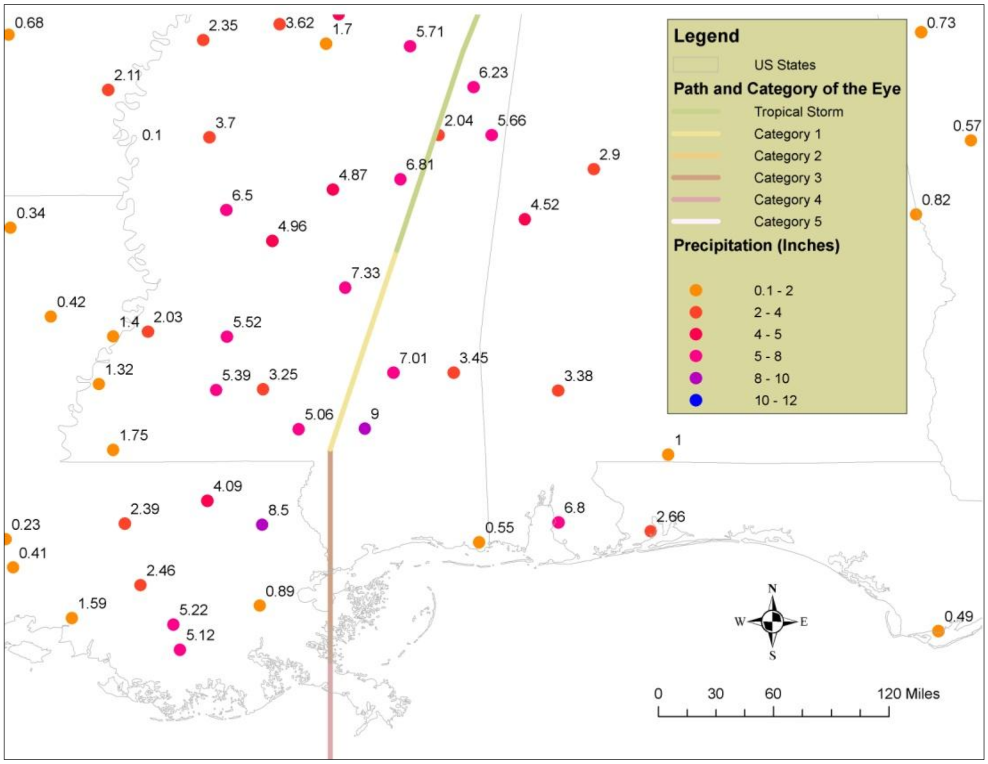

Figure 5.26: Official NWS rainfall measurements over 0.1” along the Central Gulf Coast related to Hurricane Katrina (Roth 2005).

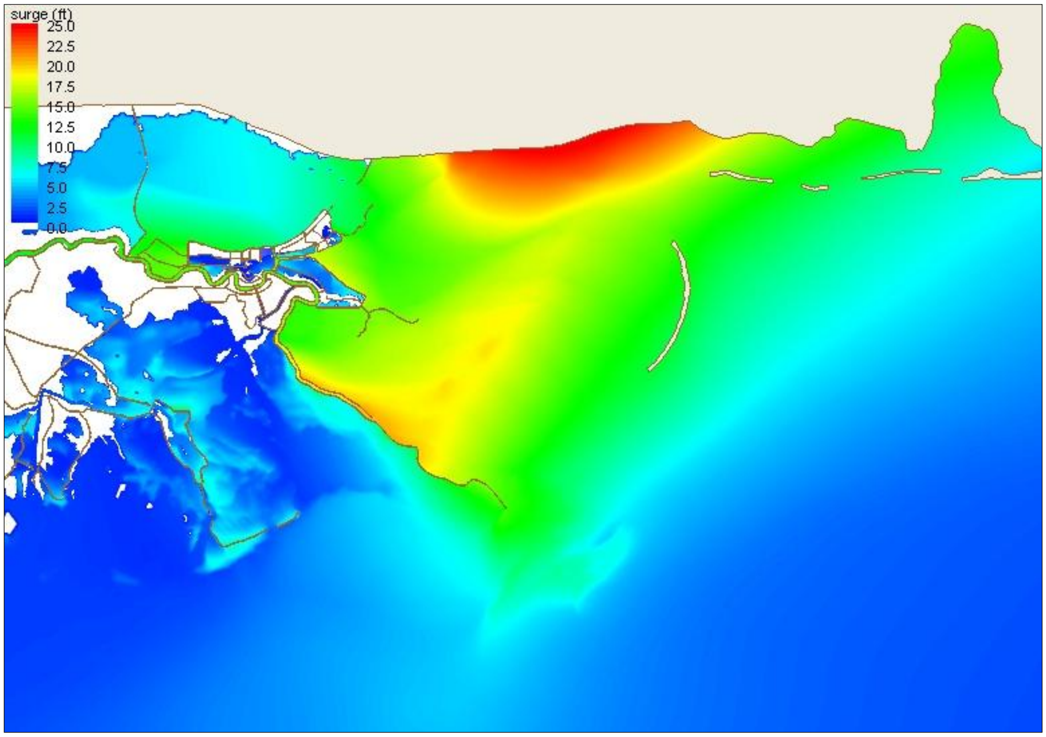

Figure 5.27: Surge Heights based on the ADCIRC simulation run at LSU (van Heerden, et al. 2007).

The highest surge heights were seen along the Mississippi Gulf Coast, with it peaking at 28 ft (8.5 m) near Bay St. Louis, Mississippi. The entire Mississippi Gulf coast experienced surge heights above 18 ft (5.9 m).

Hazards in Southeast Louisiana and Metro New Orleans

Southeast Louisiana, along with coastal Mississippi, bore the brunt of this gigantic storm. However, the strength of this storm does not appear to be as severe as government officials initially stated. In coastal Louisiana’s Plaquemines Parish, maximum surface windspeeds reached about 105 – 110 mph (47 – 49 m/s), just below the threshold for a Category 3 hurricane. Closer to Metro New Orleans, overland windspeeds ranged from about 100 mph (45 m/s) on the eastern end to about 85 mph (38 m/s) on the western end.

Like many things Katrina, rainfall measurements in Metro New Orleans have been the subject of some uncertainty. The official National Weather Service gauges (Roth 2005) measured rainfall amounts in the 5 inches (13 cm) range, though the Interagency Performance Evaluation Taskforce (2007) team claims that parts of New Orleans received 11 inches (28 cm).

While the windstorm had lost energy before landfall, the storm surge maintained much of its momentum as the storm moved across the Louisiana and Mississippi coastline. Within Metro New Orleans, the highest surge heights were experienced along the southern tip of Plaquemines

Parish, where surge run-up against the Mississippi levee lead to 17 – 18 feet (5.1 – 5.5 m) surge heights. Closer to downtown New Orleans, surge heights neared 15 feet (4.5 m) on the western edge of Lake Borgne, where it meets the Mississippi River Gulf Outlet / Gulf Intracoastal Waterway (MRGO / GIWW). Along the shores of Lake Pontchartrain, the storm surge reached 10 feet (3 m) around Slidell, Louisiana in St. Tammany Parish on the Northshore, while reaching 9 feet (2.7 m) to the south along the shores of Orleans Parish.

Of note, it is believed that the storm surge itself lead to isolated overtopping of some levees around New Orleans and limited flooding with the central urban area (see Figure 5.29). However, these limited flood waters would not have led to the catastrophe that unfolded.

While flooding due to surge overtopping was limited, flooding due to numerous levee failures and construction flaws turned out to be catastrophic. Within Southeast Louisiana, over 50 incidences of levee breach, erosion, other degradation, or construction flaws allowed a massive volume of water to flow, mostly unimpeded, into the urban, suburban, and rural areas of Metro New Orleans. The figures below depict the flood hazards that were experienced following the levee breaches. Flood depth, provided by Cunningham, et al. (2006), is based on observational data regarding the water level and LIDAR elevation data. The figures showing rate-of-rise, flow velocity, flow velocity time depth, and arrival time are based on SOBEK simulations provided by Maaskant (2007); these simulations are only available for the Central New Orleans polder and the St. Bernard / Lower 9th polder. The flood conditions depicted in these maps form the important hazard characteristics for the analysis of flood deaths in Chapter 8.

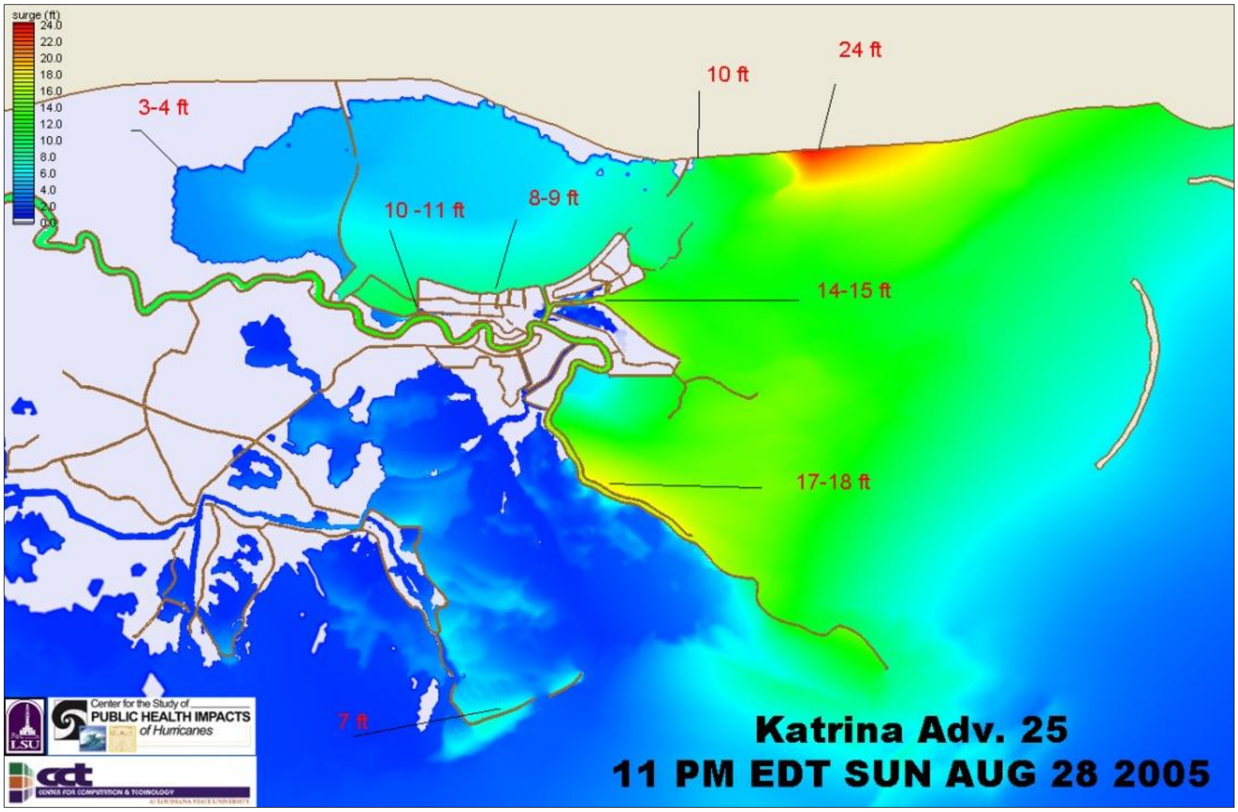

Figure 5.28: The maximum surge height of Hurricane Katrina based on an ADCIRC simulation (van Heerden, et al. 2007).

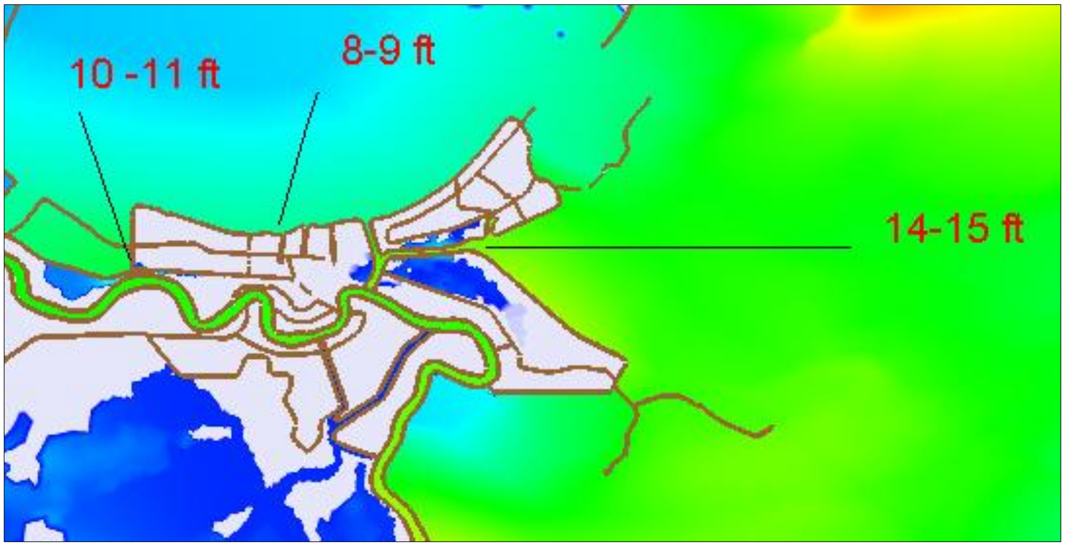

Figure 5.29: The maximum surge height of Hurricane Katrina based on an ADCIRC simulation zoomed to the central urban area of New Orleans central urban area. Note that some flooding due to overtopping was predicted under the assumption that the levees held (van Heerden, et al. 2007).

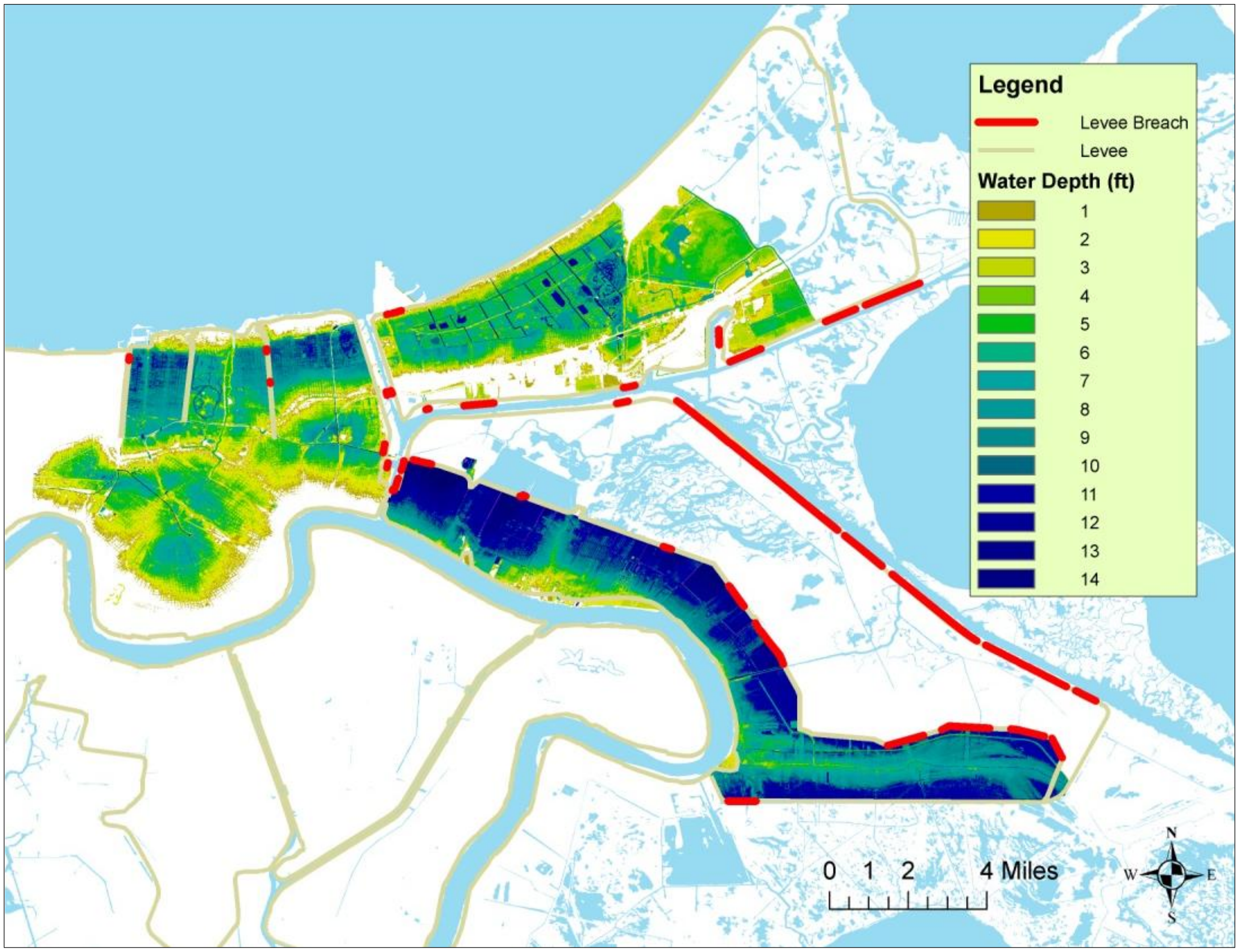

Figure 5.30: Maximum flood depth (ft) for the flooded polders in Orleans and St. Bernard parishes along (Cunningham, et al. 2006) with levees and levee breaches (van Heerden 2007).

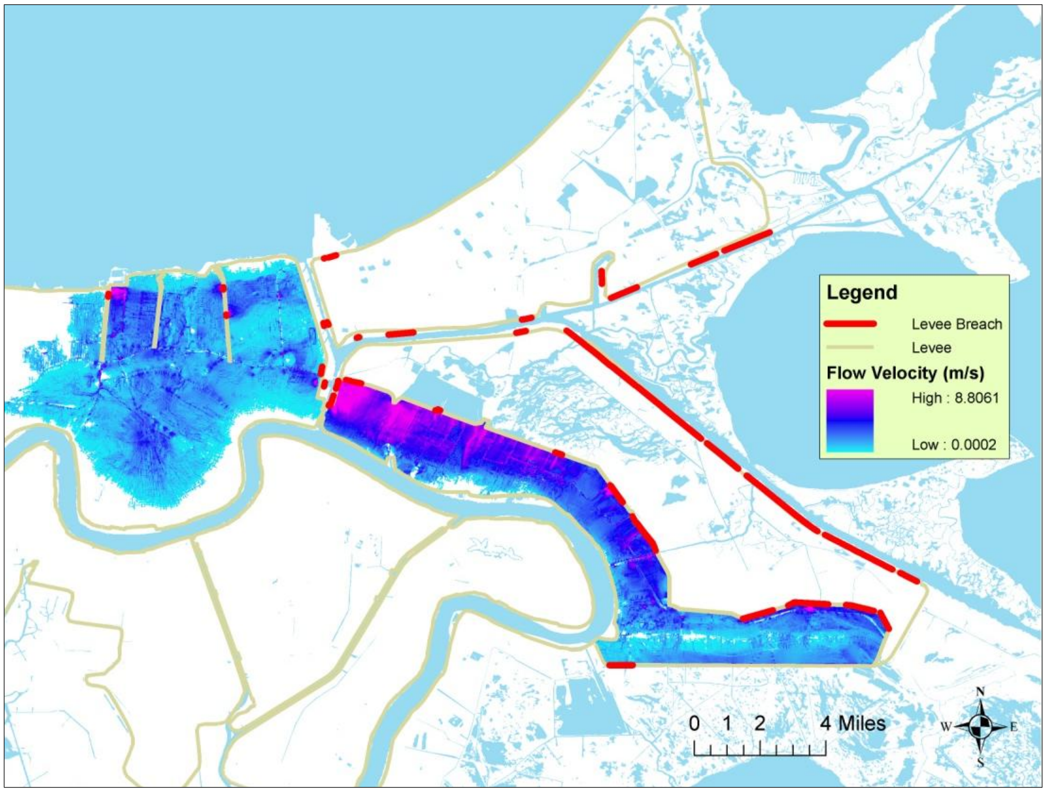

Figure 5.31: Flow velocity of floodwaters based on the SOBEK simulation (Masskant 2007).

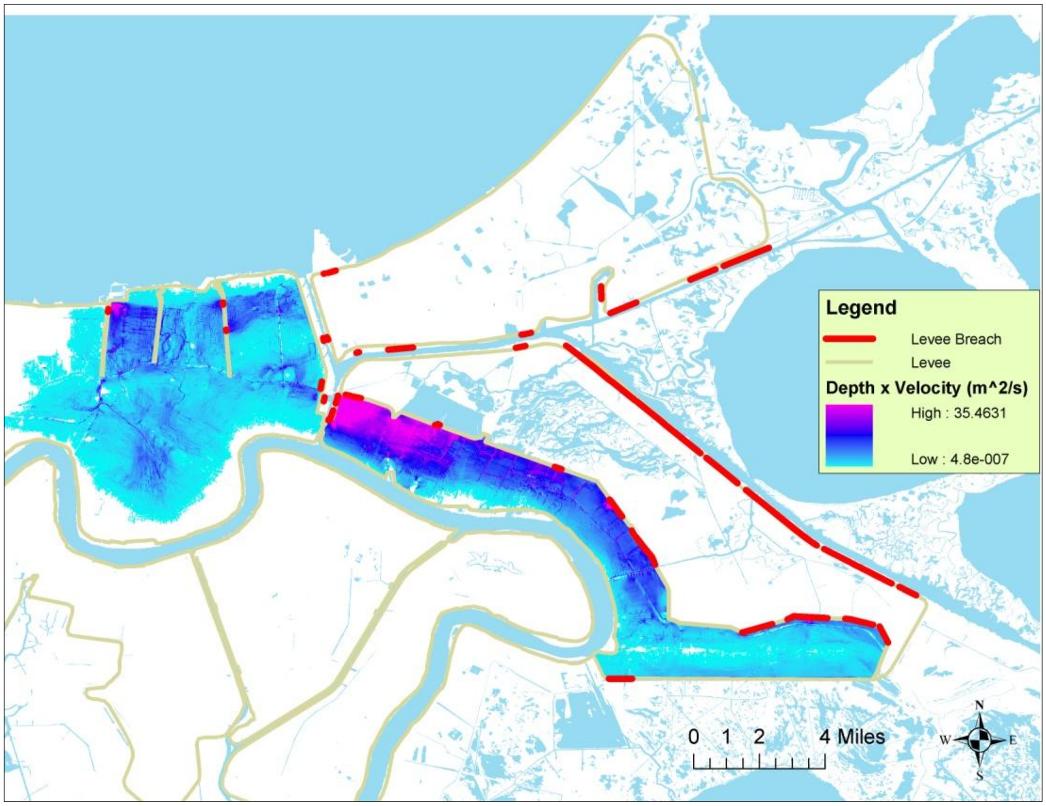

Figure 5.32: Water depth times flow velocity from the SOBEK simulation (Masskant 2007).

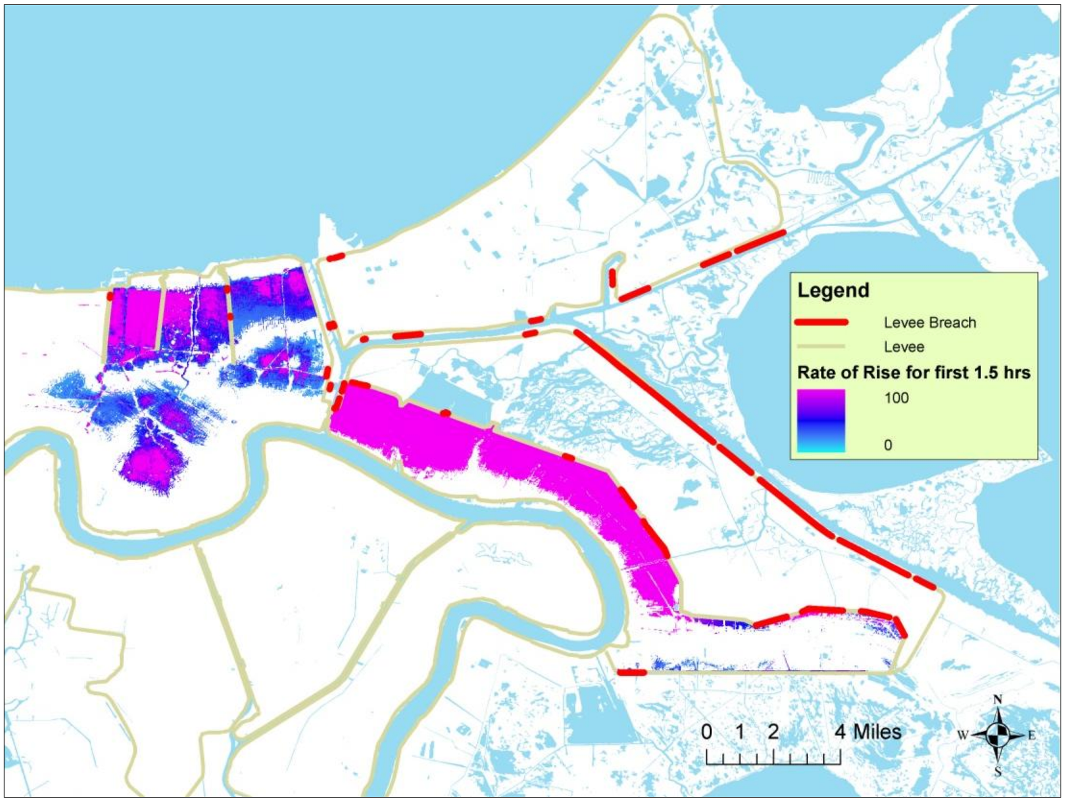

Figure 5.33: Rate-of-rise of flood waters from the SOBEK simulation (Masskant 2007).

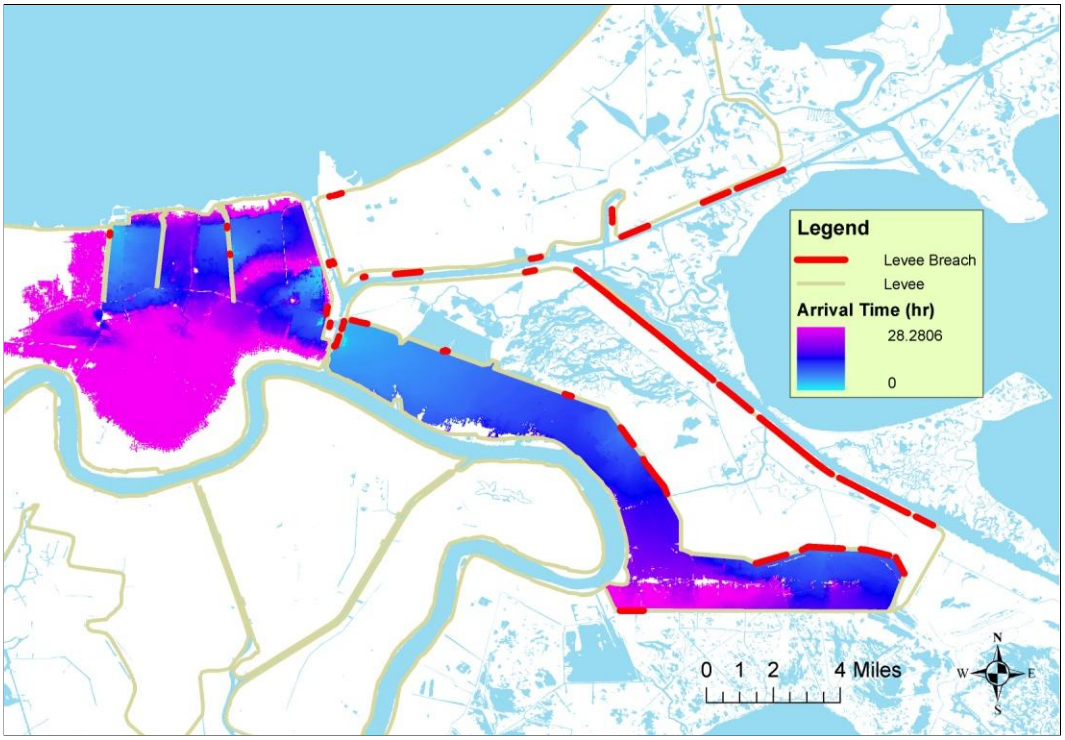

Figure 5.34: Arrival time of floodwaters based on the SOBECK simulation. This is measured from the time of initial breach for each polder and is not concurrent for the two folders (Masskant 2007).

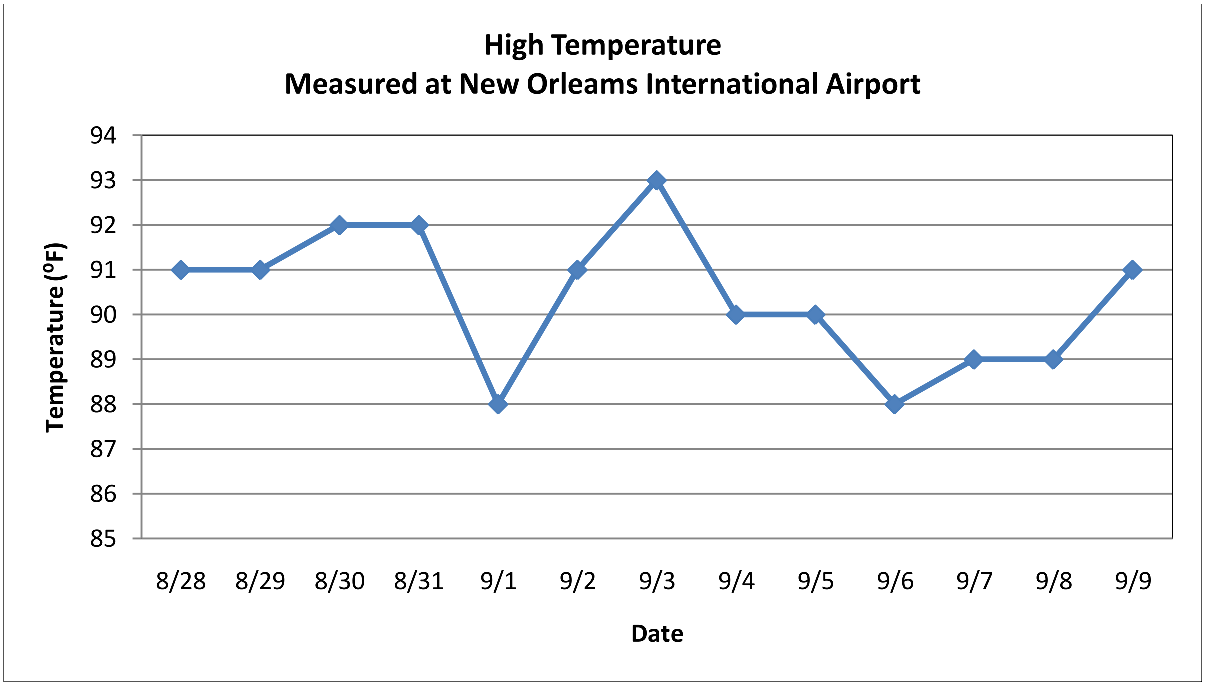

Figure 5.35: Daily high temperature measured at the New Orleans International Airport, located Kenner, Louisiana. Recall from Chapter 4 that large scale search and rescue efforts last until September 8 and the evacuation of emergency shelters lasted until September 9.
Source: Data provided by the Southern Regional Climate Center.

After the wind and rain died down and the storm surge began to recede, the impacted population faced an additional environmental hazard associated with adverse health outcomes: heat. Figure 5.35 shows the daily high temperature for the two weeks surrounding Hurricane Katrina. For most of the ten days that followed Katrina, daily time high temperatures where over 90 °F (32 °C). Generally speaking, the outside temperatures were not high enough for an extended enough time for the conditions to be considered a heat wave. However, at the same time, the traditional coping mechanisms, such as chilled fluids and air condition, were unavailable plus many people were located in crowded shelters with poor circulation or in an attic where temperatures reached as much as 105 °F (41 °C).

Any assessment of the hazards related to Hurricane Katrina and the flooding of New Orleans would not be complete without an assessment of the region's environmental contaminants and the possible release of these contaminants during Katrina's winds and flooding. While a complete depiction of Louisiana's "Toxic Landscape" is beyond the current scope, some readily available data shows the presence of a select source of potential environmental contaminants. Figures 5.36 and 5.37 below show that, without a doubt, the natural hazards of Hurricane Katrina interacted with a toxic landscape in southeast Louisiana. Each site depicted on the map is a potential major source of oil, arsenic, or other hazardous elements, and many of them were susceptible to release following the battering winds and flood waters. Not shown in the map are the numerous small scale sources, including gas stations, garages, warehouses, and workshops.

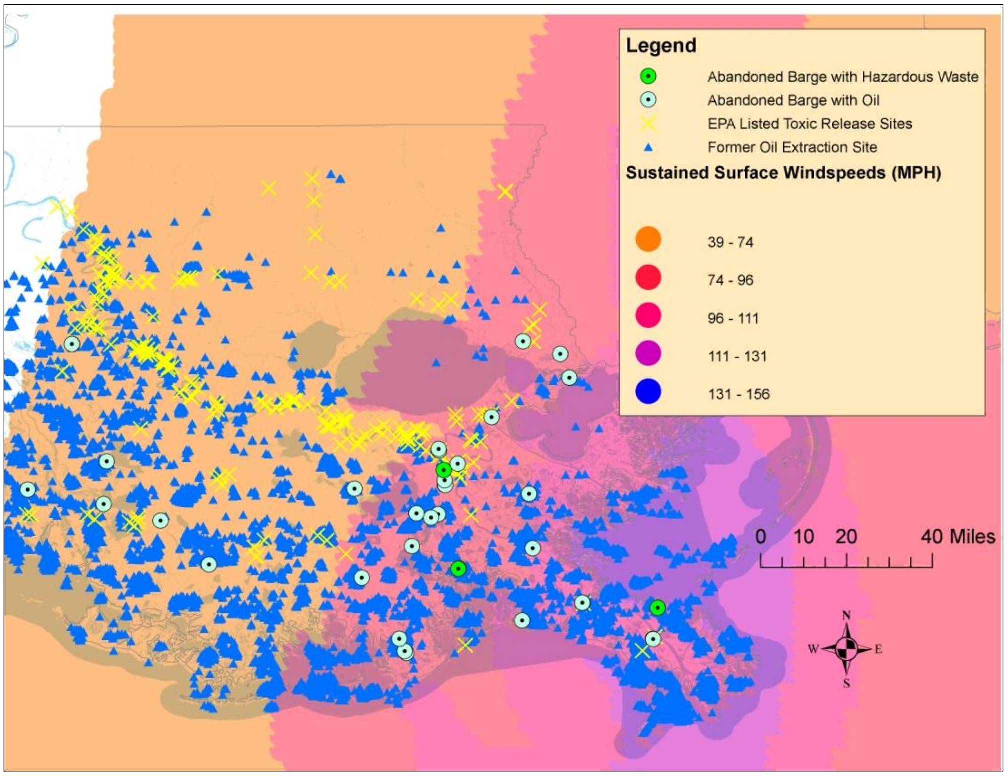

Figure 5.36: Katrina's windspeeds laid over Louisiana's toxic landscape (Guidry and Gisclair 2007).

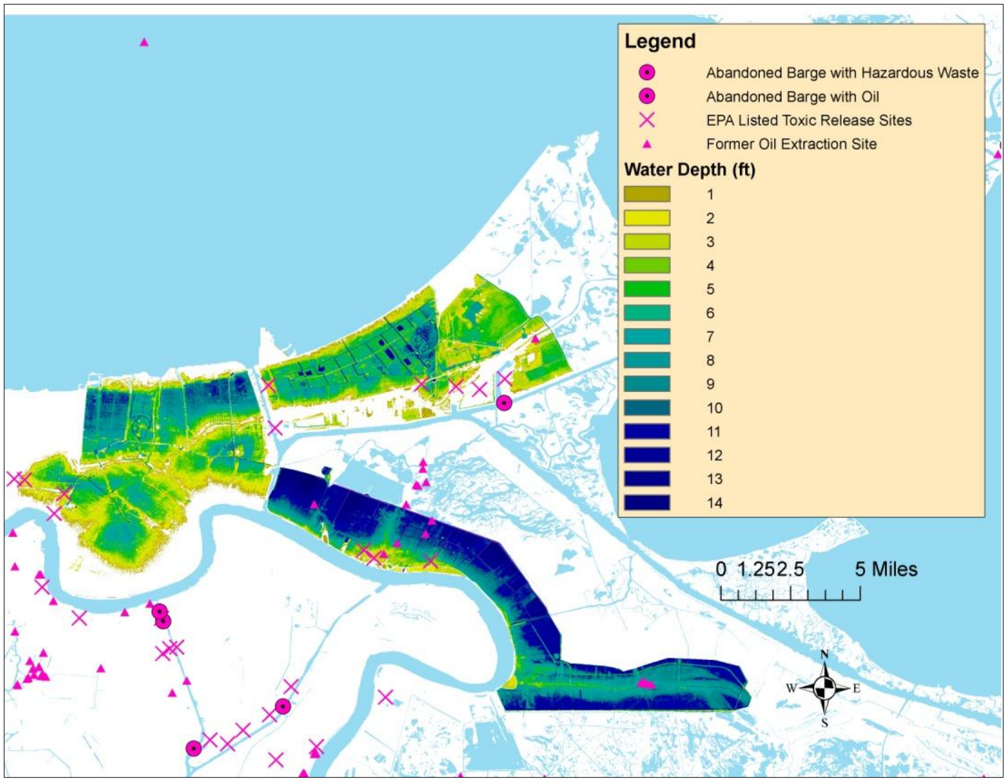

Figure 5.37: Metro New Orleans flood depths (Cunningham, et al. 2006) laid over the toxic landscape (Guidry and Gisclair 2007).

Figure 5.38: Photo of possible small source pollution located in a residential section of the Lakeview Neighborhood. The spray paint markings identify possible hazardous materials, "HM" on the top right, behind the building. A peek behind the building revealed this collection of drums containing unknown substances. The water stains shows very clearly that they had been inundated with flood waters, allowing for possible mixing of the substances with the floodwaters (Photos by Author).

A number of environment hazards have been realized throughout the affected regions. The Murphy Oil Spill is probably the greatest impact. Located in St. Bernard Parish between Chalmette and Meraux, the Murphy Oil facility consisted of a number of large oil storage tanks. One of these tanks was about half full when pressure from the flood waters caused it to rupture. About 25,000 barrels of crude oil was released from this tank, where it spread across flood waters, eventually impacting 1,700 homes in the adjacent neighborhoods. Similarly, the Louisiana Bucket Brigade documented a number of releases due to wind damage on refineries (Louisiana Bucket Brigade 2009). Throughout the recovery period, various sampling programs found health concerns due to water, soil, and air quality assessments. Additionally, individuals, including residents, workers, and volunteers, involved in the cleanup and rebuilding experienced mold exposure, while residents and workers living in temporary travel trailers experienced formaldehyde exposure. In Louisiana's coastal zone, oil spills introduced toxins into estuarine ecosystems that form an important part of the regions food supply.

5.4 Conclusion

This chapter introduced to the reader the landscape, the population, and hazard conditions that will be assessed in the chapters that follow. Hurricane Katrina and the subsequent flooding of New Orleans was a complex disaster with multiple hazards impacting multiple populations. The hazards of this event varied considerably across space. As such, one study region is not sufficient for depicting in totality the impacts of this disaster, so a multi-focused look at the regions impacted by the different hazards of this event has been provided.

Focusing on Louisiana, the state's population of approximately 4 million was discussed and described. It was shown that this population possesses many of the characteristics associated with vulnerability to disasters, including poverty, lack of education, and lack of vehicle access. It was also shown that these vulnerability factors were highest in the New Orleans area, which contained a large number of urban African-Americans.

When discussing the hazards of Katrina, it was shown that extreme winds and rainfall affected a large region within the United States. While, the most lethal hazard, the storm surge, did not extend far inland like the wind and rain, the surge still impacted a large stretch of central Gulf of Mexico coastline with tide levels over 15 ft (4.6 m) along the southeast Louisiana coast and over 20 ft (6 m) for most of Mississippi's Gulf Coast. Two additional hazards, which are often overshadowed by the wind, rain, and surge, were also discussed: the extreme heat that gripped the region and the release of numerous toxic substances due to wind and flood damage.

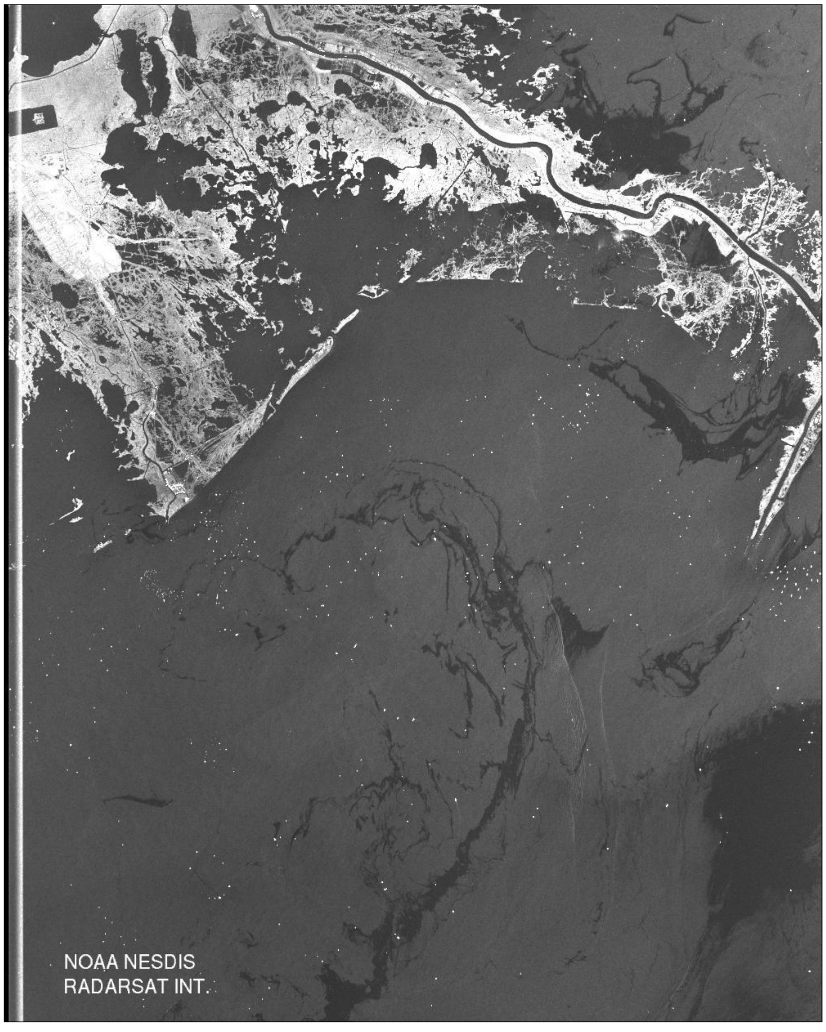

Figure 5.39: Satellite image showing Hurricane Katrina induced offshore oil slicks in recreational and commercial fishing zones along with oyster harvesting areas (Earth Scan Lab 2008).

Chapter 6: Fatalities Associated with Hurricane Katrina's Impacts on Louisiana

This chapter presents a descriptive overview of the available data on Katrina related fatalities. First, the available sources of information on deceased victims are described, along with steps taken to compile these sources into one database. Then, a series of basic descriptive statistics are presented. This chapter concludes by describing the results of classifying the victims using a three category scheme that describes the circumstances of death. The categories are (i) direct flood deaths, (ii) emergency circumstances deaths, and (iii) displacement/evacuation deaths.

6.1 Overview of Data on Katrina Related Fatalities

Deceased Victim Recovery Operations and Records

In addition to damaging many homes, the widespread flooding also impacted local coroner offices and many funeral homes. Reflecting both the reduced local capacity to handle the remains of victims and the sheer number of victims, state officials assumed the primary role in recovering and identifying the remains of victims.

The State Medical Examiner, Dr. Louis Cataldie, received authority to complete this task through Louisiana Executive Order KBB 2005-39, "Declaration of a Public Health Emergency for Control and Disposition of Human Remains." This order authorizes the secretary of the Department of Health and Hospitals (DHH) to create a State Medical Examiner within the Office of Public Health. Primarily tasked to set-up, operate, and oversee a regional facility for processing victims of the storm, the State Medical Examiner also approved the victim's identification when possible along authorizing death certificates and burial or cremation permits.

State officials created a temporary morgue in St. Gabriel, Louisiana, just south of Baton Rouge and, on September 13, contracted Kenyon International Emergency Services, a private company specializing in recovering disaster victims, to complete the actual recovery of hurricane victim remains. While Kenyon recovered most of the victims, other agencies also recovered victim remains. Specialists from the Federal Disaster Mortuary Operational Response Team (DMORT) provided assistance in examining victims remains. Over the next three months, Kenyon and others would recover the remains of nearly 800 victims. When the St. Gabriel facility closed on December 1, 2005, DHH and DMORT officials had examined 910 bodies, thirty-five of which were considered not storm related (LFAC 2006). Following the closure of the St. Gabriel facility, deceased operations moved to a second facility constructed by FEMA in nearby Carville, Louisiana called the Victim Identification Center (VIC). Another twenty-three victims were examined there before it ceased operations on February 24, 2006.

Initially, DMORT and local parish coroners worked in conjunction with the State Medical Examiner's Office to identify victims. DMORT demobilized on March 3, 2006 and victim identification was returned to the parish coroners. An unknown number (believed to be around 40 - 50) of Katrina related victims have been recovered and processed by parish coroners after the closure of the VIC. Also overseen by SMEO, the Louisiana Family Assistance Center (LFAC) handled reports of missing persons until August 14, 2006. When the LFAC closed, the cases of the 135 people who remained missing were handed over to local law enforcement agencies. Anecdotally, officials from the SMEO have reported that in just the first few days after receiving these cases, the Jefferson Parish sheriff's office found five such persons alive (Cataldie and Kosak 2006).

Victim recovery operations were not confined to SMEO and DMORT. While not all victims went through the St. Gabriel or Carville facilities, two datasets compiled by the SMEO list these victims. Some parish coroners chose not to collaborate with the state recovery team, and these victims have been reported in a list of "Out-of-Parish" victims. For these 243 victims, local officials provided summary data on the victims to the SMEO, and these are counted in the official total number of victims. Additionally, the SMEO received death certificates for 446 Louisiana residents who died while displaced out-of-state. After reviewing these cases, labeled "Out-of-State victims", the SMEO determined that 346 of these deceased persons fit the criteria for being counted as a Katrina victim[1]. Finally, not counted in the SMEO figure are approximately 50 victims, labeled "post-SMEO victims," recovered by local Orleans and St. Bernard officials after the SMEO ceased operations. Table 6.1 summarizes the summary statistics of the SMEO data.

The Louisiana Family Assistance Center served "as the national collection point for information on separated family members or those who may have perished" (Louisiana Family Assistance Center 2006, p. 5). Originally operating under the name the Find Family Call Center, the LFAC opened in October 2005 and continued operating until August 14, 2006. It was a joint State-Federal operation under the direction and oversight of the State Medical Examiner.

Table 6.1: Summary of information on the deceased and missing published by the Louisiana Department of Health and Hospitals on August 2, 2006 (Louisiana Department of Health and Hospitals 2006a).

Deceased

1,464 deceased victims related to Katrina's impacts in Louisiana, of which:
    875 recovered within Louisiana and reported by the SMEO, of which:
        853 listed in public dataset with individual characteristics
        864 listed in unpublished recovery locations dataset
    243 recovered within Louisiana and reported by parish coroners
    346 deaths among evacuated residents reported by out-of-state coroners

Missing

13,197 initially reported as missing, of which:
    13,062 have been found alive by the LFAC
    135 cases turned over to local law enforcement agencies

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[1] In an interview, SMEO officials described a process where they meet with the local coroners from Orleans and St. Bernard parishes reviewed these victims on a case-by-case basis and reached a professional consensus judgment on the cases where storm related.

With the closure of the LFAC, a final report was published on the DHH website on August 2, 2006 (DHH 2006a). With this final report, the LFAC listed 1,464 deceased victims due to Katrina's impacts on Louisiana. Most of these cases are Louisiana residents that died in Louisiana, but the total also presents Louisiana residents displaced out-of-state and a handful of out-of-state who happened to be in the impacted areas of Louisiana at the time. Of the reported fatalities, 875 were examined by the State Medical Examiner's Office at either the St. Gabriel or Carville facilities, 20 were reported by Orleans Parish coroner, 223 were reported from other parish coroners and 346 from out of state. The report gives information on race, gender and age for 853 fatalities. The report also gives information on the missing. While in operation, the LFAC handled 13,197 missing person reports, of which only 135 cases remained unresolved (Table 6.1). Many of the fields in the table are further discussed in later sections. However, it is important to realize that 1,464 deceased victims reflects an operational definition of "Katrina related death" used by the SMEO along with the operational constraints under which the office worked.

An independent analysis of fatality records conducted by CDC and LDHH epidemiologists concludes that the number of victims that fit the standard definition of disaster related is much lower than the total provided by the SMEO. Basing their analysis on the same SMEO records, Brunkart, Namuland, and Ratard (2008) classified these deaths using the *International Classification of Diseases* coding which includes a category for victims of cataclysmic storm. They write: "A systematic review of all of the records in the DMORT database and of Louisiana death certificates yielded a final database of confirmed victims" (p.2). In contrast to the 1,464 figure provided by the SMEO, these authors "identified 971 Katrina-related deaths that occurred in Louisiana and at least 15 deaths that occurred among Louisiana Katrina evacuees in other states, for a conservative storm-related death total of 986 victims" (p.2). The discrepancy in numbers relates to counting the out-of-state deaths, regarding which the authors note: "The state coroner was forwarded 446 out-of-state death certificates for Louisiana residents. Of these, 15 were clearly related to Hurricane Katrina, and 431 were classified as indeterminate because no indication of hurricane association was listed on the death certificate" (p.2).

Of course, neither count includes victims that were not listed in the SMEO records. As described later, around 20 victims were recovered shortly after the storm by Jefferson Parish officials, but these records where never shared with the SMEO. Likewise, after the SMEO closed, search teams and clean-up crews found and recovered around 40 victims from Orleans Parish, mostly from the Lower Ninth Ward. Also, victims that died as a result of violence were not counted as Katrina-related deaths by the SMEO, even if the evidence shows a clear link with the circumstances created by the disaster. Finally, indicative of the Katrina confusion and resulting uncertainty regarding the total number of victims, a memorial listing victims in St. Bernard Parish contained with a number errors. Initially, the memorial erroneously listed victims who were known to be alive (Anonymous 2008). Then, after a public vetting, the final number of victims listed differs from the official SMEO figures for that parish.

Primary Data on Katrina Related Fatalities in Louisiana

For each victim that was recovered through the effort led by the SMEO, there exists a "Receipt of Remains." This form includes basic information such as the date, time, and location of recovery along with the agency that recovered and the agency that transported the remains. It also includes some basic comments about the scene and sometimes lists a presumptive identification of the victim. Importantly, the "Receipt of Remains" forms were not standardized for all recoveries and were often incomplete. Some even appear to have been filled out in the offices in St. Gabriel or Carville, instead of at the recovery locations. Using these forms, the SMEO created a "Recovery Locations" spreadsheet which, after several iterations, listed most of the 910 victims examined by the SMEO.

Once the remains of a victim were recovered, they were transported to either the temporary morgue in St. Gabriel or to the VIC in Carville. At these facilities, post-mortem inspection of the victim remains, information from the Receipt of Remains, the recovered personal effects, dental examinations, and DNA tests were used to identify the victim. Once the victim had been examined and identified, the parish coroner would release a death certificate and the State Medical Examiner would authorize the release of the remains to the family.

Given the large number of deceased and the pressing need to quickly identify them, little information on cause of death is available. Autopsies were only conducted on victims recovered from hospitals, nursing homes, and other high profile locations, and most results have not been made public due to legal proceedings. Most of the death certificates simply note "Hurricane Katrina Related" as cause-of-death. In the absence of cause-of-death information, the available data are used to draw inferences on the causes and circumstances of death for the victims in a later section.

Deceased and Missing Reports, Vital Statistics Reports

As part of the state's effort to quickly provide the most-up-to-date information during the weeks and months that followed Hurricane Katrina, DHH's "Katrina Missing" website provided a public source of regularly updated information related to those who died. The website's "Deceased Reports" contained regularly updated summary statistics, while the "Vital Statistics of All Bodies at St. Gabriel Morgue" reports listed the identified victims along with basic demographic information. The last "Vital Statistics…" report was released on February 23, 2006 (DHH 2006b). It lists the names of 824 victims and provides basic information such as name, age, and parish of residence. The final report by DHH (2006b) that was published on August 2, 2006, gives summary information on race, gender and age for 853 fatalities. In addition to providing information on the known deceased, the DHH website also provided information on the personal characteristics of the people reported as missing. The final listing, posted on the website on August 9, 2006 lists 135 people who remained missing at that time (DHH 2006c), along with descriptive summaries of this population. This report notes that 65% of the missing persons are African-American, 84% are male, and 82% are from Orleans Parish (DHH 2006c). However, some of these victims have since been found alive.

Recovery Locations Dataset

In mid-October, the author began a collaborative effort with the State Medical Examiner's Office. As part of this collaboration, the SMEO provided the HC with data on the recovery locations for the deceased victims. This "Recovery Locations" dataset provided by the SMEO lists the recovery location (as listed in the receipt of remains) for each victim recovered by the joint State-Federal victim recovery effort. Most of these locations are listed as a standard street address with a number and a street, some are listed simply as street corners (for example Magazine Street and Jackson Avenue), some listed simply as a street or section of highway (for example I-10), and for 78 victims the street address is listed as "Unknown." The most recent dataset, obtained on September 14, 2006, lists 864 victims recovered throughout the State of Louisiana. According to the summary statistics published on the DHH website, this corresponds to 77% of the total number of victims recovered within the State.

This "Recovery Locations" dataset is based on the "Receipts of Remains" provided to DHH by the victim recovery teams. The dataset includes the following information fields: Date of Recovery, Type of Facility, Facility Name, Street Address, Nearest Cross Street, City, State, Zip Code, Parish, Comments, Transported By, and Scene. Each entry in the dataset describes the recovery of one victim. In some cases, multiple victims are recovered from a location; these are listed as separate entries with identical addresses. Since this dataset is based partially on receipt of remains, many of which were incomplete, it does not have complete entries for all cases.

Other SMEO Provided Data

In addition to the detailed records for the 910 victims whose remains were physically processed at the St. Gabriel Temporary Morgue or the VIC, the SMEO also received basic information from local coroners both within Louisiana and outside of the state. The information available for the "Out-of-Parish Victims" is limited to just the basics – residence, parish where death occurred, age, gender, race, etc. Also the listing of "Out-of-State Victims," only provides basic information. Data on these victims originates from the death certificates forwarded to the SMEO from coroners and medical examiners outside of Louisiana.

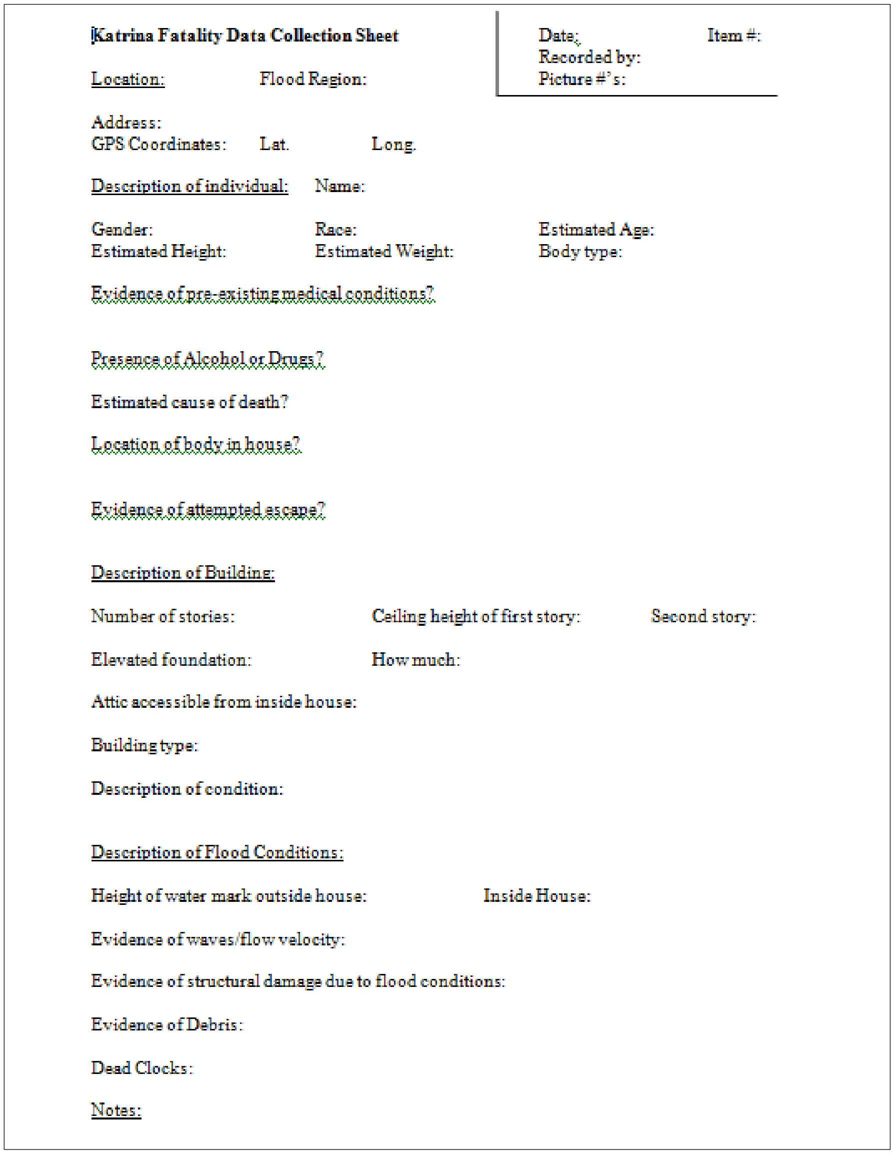
Additional Victims Recovered from Heavily Impacted Parishes

As described in Appendix A, additional victims have been listed in the media or described by parish officials. This includes about 20 victims from Jefferson Parish listed by The Times-Picayune, 6 victims described by the Plaquemines Parish emergency manager, around 40 victims found in Orleans Parish after the SMEO ceased operations, and other victims identified in individual media accounts, but not found in the SMEO data.

Field Observations of Recovery Locations

Utilizing the list of victim recovery locations provided by the SMEO, the author commenced a field study beginning in October 2005. The goals of this rapid post-disaster survey included (i) verifying cases listed by the SMEO, and (ii) investigating the characteristics of the location for these cases. These field investigations were limited to residents, businesses, and public places located in the heavily impacted regions of Orleans and St. Bernard parishes; most, but not all, of these locations were within the flood zone. In total, 427 locations and structures where victims had been recovered were surveyed. This includes 368 unique residential addresses out of approximately 400 addresses listed by the SMEO. In addition to the residential addresses, another 59 businesses and public locations were also surveyed.

Upon visiting a recovery location, the field team completed a data entry sheet (see Figure 6.1) to systemically collect important information on the location. First, the field investigation team (consisting of the author along various other student assistants from LSU) photographed search and rescue markings spray painted on the structure, and used these to verify that a deceased victim was actually recovered from the address listed. Additionally, we recorded the type of structure, the number of stories, the elevation of the first floor, and the elevation of the flood line above the ground and above the floor. We also noted evidence of structural damage (beyond inundation) to the structure, destructive storm conditions, or attempted escape.



Katrina Fatality Data Collection Sheet

Date:
Item #:
Recorded by:
Picture #'s:

Location: Flood Region:

Address:
GPS Coordinates: Lat. Long.

Description of individual: Name:

Gender: Race: Estimated Age:
Estimated Height: Estimated Weight: Body type:

Evidence of pre-existing medical conditions?

Presence of Alcohol or Drugs?

Estimated cause of death?

Location of body in house?

Evidence of attempted escape?

Description of Building:

Number of stories: Ceiling height of first story: Second story:

Elevated foundation: How much:

Attic accessible from inside house:

Building type:

Description of condition:

Description of Flood Conditions:

Height of water mark outside house: Inside House:

Evidence of waves/flow velocity:

Evidence of structural damage due to flood conditions:

Evidence of Debris:

Dead Clocks:

Notes:

Figure 6.1: Data entry sheet used in field inspections of victim recovery locations.

Louisiana Hurricane Katina Victim Master Database

As the above sections make clear, there is no single spreadsheet or database that lists all confirmed or potential deceased victims due to Hurricane Katrina's impacts on Louisiana. In fact the victims appear in lists across multiple sources that utilize different criteria and formats. As such, compiling these lists into a single database was an important first step in a more comprehensive analysis of loss-of-life related to Katrina's impacts on Louisiana.

To do this, an Access database was created, and the victim datasets described above were imported into the database as separate tables. Then Simple Query Language (SQL) queries were used to aggregate tables into a single table and then to identify and remove duplicates (identical victims listed more than once). These steps, which are described in detail in Appendix A, resulted in the Louisiana Hurricane Katrina Victim Database. Table 6.2 summarizes the information in this database, referred to as the "Katrina Victim Database". While certainly not complete, this database, which includes 1572 victims, represents the most complete listing of Katrina victims currently available. (It also provides an easy to use template for including victims listed by additional sources).

Table 6.2: Summary of the data included in the Louisiana Katrina Victim Database created by the author from multiple official and unofficial sources.

Summary of Database Content	1572 victims with 120 total columns, 70 columns with useful, non-redundant data
Victim Attributes	Name, Age, Race, Gender
Victim Residence	Street Address, City, Parish, Zip, State
Victim Recovery Location	Street Address, Cross, Street, City, Parish, Zip, State, Scene, Structure Type, Facility Name
Dataset "Catch All" Comments	11 columns that contain concatenated data from source datasets. One column for each source dataset.
Field Assessments Data	Field Address, Building Type, Building Condition, Number of Stories, Ceiling Height, Elevated / How Much, Height of watermark above ground, Height of watermark above floor, Dead Clocks, Structural Damage, Accessible Attic, Attempted Escape, Disable Resident, Waves, Debris, Comments,
GIS Data	Coordinates for Geocoded Residence and Recovery Location, Max Windspeed, Flood Depth (LSU Grid & SOBEK), Flow Velocity, Depth x Velocity, Arrival Time, Rate-of-Rise, Polder
Circumstances of Death	Based on the available data and classification rules (see Appendix C) each victim is classified into one of three major categories of circumstances.

Sources: Victim Recovery Locations provided by the SMEO, public listing of victims published on DHH website, out-of-parish and out-of-state victims provided by SMEO, Field Assessments dataset, LSU Flood Depth Grid, SOBEK Flood Simulations Grids, H*Wind Maximum Wind Grid

Issues in Data Collection and Interpretation

Interpretation of the available data presents a number of difficulties. As with any attempt to observe and measure a public health outcome, there are many inherent uncertainties. Uncertainties in the current dataset include unrecorded victims and missing information on the listed victims. Some number of the unrecorded victims is likely included in the missing, but even that number is uncertain.

Officially, when the SMEO closed operation in August 2006, 135 people remained missing, out of over 13,000 who were originally reported. These cases were then handed over the local law enforcement, and this figure has not been officially updated. However, anecdotally, SMEO officials reported that five of those cases were found alive by Jefferson Parish Sheriff's Officers in just the first week following the handover. Given how quickly one parish resolved five cases, it should be assumed that other cases have also been resolved with the victim found alive. Since no other information is currently available, the number of missing currently stands at 130, and some portion of these cases are presumed to be deceased victims whose remains were never recovered.

In regards to the missing, it is also worth noting that the tally of victims is based on calls from friends or family members. Potentially some hurricane victims among transient and socially isolated populations may not been counted because a body was never recovered and no one reported the person missing.

With the known deceased victims recorded in the database, there are many missing fields. Approximately 200 victims lacked basic information such as age, gender, and race. Detailed victim recovery information is available for only around 800 victims, though this does always correspond to location of death. In fact, some cases have specific information that indicates the body had been moved by either the flood or people. Most of the bodies though were recovered in buildings, and it is expected that for these cases the recovery location is identical to the location of death. For the 200 in-state victims and nearly 350 out-of-state, the available information is limited to victim's basic demographics plus their parish or state of death.

At this point, it is worth noting that many of the original datasets had a column for general comments, which were also included in the database. While generally blank and sometimes related to the details of victims processing, these also sometimes provided insights into the victim and the circumstances for death. For example, some victims have a presumptive cause of death listed in the general comments columns.

In regards to the "Out-of-State" victim data, incomplete sampling creates another limitation. Essentially, the data for these victims is limited to the states that chose to report the information to the SMEO, and not all states provided information to the SMEO. However, it should be noted that most of the states not reporting victims did not have a large number of evacuees and surrounding states only reported small number of deaths. So, while possibly incomplete, this sample is still likely representative of the out-of-state victims.

During the field assessment, seventeen locations listed in the SMEO dataset that did not have markings to indicate a victim had been recovered from that location, and two listed locations for which the address did not exist. We also serendipitously found three locations that bore markings to indicate a recovery location, but could not be found listed in the SMEO dataset.

In the GIS steps to determine the hazard conditions at the victim's residence and recovery location, there are a number of basic uncertainties. These uncertainties start with the address itself. Only about 800 cases possess sufficient information to map this location. Most of these are address with a street, number, and city, while others are specific street corners, interstate on-ramps, or other identifiable locations. Regardless of the level of information, there are always uncertainties in the geocoding process. Then there are measurement and computational uncertainties in the hazard conditions, which are provided as grids based interpolation of limited measurements, which are sometime inconsistent.

Lastly, the final tally reflects varying criteria applied by different medical professionals to determine whether or not a recovered victim was related to the storm. The SMEO physically processed the remains of 910 victims, but determined that 35 cases, mostly involving violence, where not storm related. For the other officially listed victims, the SMEO had to rely on data provided by parish and state officials who applied their own criteria for including and excluding deaths amongst the displaced population within their jurisdictions. The out-of-state victims then got a second review by the SMEO, who actually received information on 469 victims. Upon determining that 364 of these cases constitute storm victims, the SMEO arrived at the official tally of 1,464. However, upon review of these same cases, Brunkart, Namuland, and Ratard (2008) determined that only 986 victims fit the definition for a "victim of a cataclysmic storm" published by the *International Classification of Diseases*.

In compiling the victim database, I sought to cast as a broad a net as possible. Looking beyond just direct victims of a storm, I sought to list persons that died due to circumstances related to the storm and its initial aftermath, including a three nursing home residents that died of heat stress during the evacuation and a displaced toddler that drowned in a tub in a Houston hotel room. Also included are victims that died in hospitals that provided the victim safe refuge from the wind and water, but not from the lack of essential services, including electricity. However, in casting this broad net I also remained within the operation time span set by the SMEO, which includes the first month after the hurricane passed. So, for example, I would include on principle all of 35 cases of violent deaths that the SMEO excluded, and I did include these victims when the data were available.

Regardless of all of the shortcomings, the victim database provides the most complete compilation of persons who died due to circumstances related to Hurricane Katrina and its impacts on Louisiana.

6.2 Characteristics of Katrina Related Fatalities in Louisiana

This section discusses the basic characteristics of fatalities related to Katrina's impacts on Louisiana. The figures presented here are all based on the combined database of 1572 victims.

Previous published analyses (Brunkart, Namuland, and Ratard 2008, Jonkman 2007, Jonkman et al. 2009, Sharkey 2007, and Interagency Performance Evaluation Taskforce 2009) have been based on the previous data that includes only victims recovered and processed by the SMEO. As such, these figures will differ substantially.

Age

Age is an important demographic factor in the analysis of the fatalities. In fact, the distribution of this variable (see Figure 6.2) shows the considerable deviation from the distribution of this variable for the general population. The majority of victims were elderly, while only a small number were children. Out of 1373 victims for whom age is known, 1.3% were age ten or under and 2.5% were twenty or under. These percentages include 13 victims for whom the age list is "0", which likely means still-borns. In comparison, 86% were age 50 or older, 67% are 65 or older, and 23% were age 80 or older. As shown in Figure 6.2, the age distribution of fatalities peaks in the 80-85 age range. However, it is worth noting that the figure shows evidence of a bimodal distribution with a secondary peak in the 45 – 55 age range. A GIS analysis that overlayed the flood zone with the U.S. Census age-population layer revealed that 60,000 persons over age 65 in Orleans and St. Bernard Parish resided in flooded regions, which corresponds to approximately 15% of the total number of residents whose homes flooded. For the age 65 and over group, the difference between the victim percentage (67%) and the flooded population (15%) is substantial and cannot be attributed to measurement uncertainty.

Race

Table 6.3 presents data on the racial distribution of fatalities. African-Americans and Caucasians comprise most of the deceased victims, just as they made up over 97% of the affected population. Of the 1348 victims for which a race is listed, 637 (47%) are African American and 674 (50%) are Caucasian. Of the remaining victims, 21 (2%) are listed as Hispanic, 9 (<1%) are listed as Asian-Pacific, 3 (<1%) are listed as Native American, and 4 (< 1%) are listed as other. In Table 6.3, these figures are compared to the estimated racial background of the flooded population derived from census data and flood maps (see Appendix I for details of this calculation). Upon comparison with the population of the four flooded parishes, it appears Caucasians are over represented amongst the fatalities. However, the race is unknown for 13% of the victims, and this uncertainty in the data limits such a comparison.

Gender

The available data does not indicate that gender played a dominant role in the Katrina deaths in Louisiana. For the 1456 victims for which gender is known, 715 (49%) are male and 741 (51%) are female. While males are slightly overrepresented, this breakdown mostly corresponds with the gender distribution of the affected population. According to the U.S. Census 2005 American Community Survey statistics for the New Orleans metropolitan area, males comprise 47.5% of the population, while females comprise 53.5% (US Census 2005). Again, given that gender is unknown for 7% of victims, the observed differences may be a result of the measurement uncertainty.

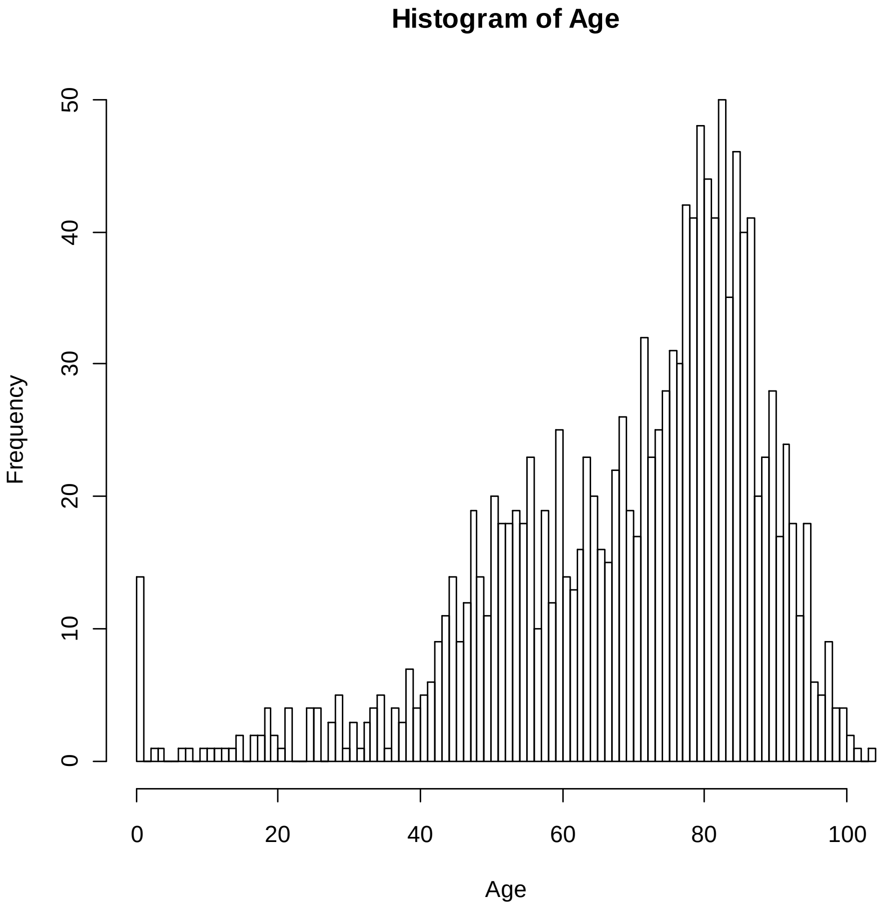


Figure 6.2: Age distribution of 1374 victims for which age is known (based on Katrina Victims Database).

Table 6.3: Racial distribution of 1369 victims for which race is listed (based on Louisiana Katrina Victims Database).

Race	Number of Fatalities	Percent of Known Victims (%)	Percent of Flooded Population (%) (*)
African-American	637	47	58
Caucasian	674	50	37
Hispanic	21	2	n/a
Asian/Pacific	9	<1	2
Native American	3	<1	0
Other	4	<1	2
Total Known	**1369**		

(*) See Figure 5.4

Disability Status

While we do not have direct information regarding the number of persons with disabilities that perished, evidence from field investigations indicate that a significant number of the deceased were disabled. During the field survey, we attempted to note and document any evidence that indicated that the household included a resident with a disability. At least 40 out of the 427 surveyed residential recovery locations showed evidence of some sort of disability for a resident at that location. Figure 6.3 shows the type of evidence found at the recovery locations that suggests that the deceased victim was disabled. Additionally, 221 victims were recovered from hospitals, nursing homes, and similar facilities. While we cannot determine that each one of these victims was disabled, it is reasonable to expect that a significant portion of those that died in medical and elder care facilities possessed some type of disability. According the 2005 American Community Survey (US Census 2005), 15.6% of the metropolitan region's population over 5 years of age was disabled. Given the lack of the direct information related to the victim's disability status, the available data does not allow a comparison with the percentage of victims to the background population.

Wheelchair and ramp in front of house indicated that the deceased victim was mobility impaired.

License plate in driveway indicates a disabled resident

Sign in window indicates that resident required oxygen tanks

Figure 6.3: Evidence of disabled resident at recovery locations (Photographs by Author)

Stratified Analysis of Victims' Characteristics

Moving beyond the basic demographic statistics of victims, a stratified analysis of victim demographics indicates some interesting results (Tables 6.4 - 6.6). Among the victims as a whole, Caucasians are more common (Table 6.3 above). However, Table 6.4 below shows that, when stratified by age, this is only true for the over 65 age group. Interestingly, when stratified by gender (Table 6.5), the role of race varies: most female victims were Caucasian, while most male victims were African-American. Finally, Table 6.6 shows gender stratified by age. For the under 65 group, males are most common, while females are more common for the over age 65. In fact nearly 40% of the victims are females over age 65.

Table 6.4: Race of victims stratified by age (Based on Louisiana Katrina Victims Database).

Age / Race	**Number of Victims**		**Percent of Known**	
18 and under	27		2.01%	
African American		20		1.49%
Caucasian		7		0.52%
19 – 64	409		30.41%	
African American		244		18.14%
Caucasian		154		11.45%
65 and older	909		67.58%	
African American		364		27.06%
Caucasian		500		37.17%
Grand Total (*)		**1345**		

* Includes cases for which both age and race are known

Table 6.5: Race of victims stratified by gender (Based on Louisiana Katrina Victims Database).

Gender / Race	**Number of Victims**		**Percent of Known**	
Female	700		51.93%	
African American		298		22.11%
Caucasian		381		28.26%
Male	648		48.07%	
African American		339		25.15%
Caucasian		293		21.74%
Grand Total (*)	**1348**			

* Includes cases for which both race and gender are known

Table 6.6: Gender of victims stratified by age (Based on Louisiana Katrina Victims Database).

Age / Gender		Number of Victims		Percent of Known	
18 and under		29		2.12%	
	Female		12		0.88%
	Male		17		1.24%
19 – 64		419		30.58%	
	Female		156		11.39%
	Male		263		19.20%
65 and older		922		67.30%	
	Female		544		39.71%
	Male		378		27.59%
Grand Total (*)		**1370**			

* Includes cases for which both age and gender are known

6.3 Spatial Distribution of Victims Residences and Recovery Locations

Residence of Victims

The overwhelming majority of deceased victims were Orleans Parish residents, while St. Bernard and Jefferson also provided a large portion (see Table 6.7). Of 1390 victims for which residence is available, 61% were from Orleans Parish, nearly 13% were from St. Bernard Parish, and 12% were from Jefferson Parish. Plaquemines and St Tammany parishes both account for 2% each, while Washington Parish accounted for 1%. Each of the remaining parishes accounted for less than 1%.

Figure 6.4 below shows the geocoded locations of victims' residences with respect the extent of wind impacts. While it shows that the majority of the victims resided in areas that experienced hurricane force winds, it also shows that a significant number of victims resided in parts of the state that did not experience any winds stronger than tropical storm force.

Spatial Distribution of Victim Recoveries

This section presents data on the spatial distribution of recoveries at different aggregation levels. At the national level, Figure 6.5 presents the number of deaths per state. It shows that most of the fatalities occurred in Louisiana, though a number of deaths also occurred in nearby states, such as Texas, Mississippi and Alabama, where many displaced persons initially settled (Kent 2005).

Zooming to Louisiana, Figure 6.6 shows the recovery locations of victims for whom this could mapped. Most of the victims were recovered within Metro New Orleans. However, a cluster in

Baton Rouge is also seen in the map, while clusters in Lake Charles and Shreveport are not shown because a geocodable recovery address was not available for these victims.

Parish of Recovery

The majority of victims were recovered from Orleans and St. Bernard parishes, see Table 6.8. Of 1088 victims for which a recovery parish is listed, nearly 56% were in Orleans Parish, nearly 12% were in East Baton Rouge Parish, and nearly 10% were in St. Bernard Parish. Roughly 79% of the flood exposed population lived in Orleans Parish, while approximately 11% resided in St. Bernard Parish (Boyd, Wolshon and van Heerden 2009). Baton Rouge was not impacted by flooding and only experienced tropical storm conditions.

Table 6.7: Parish of Residence for 1390 victims for whom this information is available.

Parish	**Number of Victims**	**Percent of Total Known**	**Parish**	**Number of Victims**	**Percent of Total Known**
Orleans	853	61.37%	Evangeline	2	0.14%
St Bernard	177	12.73%	Jefferson-Davis	2	0.14%
Jefferson	171	12.30%	Lafayette	2	0.14%
Plaquemines	31	2.23%	Livingston	2	0.14%
St Tammany	31	2.23%	Ouachita	2	0.14%
Washington	18	1.29%	Webster	2	0.14%
Calcasieu	12	0.86%	Bossier	1	0.07%
E Baton Rouge	12	0.86%	Catahoula	1	0.07%
Concordia	7	0.50%	E Carroll Parish	1	0.07%
Lafourche	6	0.43%	Grant	1	0.07%
St Charles	6	0.43%	Iberia	1	0.07%
Jackson	4	0.29%	Jeff Davis	1	0.07%
Madison	4	0.29%	Natchitoches	1	0.07%
Tangipahoa	4	0.29%	Pointe Coupee	1	0.07%
Beauregard	3	0.22%	Rapides	1	0.07%
Caddo	3	0.22%	River Region	1	0.07%
Lincoln	3	0.22%	Sabine	1	0.07%
St John	3	0.22%	St Joseph	1	0.07%
St Martin	3	0.22%	St. Tammany	1	0.07%
St Mary	3	0.22%	Vermillion	1	0.07%
Terrebonne	3	0.22%	W Feliciana	1	0.07%
Acadia	2	0.14%	West Carroll	1	0.07%
Baton Rouge	2	0.14%	West Monroe	1	0.07%
			Total Known	**1390**	

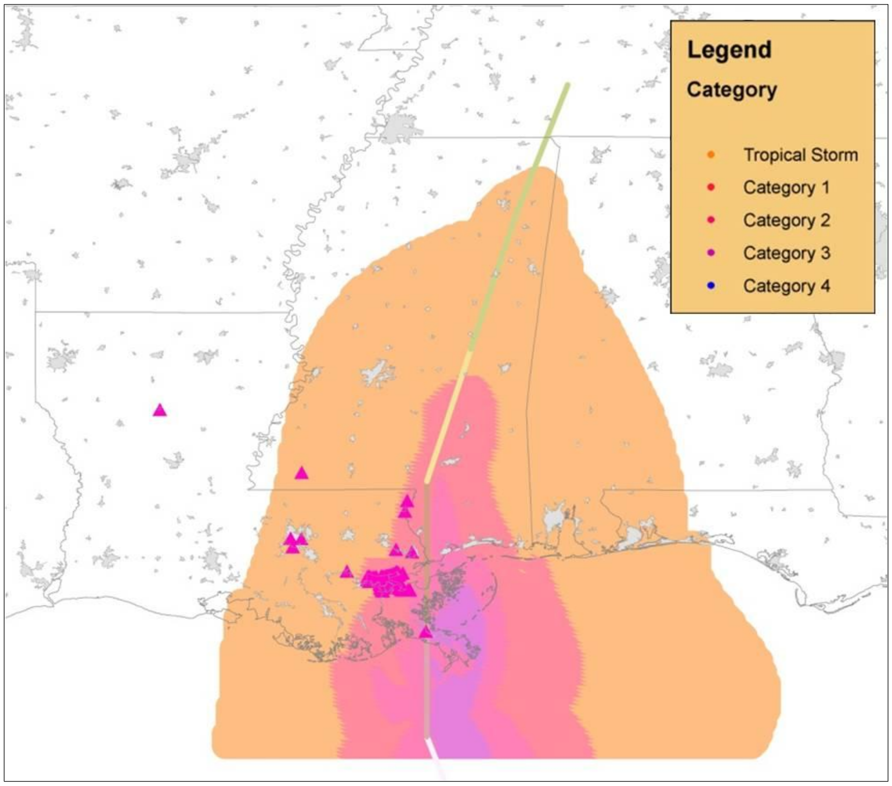


Figure 6.4: Residences of victims of Hurricane Katrina's impacts in Louisiana and the extent of wind effects. Most, but all victims that died due to impacts in Louisiana, were residents of Louisiana. One resident of Mississippi is shown, while another resident of Mississippi could not be mapped. Not shown are one resident each of Connecticut, Texas, West Virginia, Missouri, and South Carolina along other victims whose residential address could not be mapped that perished due to Hurricane Katrina's impacts on Louisiana.

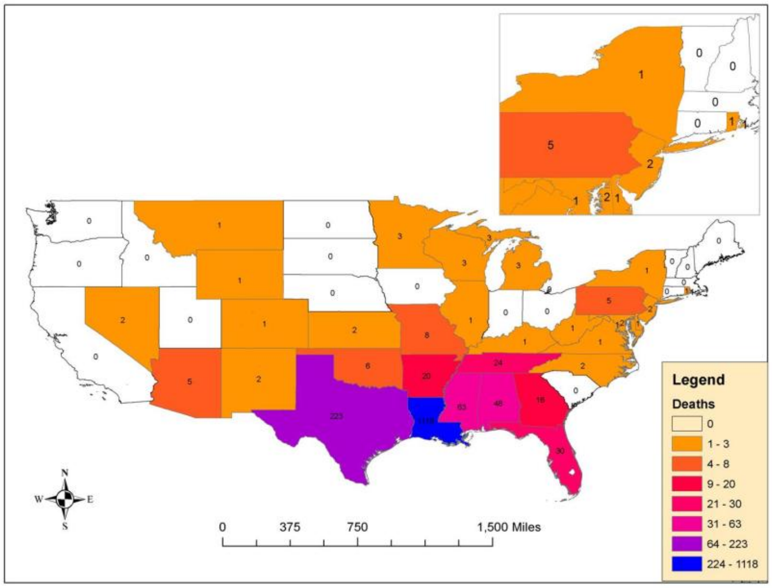


Figure 6.5: Total number of deaths per state (and District of Colombia) related to Katrina's impacts on Louisiana (Louisiana Department of Health and Hospitals 2006a).

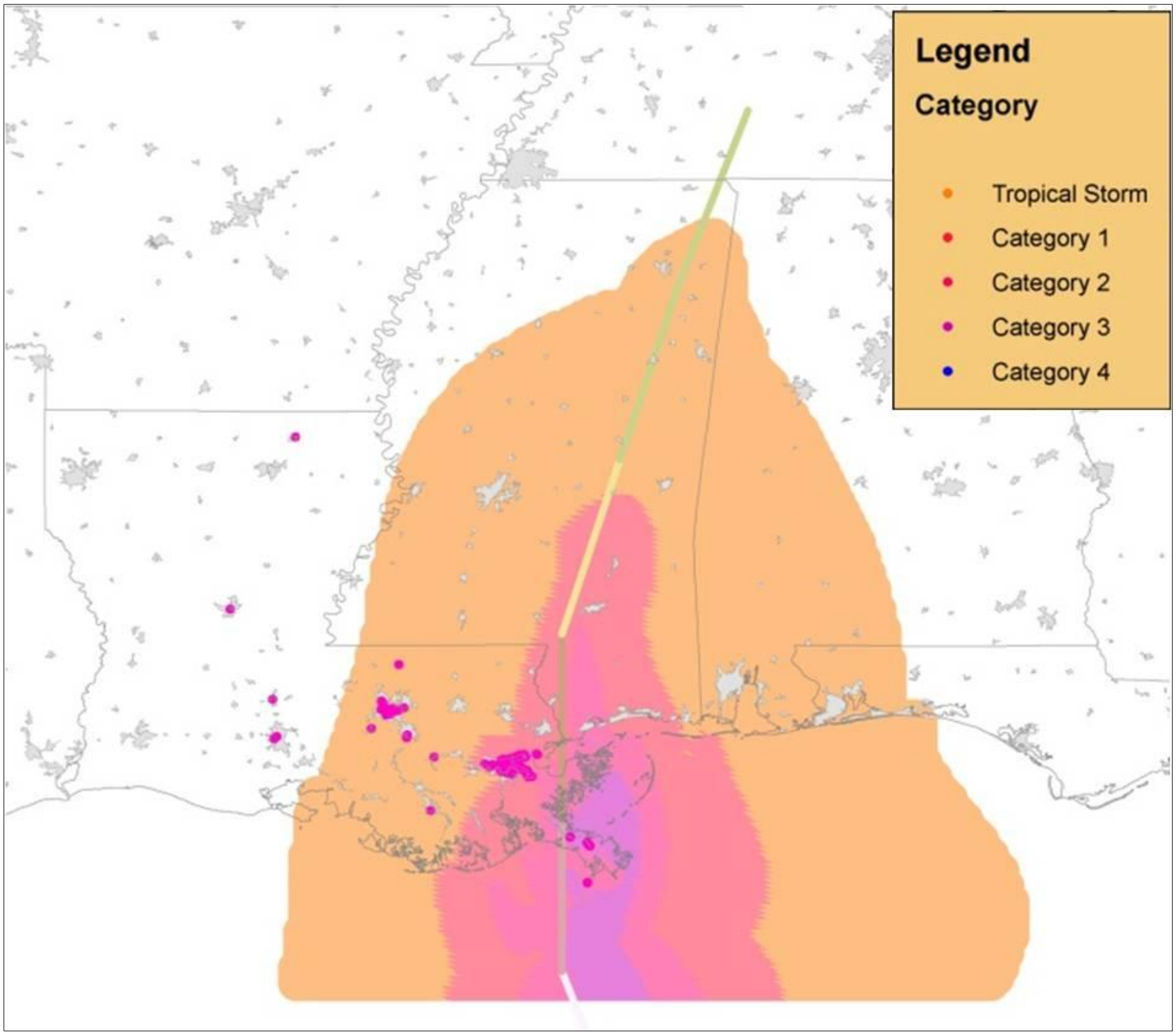


Figure 6.6: Distribution of recovery locations around Louisiana for 828 victims listed in the victim database with a geocodable recovery location. Each dot represents one victim, though overlapping dots may not be distinguishable. Not shown on the map are victims recovered in Shreveport, Lake Charles, or other localities where the local coroner did not provide a specific recovery location to the SMEO.

Table 6.8: Number of victims recovered per Louisiana parish of recovery for the 1088 victims for which the parish of recovery is listed. Also shown is a basic synopsis of the disasters impacts in each parish.

Parish	Number Recovered	Percent of Known	Disaster Effects
Orleans	605	55.61%	80% flooded; Winds up to 95 mph
E Baton Rouge	127	11.67%	Tropical Storm Force Winds; ~200,000 Evacuees
St Bernard	107	9.83%	100% flooded; Winds up to 100 mph
Jefferson	30	2.76%	Moderate Flooding; Winds up to 85 mph
Rapides	30	2.76%	No Significant Storm Effects
Caddo	19	1.75%	
Lafayette	19	1.75%	Tropical Storm Force Winds; ~30,000 Evacuees
Ouachita	15	1.38%	No Significant Storm Effects
Plaquemines	15	1.38%	
Calcasieu	10	0.92%	
St Tammany	10	0.92%	
St Charles	9	0.83%	
Terrebonne	9	0.83%	Winds up to 80 mph; ~20,000 Evacuees
Lincoln	8	0.74%	
Avoyelles	6	0.55%	
Iberville	6	0.55%	Tropical Storm Force Winds
Morehouse	6	0.55%	No Significant Storm Effects
Iberia	5	0.46%	
Jefferson-Davis	5	0.46%	
Livingston	5	0.46%	
Natchitoches	5	0.46%	
Jackson	4	0.37%	
Bienville	3	0.28%	
Pointe Coupee	3	0.28%	Tropical Storm Force Winds
St Landry	3	0.28%	
Ascension	2	0.18%	Winds up to 65 mph; ~20,000 evacuees
Catahoula	2	0.18%	
E Carroll Parish	2	0.18%	
Grant	2	0.18%	
Lafourche	2	0.18%	
Madison	2	0.18%	
Sabine	2	0.18%	
W Baton Rouge	2	0.18%	
Allen	1	0.09%	
Bossier	1	0.09%	
E Feliciana	1	0.09%	Tropical Storm Force Winds
LaSalle	1	0.09%	
St James	1	0.09%	Winds up to 60 mph
St John	1	0.09%	
W Carroll	1	0.09%	
W Feliciana	1	0.09%	
Total Known	**1088**		

Note: Flood impacts from Cunningham, et al. (2006) and windspeeds from Hurricane Research Division (2006). The stated number of evacuees for each parish is a rough estimate based on a variety of sources, and it should be assumed all parishes of Louisiana received some number of evacuees.

Out of the 41 parishes listed above, only five parishes experienced significant flooding due to Hurricane Katrina's storm surge or the associated levee failures. These parishes include Orleans, St. Bernard, Plaquemines, Jefferson and St. Tammany, and they account for 767 of the victims, which implies that many deaths occurred outside the flooded areas. Likewise, a number of victims were recovered from parishes that experienced moderate or no significant windstorm effects.

For many victims, "Parish of Residence" differs from "Parish of Recovery." These cases most likely are either evacuees from the New Orleans area that died outside of their home parish or persons from the surrounding parishes that evacuated to the relative safety of shelters and hospitals in Orleans Parish. For example, over 11% of the deceased victims were recovered from East Baton Rouge Parish, while less than 1% of the victims actually were residents of this parish (see above). This parish did not experience any flooding or significant wind effects. Likewise, over 30 fatalities that occurred in Orleans Parish were elder care patients transferred from a facility in St. Bernard Parish to a hospital in Orleans Parish just before the storm.

Using the geocoded resident and recovery locations, it was possible to assess the distances between residence and recovery location for 401 victims. Over 75% of victims were recovered close to home. The shortest distance between the victim's residence and recovery location was 1.2 m (3.9 ft). The longest distance was 21,000 km (1,305 miles). The mean distance is 31 km (19 miles), however the distribution is not normal:

10.5% less than 100 m (0.06 miles)
31.7% less than 1,000 m (0.62 miles)
67.3% less than 10,000 m (6.2 miles)

Of note, the measured distance is not directional, so a New Orleans resident who evacuated 200 km m and then died would have the same distance as a transient that died in New Orleans but resided 200 km from New Orleans.

Recovery of Victims from the Flooded Areas of Greater New Orleans

Figure 6.7 shows the recovery location for victims recovered from the flooded regions of the Greater New Orleans area. While many of these victims died in flooded homes, others also died at hospitals, shelters, and homes that did not flood. Also shown in the figure are the estimated flood depths (from the LSU grid) along with levee breach locations.

Results of aggregating victim recoveries by neighborhood (Orleans Parish) or Zip Code (St. Bernard Parish) are presented in Figure 6.8, while Table 6.9 provides this information in a tabular form. The number of recoveries varies greatly between neighborhoods. The Lower 9th Ward in Orleans Parish experienced the largest number of fatalities: 78. This neighborhood suffered from the catastrophic effects of the Mississippi River Gulf Outlet (MRGO) storm surge funnel and the breaches in the levees along the Inner Harbor Navigational Canal. Approximately, forty-four deaths occurred in Chalmette, which also suffered from catastrophic flooding related to the MRGO. In Orleans Parish, 43 fatalities occurred in the Freret neighborhood, where 41 patients died in the Memorial Medical Center Hospital (which includes the previously mentioned elder care transfer patients). Further analysis and discussion of the factors influencing the spatial patterns in fatality numbers and fatality rates is discussed section 4.

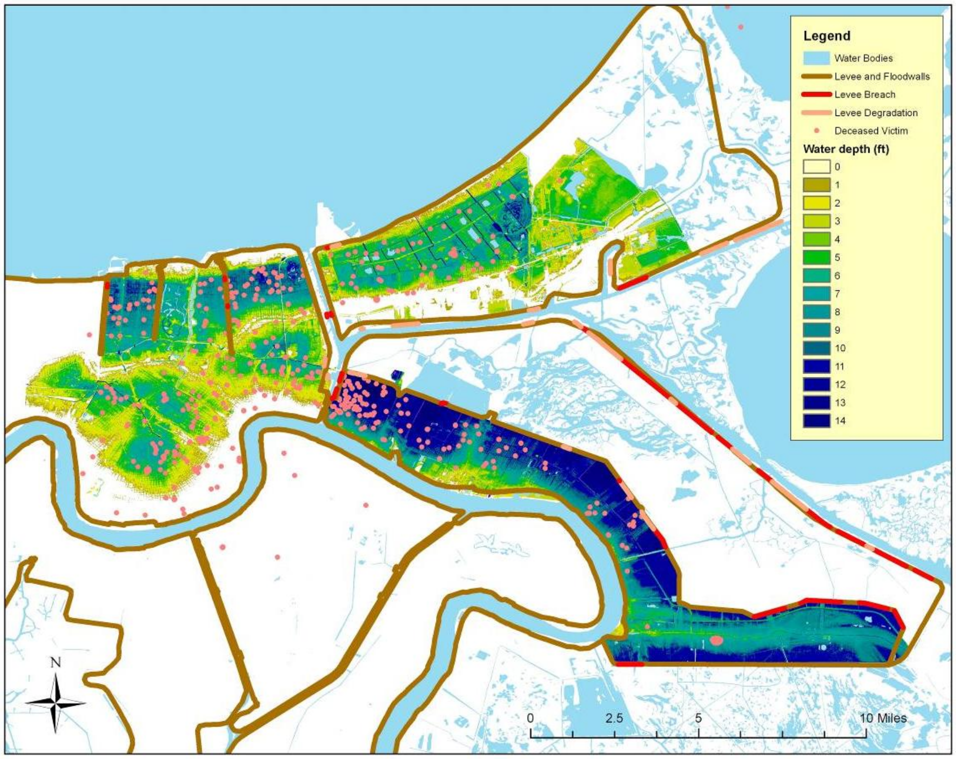


Figure 6.7: Recovery locations overlayed on maximum water depth for flooded portions of Greater New Orleans. In this map, each dot represents one victim and overlapping dots have been manually separated (Louisiana Katrina Victim Database; Cunningham, et al. 2006; van Heerden, et al. 2007).

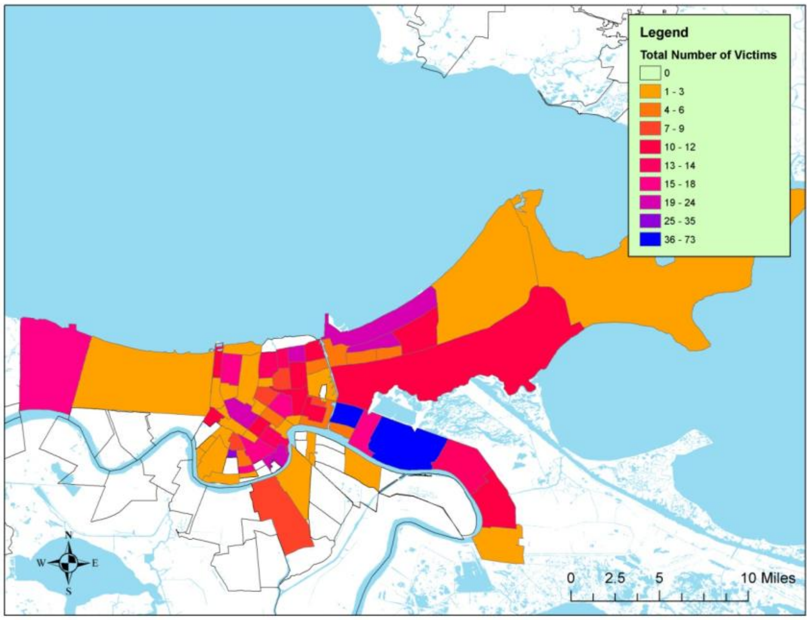


Figure 6.8: Number of victim recoveries by neighborhood (Louisiana Katrina Victim Database, Greater New Orleans Community Data Center 2006, LSU CADGIS Lab 2003).

Table 6.9: Recovered victims per neighborhood (Orleans Parish) or place (St. Bernard Parish), based on the geocoded recovery locations dataset (Louisiana Katrina Victim Database).

Neighborhood	**Total Recovered**	**Neighborhood**	**Total Recovered**
Lower Ninth Ward Neighborhood	72	Pines Village	4
Chalmette (St. Bernard)	44	Bayou St. John	3
Freret	43	Dixon	3
Mid-City Neighborhood	27	French Quarter	3
Touro	26	East Carrollton	2
West Lake Forest	26	East Riverside	2
Little Woods	23	Florida Development	2
Milneburg	23	Gert Town	2
Central City Neighborhood	21	Iberville Development	2
Lower Garden District Neighborhood	20	Marlyville/Fountainebleau	2
Lakeview Neighborhood	18	Navarre	2
Seventh Ward	16	Village de l'est	2
Arabi (St. Bernard)	16	West Riverside	2
Fillmore	14	Audubon	1
Tulane/Gravier	14	B.W. Cooper	1
St. Anthony	13	Black Pearl	1
St. Roch	13	City Park	1
Meraux (St. Bernard)	13	Fischer Project	1
Central Business District	12	Irish Channel	1
St. Claude	12	Lake Catherine	1
Viavant/Venetian Isles	12	Lakeshore/Lake Vista	1
Read Blvd East	10	Leonidas	1
West End	10	Marigny	1
Violet (St. Bernard)	10	Old Aurora	1
Dillard	9	St. Bernard Area	1
Florida Area	9	St. Thomas Development	1
Hollygrove	9	Whitney	1
Pontchartrain Park	9	Violet (St. Bernard)	1
Gentilly Terrace	8	Algiers Point	0
Broadmoor	6	Behrman	0
Fairgrounds	6	Desire Development	0
Gentilly Woods	6	Garden District	0
Plum Orchard	6	Lake Terrace & Oaks	0
Holy Cross	5	Lakewood	0
Milan	5	McDonough	0
Read Blvd West	5	New Aurora/English Turn	0
Treme'/Lafitte	5	Tall Timbers/Brechtel	0
Bywater Neighborhood	4	U.S. Naval Base	0
Desire Area	4	Uptown Neighborhood	0
		Grand Total	**650**

Point Pattern Analysis of Flood Deaths

To assess the distribution of flood deaths for clusters, Figure 6.9 below shows a Kernel density interpolation of victims recovered from locations with non-zero flood death and not inside of a hospital, multi-story apartment building, or other such location that would provide refuge from flood waters. This calculation was completed with Crime Stats III (Levine 2007) with a normal kernel with an adaptive bandwidth and a sample size of 5. Output units were set to points per square mile. A 300 column grid and absolute output was selected. The figures shows that the greatest density of fatalities occurred in the Lower Ninth Ward due to flooding caused by the MRGO. A second large area of higher mortality is found in Gentilly, a low lying densely populated neighborhood, with other smaller hot spots scattered throughout central New Orleans. No increased density of flood deaths is observed in New Orleans East, while St. Bernard Parish possesses only two small areas of increased flood deaths.

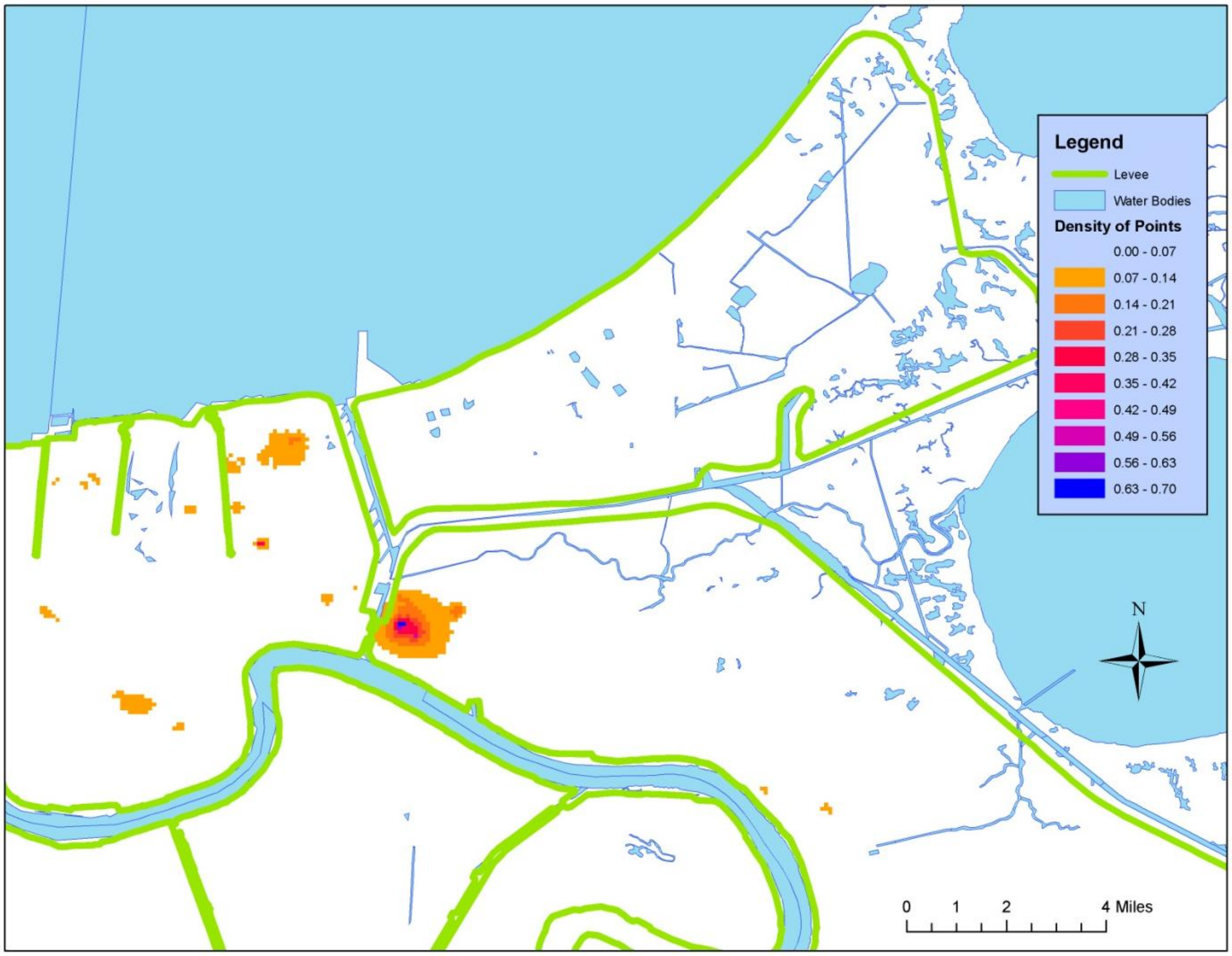


Figure 6.9: A Kernel Density interpolation of flood victim’s recovery locations (based on Katrina victim database using Levine 2007).

Type of Location Where Victims Were Recovered

The “Recovery Locations” dataset provides information on the facility type where the body was recovered for 809 victims (see Table 6.10). Of these, the majority of victims (51%) were recovered from individual residences. Our field investigations found that many of the residential recovery locations were single story homes that were either not elevated or elevated less than three feet.

Medical facilities, such as hospitals and clinics, comprise 159 (20%) of the recovery locations and nursing homes make up 62 (8%) of the recovery locations. Sixty-seven (8%) victims were recovered from a street, yard, canal, or similar public location. Thirteen (2%) victims were recovered from public buildings, such as churches and schools. Forty victims were recovered from the shelters/refuges at the Superdome (8), the Convention Center (17), and the Airport (15).

The field investigations (led the author with assistance from other LSU students and staff) provide additional information on the residences from which victims were recovered. While we surveyed a total of 427 locations, only 373 locations consisted of a structure while the remaining consisted of an outside location. Figure 6.10 shows a selection of types of houses that were observed. Out of 373 surveyed residential locations, 331 (87%) were single story structures, 38 (10%) structures had two stories, and the remaining 13 (3%) had more than 2 stories. Out of 377 survey structure, 201 (53%) had elevated foundations, while 176 (47%) did not. Of the elevated structures, 52 (26%) were elevated more than 36” above the ground level. Thus, 74% of the surveyed residential recovery locations were either not elevated or elevated less than 3 ft above grade. While we noted the type of façade (wood, brick, stucco, etc.) for the surveyed structures, no clear patterns were evident. Of note, due to the soil conditions, none of homes in the study area included underground basements.

Figure 6.11 shows the distribution of the observed water marks above the first floor for 338 flooded recovery locations for which the data were recorded. Of these, 65 (19%) are locations where the watermark was observed to be above the first floor ceiling. On the other end of the distribution, 38 (11%) had no visible interior flooding, while 42 (12%) experienced less than one foot. From the figure, it appears that the distribution peaks around 6 ft (1.9 m), and that most of the flooded residences experienced inside flood depths under 8 ft (2.5 m).

Table 6.10: Type of location where victims were recovered (Louisiana Katrina Victim Database).

Location type	**Number Recovered**	**Percent of Total**
Residence	416	51.42%
Medical facility	159	19.65%
Street, Yard, Waterbody	67	8.28%
Nursing home	62	7.66%
Public shelters	40	4.94%
School, Church, Business	13	1.61%
Morgue / coroner office / funeral home	44	5.44%
Sheriff's Office, EOC, Temp Medical Clinic	8	0.99%
Total Known	**809**	

In only 35 (9%) structures did we observe significant structural damage. In 50 (13%) of the structures, we found evidence of an attempted escape, such as a hole in the roof that appears to have been made from the inside or an open attic stairs that appeared to have been opened when the house was flooded.

Figure 6.10: Sample of flooded residences from which deceased victims were recovered (Photos by Author).

Figure 6.10 (cont.): Sample of flooded residences from which deceased victims were recovered (Photos by Author).

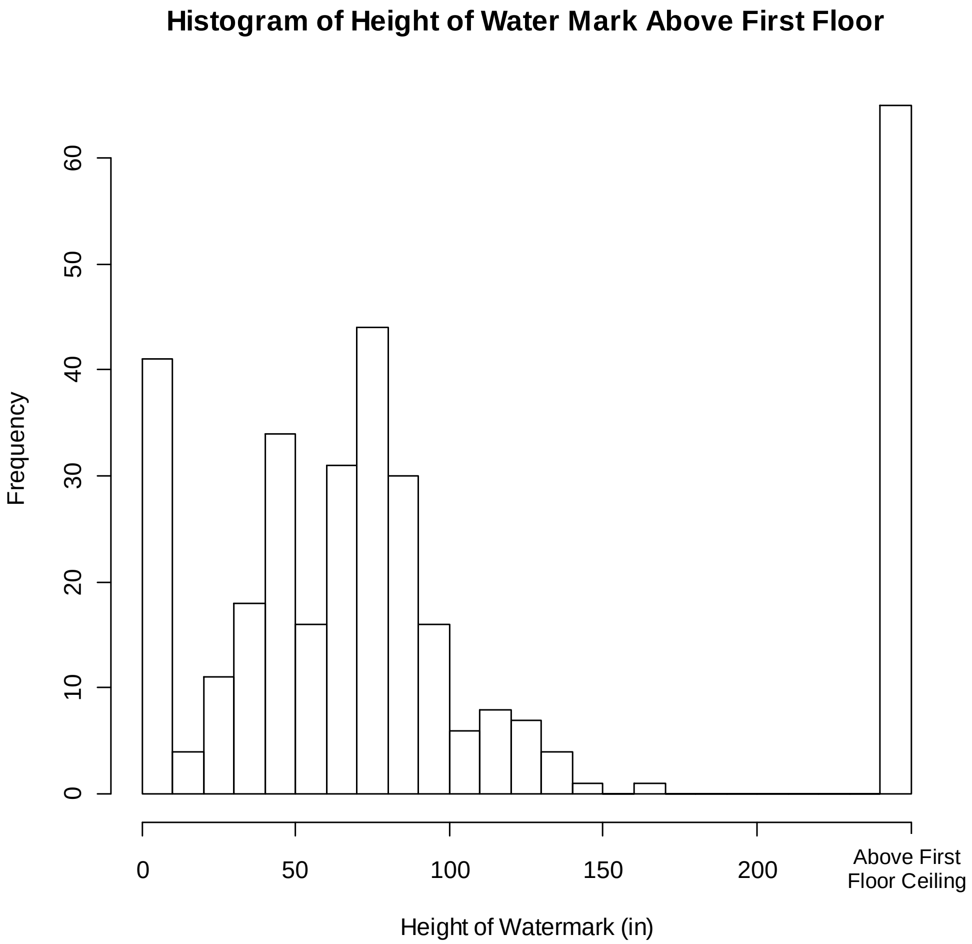


Figure 6.11: Histogram of water depth above first floor for Hurricane Katrina victim recovery locations within the flooded areas of Orleans and St. Bernard parishes (Louisiana Katrina Victims Database).

6.4 Discussion of Causes and Circumstances of Katrina Related Fatalities

In the absence of a medically determined cause of death for the victims, the available data are used to draw inferences regarding the circumstances of death. In particular, the roughly 1500 known victims can be divided into three categories based on location of death and the hazards present at that location. The three circumstances of death are the “Direct Flood Deaths,” the “Emergency Circumstances Deaths,” and the “Evacuation/Displacement Deaths.” Figure 6.12 summarizes this classification scheme while Appendix C describes the details the implementation of this classification scheme. As such, three zones characterize the geography of Katrina’s victims (see Figure 6.13). These zones are distinguished by the hazard conditions within the zone along with the population at risk, which changes constantly (as described in Chapter 4). These distinct combinations of hazard conditions and at risk populations are expected to create distinct sets of victim summary statistics, as discussed in the section.

“Direct Flood Deaths” are defined as victims whose circumstances of deaths are directly related to exposure to flood waters. These are victims that were recovered in the flood zone and not from an elevated structure that provided safe refuge from the flood. In addition to victims found in flooded homes and streets, this category also includes victims recovered from the attics of flooded homes and from rescue drop-off points in or near the flood zone. While these victims were not literally in floodwaters when they perished, they are still considered direct flood deaths because the circumstances of death are directly related to the flood conditions. The second category, “Emergency Circumstances Deaths,” includes victims whose death is linked to the emergency circumstances that existed throughout southeast Louisiana during the storm and its immediate aftermath. This category includes victims recovered from outside the flood zone but inside the heavily impacted region of southeast Louisiana along with victims recovered from within the flood zone but in elevated structures that provided refuge from flood conditions. Finally, a third category, termed “Evacuation / Displacement Deaths,” consists of victims whose death is linked to circumstances related to evacuation or extended displacement. Using these definitions, the data for each victim was reviewed to determine the most likely category. (Because limited data meant that not every victim could be determined exactly, three additional categories, which are described below, were also used).

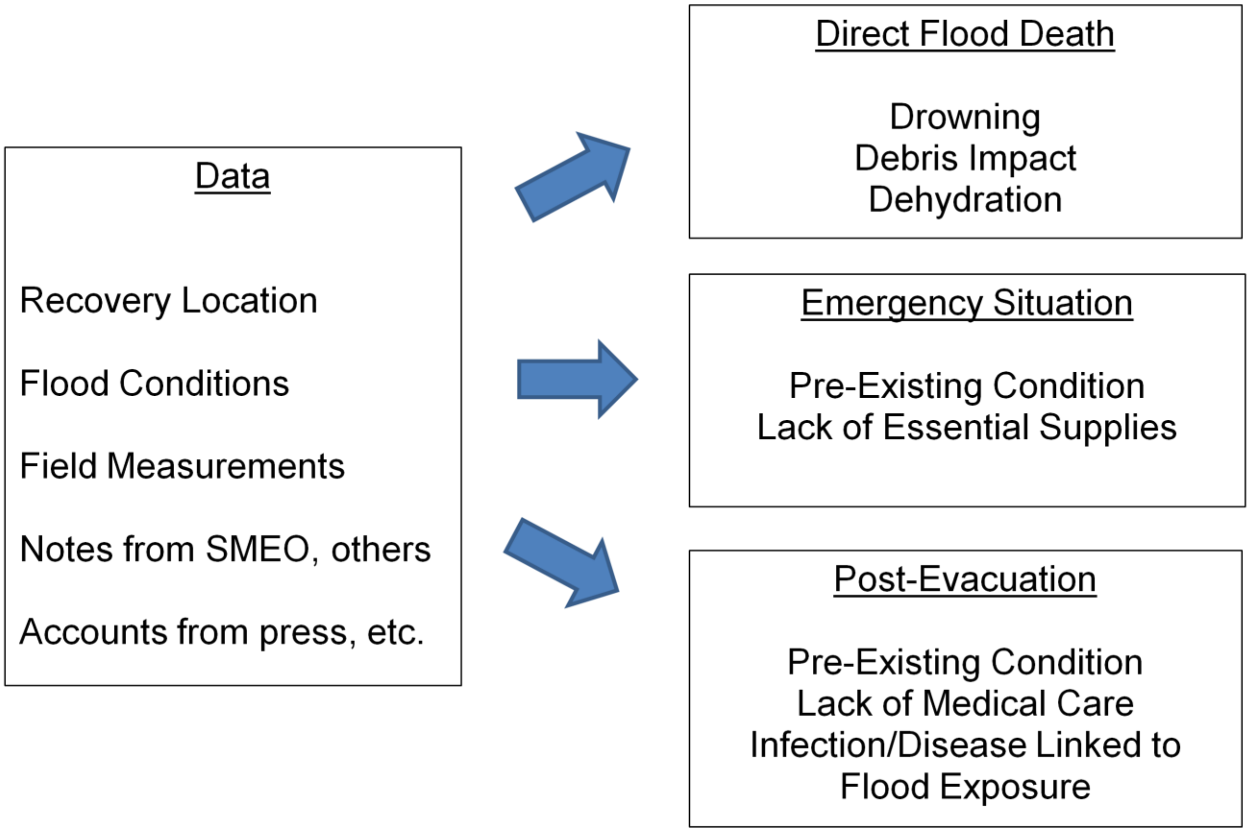


Figure 6.12: Circumstances of Death Inference Tree.

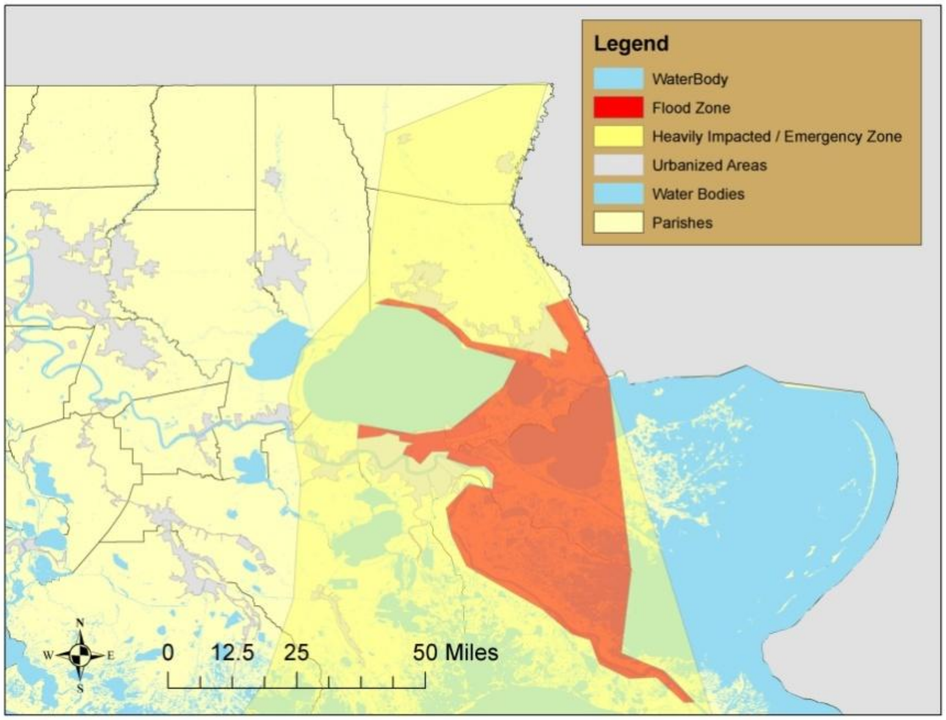


Figure 6.13: Rough Depiction of the Flood Zone and the Heavily Impacted Zone. Katrina related deaths that occurred outside these zones are considered Displacement/Evacuation deaths. Each zone has a corresponding set of hazards that resulted in distinct circumstances of deaths. It should be noted that the categories are distinguished based on the attribute queries described below, and that the spatial depiction of three zones in Figure 6.13 is a descriptive visualization of very fuzzy boundaries.

Direct Flood Deaths

Direct flood deaths were identified through two attribute queries. The first query identified victims recovered from flooded locations (specifically location non-zero flood depth according the LSU Depth Grid), while the second query eliminated the victims for whom recovery information indicates the victim perished in a building (apartment complex, hospital, etc.) with elevated stories that provided safe refuge from the flood. Excluding deaths from two flooded nursing homes, 426 deaths are believed to be direct flood deaths among the general population. Adding the 31 victims recovered from flooded nursing homes, the total number of known direct flood deaths is 557. In addition to these, there are 44 victims recovered from unknown locations. Since damage to street signs and home addresses were greatest in the flood zone, most of these victims with unknown recovery locations are believed to be direct flood deaths. These victims are labeled “Assumed Flood Deaths.” While little is known about the 130 people that remain missing, it is possible that bodies were never recovered for as many as an additional 100 direct flood deaths. Taken together, these pieces of evidence suggest that there could be as many as 700 direct flood deaths associated with flooding in New Orleans. While the exact number of direct flood deaths remains highly uncertain, the analysis of the available data suggests that number to be between 600 and 700.

While drowning is the likely the cause of death for many of these victims, some of these cases died due to other causes. Based on the observation that the inside watermark for roughly half the survey structures is over six feet (see Figure 6.11), it can be inferred that roughly half of the direct flood victims died due to drowning. Other victims died due to trauma from impacts with flood debris. Additionally, the direct flood deaths include victims that escaped floodwaters by fleeing to their attics but later succumbed to conditions there, including heat and dehydration, stress, and lack of essential medicines. Also included are victims that were rescued from flooded homes and brought to the nearest high ground, but later died due to the lack of essential medications or emergency medical assistance. Anecdotally, it is known that one case consists of a black femail in her mid-twenties that died due to a shock induced heart attack in ankle deep waters. These victims are included in the count of direct flood deaths because the circumstances of their death were directly precipitated by the flood conditions.

Emergency Circumstances Deaths

Based on the available information, 284 victims were classified as deaths related to the emergency circumstances. For another 16 victims, labeled "emergency circumstances/wind," the data suggested that they are most likely emergency circumstances, though the possibility that these may be wind related could not be ruled out. For these victims, the individual never had contact with flood waters, and flood exposure cannot be directly linked to the circumstances of death. Instead, the flood and wind damage, created a large scale regional emergency where basic public safety infrastructure and systems ceased to fully function. Of the 284 victims, 152 were recovered from hospitals, 19 from nursing homes, 42 from a shelter, school, or temporary medical clinic, 6 were recovered from a funeral home or coroner office, 32 were recovered from homes, business, or public places. The recovery structure type is unknown for 34.

The causes of death associated with this category of victims is numerous and diverse. Without specific information on these cases, it is believed that exacerbation of chronic conditions, lack of access to medical treatment and supplies, dehydration/heat stroke, and acute stress are the primary causes of deaths for these victims. This category also includes victims that died due to the widespread violence that occurred as a result of the regional emergency.

Evacuation and Displacement Deaths

An estimated 631 storm related deaths occurred outside of the region heavily impacted by Hurricane Katrina. This category includes 364 victims reported from out-of-state, the 243 victims report from out-of-parish, and 24 examined by the SMEO but determined to have died of circumstances related to evacuation or displacement. Some of these victims evacuated before the storm, while others were evacuated later. As such, some of these victims may have experienced exposure to the Katrina's flood or high wind hazards prior to rescue and/or evacuation, while others avoided such exposure.

The causes of the death for this category include the causes listed for the previous category along with additional causes, including long-term stress, trauma, and depression related to the disaster and its aftermath. It also includes accidents, disrupted health maintenance due to displacement from health services and medical records, and possible emergent effects related to exposure with contaminated floodwaters and other such environmental hazards.

Naturally, this classification scheme is not perfect, and the figures stated above have limitations. The input data possesses many uncertainties and unknowns. For the 39 cases, there was insufficient information to make even an informed guess and these deaths are unclassified. For those that are classified, the classification should be considered a best estimate based on limited information. Even with cases that have nearly complete information, there are some ambiguities. For example, if a victim acquired a lethal infection while exposed to flood waters, the death should be considered a direct flood death. However, if that victim died in a hospital in the greater New Orleans area, it would be classified as an emergency circumstances death, while if the victim died in an evacuation center in Texas it would be classified as a displacement death. In this regard, it should be noted that the classification was not done case-by-case, but rather in batch, based on attribute queries.

Despite these limitations, the figures discussed above are illustrative of the general trends in mortality related to this disaster. The next section considers how these trends impact the interpretation the victims' characteristics.

Do Circumstances Matter?

A previous section examined the statistic distribution of the demographic characteristics of the victims. This section examines how the distributions of victims' attributes vary between the three categories of circumstances. This analysis indicates that, contrary to common perceptions, the most prevalent victim group consisted of displaced elderly Caucasian females.

Figure 6.14 shows how the distribution of victims' ages varies between the three categories. From the figure, there appears to be little noticeable difference. Likewise, a comparison of the mean age between groups reveals only a slight difference. For direct flood deaths, the mean age is 69 years, for emergency circumstances deaths, the mean age is 70 years, and for evacuation / displacement it is 71 years. Only when comparing flood deaths to displacement deaths is the observed difference in the mean statistically significant, though the observed 2 year difference does not immediately suggest any substantive difference. Of particular note, there are no direct flood deaths under age 10 years.

When examining the racial distribution victims stratified by circumstances (Table 6.11), there is considerable variability between the categories. For direct flood deaths and emergency circumstances, over 50% of the victims are African-Americans, while over 60% of displacement deaths are Caucasians. As with race, there are notable differences when comparing the distribution of victims' gender between the three categories (see Figure 6.12). For direct flood deaths, males are more common, while for emergency circumstances and displacement females are more common.

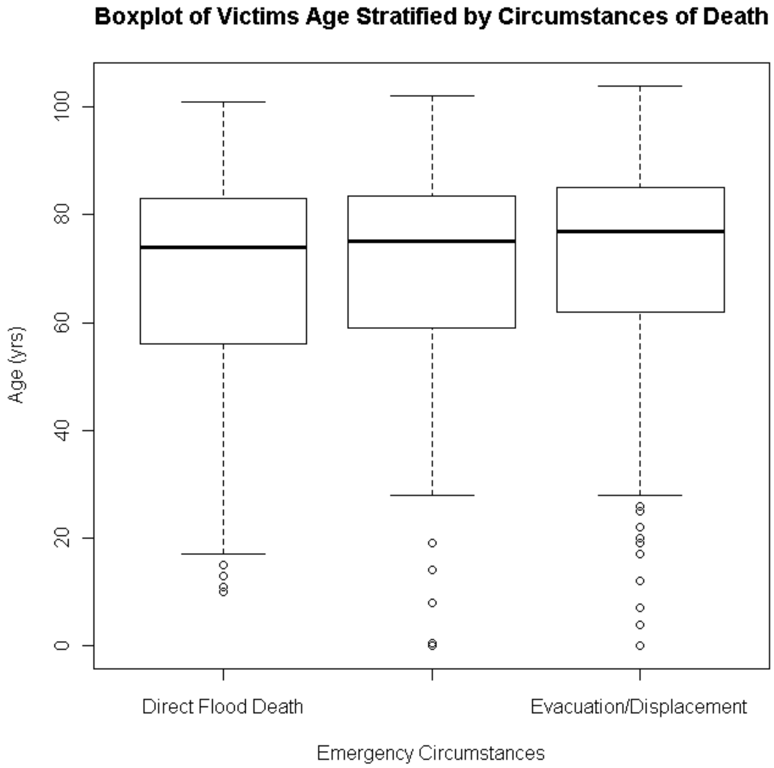


Figure 6.14: Boxplots of age for the three victim categories. Each boxplot (also called a "box and whisker" plot), depicts the distribution of age for all the victims within that category. The thick line inside the boxes represents the respective median values, while the box outline represents the upper and lower quartiles. The whiskers, the pair of lines outside the box, depict 1.5 times the quartile range, while points below the bottom line are considered outliers (Based on Louisiana Katrina Victim Database).

Table 6.11: Racial distribution of the victims stratified by circumstances. While only Caucasian's and African-American victims are shown, the percentages are based on all victims within each category for whom race is known. (Based on Louisiana Katrina Victim Database).

	Number of Victims	Percent of Category
Direct Flood Death (n = 460)		
African American	241	52.39%
Caucasian	198	43.04%
Emergency Circumstances (n = 241)		
African American	138	57.26%
Caucasian	95	39.42%
Displacement (n = 576)		
African American	218	37.85%
Caucasian	353	61.28%

Figure 6.12: Gender distribution of the victims stratified by circumstances (Based on Louisiana Katrina Victim Database).

	Number of Victims	Percent of Category
Direct Flood Death (n = 488)		
Female	226	46.31%
Male	262	53.69%
Emergency Circumstances (n = 265)		
Female	141	53.21%
Male	115	43.40%
Displacement (n = 622)		
Female	353	56.75%
Male	269	43.25%

6.5 Conclusion

This chapter provided a descriptive summary of Katrina related deaths for Louisiana. A database was compiled from numerous original sources, including information from a joint state-federal victim recovery effort. Uncertainties in the current initial interpretation result from incompleteness of the data, inconsistencies between sources, missing fields, and lack of data on important factors, especially medically determined cause of death. Despite these limitations, this dataset provides a more comprehensive dataset for the analysis of causes and circumstances for fatalities related to Hurricane Katrina's impacts in Louisiana. Of note, the victims summary statistics presented here differ from previous studies that were based in preliminary datasets published by the SMEO.

Louisiana health officials estimate that 1,464 deaths are related to the impact of Hurricane Katrina on Louisiana. Of these, 1,118 fatalities occurred in the state of Louisiana and 386 out of state deaths were reported amongst Louisiana residents. However, there is disagreement over how many of victims that perished outside of the heavily impacted southeast Louisiana should be included, while an independent analysis concluding that only 968 of these deaths met international criteria for inclusion as a "victim of a cataclysmic storm." On the other hand, including other reliable sources beyond the SMEO indentified an additional 109 victims that would likely fit the SMEOs criteria, but were not included.

Based on the information available, it is estimated that 600 to 700 victims died due to circumstances related to exposure to flood waters, approximately 300 victims died due to circumstances related to the widespread emergency in Metro New Orleans, and over 630 victims died due to circumstances related to evacuation and displacement.

An especially high number of flood deaths occurred in Lower Ninth Ward, an area that experienced large flood depths, high flow velocities and significant structural damage/collapse due to its location relative to the MRGO/GIWW.

From the analysis of the demographic characteristics, age emerges are the most important variable, with 86% of the victims age 50 or older and 67% age 65 or older. While the data are limited in regards to disability, what is available suggests that this is another important demographic variable. The initial examination of race and gender did not reveal any readily apparent trends, though the role of these factors is likely complex and warrants further investigation. However, when stratified by circumstances two trends are apparent. One, among deaths due to flood exposure, elderly male African-Americans were most prevalent. Secondly, among all victims, displaced elderly female Caucasians were most prevalent.

Chapter 7: The Flood Fatality Rate for Orleans and St. Bernard Parishes[1]

7.1 Introduction

This chapter and the next narrow the focus to one specific health outcome of this event: direct flood deaths due to levee failure flooding in Orleans and St. Bernard parishes of Louisiana. Ideally, such an analysis would include other flooded areas, but data limitations prevented this broader analysis. In this chapter, the direct flood fatality rate is estimated, mapped, and discussed. Of the approximately 1,600 deaths related to Hurricane Katrina's impacts on Louisiana, approximately 600 to 700 died to circumstances related to exposure to flood waters from storm surge and/or levee failures. In this chapter, the flood exposed population is estimated to be approximately 63,000 persons. The ratio of flood deaths to flood exposed population, termed the flood fatality rate, provides an empirical measure of flood risk. Georeferenced datasets on both the flood deaths and the flood exposed population are used to estimate and map the flood fatality rate. For the overall event, the flood fatality rate is estimated to be 9 to 11 deaths per 1000 persons exposed, which is consistent with other coastal flood disasters (Jonkman 2007). When examined at the blockgroup and neighborhood levels, the data shows that the highest values of the flood fatality rate occurred in the Lower Ninth Ward, while comparatively lower values occurred in New Orleans East.

This chapter's main focus is on the methods and data used to measure the dependent variable for the regression analysis of the next chapter, where this dependent variable is modeled using the flood hazard characteristics and the population vulnerability characteristics. What follows is a step-by-step description of the data processing steps to create a dataset based on flooding impacts in greater New Orleans. In this model, the flood fatality rate, the dependent variable of interest, is defined as the number of flood deaths divided by the number of persons exposed to flood waters. Working with data similar to what is presented here, Jonkman, et al. (2009) present a non-linear regression analysis that uses a preliminary dataset based on this flood event. This chapter presents a more refined estimate of the flood deaths, the flood exposed population (along with consistency checks from additional, independent data sources), and hence a more refined estimate of the flood fatality rate. In narrowing the focus of analysis, this chapter relies on the story told in Chapter 4.

Calculating the flood fatality rate for a given flood event requires data on both the flood deaths and the flood exposed population. If the data are in a spatially referenced format, then the flood fatality rate can be mapped. The next section describes how spatial data on the flood fatalities and the flood exposed population was obtained, and then basic descriptive statistics and maps of the flood fatality rate are presented. Reflecting the nature of available data, calculations are completed at the blockgroup and neighborhood levels, and the analysis is confined to Orleans and St. Bernard parishes because these two parishes suffered the greatest flood damage. While the actual calculation is straightforward, both conceptually and numerically, the calculation relies

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[1] Portions of this Chapter has been previous published as Boyd, Ezra C. (2010) "Estimating and Mapping the Direct Flood Fatality Rate for Flooding in Greater New Orleans Due To Hurricane Katrina," Risk, Hazards & Crisis in Public Policy: Vol. 1: Iss. 3, Article 6. Copyright 2010 Policy Studies Organization, used with permission.

on a variety of disparate data sources. Additional independent data sources are also used to verify the estimate of the flood exposed population.

Beyond just producing the dependent variable for the next chapter, the steps and results presented in this chapter also provide insight into the spatial distribution of the flood risk for this event. A basic principle of epidemiological methods posits that it is important to account for the underlying population at risk (also called the population denominator) when studying raw counts of any health impact, including flood deaths. The previous chapter took cursory steps toward this goal, but Chapter 4 makes clear that the dynamic nature of this complex disaster exposed different and changing populations to different and changing hazards. In this chapter, the focus narrows to the flood hazard and the population denominator is population exposed to flood waters. In presenting the flood deaths as a rate with reference to this underlying population at risk of death due to flood exposure, the flood fatality rate comprises a valid measure of the flood risk for this event.

Before jumping into the calculations, the next section expresses the flood fatality rate in terms of the risk equations described in Chapter 4, which sets the conceptual tone for the regression analysis in the next chapter. Then, section 3 recaps the key overall statistics from Hurricane Katrina and shows the overall flood fatality rate for the event. These numbers were discussed in previous chapters, but are repeated here so that the reader can better understand these numbers in the context of flood fatality modeling. The next two sections focus on the data collection steps and methods used to estimate the key variables. Section 4 describes the data and steps used to estimate the flood exposed population, while section 5 describes how the flood deaths were identified from the Katrina victim database. In Section 6, the overall flood fatality rate for the event is presented along with a map of this rate calculated at the blockgroup and neighborhood levels. Basic trends in observed flood fatality rate are also described.

7.2 Flood Fatality Rate as a Risk Measure

The flood fatality rate (FFR) is defined as the number of flood deaths divided by the number of persons exposed to flood waters. Jonkman (2007) terms this variable the flood mortality. This section refers to the risk equations and principles of fatality modeling from Chapter 4 and shows that the FFR forms an adequate risk measure.

Kaplan and Garrick (1981) describe three components of risk which are captured by the so-called “risk triplet.” The three components are: (i) the possible events, (ii) the probability of each of these events, and (iii) the consequences of the events. The risk-triplet is expressed by the following equation:

$$R = \{ <s_i, p_i, x_i >\}$$

In a similar manner, Jonkman (2007) describes three components of loss-of-life estimation methods: (i) the physical hazard characteristics of the event, (ii) the number of people exposed to hazard, and, (iii) the mortality (i.e. fatality rate) for the exposed population. While not exactly the same formulation as Kaplan and Garrick (1981), these three components of loss-of-life estimation bear a strong resemblance to the three components of risk.

In this particular case, we are interested in the risk of death due to hazard exposure during a specific event: the 2005 flooding in Orleans and St. Bernard parishes that resulted from breaches in the levee system. For this event, we seek a valid measure of individual risk of death due to exposure to floodwaters that is consistent with the above principles.

In this context, a particular scenario, which is denoted s_k, is specified, and the risk triplet reduces to a doublet:

$$R_k = < p_k, x_k >$$

Since we are interested in the individual risk of death, $x_k = 0$ (lives) or 1 (dies). From here, if we follow Jonkmans's three steps, we have an estimate of the FFR which is shown to equal p_k and hence R_k.

Kaplan and Garrick (1981) stop short of providing an actual formula for R_k. To overcome this limitation, a common trick in solving differential equations is utilized: express the unknown function as a power series, and then take the first order approximation. For a univariate function, a power series expansion of a function is defined as an infinite series of higher power terms,

$$f(x) = a_0 + a_1x + a_2x^2 + a_3x^4 + \cdots.$$

For a multivariate function, the equation is more complicated but follows a similar form. In principle, any $f(x)$ can be specified exactly as an infinite power series, while in practice the k^{th} order approximation is obtained by summing the first k terms of the expansion.

As a first-order approximation for the R based on the first term in the power series, we have

$$R_k \approx p_k \text{ x } x_k$$

which is the common definition of risk. Considered in this context, the common definition of risk as probability times consequences is just the first term of the power series expansion of the risk doublet for a particularly scenario, while a higher-order expansions are necessary to look at cases such as low probability, high consequence events.

In modeling the individual risk of dying, the outcome is a dichotomous variable with $x_k = 0$ (lives) or 1 (dies) and the above formula reduces to

$$R_k \approx p_k$$

Following the practice of using measures of frequency to calibrate the probability scale we have that

$$p_k = \text{flood deaths / flood exposed population}$$

$$= n_{fatility} / N_{exposed}$$

and

$$R_k = n_{fatility} / N_{exposed}.$$

When looking at a specific individual flood event, the flood fatality rate forms a measure with regards to this class of consequences. Naturally, this expression is a simplification of a complex, multi-dimensional function of unknown form that is only on applicable in specific contexts. The subset k indicates that we are looking at just one event. While the subscripts on n and N indicate that we are looking at only one consequence for a specific population. Namely we are assessing the risk of death for the flood exposed population for the specific scenario. This expression does not include other outcomes of this event, other types of flood events, or other types of scenarios, all of which are necessary for a complete specification of R.

The rest of this chapter focuses on the measurement of the FFR, while the next chapter relates this risk measure to $R = H \times (V/C)$, where H describes the physical characteristics of the hazard and (V/C) refers to the vulnerability characteristics and response capabilities of the affected population (U. N. Interagency Secretariat; International Strategy for Disaster Reduction 2002) to derive the flood fatality model formulated by Jonkman (2007).

7.3 Summary of Relevant Data

When Hurricane Katrina made landfall along coastal Louisiana on Monday, August 29, 2005, it pushed an unprecedented storm surge inland and caused catastrophic and deadly flooding over a major portion of the U.S. Gulf Coast. In southeast Louisiana, three separate polders in Orleans and St. Bernard parishes, all of which lay adjacent to the MRGO/GIWW, suffered unprecedented flooding after the tidal surge overwhelmed the region's hurricane flood protection system.

The evacuation of southeast Louisiana had begun approximately 2 days before Katrina's landfall, early on the morning of Saturday, August 27. During a brief 42 hour emergency preparation period, over 1 million people are believed to have evacuated the flood prone areas in southeast Louisiana (Wolshon 2006, Louisiana Office of Homeland Security and Emergency Preparedness 2006). For Orleans and St. Bernard parishes, the two parishes that would suffer the greatest flood damage, the evacuation rates were 80% (Russell 2005) and 92 – 93%, respectfully (Select Bipartisan Committee 2006). Based on these figures along with the estimated 2005 population, an estimated 200,000 people remained in the metro New Orleans (which also includes Jefferson and Plaquemines parishes) as the heavy winds and floodwaters brought chaos and destruction to the region. While an estimated 65,000 people utilized shelters provided by local governments (Select Bipartisan Committee 2006), much of the non-evacuated population is believed to have stayed in their own homes or the homes of friends and relatives.

The ensuing flooding in Orleans and St. Bernard parishes trapped an estimated 62,000 people in flooded homes and neighborhoods and resulted in 600 – 700 direct flood deaths. The next two sections describe how these numbers were obtained, and the section that follows those uses these numbers to calculate the flood fatality rate. From these numbers, the overall fatality rate for the event (meaning exclusively flooding in Orleans and St. Bernard parishes) is estimated to be 9 to 11 deaths per 1,000 persons exposed. This observed rate is consistent with Jonkman's (2009) "1% mortality rule," which states that approximately 1% of the flood exposed population perishes during coastal flood events.

7.4 Methods and Data: The Flood Exposed Population

A key variable in modeling flood deaths is the flood exposed population. This section presents a method for estimating the size and distribution of the flood exposed population using GIS data and evacuation rates stated by public officials. Verification of this estimate is done using figures found in reviews of search and rescue operations.

Methods and Data Sources

A number of data sources enable an estimation of the size and distribution of the population exposed to floods. Essentially this data layer derives from three sources: (1) census based population estimates, (2) estimates of the percent of people who evacuated and sheltered before the storm, and (3) a flood depth raster that shows the maximum extent of flooding. Additional data sources help verify results of this calculation. This estimate for the non-evacuated population is cross-checked against estimates of the sheltered population and head counts from the final evacuation. Similarly, the estimate of the flood exposed population can be cross-checked against counts by search and rescue teams. This section sketches the steps in the calculation and summarizes the results. Chapter 3, along with Boyd (2007) and Boyd, Wolshon, and van Heerden (2009) contain further details of this attempt to account for the people impacted by the hurricane and flood.

Baseline Population

The 2000 Census Summary File 3 (SF3) provides the initial population data used to estimate the flood exposed population (US Census 2002). SF3 blockgroup level population shapefiles for Orleans and St. Bernard parishes were obtained from *Atlas: The Louisiana Statewide GIS*. These polygon shapefiles depict the total number of residents for the 534 blockgroups that comprise the two parishes of the study area. Additionally, the 2005 American Community Survey (ACS) shows a net population decrease for both parishes (US Census 2005). In 2000, these two parishes had a population of 551,903. However, by the time Hurricane Katrina hit in 2005 the population had dropped to 501,783.

While the 2000 Census SF3 data provides population estimates at the blockgroup level, the 2005 ACS only provides parish level data. As such, the estimated 2005 population at the blockgroup level is simply the 2000 population for the blockgroup times the retention rate for the parish. This estimate does not reflect variation in the retention rate within each parish. Figure 7.1 depicts the estimated August 2005 distribution of the residents of Orleans and St. Bernard parishes. For the most part, these are the residents who woke up in their homes on the Saturday morning before Katrina's landfall to hear evacuation calls from their local officials.

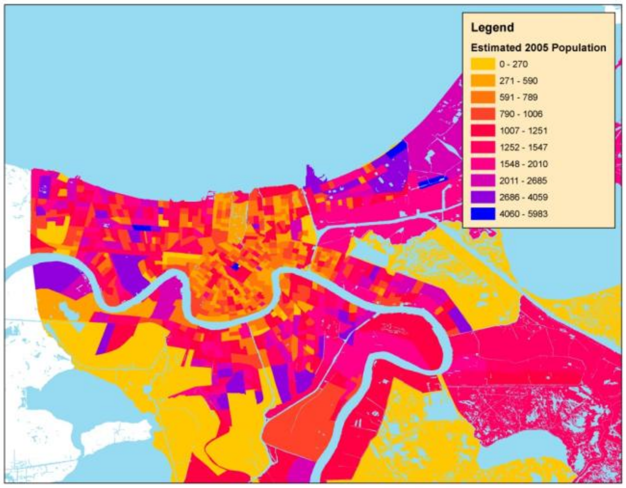

Figure 7.1: Estimated August 2005 population by blockgroup for Orleans and St. Bernard parishes. Based on data from the U.S. Census (2002, 2005).

Of note, the sections that follow describe the steps at the blockgroup and the neighborhood levels of analysis. The blockgroup level, which provides a finer resolution than the neighborhood level, suffers from the small population of the blockgroups, whereby some did not experience a flood death. While the calculated value of the FFR equals zero for these blockgroups, the flood risk is not zero. Because of this issue, using the blockgroups in the regression analysis of the next chapter would create a bias in those results. For this reason, the calculations were also completed using data at the neighborhood level. While the calculations are exactly the same, these units are large enough to ensure that all of flooded units experienced a FFR greater than zero.

Evacuation and Sheltering

The evacuation of southeast Louisiana for Hurricane Katrina began early on the Saturday morning before landfall and continued through Sunday evening, when the region had begun to experience Katrina’s winds, rain, and surge. In addition to traffic count data, which indicates that approximately 1.1 million people evacuated the region, estimates of the evacuation effectiveness for each parish has been provided by parish officials. Orleans Parish officials claim an 80% evacuation (Russell 2005), while officials in St. Bernard Parish claim that 92 - 93% of residents evacuated (Select Bipartisan Committee 2006).

Based on the 2005 population along with the stated evacuation rates, it is estimated that 85,000 people remained in the soon to be flooded Orleans and St. Bernard parishes. As it was well known that 100% evacuation compliance would not be achieved, local governments provided shelters of last resort and transportation assistance to these shelters. In Orleans Parish, an estimated 10,000-12,000 people rode out the storm in the Superdome (Taskforce Pelican 2005), while approximately 800 people utilized the two shelters provided in St. Bernard Parish (Select Bipartisan Committee 2006). This leaves approximately 73,000 people at risk from Katrina’s extreme wind, rain, and surge. Figure 7.2 shows the distribution of this population, which is estimated by multiplying the 2005 blockgroup level population by the percentage that did not

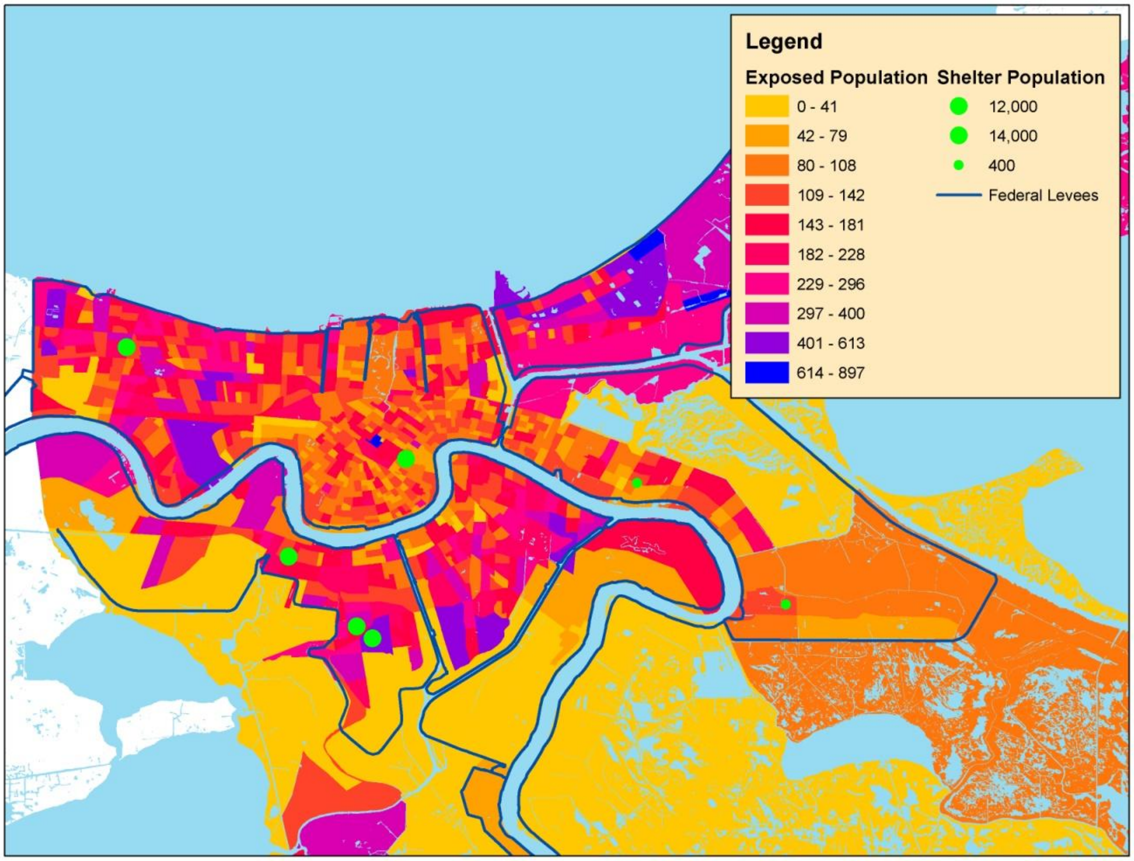

Figure 7.2: Approximate Distribution of the Non-Evacuated, Non-Sheltered Population in Orleans and St. Bernard parishes during and after Hurricane Katrina, August 2005. Also shown are refuges-of-last resort opened in Orleans, Jefferson, and St. Bernard parishes. Based on data from the U.S. Census (2002, 2005), Select Bipartisan Committee (2006), Louisiana National Guard (2005), and Russell (2005).

evacuate or shelter for the corresponding parish. Again, there is very little reliable information on inner-parish variability in evacuation rates, so this method does not account for such variability in the evacuation rates.

Flood Depth Raster

Using satellite imagery showing the extent of floodwaters, LIDAR elevation data, and field measurements of high water marks, LSU geospatial scientists working in the state's Emergency Operations Center quickly developed a raster dataset depicting the depth of floodwaters throughout the flood impacted region (Cunningham 2006). Basically, the flood depth for a raster cell was calculated as the height of the water surface (estimated from the satellite imagery and field measurements) minus the elevation (from LIDAR). A preliminary version of this flood depth raster was provided to emergency managers who used it to assist ongoing emergency response operations, while later refinements to this flood depth raster were made as better data became available. For the current purposes, the revised flood depth raster (obtained from the creators in October 2005) is used to identify blockgroups and neighborhoods that experienced flood conditions and to calculate the mean flood depth for the blockgroups and neighborhoods.

Flood Exposed Population

The number of people exposed to floodwaters can be estimated by overlaying the flood depth grid with the non-evacuated, non-sheltered population (see Figure 7.3). This task was accomplished by using the Zonal Statistics tool (Arcview 9.1 2005) to calculate the mean value of flood depth for each blockgroup and then identifying the blockgroups and neighborhoods with a non-zero mean flood depth. These are termed the “flooded areas.” Summing the non-evacuated, non-sheltered population for these flooded areas gives an estimated 63,260 people exposed to flood waters (Table 7.1).

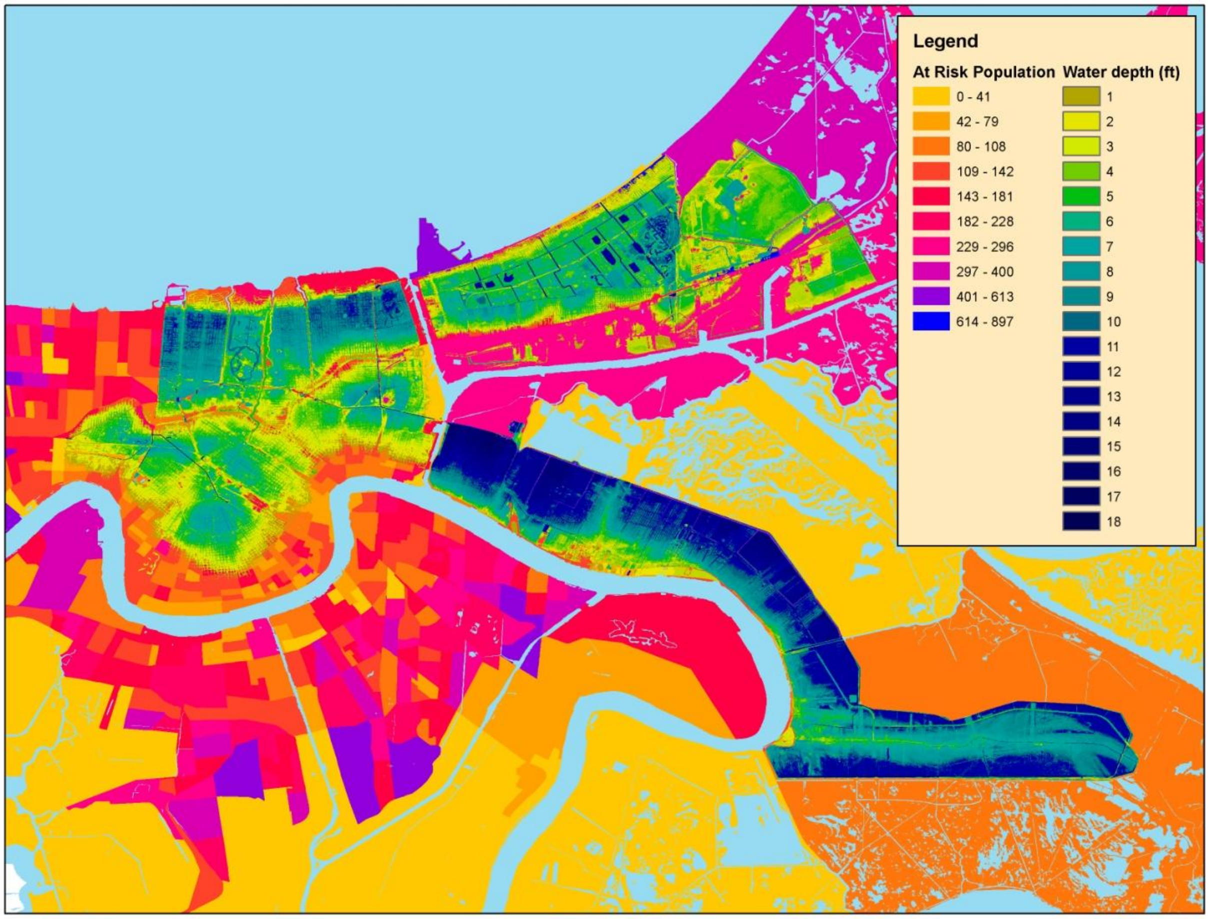

Figure 7.3: The flood exposed population was estimated by laying the flood depth grid over the non-evacuated, non-sheltered population (Figure 7.2) in Orleans and St. Bernard parishes during and after Hurricane Katrina, August 2005. Based on data from the U.S. Census (2002, 2005), Select Bipartisan Committee (2006), Russell (2005), and Cunningham, et al. (2006).

Table 7.1: Flood exposed population (Based on Figure 7.3).

Average Flood Depth (ft)	People Exposed (n)
0 - 4.9	37,419
5 - 9.9	20,877
10 - 15.8	4,964
Total Exposed	**63,260**

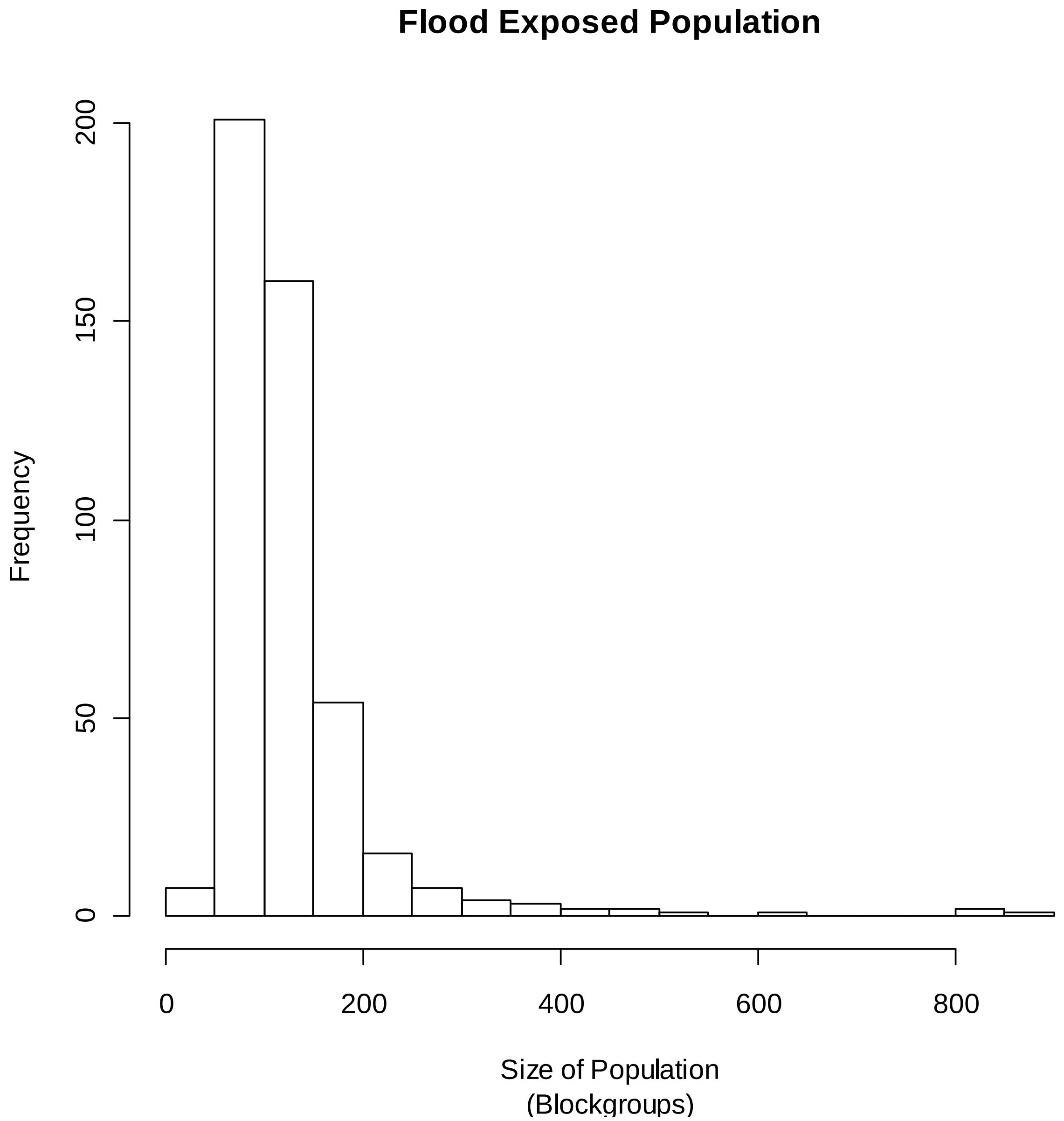

Figure 7.4: Histogram of flood exposed population at the blockgroup level in Orleans and St. Bernard parishes during and after Hurricane Katrina, August 2005 (Based on Figure 7.3).

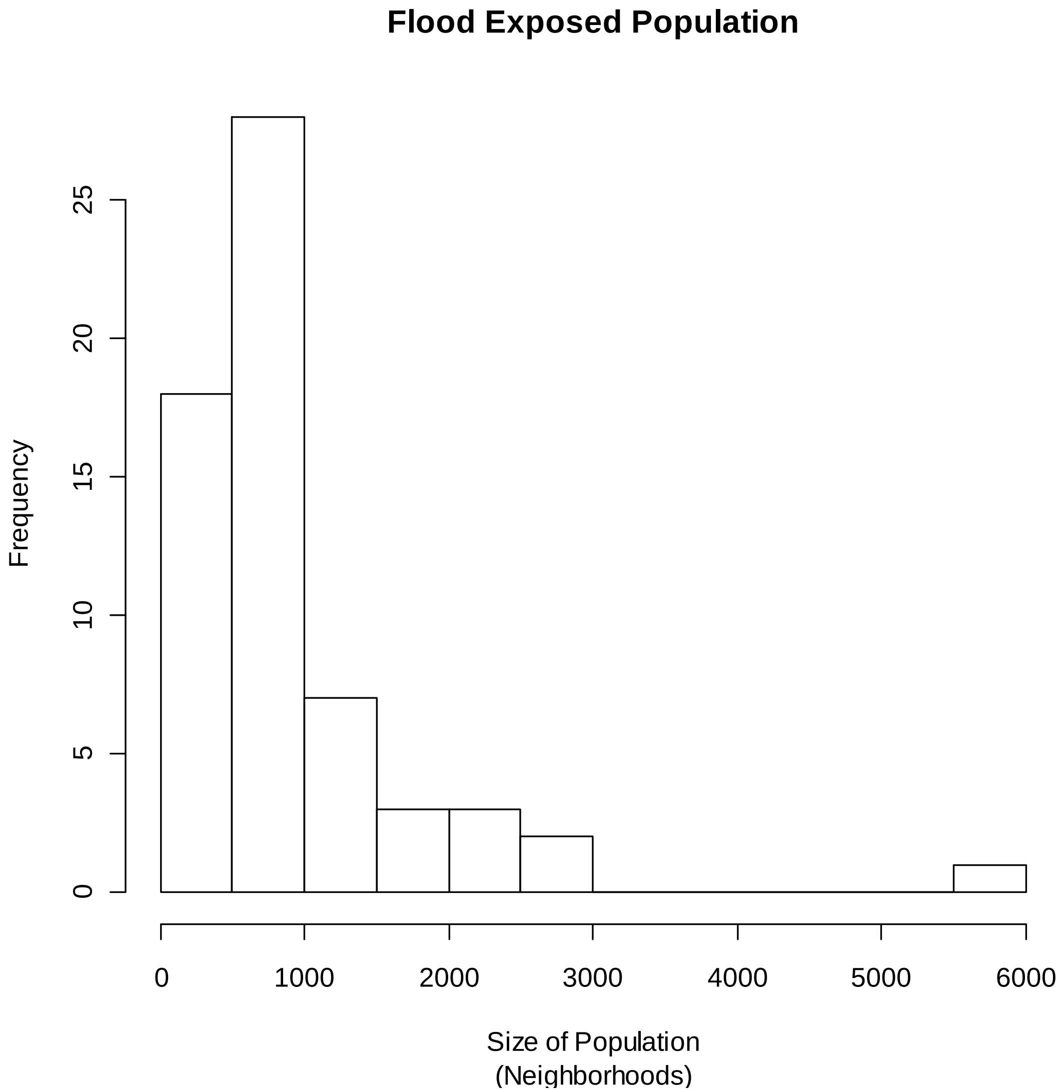

Figure 7.5: Histogram of flood exposed population at the neighborhood level in Orleans and St. Bernard Parishes during and after Hurricane Katrina, August 2005 (Based on data similar to Figure 7.3, except at the neighborhood level).

Cross Check: Search and Rescue

This unprecedented urban flood disaster necessitated an unprecedented urban search and rescue (S&R) mission, which is recounted in detail in Chapter 4. The Louisiana Office of Homeland Security and Emergency Preparedness estimates that S&R teams rescued approximately 62,000 from floodwaters (Louisiana Office Homeland Security Emergency Preparedness 2006), a figure that is consistent with the estimate presented in Table 7.1. This consistency check demonstrates the overall reliability of this estimate of the size of the flood exposed population.

While information on the spatial distribution of the rescued population is limited, one source does provide a figure that allows a consistency check of the flood exposed population at the neighborhood level. A Louisiana Department Wildlife and Fisheries (LDWF) search and rescue team working in the Lower Ninth Ward estimated that they rescued approximately 2,000 persons from this neighborhood (Louisiana Department Wildlife and Fisheries 2005). In comparison, the GIS analysis indicates that the flood exposed population of that neighborhood was approximately 2,300. It should be noted that nearly 100 persons perished here during the disaster and that anecdotal accounts from eye-witnesses describe hundreds of people walking from this neighborhood without assistance from S&R teams. Further, the LDWF figures are rough estimates based on capacity of each boat and the total number of trips for each boat. While these numbers do not match exactly, these two independent estimates exhibit overall consistency, further demonstrating the reliability of the method described in this section. The LWF provides rescuee estimates for other flooded areas, the author was not able to associate their estimates with defined spatial units, such as a neighborhood or set of blockgroups.

However, available reports and anecdotal evidence allow a similar cross-check for St. Bernard and Plaquemines parishes. For St. Bernard Parish, the GIS based analysis estimated that 5,322 people remained in that parish after the evacuation, while the Louisiana Department of Transportation and Development "Katrina Activity Report" (2005) describes evacuation of 6,000 people from that parish via ferry to Algiers Point. Similarly, the GIS analysis estimates that 803 people remained in Plaquemines Parish, of which about 1/3 or 277 were exposed to flood waters, while the parish emergency manager stated that the local Sheriff's Office rescue 250 people there (St. Amant 2006).

Additional verification, though not as strong, comes from comparing the estimated number of non-evacuated people with the population estimates from the post-storm emergency shelters and with the head counts for the final evacuation buses and planes. Based on the population based analysis (Table 4.1), it is estimated that nearly 129,000 people remained in the four hardest hit parishes of metro New Orleans (Orleans, Jefferson, St. Bernard, and Plaquemines). In comparison, an estimated 99,000 were counted at the shelter or in the buses evacuating these shelters (Table 4.3). Again, both figures are estimates with their own uncertainties. Further, some portion of 129,000 people who did not evacuate before the storm resided in relatively unaffected areas such as the Westbank, and so are not reflected in the number from the emergency shelters or evacuations. Also, some number of individuals self-evacuated after the storm. While these two figures do not match exactly, given the uncertainties and caveats, they do reaffirm the general consistency between the GIS based population analysis and the independent figures provided by rescue operations.

Uncertainties

As with any empirical measure of a public health indicator, there are uncertainties in the measurement of the flood exposed population. These include the variability within parishes in both the 2000-2005 retention rate and in the pre-storm evacuation. While beyond the scope of the current analysis, pre- and post-Katrina evacuation surveys may provide some measure of the inner-parish variability in the evacuation rate. Also, it should be noted that the present analysis is limited to only Orleans and St. Bernard parishes, even though flood exposure and flood deaths occurred in other parts of the region. Likewise, flood exposure also occurred in Jefferson and St. Tammany parishes in Louisiana, and along the Mississippi and Alabama Gulf Coast.

One final uncertainty results from deceased among the missing and deceased with unknown recovery locations. Presumably, these victims died in locations, many in the Lower Ninth Ward, where extreme flood conditions created obstacles to recovering the victims' remains or accurately recording the recovery location. If so, this trend would imply an underestimate of the flood deaths in these locations, which creates a systematic bias in the subsequent presentation and analysis of flood deaths.

7.5 Methods and Data: Flood Deaths

The previous chapter described the Katrina related victim database along with basic descriptive statistics on the victims. To better understand the diversity of circumstances that lead to Katrina related deaths in Louisiana, a basic three-category classification scheme was also presented. One of these categories consisted of direct flood deaths, defined as deaths due to circumstances related to flood exposure. This section describes in greater detail the steps used to identify the direct flood deaths.

Direct Flood Deaths Among the General Population

Direct flood deaths were identified by overlaying the geocoded victim recovery locations with the flood depth raster to determine deaths that occurred within the flood zone (i.e. a location with non-zero flood depth according to the flood depth raster), and then eliminating those for whom information in the dataset indicates the victim perished in a building with elevated stories that provided safe refuge from the flood. This step was accomplished through GIS-based analysis. First, the geocoded victim recovery locations were laid over the flood depth raster, and the cell value for the flood depth raster was assigned to each deceased victim. Next, an attribute query eliminated victims recovered from locations where the flood depth was zero. Finally, a second set of attribute queries eliminated those victims recovered from facilities, such as hospitals and multi-story apartment buildings, which provided safe refuge above flood waters. Also eliminated were deaths from a flooded nursing home in St. Bernard Parish. While these victims certainly meet the above definition of direct flood death, the unique vulnerabilities of this location would create a bias in the representation of flood risk to the general population. The result was a GIS layer of 462 deaths believed to be representative of the direct flood deaths among the general population.

The count of 462 victims included in the direct flood death layer differs from the total estimate of direct flood deaths for a number of reasons. First, there are 31 victims recovered from flooded nursing homes. These deaths are included in the total number of flood deaths, but are not included in this analysis of flood deaths among the general population because they would bias the results. Additionally, there are 100 victims whose recovery information lacked sufficient information to geocode. Many of these are believed to be direct flood deaths because teams that recovered the victim remains had the hardest trouble recording a street address in the flood zone. Finally, given that 130 people remain missing, it is reasonable to expect that there may be as many as an additional 100 direct flood deaths for which bodies will never be recovered. Taken together, these pieces of evidence suggest that there could be as many as 600 - 700 direct flood deaths associated with flooding in New Orleans. However, the exact number of direct flood deaths remains highly uncertain, and the 462 should only be considered a conservative representative sample.

While drowning is believed to be the cause of death for most of these victims, it is also known that other causes of death apply to these cases. Some victims died due to trauma from impacts with flood debris. Additionally, the direct flood deaths include victims that escaped floodwaters by fleeing to their attics but later succumbed to dehydration, heat, and chronic medical conditions. Also included are victims that were rescued from flooded homes and brought to the nearest highway overpass where they died due to the lack of essential medications or emergency medical assistance. Anecdotally, it is known that the direct flood deaths includes one case of a 20-something female who had a heart attack while wading through knee deep waters. These victims are included in the count of direct flood deaths because the circumstances of their death were directly precipitated by the victim's exposure to flood conditions. To state it simply: their feet got wet before they died.

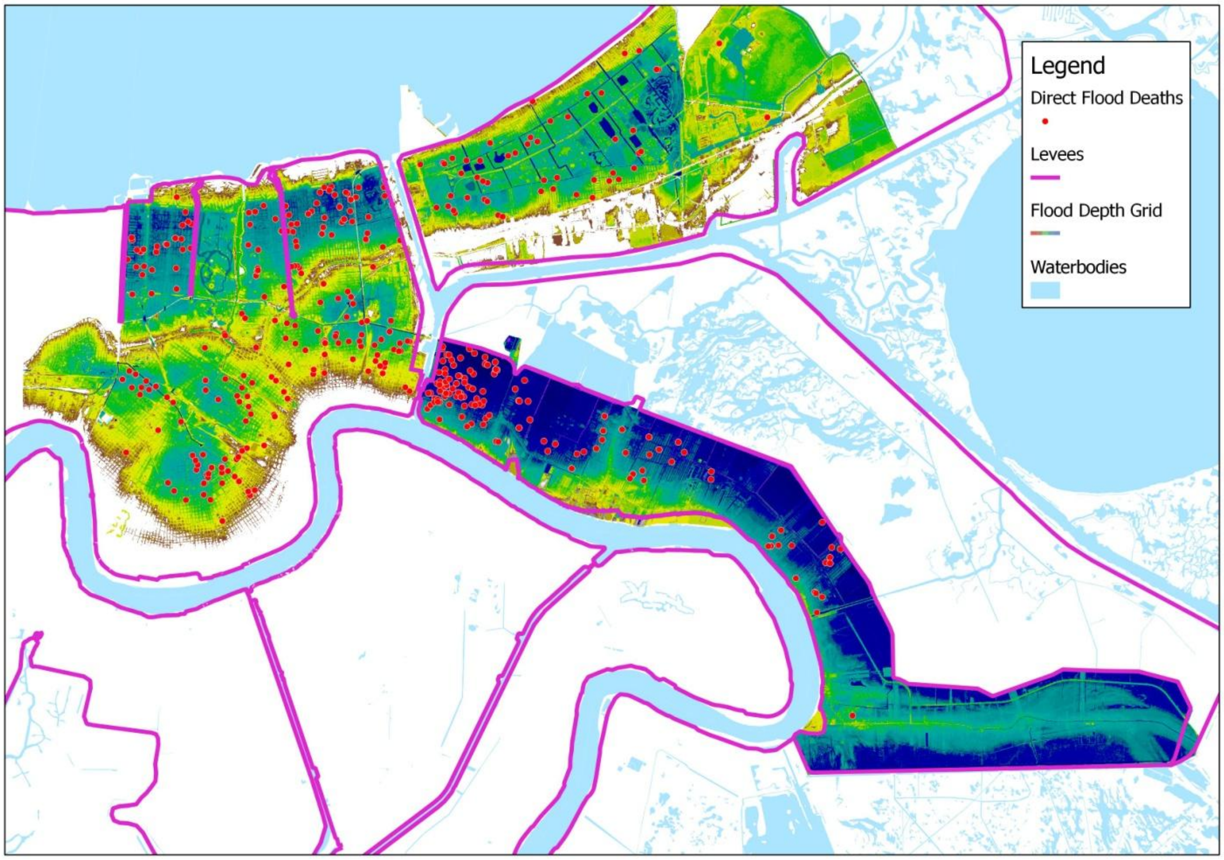

Figure 7.6: Direct flood deaths with flood depth and levees in Orleans and St. Bernard Parishes during and after Hurricane Katrina, August 2005 (Based on Louisiana Katrina Victim Database and Cunningham, et al. 2006).

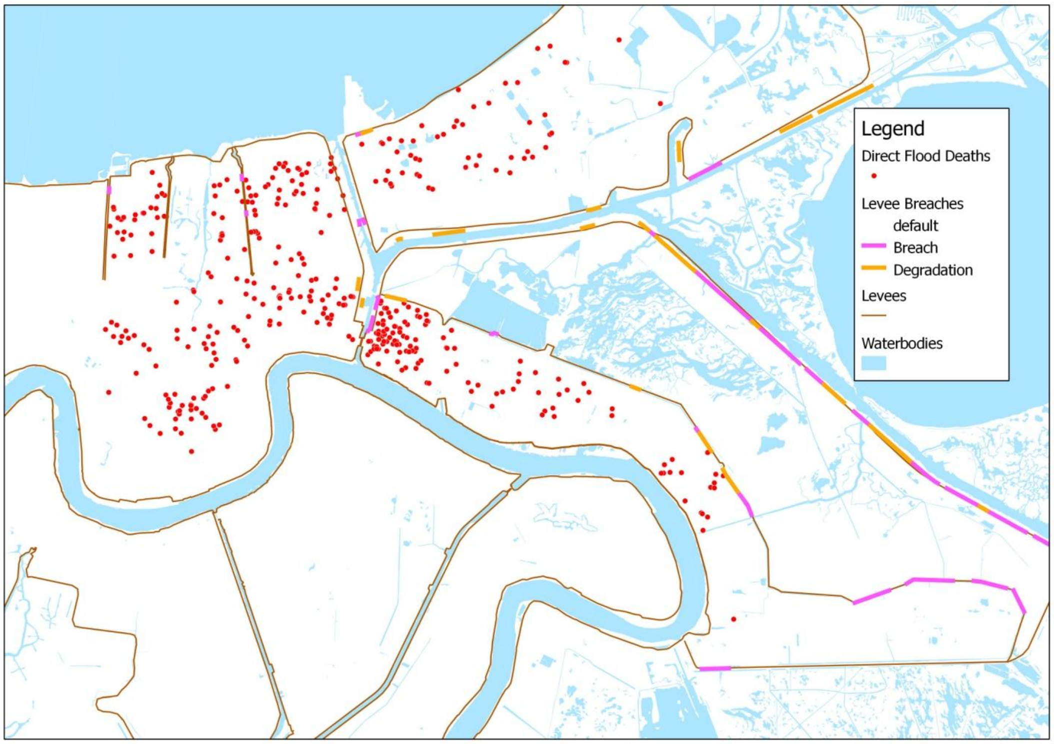

Figure 7.7: Direct flood deaths with levees and levee breaches in Orleans and St. Bernard parishes during and after Hurricane Katrina, August 2005 (Based on Louisiana Katrina Victim Database and van Heerden, et al. 2006).

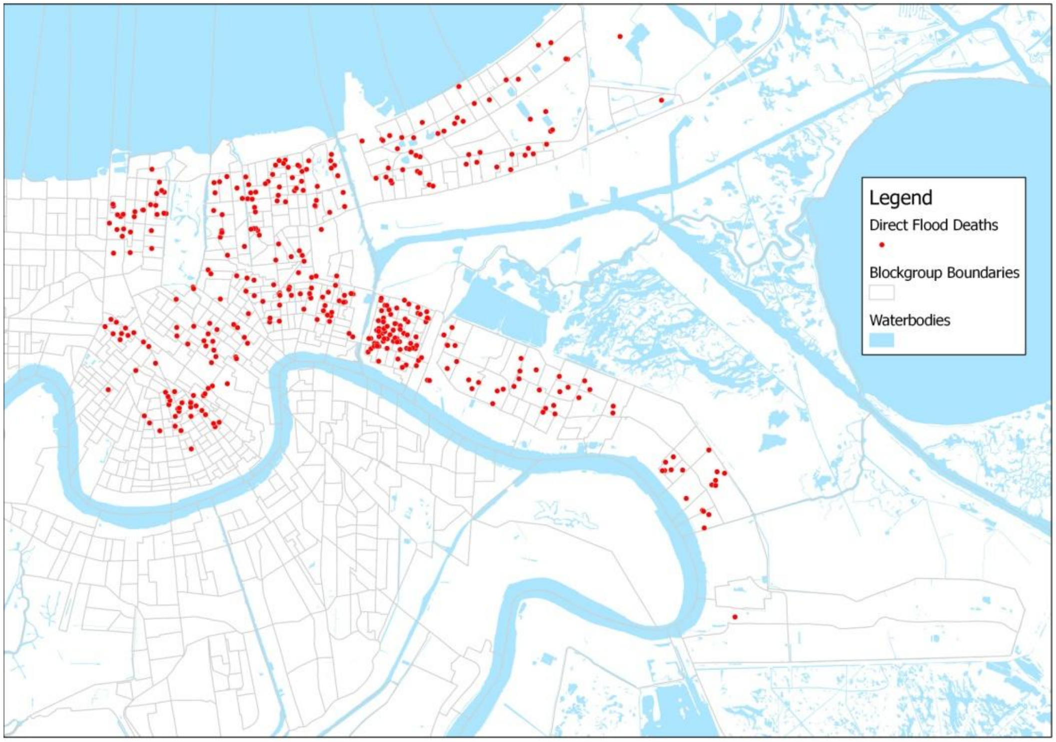

Figure 7.8: Direct flood deaths with Census blockgroup outlines in Orleans and St. Bernard parishes during and after Hurricane Katrina, August 2005 (Based on Louisiana Katrina Victim Database).

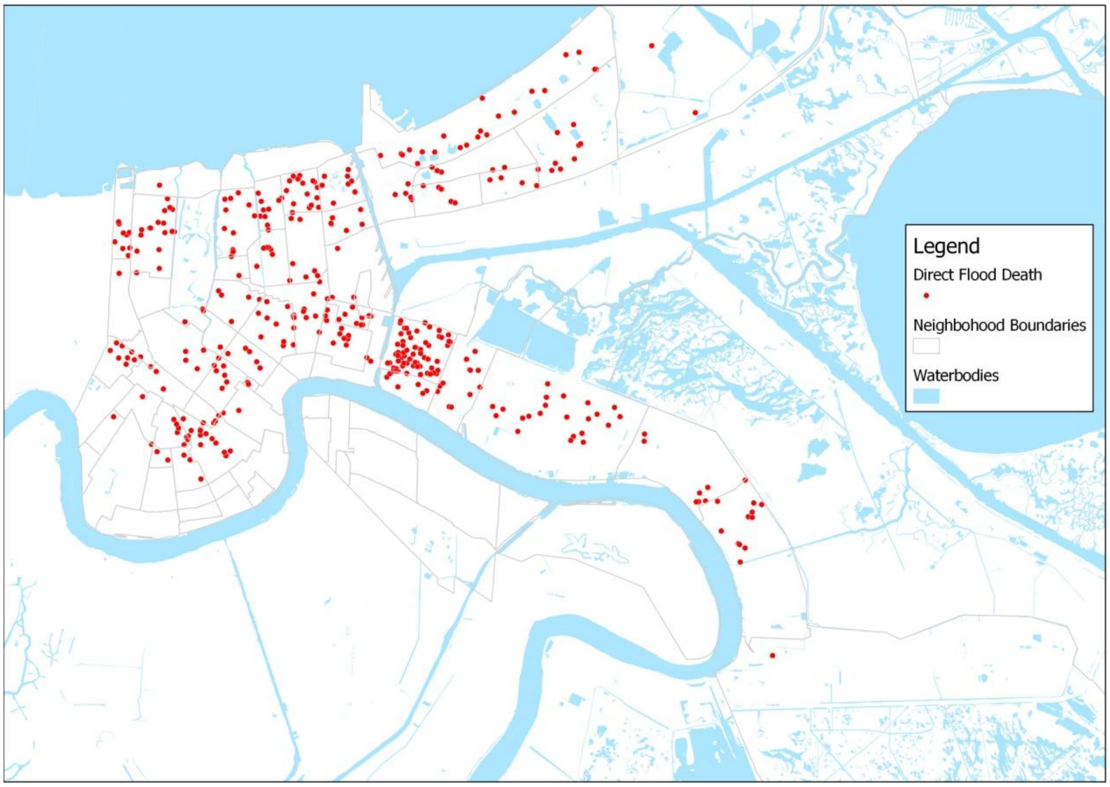

Figure 7.9: Direct flood deaths neighborhood boundaries in Orleans and St. Bernard parishes during and after Hurricane Katrina, August 2005 (Based on Louisiana Katrina Victim Database).

7.6 Basic Trends in the Flood Fatality Rate

Based on the listed and locatable 462 direct flood deaths among the general population and an estimated 63,000 persons exposed to flood waters, the flood fatality rate for the general population is calculated to be 7 deaths per 1000 people exposed. If the higher estimate of 700 direct flood deaths is used, then the flood fatality rate is calculated to equal 11 deaths per 1000 people exposed. For means of comparison, these values are consistent with the 1% mortality rule-of-thumb for coastal flood events proposed by Jonkman (2007).

The flooded region of greater New Orleans consists of three hydrologically separated polders, which are collections of neighborhoods within a system of ringed levees. The FFR can be calculated at the polder level by first counting the number of deaths per polder and then dividing by the flood exposed population of each polder, which is shown in Table 7.2. Central New Orleans, which had the largest exposed population, appears to drive the overall rate stated above. At the polder level, the Lower 9th Ward / St. Bernard Parish had the highest flood fatality rate, which can be attributed to the flood conditions created by the MRGO/GIWW (van Heerden 2007, Shaffer 2009). These conditions include the high water depths along with high flow velocities which destroyed every building over a ten square block area adjacent to breaches and a quick arrival time and rate of rise which left people little time to take protective actions (see Figures 5.30, 5.31, 5.33, and 5.34). Comparatively, New Orleans East had the lowest fatality

Table 7.2: Flood fatality rate per polder.

	Flood Deaths	Flood Exposed	Flood Fatality Rate (Deaths per Exposed Person)
Central New Orleans	250	39,913	0.00626
Lower 9th / St. Bernard	158	6,914	0.02169
New Orleans East	54	12,800	0.00007
Plaquemines Parish (*)	6	250	0.024
Total	468	59,877	0.00782

(*) Data for Plaquemines, which actually consists of two polders separated by the Mississippi River, provided by the parish emergency director (St. Amant 2006) and included for means of comparison.

rate, also a reflection of the flood conditions. Here, levees largely held and pump stations remained operational. Slowly rising flood waters consisted mostly of rainfall along with some water for isolated cases over levee overtopping or degradation/erosion. The next chapter examines how the flood fatality rate relates to the flood hazard conditions.

In a similar manner, the FFR can be calculated at the blockgroup and neighborhood levels. These steps produced a spatial measure of the risk of death for the population exposed to floodwaters due to the levee failures that occurred during Hurricane Katrina. With this dataset, it is possible to quantitatively assess factors believed to influence risk of this disaster outcome, an issue that has been the subject of considerable debate. The rest of this section presents statistical summaries of the fatality rate and the spatial distribution of this risk measure.

While the blockgroup level analysis provides a high degree of spatial resolution with low variability in the flood conditions over the unit, this spatial unit suffers from a low population denominator problem. For this reason, neighborhoods, which are larger than blockgroups, are preferred for the analysis in the next chapter. In choosing this unit-of-analysis, it was decided that the variability in flood conditions was acceptable when compared to problems created by the low population denominators. In the regression analysis, the variability within the neighborhoods creates random errors that impact the error term, while the zero observations when using blockgroups creates bias in the coefficient estimates.

Calculations for both spatial units follow the same general steps described above for the polders. The major distinction between these two steps is that each starts with a different polygon shapefile. One represents Census blockgroups (LSU CADGIS Research Laboratory 2003). The other consists of neighborhoods in Orleans Parish provided by the Greater New Orleans Community Data Center (2006) and was augmented using a Census zip code layer for St. Bernard Parish (LSU CADGIS Research Laboratory 2003). For each polygon layer, the FFR was estimated by counting the number flood deaths then dividing by the flood exposed population.

Figure 7.10 depicts the statistical distribution of the observed values for the flood fatality rate for the blockgroups with non-zero flood depth. As noted above, the small population of the blockgroups implies units with zero deaths and zero FFR, despite the very clear flood risk that exists in these blockgroups. Further, the small population problem also leads to artificially high estimates due to the effects of random clustering of 2-5 deaths in a unit with a small population denominator. For the blockgroups with FFR > 0, the fatality rate ranges from 1.1 deaths per 1000 people exposed to a high of 129 deaths per 1000 people exposed (located in the Lower Ninth Ward neighborhood in the vicinity of levee breaches along the INHC). The mean and median values are 18.7 and 12.6 deaths per 1000 people exposed. For 10% of the blockgroups, the FFR was greater than 40 deaths per 1000 exposed and for four blockgroups it was greater than 50 deaths per 1000 exposed. Spatial trends in the FFR are discussed shortly.

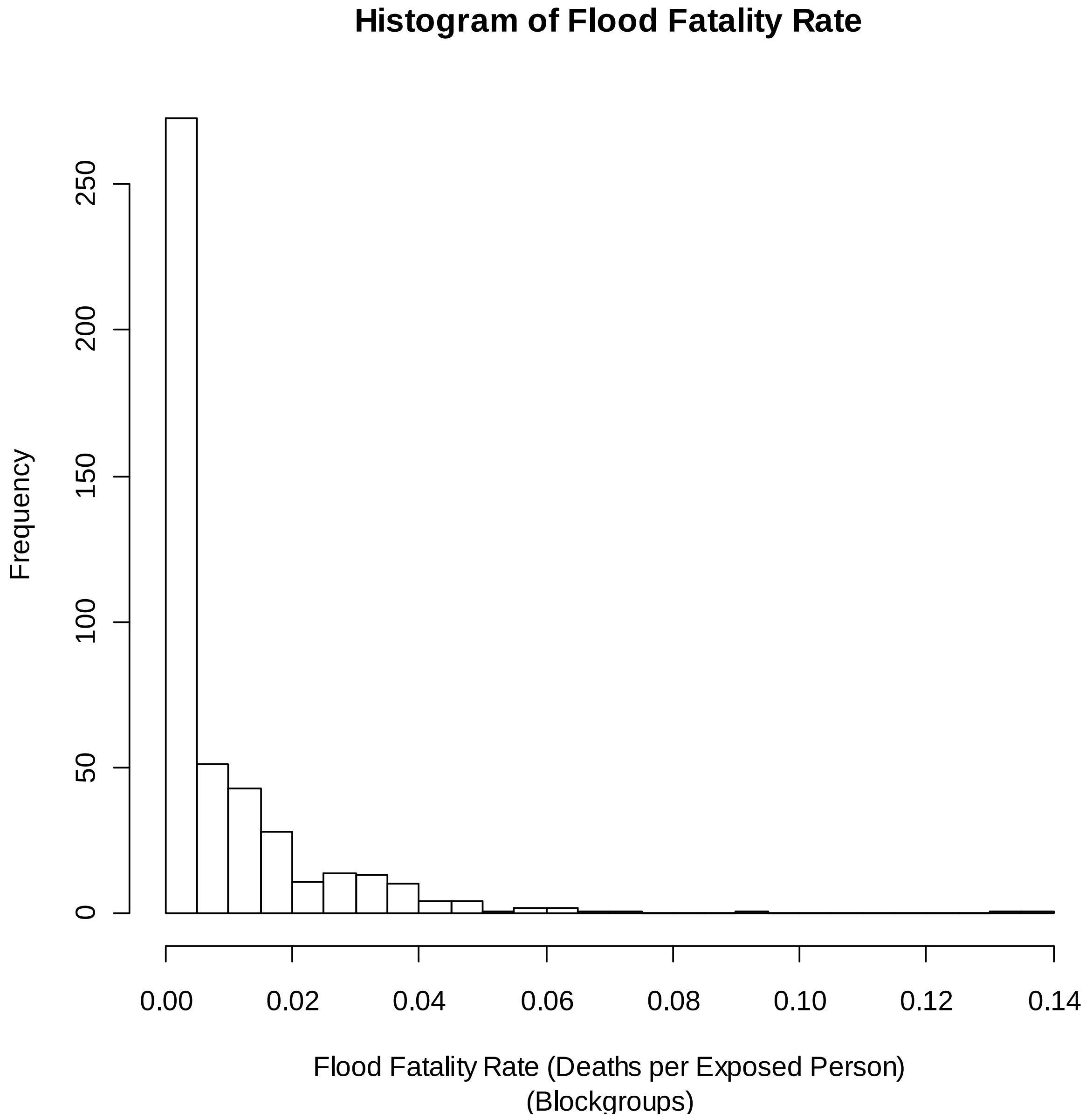

Figure 7.10: The observed Flood Fatality Rate in Orleans and St. Bernard Parishes during and after Hurricane Katrina, August 2005 at the blockgroup level.

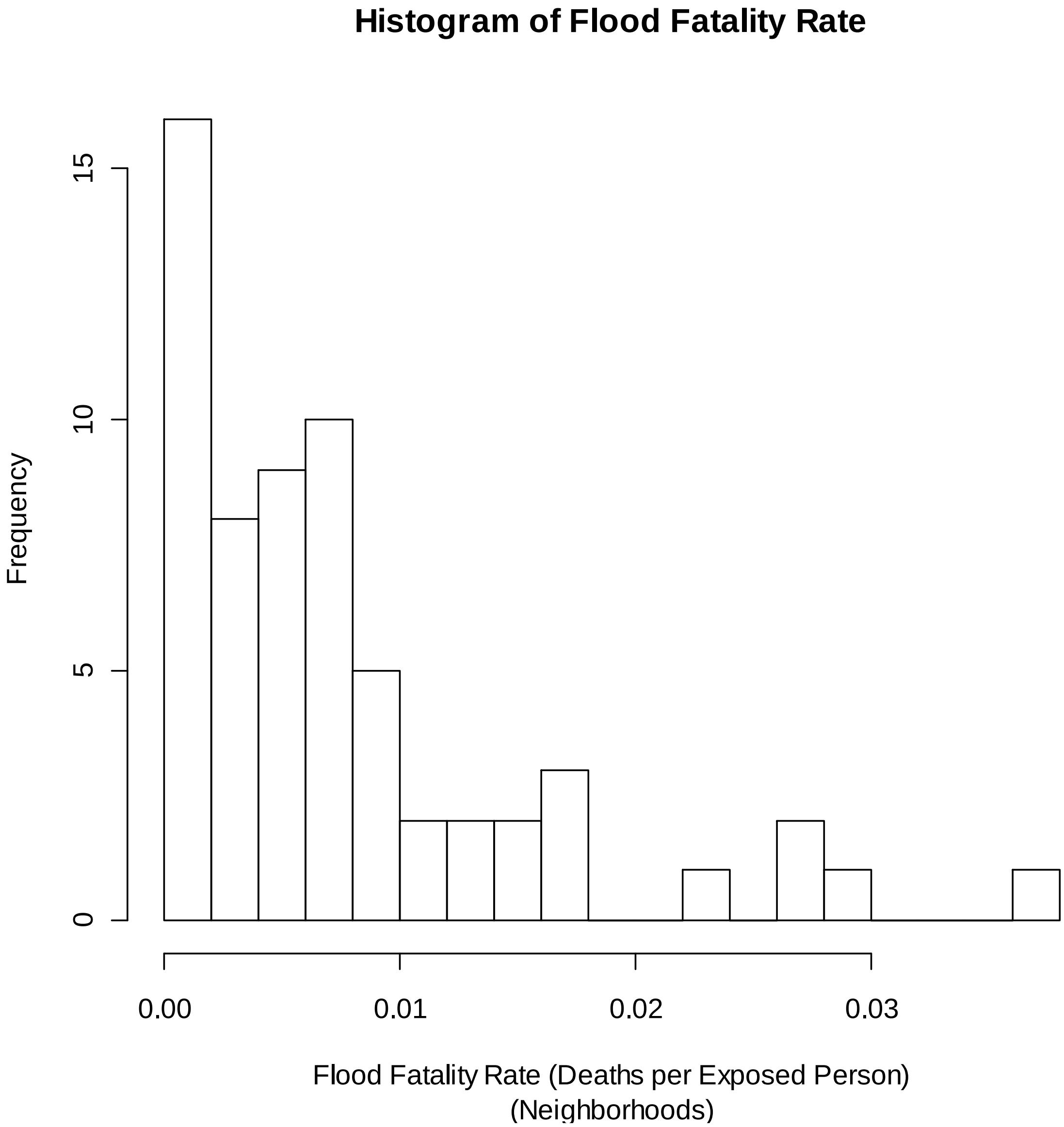

Figure 7.11: The flood fatality rate in Orleans and St. Bernard Parishes during and after Hurricane Katrina, August 2005 at the neighborhood level.

In comparison, the FFR estimated at the neighborhood level span from 0 to 37 deaths 1000 per exposed. For 9 neighborhoods with non-zero flood depth (14% of the total number) the FFR = 0. Only two of these experienced mean flood greater than 2 ft. In sharp contrast, 57% (264 out of 462) flooded blockgroups had an FFR = 0, some of which the mean flood depth reached 14 ft. For 58 neighborhoods, the FFT < 1.7, for 5 the FFR > 2, and for one only is the FFR > 3.

Figures 7.12 and 7.13 show the spatial distribution of the flood fatality rate, at the blockgroup and neighborhood level respectively. Red indicates a higher fatality rate, while green indicates lower. Blockgroups for which the observed fatality rate equaled to zero are white. Two bands of higher fatality rates are observed.

One band, near the center of the figure, extends across the banks of the IHNC through the Lower Ninth Ward and beyond Chalmette in St. Bernard Parish. Flooding along this band resulted from overtopping and breaching along the Industrial Canal with additional flood waters entering via the Central Wetlands (north of Chalmette) after the levee along the MRGO disintegrated. This band of increased flood risk can be attributed to the conditions created by the MRGO/GIWW/INHC system. Most notably, this system created a storm surge funnel that directed violent flood conditions into this neighborhood. After knocking down massive floodwalls, the fast moving and powerful storm surge impacted the Lower Ninth Ward with fast moving and quick rising floodwaters. In addition to the funnel effect, wetland loss related to the MRGO also contributed to flood risk here by reducing the ecosystems capacity to absorb and reduce storm surge (van Heerden, et al. 2007; Shaffer, et al. 2009).

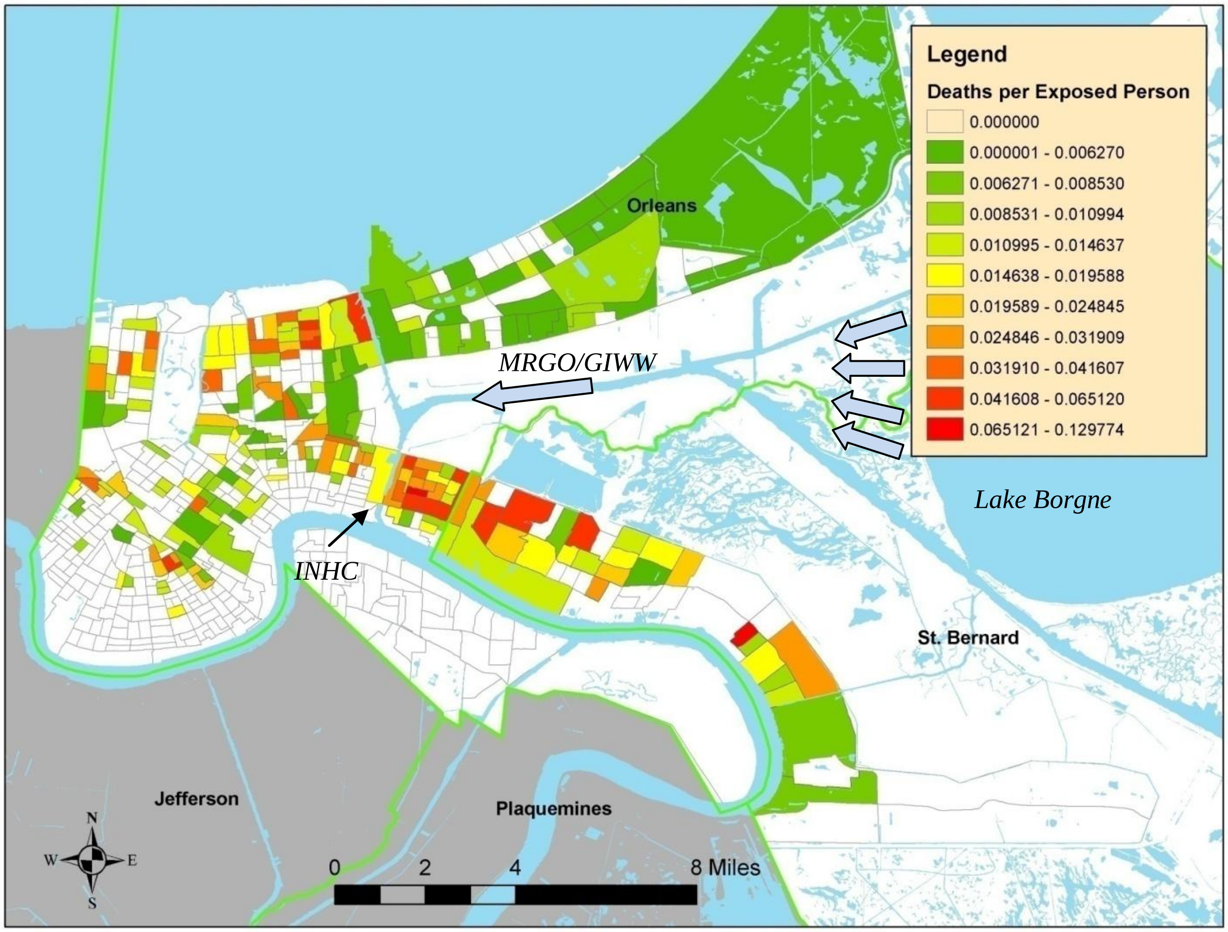

Figure 7.12: The observed flood fatality rate at the blockgroup level in Orleans and St. Bernard Parishes during and after Hurricane Katrina, August 2005. The storm surge funnel is depicted schematically through the blue arrows. In Lake Borgne, the easterly winds pushed the storm surge toward the convergence of the MRGO and GIWW. Continuing to move west, the flow velocity increases as the volume of water must travel down a confined channel. Then the southerly curve into the INHC creates a turbulent curvature (not shown) that directed the high velocity flow toward the Lower Ninth Ward (van Heerden, et al. 2007).

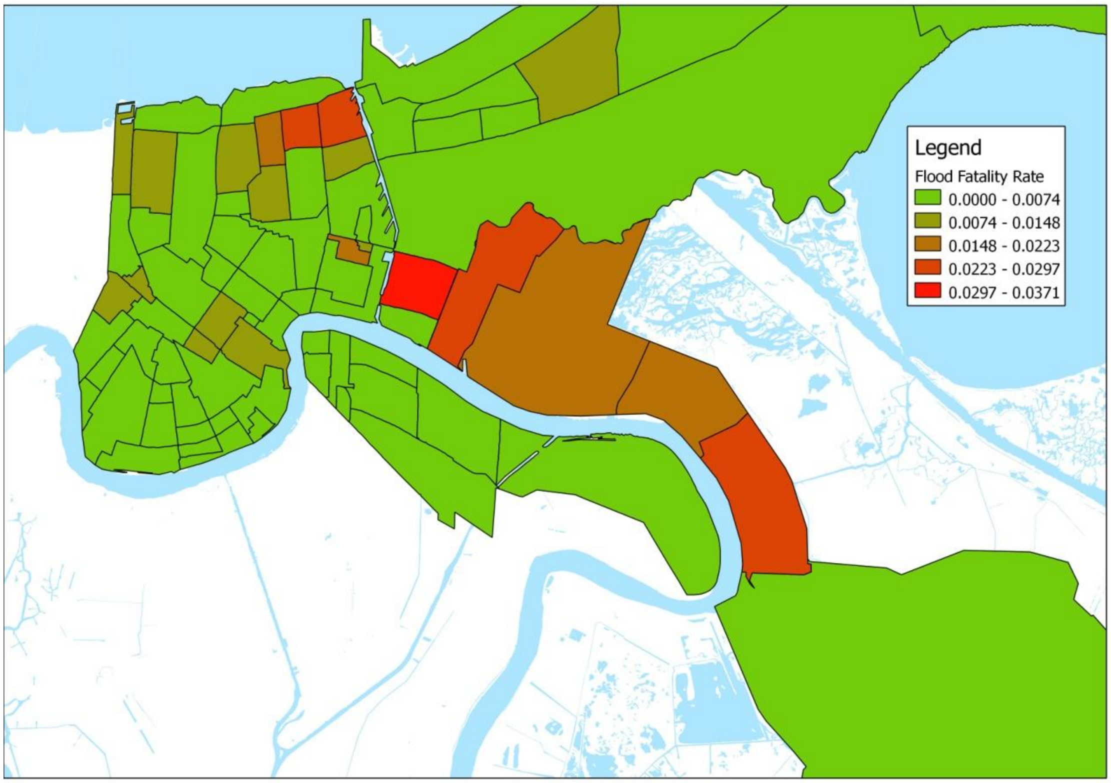

Figure 7.13: The observed flood fatality rate at the blockgroup level in Orleans and St. Bernard Parishes during and after Hurricane Katrina, August 2005.

A second band of higher flood fatality risk, located toward the top-left of the figure, runs from the Lakeview area west though Gentilly and Pontchartrain Park. Flooding in these areas largely resulted from design failures and levee breaches along the 17th Street and London Avenue drainage canals. Here flood dynamics were driven by gravitational flow once the levees failed and elevated lake water poured into the low lying neighborhoods.

Within the flooded area, it is observed that a band of comparatively lower risk extends across New Orleans East. This area contains some of the lowest land in New Orleans, but benefited from levee protection that largely survived the storm. While there were isolated areas of levee degradation, there were no incidences of levee failure here. Mostly important, pump stations were never overwhelmed. Rainfall and isolated cases of levee overtopping or failure resulted in floodwaters in New Orleans East that were lower and less violent than the two other flooded regions.

7.7 Conclusion

With 600 - 700 flood deaths out of approximately 63,000 flood exposed population, the overall flood fatality rate for the flooded portions of Orleans and St. Bernard parishes is 9 – 11 deaths per 1000 flood exposed persons. Based on research in this area, this value is consistent with the estimated FFR for other coastal flood disasters. Two FFR layers were calculated based on 462 geocodable flood deaths amongst the general population. The highest flood fatality rates were observed in the Lower Ninth Ward and extending into Chalmette. High values were also observed in the neighborhoods just along the northern portion of the Central New Orleans polder, which includes Lakeview and Gentilly. The data also indicate that the flood risk is relatively lower throughout the New Orleans East polder. While these trends can be explained by dynamics of the flooding, these results, based on a single event, should not be used to make general observation regarding the flood risk for these areas. In the next chapter, regression analysis is used to examine how the flood fatality rate relates to the flood hazard conditions and the population vulnerability characteristics.

Chapter 8: Regression Analysis of the Flood Fatality Rate

This chapter presents results of several regression models that examine relationships between the flood fatality rate and several hypothesized independent variables. In this analysis, the potential independent variables fall into two groups. One group describes the physical characteristics of the flood hazard, while the second group of variables describes the vulnerability characteristics of the flood exposed population. In addition to examining multiple variables, different functional relationships for the primary flood characteristics are also examined. What follows is an inductive, hierarchical approach to the analysis that begins with a univariate, linear model that relates the flood fatality rate to flood depth. Building from this basic model, additional variables and different functional relationships are examined to determine the best-fit model. At that same time that this non-linear, multivariate relationship is examined inductively, risk-based theoretical principles are also presented to rationalize the particular relationships.

First the linear, depth-only model is presented. This model provides a simplicity that can readily be applied by responders to identify potential areas of high fatalities during emergency situations when information is sparse. Elaborating on the linear model, different variables are added and examined to determine multivariate, linear coefficients. Then conceptual arguments in support of a non-linear, s-shaped relationship involving depth, velocity, and depth time velocity are presented, followed by an examination of non-linear regressions to test the s-shaped models. Once the best model involving the flood variables is found, attributes that represent the population vulnerability characteristics are examined.

The goal is to determine the variables and parameters for a dose-response relationship of the following form:

$$f = f(H_1, H_2, \ldots, V_1, V_2, \ldots)$$

where f is the flood fatality rate, H_i are the possible flood hazard characteristics, and V_i are the population vulnerability characteristics.

8.1 Linear-Depth Only Model

The linear, depth only model is the first model examined. Here $H_1 = d$, the flood depth, is the only variable and the dose-response relations follow a linear relationship:

$$f(d) = A + B \times d + \varepsilon$$

d is the mean depth (in meters), A and B are the regression coefficients, and ε is the error term. The simplicity of this model means that it will be the most useful during emergency situations to aid search andrRescue planning and deployments when only the flood depth and exposed population are known. During these circumstances, this linear model can be used to obtain order-of-magnitude estimates of total number of possible fatalities along with identifying areas within the flooded region where the risk of fatalities may be greatest. During these emergency circumstances the nuances of a more complicated dose-response relationship become overshadowed by limited situational awareness. In contrast, the multivariate, non-linear best-fit model will be more useful in planning situations where prescribed scenarios include precise, though hypothetical flood simulations and evacuation rates. Naturally, in any circumstance where the deployment of response assets or planning decisions can have life or death consequences, this model should only be considered as guidance to be skeptically considered with all of the other available information. Limitations of the model and its use are discussed in a later section of this chapter.

Table 8.1 below presents the regression results for the simple linear, depth only model. Here the independent variable is the mean depth from the LSU depth grid. The results were obtained using the `lm` procedure in R (Venables, Smith, and R Development Core Team 2010). Mean depth is found to be highly significant with a slope of 0.002 (deaths/exposed person) per foot and the standard error of 0.0002. The adjusted R-squared is 0.555, which is generally considered noteworthy and the residual squared error is 0.0052.

8.2 The Linear, Multi-Variate Model

Building from this univariate, linear regression, we can examine the general effects of other flood characteristics. Linear regression models utilizing the following flood hazard characteristics are assessed: velocity, depth x velocity, arrival time, rate-of-rise. These variables were obtained from the SOBEK simulation (Masskant 2007), which is a hydrodynamic code used to simulation flooding off low lying land due to a levee breach, and are available for only the metro Orleans and Lower 9th / St. Bernard folders. Of note, the SOBEK simulation, produced both a grid for the flow velocity along with a separate grid for water depth time flow velocity. Figure 8.2 shows the pairwise scatterplots of this set of variables, while Table 8.2 shows the correlation matrix.

Table 8.1: The OLS regression of the flood fatality rate (FldFatRate) with the mean flood depth (MeanDepth).

```
> summary(Reg1)

Call:
lm(formula = FldFatRate ~ MeanDepth, data = data1)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0133021 -0.0033471  0.0000067  0.0021051  0.0173643

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -0.0013753  0.0011853   -1.16    0.250
MeanDepth    0.0020347  0.0002299    8.85 1.54e-12 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.005245 on 61 degrees of freedom
Multiple R-squared: 0.5622,     Adjusted R-squared: 0.555
F-statistic: 78.32 on 1 and 61 DF,  p-value: 1.540e-12
```

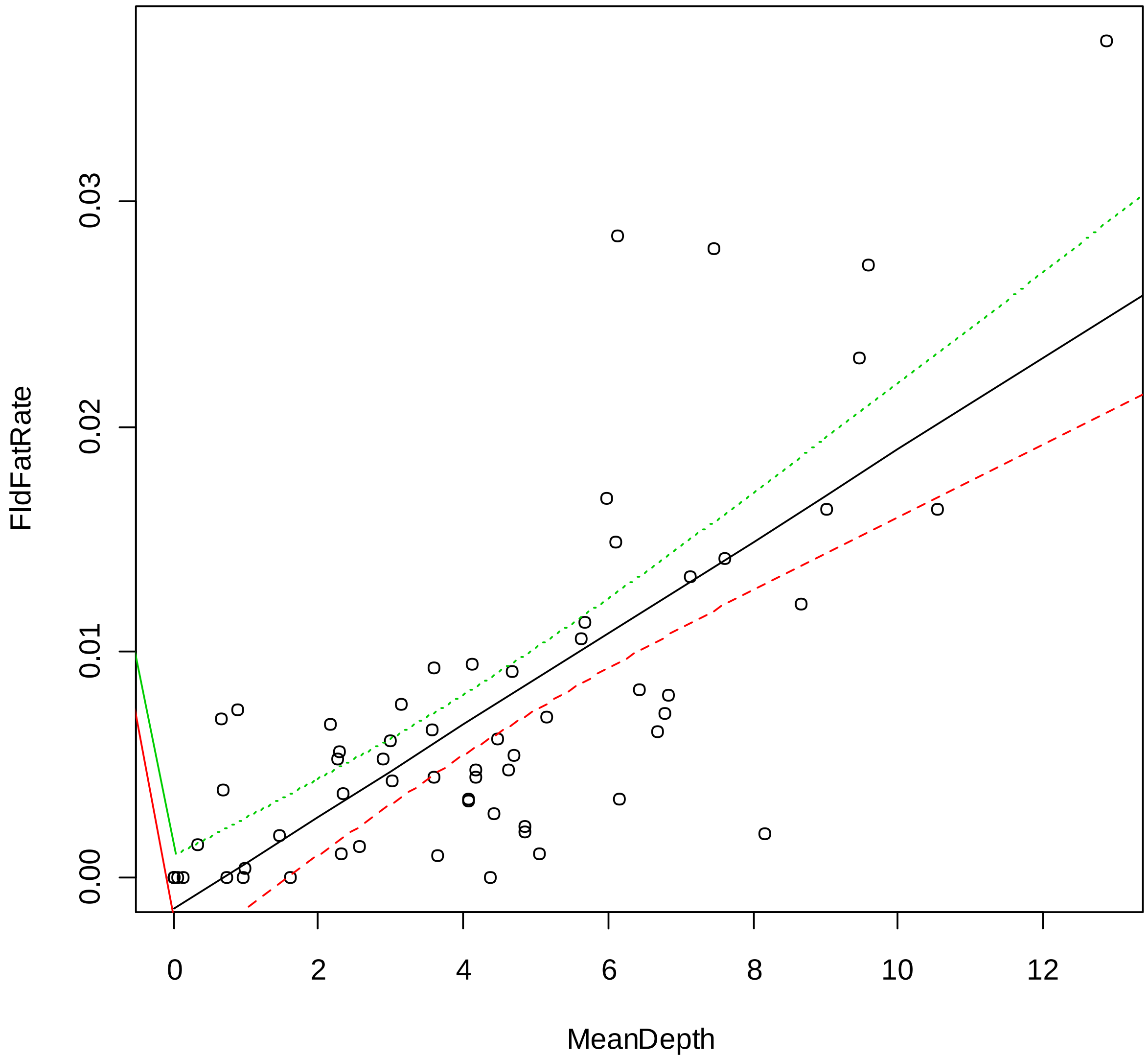

Figure 8.1: Best-fit curve along with confidence intervals for the OLS regression of the flood fatality rate (FldFatRate) with the mean flood depth in feet (MeanDepth).

In examining the regression results (see Table 8.3), it was found that replacing depth with velocity decreased the adjusted-R^2 noticably, but that using depth x velocity as the single predictor variable had positive impact. The best adjusted R-squared was found with a two variable model of the form

$$f(d) = A + B \times d + C \times dv + \varepsilon$$

where *dv* is the depth-velocity product. From here adding arrival time, rate-of-rise, or both, decreased the adjusted-R^2. While colinearity was not examined with the linear models, given the high degree of correlation between the predictor variables, it should be assumed that collinearity affects these regression results.

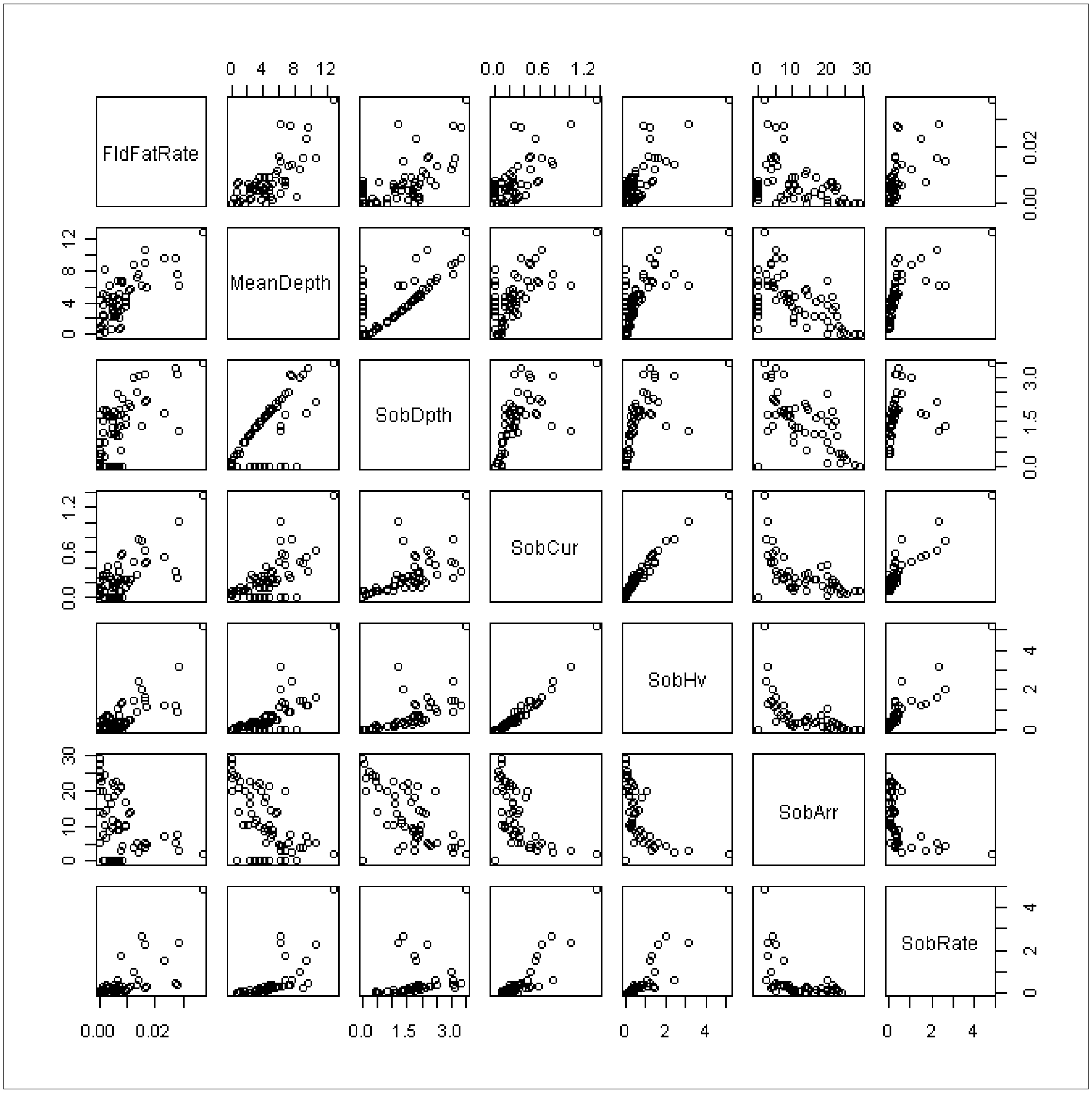

Figure 8.2: Pairwise plots of flood fatality rate and the flood hazard characteristics based on data from Orleans and St. Bernard parishes during Hurricane Katrina, August 2005. Each box within the figure shows the intersecting variables plotted against each other. For example, the 2nd box on the first row shows the flood fatality rate (FldFatRate) versus the mean observed depth in feet (MeanDepth). The other flood variables, obtained from the SOBEK simulation, are the simulated depth in meters (SobDpth), the flow velocity (current) in m/s (SobCur), the product of depth and velocity in m^2/s (SobHv), the arrival time from initial breach for the respective polders in hours (SobArr), and the rate-of-rise for the first 1.5 m in m/hr (SobRate).

Table 8.2: Correlation matrix of flood fatality rate and the flood hazard characteristics based on data from Orleans and St. Bernard parishes during Hurricane Katrina, August 2005. Each cell gives the correlation coefficient for the intersecting variables. For example, the 2nd cell on the 1st column shows the correlation between flood fatality rate (FldFatRate) and the mean observed depth in feet (MeanDepth). The other flood variables, obtained from the SOBEK simulation, are the simulated depth in meters (SobDpth), the flow velocity (current) in m/s (SobCur), the product of depth and velocity in m^2/s (SobHv), the arrival time from initial breach for the respective polders in hours (SobArr), and the rate-of-rise for the first 1.5 m in m/hr (SobRate).

	FldFatRate	**MeanDepth**	**SobDpth**	**SobCur**	**SobHv**	**SobArr**	**SobRate**
FldFatRate	1						
MeanDepth	0.7497742	1					
SobDpth	0.6374599	0.7201295	1				
SobCur	0.7276568	0.6796273	0.7058271	1			
SobHv	0.7908598	0.7077362	0.6646214	0.967075	1		
SobArr	-0.396081	-0.5644695	-0.133928	-0.205907	-0.291873	1	
SobRate	0.6922688	0.6906584	0.3808277	0.8836619	0.8952234	-0.491247	1

Table 8.3: OLS regression results of the flood fatality rate with various flood hazard variables based on data from Orleans and St. Bernard parishes during Hurricane Katrina, August 2005. Each cell gives the regression coefficient for the respective linear term. For example, the first row first the regression coefficient along with the R^2 and the Residual Squared Error (RSE) for flood fatality rate (FldFatRate) as a function of the mean observed depth in feet (MeanDepth). The second row shows the results from a two-term linear model consisted of depth and velocity, while the third row shows one-term model using depth times velocity. The other flood variables, obtained from the SOBEK simulation, are the simulated depth in meters, the flow velocity (current) in m/s, the product of depth and velocity in m^2/s), the arrival time from initial breach for the respective polders in hours, and the rate-of-rise for the first 1.5 m in m/hr. As measured by the R^2 and RSE, the multivariate model consisting of a term for depth plus a term for depth times velocity (highlighted) produces the best fit with the data.

Model	**A**	**B**	**C**	**D**	**E**	**R^2**	**RSE**
Depth (ft)	0.0020347					0.555	0.00525
Velocity		0.022054				0.5218	0.00544
Depth (m), Velocity	0.005312	0.00992				0.6729	0.00486
Depth x Velocity			0.0071888			0.6193	0.00485
Depth (m), Depth x Velocity	0.004422		0.0039944			0.7117	0.00457
Depth (m), Depth x Velocity, Arrival Time	0.00468		0.00402	0.0000425		0.7063	0.00461
Depth (m), Depth x Velocity, Rate-of-Rise	0.0047796		0.004001		-0.000170	0.6697	0.00491
Depth (m), Depth x Velocity, Arrival Time, Rate-of-Rise	0.00489		0.00406	0.0000234	-0.000205	0.6618	0.00497

Note: Results for last four are even worse when velocity was substituted for depth x velocity.

8.3 The Non-Linear, S-Shaped Model

While the linear model gave a reasonably good fit, there are theoretical reasons to believe that an s-shaped curve may give a better fit to the data. This section first sketches the conceptual reasons for an s-shaped curve, and then uses the data to test this model.

Theoretical Reasons to Expect an S-Shaped Relationship

For an individual standing in flood waters of depth d, we can consider how the probability of drowning for the individual depends on the depth of water. In the most simplistic sense, one would expect the drowning probability function to be a single step function that goes from $p = 0$ for $d < d_c$ to $p = 1$ for $d \geq d_c$ where the critical depth, d_c. For simplicity, we can say that this critical depth equals the height of the person's mouth above ground. At this depth, water begins to enter the mouth and lungs of a stationary, non-buoyant person at ground level and that person drowns. However, this simplistic model fails to account for a number of important processes related to survival or drowning.

Our individual may fall over while exposed to the flood waters or the person may tread water, float, or find refuge. If a person falls over, water may enter the lungs before the water depth reaches the critical height, thus the probability of drowning is greater than zero for $d < d_c$. Likewise, if a person treads water, floats, or finds refuge, water may not enter the lungs even though the water level is above head level, thus the probability of drowning is less than 1 for $d \geq d_c$.

These considerations suggest that the probability of drowning follows an s-shaped function of the water depth, as shown in Figure 8.3. As the water rises from zero to some moderate height (say around the individual's chest level), the probability of drowning rises roughly linearly with a slight-to-moderate slope. As the water rises from just below neck level to just above head level, the exposed individual faces a rapidly increasing probability of drowning. Then, as the water continues to rise above head level, the exposed individual implements personal protective actions to sustain life, such as treading water, finding floating debris, or swimming to elevated refuge. Since the effectiveness of the protective actions varies little as the water depth continues to increase, the probability of drowning does not change greatly at these depths. These considerations suggest a dose-response curve that consists of a low probability region at low water depths, a rapid transition range as the water depth approaches and becomes greater than head level, and a high probability region when the water depth is greater than head level. At this point it is worth noting, that we cannot assume that the probability of drowning will ever reach one. Rather, we must conceive of an unknown upper limit or asymptote.

Thus, it is believed that for the i^{th} individual, the probability of drowning is an s-shaped function of the depth of water at the individual's location, d_i, which we can denote as $s_i(d_i)$. Note that the subscript on s_i denotes the s-shaped function is particular to the individual.

From a few basic assumptions, it is shown that the flood fatality rate for a flood exposed population follows a similar dose-response relationship. In the most simplistic case (shown in Figure 8.4), a group of N identical individuals is exposed to uniform flood depth, d. For each of

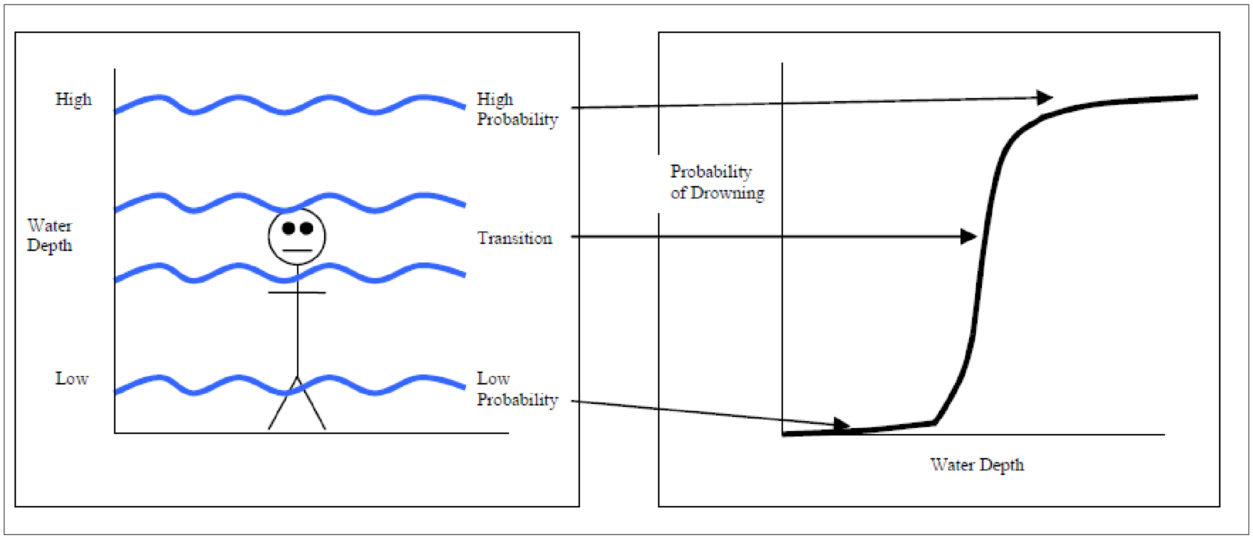

Figure 8.3: Hypothesized s-shaped relationship between probability of an individual drowning verses immersion in various water depths. (Figure by author).

these individuals, the probability of drowning is given by $p_i = s(d)$. Since the individuals are exposed to a uniform flood depth, *d* is equal for each of them and since the individuals are identical *s* is likewise identical for each of them. Based on the assumption that the probability of drowning is independent for each individual and equal to frequency of drowning for the group, the expected number of drownings, denoted *n*, is easily given by,

$$n = p \text{ x } N = s(d) \text{ x } N.$$

Thus, the fatality rate, which describes the population (as opposed to an individual) is given by

$$f = f(d) = n / N = s(d).$$

So, for a population of identical individuals exposed to a uniform flood depth, the fatality rate for the population is equal to the probability of drowning of the i^{th} individual, which is expected to follow an s-shaped relationship.

This basic relationship provides the foundation for what have been termed homogenous base units (HBU) (McClelland and Bowles 1999). An HBU is defined here as an area of the flood region where the flood characteristics and population characteristics are relatively homogenous. As such, it forms the most basic spatial element in flood fatality calculations. Naturally, the strict assumption of complete homogeneity over a region of any (significant) size is false. But, from the above discussion, we can qualify the definition of the HBU as a region where the flood and population characteristics display sufficient homogeneity such that the binomial theorem provides a reliable approximation.

Building upon the simplistic model, we can consider a collection of homogenous base units, each populated with identical individuals, as depicted in Figure 8.5. That is, we can consider a flood

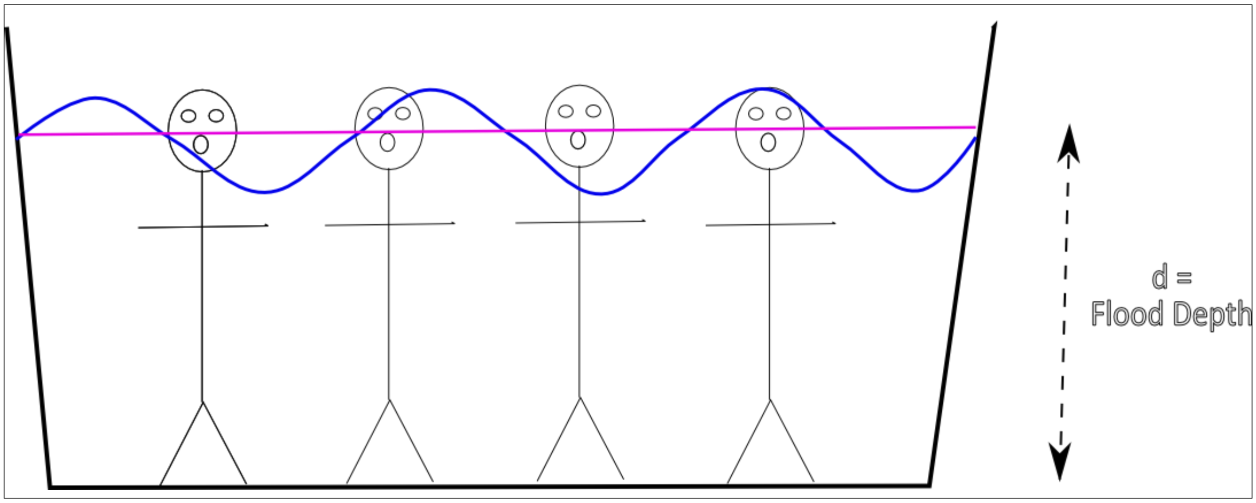

Figure 8.4: Group of Identical Individuals Exposed to Uniform Flood Depth.

region that consists of sub-regions of identical individuals exposed to uniform flood depths. In this case, the total mortality is the sum of the mortality for each of the sub-regions and the overall mortality rate is determined by dividing the total mortality by the overall population. If the subscript *j* denotes j^{th} sub-region, we have

$$n = \sum_j n_j$$

and

$$f = n / N = \sum_j n_j / N.$$

For the jth HBU, the number of fatalities is determined from equation (i) above. Thus,

$$f(d_j) = \sum_j s(d_j) \times N_j / N.$$

In other words, if the flood region consists of a set of HBU's each of which are characterized by a unique flood depth but identical drowning probability functions, the overall fatality rate for the region is just the average of the individual drowning probability function evaluated at the water depth value of the HBU weighted by the proportion of the exposed population in each HBU.

Depth Only S-Shaped Model

This section examines a depth only, s-shaped dose-response function. Following the precedent of Jonkman (2007), we first examine the cumulative normal distribution, though other s-shaped curves are also examined. Table 8.4 presents the regression results for this model, obtained using the `nls` function in R (Venables, Smith, and R Development Core Team 2010). It should be noted that the current analysis utilizes the LSU Depth Grid while Jonkman used the depth raster obtained from the SOBEK simulation grid. It can be seen that best-fit coefficients here are consistent with Jonkman's (2007) results (mu = 5.20, sig = 2.00).

Both parameters of the log-normal function are significant and the RSE decreased moderately compared to the linear model. The observed differences between the above results and

Jonkman's (2007) results in the coefficient values can be explained by differences in the input dataset. The current analysis utilizes difference estimates for the flood deaths and the flood exposed population includes New Orleans East, which Jonkman did not. This analysis also used the observed flood depth grid while Jonkman used the SOBEK simulation grid (see Chapter 5 for an explanation of these two data sources).

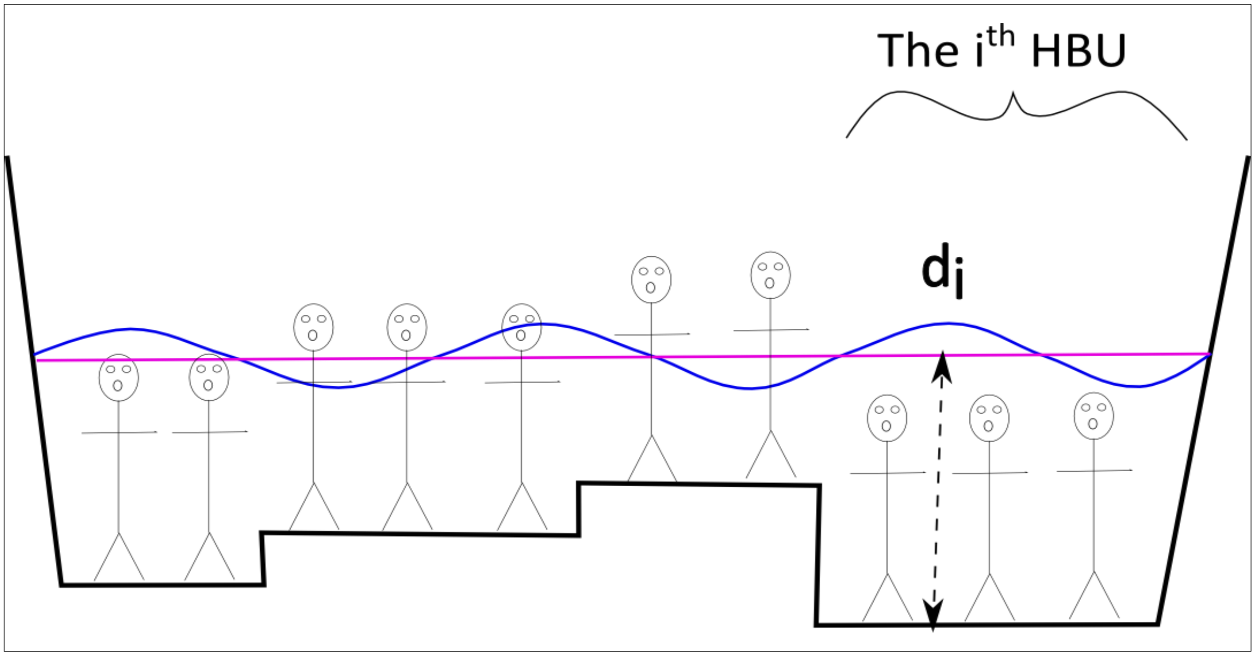

Figure 8.5: Set of Homogenous Base Units, each subject to different flood depths.

Table 8.4: Non-linear regression of the flood fatality rate as a log-normal function of a depth (in meters).

```
> funct4
function(h, mu, sig) {pnorm((log(h) - mu)/sig)}
## (pnorm is the cumulative normal distribution)  ##

> summary(Reg5)

Formula: FldFatRate ~ funct4(MeanDepth_m, mu, sig)

Parameters:
    Estimate Std. Error t value Pr(>|t|)
mu    4.4588     0.4453  10.014 1.69e-14 ***
sig   1.6560     0.2033   8.144 2.48e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.005006 on 61 degrees of freedom

Number of iterations to convergence: 10
Achieved convergence tolerance: 9.574e-06
```

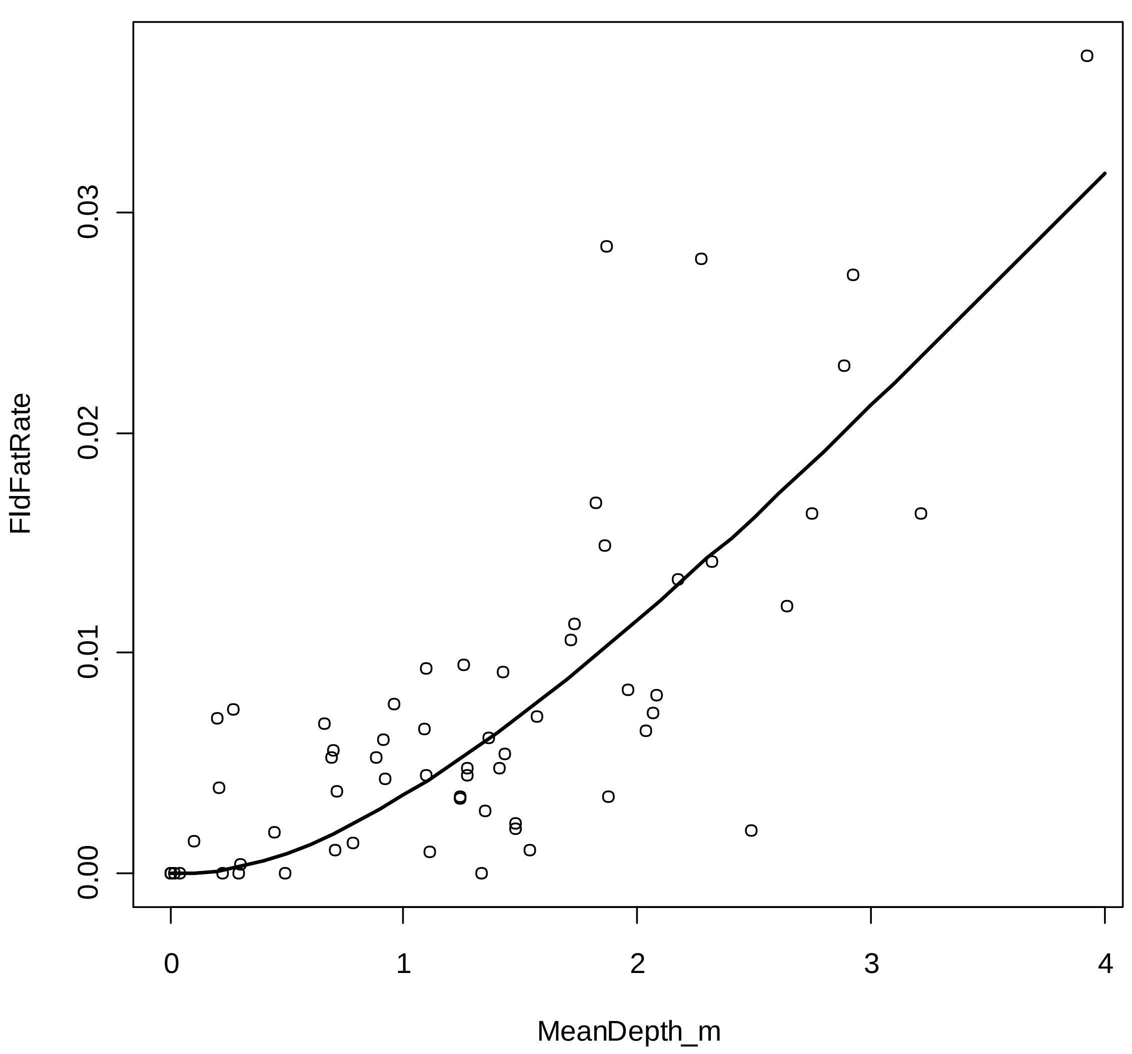

Figure 8.6: Best fit curve obtained from non-linear regression of the flood fatality rate as a log-normal function of a depth (in meters).

8.4 Depth, Velocity, and/or Depth Times Velocity

Theoretical Considerations

The previous section examined an s-shape relationship between the flood fatality rate and the flood depth. From a practical standpoint, this flood characteristic is the one that is most readily available and the most concrete for planners, responders, and public communicators. However, when looking at the linear models, it was observed that a model with depth x velocity as the lone independent variables provided a better goodness of fit than the model with depth as the independent variable, and that a two-term model that included depth plus depth x velocity provided the best fit. From the literature, recent studies have examined the role of depth and velocity in relationship to human instability during flood flows. For example, Jonkman and

Penning-Rowsell (2008), consider the flood forces that cause moment instability and friction instability of an individual exposed to moving flood waters (see Figure 8.7). In this approach to understanding flood deaths, human instability is considered the precursor to drowning. In addition to human instability, flow velocity floods also lead to structural damage of refuges (Kelman and Spence 2004).

Building on the concepts, the effects of velocity and depth x velocity can be visualized through three primary effects: human instability, loss of refuge, and debris which is shown in Figure 8.8. In a similarly manner, Figure 8.9 depicts how flood arrival time and rate-of-rise impacts our flooded HBUs. Having obtained a better fit using an s-shaped curve with depth, a set of regressions now examine results of using velocity and depth x velocity with the s-shaped curve. Several regression models where assessed, while the best goodness of fit was found with a s-shaped function of depth and another s-shaped function of depth x velocity.

Table 8.5 below shows results of a set of regression models to examine h, v, and hv using the log-normal curve. Results were obtained using `nls` (non-linear least squared) function in R (Venables, Smith, and R Development Core Team 2010). This iterative procedure starts with initial estimates of the parameter values (the default value of 1 was used here) and then uses an optimization procedure to find that parameter values that minimize the RSE. Note that this procedure does not provide an R^2 or adjusted-R^2, so the RSE is used to compare models.

It can be seen that the lowest RSE was obtained in a two variable model that uses depth and depth x velocity. Further, this RSE is lower than any of the previously considered linear models. In this model, all four coefficients are significant with $p < 0.0001$. Though, it is worth noting that similar p-values were obtained with the coefficients in the other models. Reminiscent of the linear models, adding the rate-of-rise, the arrival time, or both increased the RSE and reduced the significance of the coefficients for depth, velocity, and/or depth x velocity.

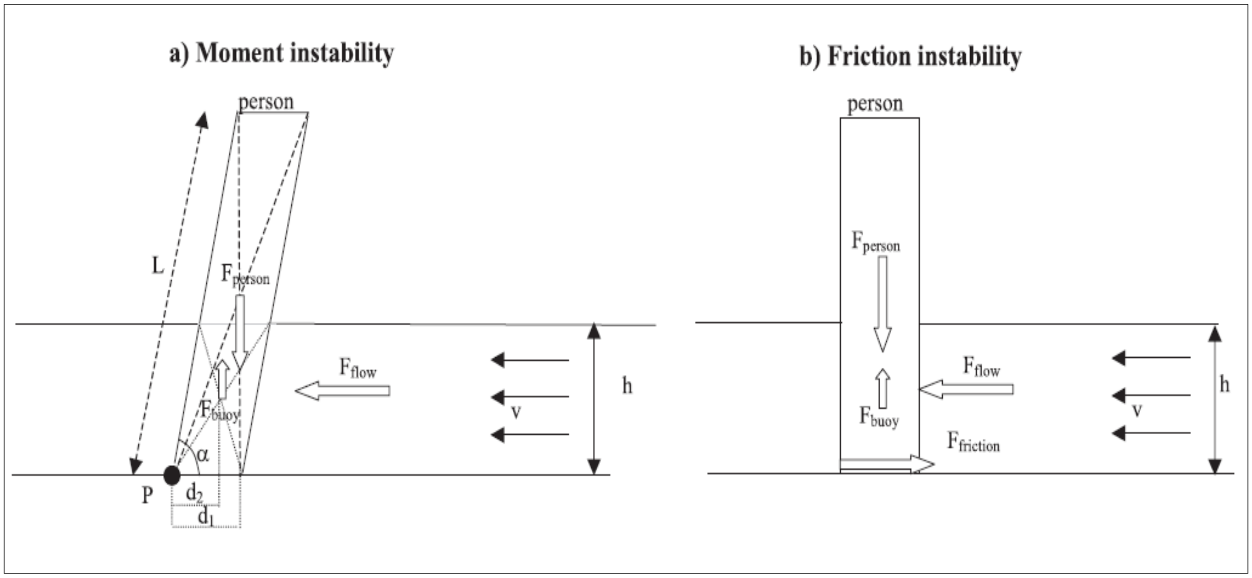

Figure 8.7: Diagrams depicting the moment and friction instabilities for human bodies trapped in flowing floodwaters. From Jonkman and Penning-Rowsell (2008).

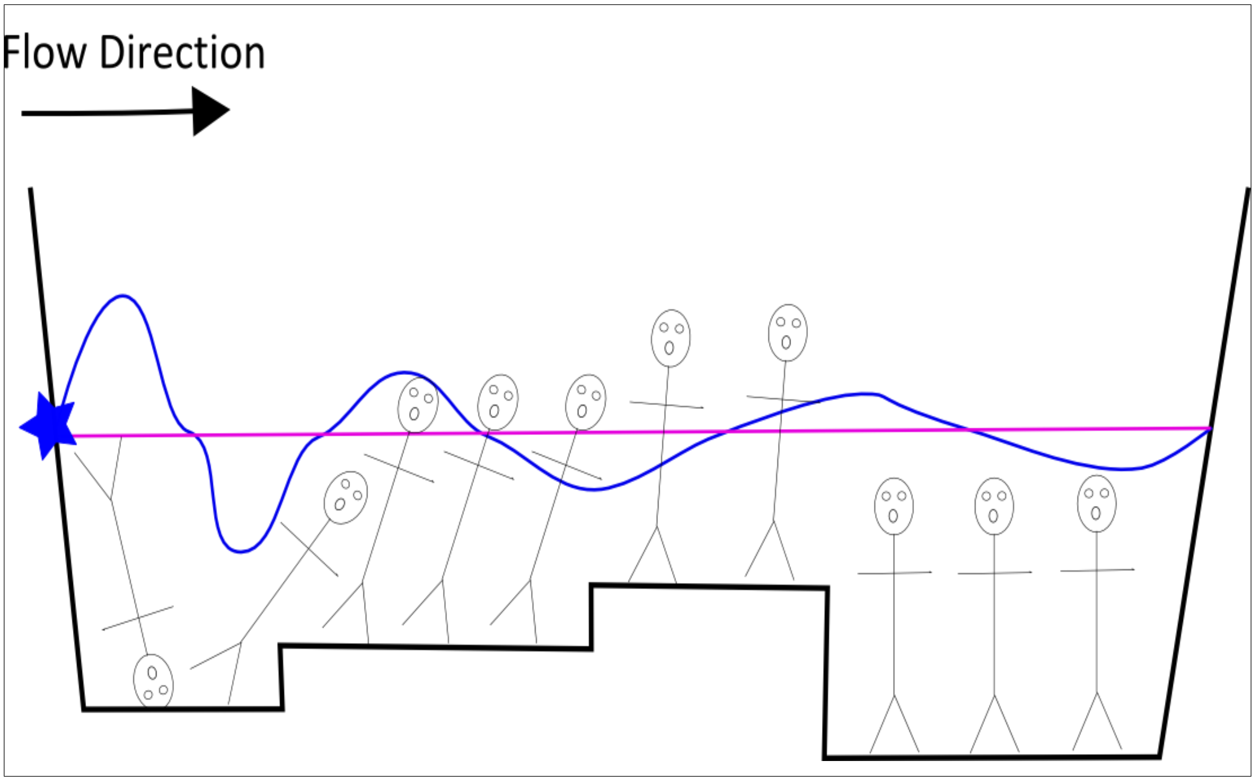

Figure 8.8: Set of HBU’s with a levee breach and flow velocity leading to human instability.

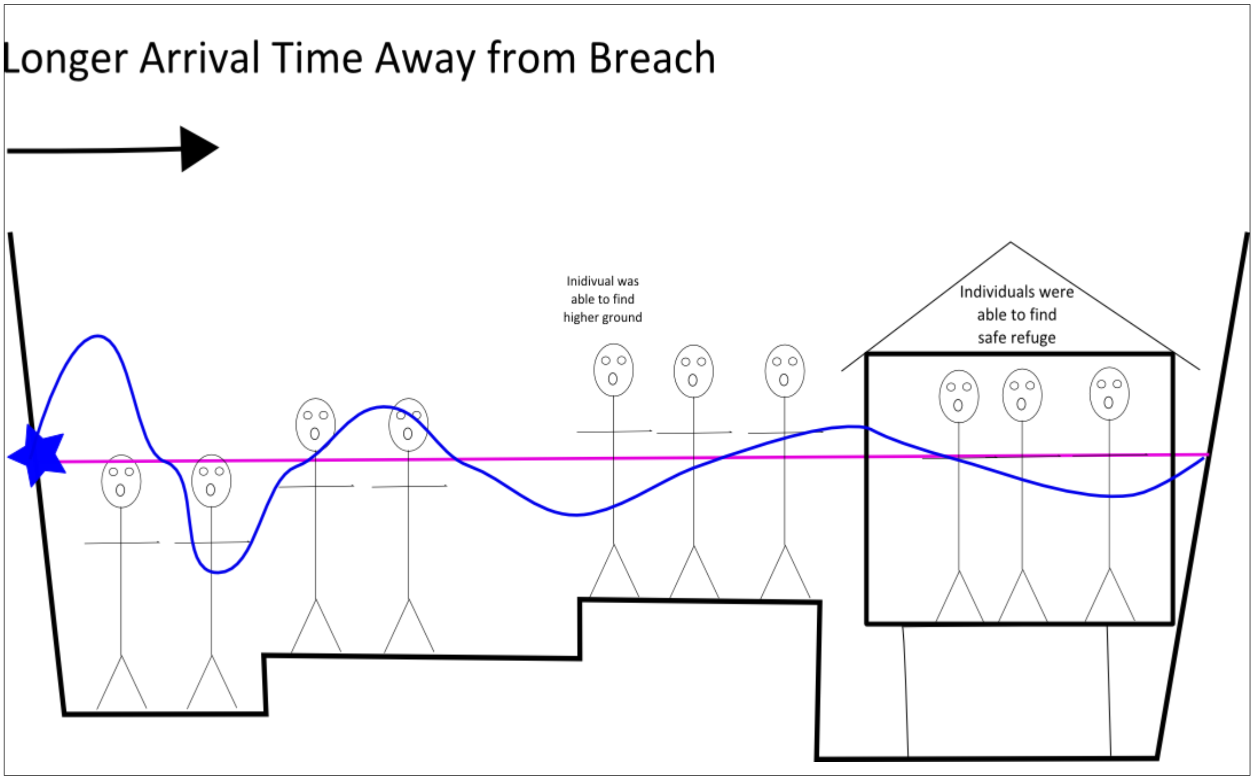

Figure 8.9: Effects of rate-of-rise and arrival time.

Table 8.5: Log-normal regression results of the flood fatality rate with various flood hazard variables based on data from Orleans and St. Bernard Parishes during Hurricane Katrina, August 2005. Each cell within the table gives the regression coefficients for the respective log-normal model. For example, the row first shows the regression coefficients along the Residual Squared Error (RSE) for flood fatality rate as a log-normal function of the mean observed depth in feet. The second row shows the results using a log-normal of velocity. The third row shows a two-term model consisting of a log-normal of depth plus a log-normal of velocity, while the fourth row shows a two-term consisting of a log-normal of depth plus a log-normal of depth times velocity. The lowest RSE was obtained with the two-term model (highlighted) of consisting of a log-normal of depth plus a log-normal of depth times velocity.

Model	mu1	sig1	mu2	sig2	mu3	sig3	RSE
Depth	4.4588	1.656					0.00501
Velocity			5.175	2.6406			0.00574
Depth x Velocity					8.0306	3.5319	0.00505
Depth, Velocity	6.1545	2.3246	2.981	1.2989			0.00457
Depth, Depth x Velocity	6.673	2.4572			6.7146	2.5371	0.00443

In addition to the log-normal, two other s-shaped functions were examined. Replacing the log-normal with a logistic function, produced slightly lower RSE with the two term depth and depth times velocity model. For the two-term logistic model, RSE = 0.004391, compares to RSE = 0.00457 with the log-normal. Mostly, this result shows that the relationship appears robust under different types of s-shaped functions for the dose-response relationship. It is worth noting that like above logistic functions of just depth, just velocity, and just depth time velocity were assessed, but that these did not yield better results than the two term model.

I also attempted to assess a model that uses a Kappa function (Finney 2003), which is a more complicated formula that reduces to the logistic as special case. Its main advantage is that it allows for the two ends to be asymmetrical. In both the log-normal and logistic curves, the upper half of the curve is a mirror image of the curve. However, it should not be assumed that the dose-response relationship shows such symmetry.

Attempts to assess the Kappa function did not yield any results, just the following error message: “Missing value or an infinity produced when evaluating the model.” The Kappa function has a term that is raised to the power (1/k) and it reproduces the logistic function in the limit of $k \rightarrow 0$. In fact, as k is reduced, the curve becomes more symmetrical (Finney 2003). Given that the logistic provides such a good fit, it seems likely the error message is explained by the low value of k. If this is the correct explanation for the infinity, then that would suggest that any asymmetries in the curve are minor. Of course, this explanation is highly speculative, and it still should not be assumed the true curve is roughly symmetrical.

8.5 Does Population Vulnerability Matter?

A final set of regressions sought to examine how the population vulnerability attributes influence the FFR. Having found that the flood hazard characteristics provide good models for the FFR, numerous population attributes, based on 2000 Census SF3 data (Census 2002), were joined to the dataset, and then added to the model as linear terms. These variables are listed in Table 8.6. This preliminary examination of the role of population vulnerability simply added the population variables individually to some of the better models described above to determine which variables are significant and improve the model.

This preliminary analysis examined the effects of individually adding a linear term consisting of the population vulnerability variables to the non-linear models described in the previous section. The three non-linear models are the logistic of depth, logistic of depth times velocity, and the logistic of depth plus logistic of depth times velocity models of the previous sections. In the series of regressions below, each of the population attributes were examined individually as a linear term. This preliminary examination did not assess combinations of population attributes or non-linear relationships involving the population attributes.

Conceptually, a variety of individual characteristics, including age, gender, and disability status, are expected to influence how the individual responds to a set of flood hazard conditions. Likewise, characteristics such as poverty status, vehicle ownership, and housing type also influence the individual's response to deadly flood conditions. Thus, it the dose-response curve for the i^{th} individual, $s_i(H_1, H_2, H_3, \ldots)$, the parameter values represent the individual's characteristics. When aggregated to an HBU, the dose-response curve reflects the average response for the persons, and is thus a function of population attributes that are average values for the group. A full theoretical examination of how these individual characteristics are aggregated to derive a dose-response function for the HBU that depends on population attributes is beyond the current scope. For the current purposes, Figure 8.10 below illustrates how the individual characteristics are aggregated into the HBU's dose-response relationship.

Table 8.6: List of population attributes (data from the Census 2002).

Population Vulnerability Attributes	
Percent of the Population Over 65	Percent Owner Occupied Households with No Vehicle
Percent of the Population that is Male	Percent Renter Occupied Households with No Vehicle
Percent that is African-American	Total Houses
Percent of the Population that is Disabled	Total Owner Occupied Houses
Percent of the Population Below Poverty Limit	Total Renter Occupied Houses
Per capita Income (Black only)	Median Year Structure Built
Per capita Income (White only)	Percent of Households with No Telephone
Median House Value	Percent of Owner Occupied Households with No Telephone
Percent of Households that are Owner Occupied	Percent of Renter Occupied Households with No Telephone
Percent of Households with No Vehicle	Percent of Population Over 25 with H.S. Diploma

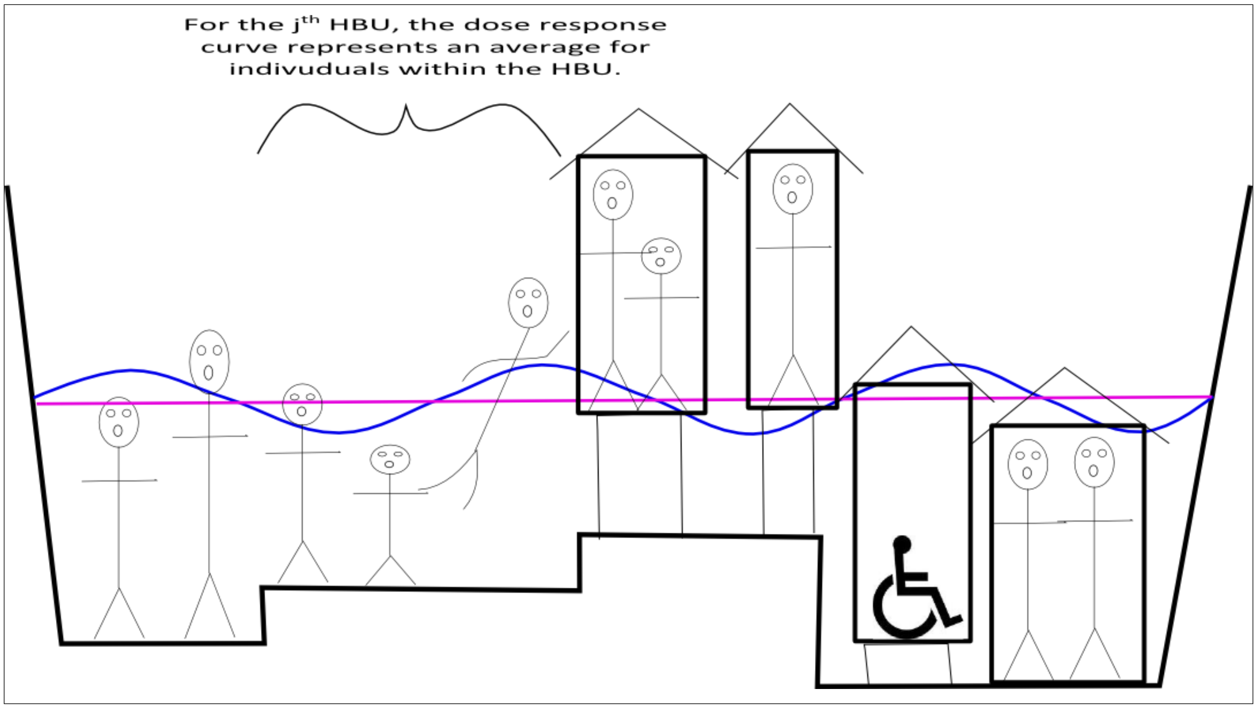

Figure 8.10: Illustration of role of the population attributes. Physical attributes such as height and swimming ability affected how an individual responds to a given flood depth, as do socio-demographic attributes such as housing type and disability status. While individual responses are complicated, aggregating the response to HBU level sets the stage for utilizing the population attributes available through the Census Summary File 3 (Census 2002).

Three sets of regression models that added linear terms for the population vulnerability to the best fit models from above were examined. They are,

$$f = logistic(h) + A \times \ Population\ Attribute + \varepsilon$$
$$f = logistic(hv) + A \times \ Population\ Attribute + \varepsilon$$
$$f = logistic(h) + logistic(hv) + A \times Population\ Attribute + \varepsilon$$

where the "*Population Attribute"* refers to one of the variables listed in Table 8.6.

In general, results of this final step were largely inconclusive. While a few individual population attributes were found to be significant and lowered the RSE of a specific model, there were no clear, consistent trends when results were examined as a whole. In many cases, regression results were not obtained because the `nls` procedure gave a *singular gradient* error message, which indicates the presence of a computational singularity (infinity) when calculating the change between iterations.

During the first stage, the population attributes were added to the logistic of depth model, the most notable result was found with the percent of population over 65. Without any additional variables, the logistic of depth model produced an RSE = 0.004908 and two of coefficients were significant at $p < 0.001$ level. When adding a linear term for percent of population over 65, the

RSE = 0.004612, a modest improvement from before, and all of the coefficients of this model were significant at $p < 0.05$ level of above. The coefficient for the population variable is A = 0.0227 ($p < 0.01$) is consistent with the expectation that older people are more vulnerable.

Additionally, when the total number of houses, total number of houses that are renter occupied, and the median year structure built were added to the model, each were individually significant, but did not reduce the overall RSE. It should be noted a number of "singular gradient" errors where obtained when adding particular population attributes to the logistic of depth model.

When examining the population attributes added to the logistic of depth times velocity models, no errors were obtained so every population attribute was examined. Of the set of 20 population attributes examined, five improved the RSE when added to the model. These five are: percent of the population that is African-American, per capita income (white only), median house value, percent homes that are owner occupied, and the median year structure built. Without the population attributes added, the logistic of depth times velocity model produced an RSE = 0.005013. Of population attributes considered, the median house value produced the lowest RSE, $RSE = 0.004745$, and the coefficient was significant at the $p < 0.001$ level. The other coefficient values (each with $p < 0.001$) were consistent with the coefficients of the logistic of velocity model, and the coefficient for median house value, $A = -1.94 \times 10^{-8}$ is consistent with the expectation that vulnerability deceases with higher home values, though the small coefficient value indicates a very small impact of this variable.

Percent of the population that is black was also significant with modest improvement in the RSE, and the coefficient value, $A3 = 0.0039$ $(p < 0.05)$, indicates that the FFR increases meaningfully as the percent of the population that is black increases. Likewise, per capita income (White only) was also significant with modest improvement in the RSE. The coefficient for this variable indicated that vulnerability decreased with income, though with $A = -9.77 \times 10^{-8}$ the effect is very small. Percent owner occupied showed similar results, though with $p < .1$, this variable could be considered barely significant. The positive coefficient suggests that vulnerability increases as percent owner occupied increases. While median year structure built improved the RSE modestly the coefficient of this term was not significant, and only one coefficient in this model was significant at the $p < 0.1$ level.

A final set of regressions looked at adding the population attributes to the two-term logistic of depth plus logistic of depth x velocity model. Like the logistic of depth model, a number of "singular gradient" errors were encountered, so not every population attributed listed in Table 8.6 could be examined. In this set of models, two variables, percent of the population that is black and median house value, produced noteworthy results. When percent of the population that is black was added, the coefficient was significant and RSE lowered to 0.004111. Including this term makes the other coefficients significant, and with $A = 0.004646$, results are consistent with the expectation that minority populations are more vulnerable. Median house value was also found to be significant with a modest improvement in the RSE though the small value of the coefficient $A = -1.58 \times 10^{-8}$ indicates that this variable only has a minimal impact.

If nothing else, examination of population attributes demonstrated the robustness of three models based on the flood hazard conditions. By and large, when the population variables were added the coefficient values were consistent with the coefficient values observed without the population variables. In some cases, coefficients that were not significant in the flood characteristics only models were significant when population attributes were added. In a few special cases, the coefficients of the logistic term(s) changed noticeably when a population attribute was added, though this likely resulted from co-linearity in the model.

In the end, only modest evidence was found that a few of the possible population vulnerability attributes actually influenced the FFR. When first accounting for role of water depth, adding the percent of the population over 65 produced a modest improvement in the model. Of note, all of the coefficients of this model were significant and the coefficient value for the age term, $A = 0.0227$ $(p < 0.01)$, indicates that age exerts a meaningful influence. When added to the logistic of depth x velocity model, it was found that five population attributes improved the model in meaningful ways. Of these, median house value resulted in the greatest reduction in the RSE. However, though this coefficient was significant at $p < 0.001$ the very low value of the coefficient suggests very little meaningful impact of this variable. Holding depth time velocity constant, a $10,000 increase in median property value only changes the FFR by -0.000194.

While percent of the population that is African-American did not lower the RSE as much as median house value, the coefficient of this variable was statistically significant and meaningful. According to this model, a 10% increase in the percent of the population that is black (while holding depth times velocity constant) would increase the FFR by 0.039. The coefficient for per capita income (white only) was significant, though its small value indicates only a minimal impact. Finally, while both percent homes that are owner occupied and median year structure built reduced the RSE, the coefficients of these variables were barely significant ($p < 0.1$). With the logistic of depth plus logistic of depth time velocity models, two population attributes improved the RSE when added: percent of the population that is black and median house value. Furthermore, like with logistic of depth time velocity models, the coefficient of percent black, $A = 0.0046$ $(p < 0.001)$, indicates that percent black has significant and meaningful impact. Likewise, the coefficient for median house value, $A = -1.58 \times 10^{-8}$ $(p < 0.05)$, suggest that while statistical significant, its impact is only modestly meaningful.

In summary, examining the role of population attributes once the flood conditions have been controlled for, suggests that only age and percent of the population that is black has any meaningful impact on the flood fatality rate.

8.6 Limitations and Next Steps

As with any attempt to model a disaster outcome, the currently described model contains a number of limitations that limit its applicability to other flood events. Measurement uncertainty is one such limitation that is present in every step of the analysis. Uncertainties from measuring the dependent variable, including unknown recovery locations and the unknown fate of the missing, have been discussed in the previous chapter. Likewise, the sources for the independent variables also discuss uncertainties in this data.

Beyond just measurement uncertainty, a fundamental limitation exists in regards to the generalizability of the model. Ideally, one seeks a flood fatality model that universally applies to all flood events, as demonstrated by convergence of the functional form of the model along with the parameter values. While this dissertation presents a method can be applied to other flood events, it does not attempt to establish a model that can be applied to other real or potential flood events. This goal requires much more analysis and research. To be certain, all flood events are unique, and the event from which the data has been drawn is particularly unique. So, for example, it has been observed that age and race are population attributes with statistically significant and substantially meaningful coefficient values. What is not clear is if this finding reflects universal trends regarding how these groups respond to flood events or if it simply reflects the social-demographics of the flood affected population. While the reader needs to keep these limitations in mind if attempting to apply this model to other flood events, it is also worth pointing out that the coefficient values obtained with the log-normal of depth model are consistent with what Jonkman (2007) found when looking at the 1953 Dutch flood event.

The dataset that has been created for this analysis opens up a number of possible analyses, and it would be impossible to cover every possible regression equation. In particularly, a number of important next steps are suggested below. The regression above did not examine how windspeed influences that FFR. This could be accomplished using the H*Wind maximum windspeed grid. Additionally, two separate stratifications of the data should be examined. Stratifying the analysis by polder, would separate the dataset into three datasets based on qualitatively different flood conditions for each polder. Likewise, stratification by parish would create two separate regressions based on qualitatively different populations. Finally, the previous sections did not include an examination of the regression diagnostics or possible spatial effects in the model.

8.7 Conclusion

This chapter sought to refine and extend Jonkman's (2007) flood fatality model based on the data accumulated from impacts of levee failure induced flooding that occurred in greater New Orleans during Hurricane Katrina. In addition to incorporate new, more refined data on the dependent variable, this section also extended the flood fatality model by considering additional variables and functional relationships.

As a linear model, the flood fatality rate was regressed against the flood depth using OLS. This univariate, linear model obtained a reasonably good fit and a highly significant coefficient. Given the good fit obtained here along with the simplicity of the model, it is suggested that such a model can be used to obtain rough estimates of the flood fatalities during the emergency situations. Of course, in such applications it is important to keep in mind how the flood event differs from the one the used to determine the regression equation.

The best fit model was non-linear and multivariate. After examining various s-shaped functions along with other possible flood characteristics, it was found that an equation containing a logistic of depth plus a logistic of depth x velocity curve provided the best fit based on just the flood the conditions.

Extending the model beyond just the flood conditions, a set of regressions where used to examine the impact of adding a linear term consisting of one of many possible population vulnerability attributes. This step failed to produce consistent and reliable results, though they do suggest that percent of the population over 65 and percent of the population that is African-American may have a significant, though small impact of the flood fatality rate.

Chapter 9: Conclusion

9.1 Summary of Dissertation

In southeast Louisiana, approximately 1,500 lives were lost when Hurricane Katrina's storm surge overwhelmed the region's poorly designed and constructed levee system. While this event has been described as an unprecedented catastrophe, it is also true that disasters with large death tolls are common globally and not unheard of in the U.S. Both for the benefit of the residents of southeast Louisiana and for everyone that lives with risk from natural hazards, it is important that lessons learned from the Katrina disaster are based on objective analysis of data and are not based on media hype, political spin, or elitist ideology. Toward this goal, this dissertation compiled the relevant data for understanding loss-of-life due to Katrina and the failure of the hurricane protection system and provided an objective, data-based investigation of the important factors that have contributed to the death toll of this disaster.

Jonkman's (2007) dissertation on flood fatality modeling provides the foundation for this research. While the flood disaster in Louisiana provides a wealth of data for improving this model, this model also provides many useful concepts that help us interpret these data. The flood fatality rate (also termed the flood mortality by Jonkman) is defined as the flood deaths divided by the flood exposed population. It was shown that this comprises a valid risk measure with respect to this specific outcome of this type of event. While the calculation is relatively straightforward, obtaining the data in the right format required a number of complicated data processing steps. This calculation also required piecing together a complicated story of a dynamic population experiencing exposure to numerous hazards. As this story was pieced together, it became apparent that floodwaters were just one of many hazards. In fact, deaths due to flood exposure constituted less than half of the total deaths attributed to the disaster. Additionally, it was clear that the population denominator could not be described as a single, static "at-risk" population. Instead, it became clear the overall "at-risk" population, defined as the persons residing in or visiting the impacted area, consisted of numerous "exposed populations" defined in terms of hazard exposures specific to both place and time.

Beyond advancing the flood fatality model, this event, the data it produced, and the analysis presented here provides insight to some of the most fundamental questions of geography. Barrows defined geography as the study of the "relationships between man and the earth which result from his efforts to get a living" (Martin and James 1993, p. 345). Naturally, our efforts to earn a living, which begins with harvesting the resources of Earth, entails exposure to some hazards of Earth, such as floods. Over the course of this ancient field of study, many views have emerged on the relationship between humans and Earth.

Study of flood disasters and the resultant debate of flood reduction policies reflects one of everlasting dichotomies of disasters. In many ways, the structural approach to flood reduction, meaning the prevention of floods through control structures such as levees and dams, resembles the geographic paradigm of human agency, which contends that humans are willing and capable of modifying the landscape to meet their need. The opposite view, the non-structural approach to flood reduction resembles the geographic paradigm of environmental determinism which contends that Earth's natural forces determine the course of human events. Since much of the world's population and most of the world's economy resides on floodplains, this important issue demands a valid scientific analysis that critically examines the basic assumptions of the various arguments. Ultimately, both debates reflect an ancient geographic notion of the ekumene, the inhabitable Earth, and the non-ekumene, the uninhabitable Earth.

However, these debates, which center on two opposing views, do not capture the full set of opportunities and risks of the human experience on Earth. When Eratosthenes divided the world between the ekumene and the non-ekumene, he saw around him a hospitable and productive Europe and imagined a hostile and deadly land across the Himalayas. He could not imagine the co-existence of a thriving Asian civilization. Nor could he imagine that a Black Plague would infect Europe and kill an estimated one-third of the population. Had he witnessed Europe during the Black Plaque and seen the bodies piled up in villages across the continent, Eratosthenes might have been tempted to label Europe as part of the non-ekumene. But, we know better. We know that Europe overcame this lethal natural hazard and entered a period of renaissance and enlightenment.

Just as the ekumene versus the non-ekumene seems too simple of a concept to fully explain human's experience with a dynamic and restless planet full of hazards of many types, the same can be said about the human agency versus environmental determinism and the structural versus non-structural approaches. Earth as the home of humankind is simply too complicated for this either-or viewpoint. This is not to say these concepts are not useful. Even though Eratosthenes was clearly wrong about what lay over the Himalayas and failed to anticipate the changing hazards of Europe, the notion that the natural forces of Earth can overwhelm the human efforts to survive and thrive is important and useful. However what Eratosthenes failed to capture was the broad middle ground – the regions of Earth where natural resources provides opportunities for humans to survive and even thrive, but where considerable natural hazards place seemingly overwhelming constraints on human settlement and utilization.

Risk analysis, a relatively new and emerging field of science, provides the concepts and analytical tools to move beyond these simple views. Risk analysis begins with considering the set of possible scenarios, the probabilities of the scenarios, and the consequences of the scenarios. Together, these variables form the risk triplet (Kaplan and Garrick 1981) which facilitates identifying strategies for minimizing the expected consequences from the set of possible events. Importantly, by considering the probability of events, risk analysis explicitly accepts uncertainty, a condition that underlies all human decisions, and a concept that the non-ekumene, defined in terms of a certain outcome, does not capture.

Risk provides a central conceptual variable used in hazards analysis. Importantly, it meets Cutter's (1996) requirement that it measures an explicit spatial outcome. Consequences are an important element of risk analysis, and various models have been developed to estimate different classes of outcomes, including economic damage and deaths. One set of models provide tools to estimate deaths due to flood events. In these models, a dose response relationship expresses the flood fatality rate as a function of the flood characteristics (Jonkman 2007). While much work remains, these consequence models hold potential for fulfilling this difficult element of the risk triplet.

Risk is also a function of the hazard characteristics of the physical process and the vulnerability characteristics of the affected population (U. N. Interagency Secretariat 2002). Disasters result when a vulnerable population is exposed to a physical hazard that overwhelms the population's capacity to respond. As such, much of hazard geography concerns the spatial dimensions of hazards and vulnerability. Towards a measure of vulnerability, income, education, age and other population attributes are used to compute vulnerability indices. Recently, Burton (2010) used data on Hurricane Katrina damage along the Mississippi Gulf Coast to examining adding a Social Vulnerability Index to a hurricane damage model that includes just the hazard characteristics as independent variables.

This dissertation sought to advance this line of research by assessing the loss-of-life due to Hurricane Katrina's impacts on Louisiana and by using these data to refine the dose response relationship of Jonkman's (2007) flood fatality model. It also sought to use this event to further risk analysis in the context of human settlement and exploitation of hazardous floodplains.

Residing on a young and dynamic deltaic floodplain along the Gulf Coast and near the tropics, extreme weather and floods have been ingrained in the culture of southeast Louisiana since the first colonial outpost was flooded by the river, then destroyed by wind. Throughout the 300 year history of western influence and governance, numerous flood events prompted massive human modifications to the landscape. Because of these modifications, the risk of the Mississippi flooding New Orleans has been considerably reduced, while the persistent heavy rains became manageable. Like most American cities, experienced considerable suburbanization during the post-World War II period. With the promise of Category 3 protection from the Corps of Engineers, the urbanized settlement expanded from the natural ridge into reclaimed swamplands.

Over the last half century, growing awareness of coastal erosion and subsidence motivated emergency planning focused on protecting the population during hurricane events. Coastal landloss was first cataloged in 1968. This discovery, along with Betsy in 1965, signaled that the urban areas of metropolitan New Orleans were no longer safe from storm surge flooding. Twenty-eight years after Gagliano, Kwon, and van Beek's (1970) study, Hurricane Georges caused the first official evacuation order for New Orleans. In 2004, the first contraflow evacuation plan was tested with Hurricane Ivan. By the start of hurricane season 2005, the Southeast Louisiana Hurricane Task Force completed an intensive, regional planning effort, paved a dozen or so crossovers for contraflow, printed 1 million maps, and worked with the local media to further public awareness of the hurricane threat and evacuation procedures (Wolshon, Catarella-Michel, Lambert 2006). Similarly, the Hurricane Pam exercise produced a detailed response plan for the inevitable "Big One" hitting New Orleans. Despite these efforts at emergency preparedness and burgeoning plans to address the landloss problem, Hurricane Katrina and the resultant 50 failures in the regions levee system resulted in unacceptable loss-of-life along with other impacts.

A complex event characterized by cascading series of processes created a sequence of multiple hazards which impacted different population and sub-populations. The notion of a static "at-risk" population exposed to a single hazard does not fully capture this story. This disaster event is a dynamic story of population movements in the face of numerous real and perceived threats. Over the course of nearly two weeks, nearly 1 million people endured one or more of the following hazards: evacuation/displacement, extreme winds, flood exposure, overcrowded and undersupplied emergency shelters, hot days trapped in an attic, nights sleeping at a Lily Pad (the term used to describe the nearest dry spot where crowds flood rescuees emerged) with only minimal supplies, toxic pollution in the air, soil and water, disruption of medical services, lawlessness, and other aspects of a regional emergency characterized by the breakdown of basic public health and safety systems and infrastructure.

Waters Dark and Deep: One New Orleans Family's Rescue Amid the Devastation of Hurricane Katrina (Thomas 2006) describes these distinct stages of population movement and hazard exposure for one family. Some members of the family evacuated before the storm, while others were unable to muster the wherewithal to get out in time. The family members that stayed soon find themselves trapped in an apartment building surrounded by floodwaters. The family is further separated when the first search and rescue helicopter takes the children and one adult to the I-10 Cloverleaf, while a second helicopter takes the other adults to the New Orleans Lakefront Airport. Following their emergency, assisted evacuation from New Orleans a partial reunion occurred in Baton Rouge, and then a second reunion occurred in San Antonio. Like so many other aspects of the Hurricane Katrina, this family's story also got obscured in the "Fog of War" when national media outlets reported that, instead of being separated by search and rescue teams, the children had been abandoned by their family.

This complex sequence of population movements and hazard exposures coupled with the confused early reporting illustrated the need for a systematic, data-based approach to assessing this dynamic "at risk" population. Utilizing U.S. Census data, traffic counts, post-storm sheltering and evacuation counts, along with figures from numerous after-action reports, Chapter 4 told the story at a population level. Tracing the sequence of warnings, evacuation calls, and then evacuation observations, it was estimated that over 1 million people evacuated. While these people avoided the wind and flood hazards, they still endured risks associated with their evacuation and displacement. Once the evacuation was completed and Katrina's hazard conditions took hold, approximately 130,000 people remained in the four hardest hit parishes of southeast Louisiana. Of these, approximately 65,000 would suffer flood exposure; 99,000 would endure overcrowded and unsanitary conditions at one of five emergency shelters/collections points; 2,500 patients remained in hospitals without power or supplies; approximately 3,400 residents remained in nursing homes; hundreds spent a hot day trapped in their attics; thousands spent a night on an elevated expressway, a bridge, or some other "Lily Pad" with only minimal supplies. All told, thousands suffered from a widespread regional emergency characterized by the breakdown of basic public health and safety infrastructure and systems.

Chapter 5 systematically presented the landscape, the population, and hazard conditions that characterized this disaster. Hurricane Katrina and the subsequent flooding of New Orleans was a complex disaster with multiple hazards impacting multiple populations. The hazards of this event varied considerably across space. As such, one study region was not sufficient for depicting the impacts of this disaster, so a multi-focused look at the regions impacted by the different hazards of this event has been provided.

Focusing on Louisiana with a population of approximately 4 million, it was shown that this population possessed many of the characteristics associated with vulnerability to disasters, including poverty, lack of education, and lack of vehicle access. It was also shown that these vulnerability factors were highest in the New Orleans area, which contained a large number of urban African-Americans.

When discussing the hazards of Katrina, it was shown that extreme winds and rainfall affected a large region within the United States. While, the most lethal hazard, the storm surge, did not extend far inland like the wind and rain, the surge still impacted a large stretch of central Gulf of Mexico coastline with surge levels over 15 ft (4.6 m) along the southeast Louisiana coast and over 20 ft (6 m) for most of Mississippi's Gulf Coast. Two additional hazards, which are often overshadowed by the wind, rain, and surge, were also discussed: the extreme heat that gripped the region and the release of numerous toxic substances due to wind and flood damage.

Following the description of the study region, the impacted population, and the physical hazards, Chapter 6 provided a descriptive summary of Katrina related deaths for Louisiana. A database was compiled from numerous original sources, including information from a joint state-federal victim recovery effort. Uncertainties in the current initial interpretation result from incompleteness of the data, inconsistencies between sources, missing fields, and lack of data on important factors, especially medically determined cause of death. Despite these limitations, this dataset provides a more comprehensive dataset for the analysis of causes and circumstances for fatalities related to Hurricane Katrina's impacts in Louisiana. Of note, the victims summary statistics presented here differ from previous studies that were based in preliminary datasets published by the SMEO.

Louisiana health officials estimate that 1,464 deaths are related to the impact of Hurricane Katrina on Louisiana. Of these, 1,118 fatalities occurred in the state of Louisiana and 386 out of state deaths were reported amongst Louisiana residents. However, there is disagreement over how many of victims that perished outside of the heavily impacted southeast Louisiana should be included, while an independent analysis concluding that only 968 of these deaths met international criteria for inclusion as a "victim of a cataclysmic storm." On the other hand, including other reliable sources beyond the SMEO indentified an additional 109 victims that would likely fit the SMEOs criteria, but were not included due to resource and time constraints.

From the descriptive analysis of the demographic characteristics, age emerges as the most important variable, with 86 percent of the victims age 50 or older and 67 percent age 65 or older. It was also noted that there were no direct flood deaths under age 10. While the data are limited in regard to disability, what is available suggests that this is another important demographic variable. The examinations of race and gender did not reveal any readily apparent trends, though the role of these factors is likely complex and warrants further investigation.

Geography also played a big role in the risk of death for the affected population. An analysis of the circumstances of death led to the identification of three distinct zones characterized by specific groups of hazards. The three regions are: (i) the flood zone, (ii) the regional emergency zone, and (iii) the evacuation/displacement zone. Based on the information available, it is estimated that at least 600 - 700 victims died due to circumstances related to exposure to flood waters, approximately 300 victims died due to circumstances related to the regional emergency in metro New Orleans, and 631 victims died due to circumstances related to evacuation and displacement. Importantly, stratifying the victims' characteristics by category of circumstances reveals important trends that are not shown in the unstratified analysis. While most of the flood victims were elderly African-American males, the most prevalent victim overall were displaced elderly Caucasian females.

Further analysis of the direct flood deaths identified spatial patterns for this disaster outcome. As exemplified by the point pattern analysis of direct flood deaths, an especially high number of fatalities occurred in Lower Ninth Ward, an area that experienced large flood depths, high flow velocities and significant structural damage/collapse due to its location relative to the MRGO/GIWW. Similar hotspots, though much smaller, were observed in Gentilly and Lakeview.

The flood fatality rate (FFR) is a measure of the risk of death for the flood exposed population. With 600 - 700 flood deaths out of approximately a flood exposed population o0f 63,000, the overall FFR for the flooded portions of Orleans and St. Bernard parishes is 9 – 11 deaths per 1000 flood exposed persons. Based on research in this area, this value is consistent with the FFR observed in other coastal flood disasters (Jonkman 2007).

Consistent with the point pattern analysis, the highest flood fatality rates were observed in the Lower Ninth Ward and extending into Chalmette. High values were also observed in the neighborhoods just along the northern portion of the central New Orleans polder, which includes Lakeview and Gentilly. The data also indicate that flood risk during this event was relatively lower throughout the New Orleans East polder. New Orleans East was closer to the path of Katrina's eye and experienced high surges on both its south shore facing Lake Borgne and its northern shoreline adjacent of the Lake Pontchartrain, the levees and pump stations here performed, thus preventing the high flood depths observed in the other polders.

Having measured the FFR for Orleans and St. Bernard parishes, this dissertation used this data to refine and extend the flood fatality model (Jonkman's 2007). In addition to incorporating new, more refined data on the dependent variable, this section also extended the flood fatality model by considering additional variables and functional relationships.

As a linear model, the flood fatality rate was regressed against the flood depth using OLS. This univariate, linear model obtained a reasonably good fit and a highly significant coefficient. Given the good fit obtained here along with the simplicity of the model, it is suggested that such a model can be used to obtain rough estimates of the flood fatalities to aid search and rescue operations during the emergency situations. Of course, in such applications it is important to keep in mind how the flood event differs from the one the used to determine the regression equation.

The best fit model was non-linear and multivariate. After examining various s-shaped functions along with other possible flood characteristics, it was found that an equation containing a logistic of depth plus a logistic of depth x velocity curve provided the best fit based on just the flood the conditions.

Extending the model beyond just the flood conditions, a set of regressions were used to examine the impact of adding a linear term consisting of one of many possible population vulnerability attributes. This step failed to produce consistent and reliable results, though they do suggest that percent of the population over 65 and percent of the population that is African-American may have a significant, though small impact of the flood fatality rate.

Additionally, these data provide an opportunity to extend the flood fatality models for the other observed circumstances of death. Just as the available data were used to estimate the number of flood deaths and the size of the flood exposed population, the available data allow for similar calculations for emergency circumstances deaths.

9.2 Results and Conclusions

Throughout, three important questions guided this research:

- What factors determine and explain the loss of life due to Hurricane Katrina's impacts in Louisiana?

  The descriptive statistics of the victim's characteristics revealed that age and possibly disability status were important factors. The regression analysis of the flood fatality rate found that the flood characteristics of depth and velocity were important variables.

- Can Jonkman's flood loss of life model be further developed and refined?

  Yes. In addition to refining the measurement of the FFR, this dissertation explored different possible functional relationships for depth and velocity and found preliminary evidence that population vulnerability attributes add to the model.

- Can we extend the notion of a flood fatality model to include deaths related to the flood event but not directly caused by flood exposure?

  Yes. Using the available data, deaths related to emergency circumstances and evacuation/displacement were identified and basic trends were discussed.

Additionally, this dissertation sought to fulfill three objectives:

Objective 1: Determine the circumstances of death for Katrina-related victims

Three classes of circumstances were inferred from the available data with a minimal number of assumptions, and victims were categorized according to these circumstances.

Objective 2: Further refine and expand the flood fatality model presented by Jonkman (2007)

The goodness-of-fit for the final model was lower than for Jonkman's model.

Objective 3: Taking initial steps toward modeling indirect flood deaths.

While only exploratory, it was still found that there was considerable variance in the observed fatality rate for emergency circumstances deaths and evacuation/displacement deaths.

Ultimately, this dissertation along with an ever expanding body of scientific knowledge on this disaster shows that geography influenced risk. Going even further, this dissertation helps piece together the series of land and water-use decisions and policies that created the conditions of significant flood risk for greater New Orleans. Though not the central focus, this dissertation links with numerous studies that have examined the flooding resulting from Hurricane Katrina in the context of coastal land loss, improper design and construction of hurricane protection levees, and the construction and subsequent improper maintenance of the Mississippi River Gulf Outlet. It is suggested that further research of this disaster seek to examine how each of these factors specifically contributed to the observed fatality statistics and patterns.

For the current work, it suffices to end with a basic, but important observation. Upon comparing the storm surge flood and impacts between Hurricane Betsy in 1965 and Hurricane Katrina in 2005, some common themes emerge. For example, the ADCRIC storm surge prediction for Katrina (Figure 4.7) is nearly identical to the Betsy flood map (Figure 3.8). Similarly, the breaches along the INHC occurred at nearly identical locations (Figure 3.7 and Figure 4.11). It is also apparent that a fatality cluster was observed in the Lower Ninth Ward for both storms (Figure 3.9 and Figure 6.9). Just as important, this pattern of flooding does not appear to have occurred at any previous time during the history of New Orleans (Roth 1998). While there are significant differences between the two storms, a comparison of the storm surge flooding for the storms illustrates on key difference. Having occurred after 40 years of ecological damage from the Mississippi River Gulf Outlet, Hurricane Katrina resulted in a flood of considerably greater extent and magnitude compared to what Hurricane Betsy caused.

These observations all point to the construction of MRGO along with the subsequent damage that it caused on the landscape and ecosystem (van Heerden, et al. 2007; Shaffer, et al. 2009). When Betsy occurred, the MRGO had just been completed. This newly formed landscape feature created a funnel that directed the surge itoward the center of New Orleans. After following a curve flow path into the INHC, the high velocity flow eroded the earthen levee adjacent to the Lower Ninth Ward, flooding this neighborhood to depths up to 10 ft (3 m). Forty years later, the MRGO along with its improper maintenance had caused major damage to the marsh and swamp east of New Orleans, and, in essence, the storm surge funnel effect had been magnified considerable. When Katrina hit, the surge followed a similar path toward the center of New Orleans, and curve back east at the last exit. But, this time, less marsh and swamp meant more water, moving faster. It also meant much more severe damage – flood depths in the Lower Ninth Ward approached 20 ft (6 m) and the flooded extended over a much greater urbanized area.

Without a doubt, anthropogenic landscape changes have increased the flood risk for this region with the observed patterns in Katrina and flood related loss-of-life reflecting the human imprint on the local geography. However, many analysts (Burby 2006, Campanella 2007) have focused just on the construction of levees and pump stations that facilitated urban expansion away from the natural ridges and into wetland areas. In doing so, they have ignored the much larger influence of the MRGO storm surge funnel, which is exemplified by both cluster of flood fatalities in the Lower Ninth Ward and finding the flow velocity of flood waters had a strong impact on the flood fatality rate.

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Appendix A: Compiling the Louisiana Katrina Victim Database

A.1 Introduction

This appendix summarizes efforts made to compile a Hurricane Katrina Victims database from multiple data sets, both official and unofficial. For obvious reasons, Hurricane Katrina is often characterized by the widespread confusion and chaos that followed the storm. This confusion and chaos meant a disorganized victim recovery effort and convoluted set of archival records listing deaths associated with Hurricane Katrina's impacts on Louisiana. Added to this is the fuzziness associated with applying simple categorizations of disaster deaths (viz. direct vs indirect) to a very complex situation where such simple, generalized definitions are not applicable.

Created through an emergency declaration, the Louisiana State Medical Examiner's Office (SMEO) oversaw the process of recovery, investigation, and releasing victims' remains along with compiling the associated archival data. Through my collaboration with the SMEO, I acquired numerous datasets describing their operations. While mostly providing electronic spreadsheets, the SMEO also provided printed records. Most of the data included in master final database is from the SMEO, though other data sources are also included.

The SMEO's capabilities were limited, and many victims have not been recorded in the official datasets. Documented victims not included in the SMEO datasets include: about 20 victims from Jefferson Parish listed by *The Times-Picayune* newspaper, 6 victims described by the Plaquemines Parish emergency manager, 40 victims found in Orleans Parish after the SMEO ceased operations, and other victims identified in individual media accounts but not found in the SMEO data.

To create this master database, multiple datasets listing Katrina fatalities were imported in an Access database. Within Access, each spreadsheet comprised a table. Table relationships, SQL queries, and many hours of scanning, cutting, and pasting were involved in compiling a complete, (mostly) non-duplicated listing of the victims' names, basic demographic information, residence location, and recovery location. In addition, data obtained from post-storm field assessments of victim recovery locations in Orleans and St. Bernard parishes was appended to the victims' records.

A.2 Description of Datasets

SMEO Data

Most of the utilized data was provided by the SMEO through various electronic spreadsheets. Numerous spreadsheets were obtained from the SMEO, but one particular file "CATABLIE-DB" obtained in April 2006 was most extensively used. This single spreadsheet consisted of numerous workbooks, each of which comprised a separate listing of victims and associated data. Each workbook related to different aspects of the recovery, examination, identification, and release of the victim. Accompanying the spreadsheet was an associated “PDF farm”, a folder that contained scans of the victims’ receipts of remains. A receipt of remains is the form corresponding to each recovery of a victim. While most of these forms were completed on location during the victim recovery, others appear to have been complete at a remotely located temporary morgue. Each receipt of remains includes a DMORT#, which is an unique identifier for each victim that is included in most of the recovery operations spreadsheets. The result of an exhaustive effort by the SMEO to compile data derived from their victim recovery operations, this dataset still contains numerous unknowns and incomplete records.

Two other datasets on victims examined by SMEO where used -- “EZRA_RECOVERY_SPOOL_033106” and “DHH_041206”. The latter spreadsheet consisted recovery locations along with DMORT#’s. In contrast, the former consisted of just recovery addresses with no other unique identifier to link the cases with cases already in the dataset.

In addition, two other datasets where compiled by the SMEO based on victims examined by other entities. A spreadsheet from the SMEO, entitled “OUT OF PARISH_Cataldie091406” included victims that were recovered within Louisiana, but not as part of the SMEO led effort. This data was reported to the SMEO by the various parish coroners. Likewise, a spreadsheet named “WIP – Out of State Deaths” listed victims reported to the SMEO from out of state coroners and medical examiners. The “WIP” indicates that this file was a “Work in Progress” when the SMEO closed.

In addition to this non-public data, a public listing of victims recovered by the SMEO from February 2006 was obtained from a Louisiana Department of Health and Hospitals website. This listing was pasted into a spreadsheet, and then imported to the master database.

Early Times-Picayune List

In October 2005, *The Times-Picayune* published two lists of Katrina fatalities, one listed victim recovery locations (but not victim information) for St. Bernard Parish and the other listed victims along with their recovery locations for Jefferson Parish. While all of the St. Bernard recovery locations are listed by the SMEO, the victims listed for Jefferson Parish do not appear in the SMEO datasets. Not as heavily impacted as neighboring parishes, Jefferson did not participate in the SMEO operations. These tables were entered into a spreadsheet which was then included in the database.

Field Data

Starting in October 2005 and during the next 10 months, I conducted a field assessment program that involved visiting locations listed as victim recovery locations in the datasets provided by the SMEO. For each location I completed a basic datasheet related to characteristics of the location and flood conditions. Numerous research assistants aided this effort. This field assessment data provides additional information for approximately 400 victims.

Victims from Locations with Observed Recovery Markings But Not Listed By DHH

During the above mentioned field work, a handful of homes that were not listed by the SMEO but that bore distinct markings to indicate a victim had been recovered were surreptitiously found and then recorded. While these locations likely correspond to some of the "unknown's" in the SMEO data, these cases are currently listed as separate unique cases in the database.

For this reason, I say that the database consists of (mostly) non-duplicated victims. To be precise, approximately 11 victims listed by the SMEO from unknown recovery locations are likely duplicated by cases in the database that are described as "not listed by SMEO; recovery markings indicate victim recovery from location." For the latter cases, the database only has information on the recovery location, while the former may have information on victim. Since recovery locations and victim characteristics are analyzed separately, duplicating these cases in this manner will not affect the analysis.

Victims Listed From Other Sources

Using the available information, I compiled limited information on additional victims from the following sources:

- Six victims described by the Plaquemines Parish Emergency Manager.
- 20 victims reported by *The Times-Picayune* found post-SMEO operations
- 3 unlisted victims found in a scan of 40 news and other media accounts

Data Not Included

At this time, the following data is not included in the database, though some of these items (particularly the first 3 -4) will likely be included soon.

- "Official" Plaquemines or Jefferson Parish data
- Brunkart, et al dataset: includes medical cause of death for some SMEO victims
- Mutter's list: independent list compiled from submission provided by the public
- Other lists obtained from SMEO, including the printed lists.
- Any lists of the missing
- Gambit Weekly: Five hurricane affected Louisiana residents have died in fires in FEMA trailers due to propane explosions. State Fire Marshal – 71 fatal fires with 96 deaths during 2005-06 fiscal year. 50 fatal fires per year is the norm.
- No attempt to compare my maps to other published maps.
- Media accounts of long term deaths related to strained local health services.
- Stevens, et al. estimated 2,300 excess deaths Jan – Jun 2006.

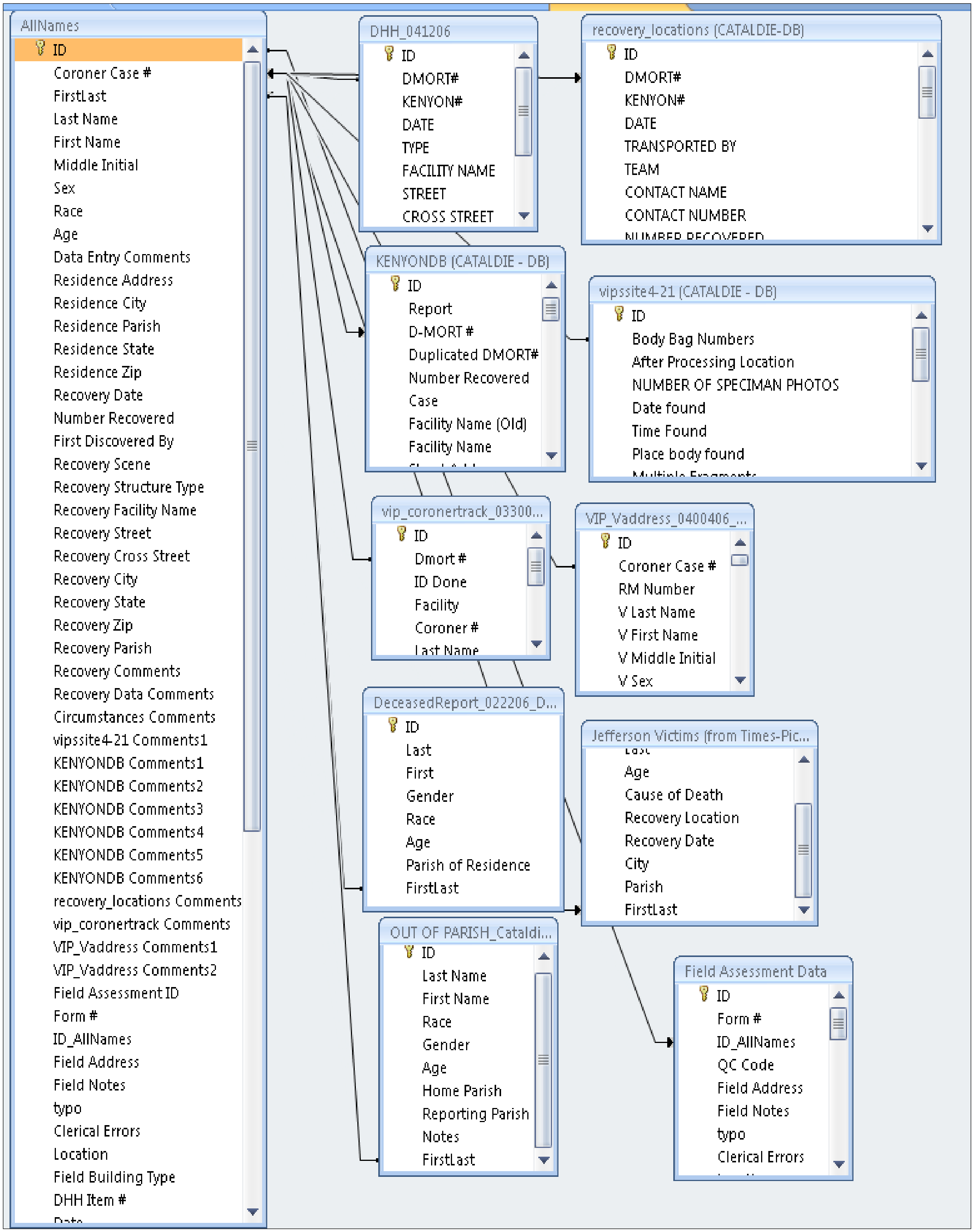
Note on The Unknowns

Unknowns relate to both the victims name and recovery address. Since the multiple sources use different codes for unknown data, for example "Unknown", "N/A", "Unknown male," it is possible that a single unknown might be listed differently in two datasets. Further, it could be possible that a "Find Unique Cases" query on the combined table might list the cases as two separate cases. If the combined table lists "Unknown" and "N/A", then it is possible that these two cases may be identical. During the process of merging the datasets, this issue was carefully addressed by manually scanning the additional information on the various forms of ‘unknown’ to identify information, such as age, gender, and race, that identify the cases as unique. In addition, once the final dataset was finished, filters were used to list the multiple codes for ‘unknown’ in a single view which was then manually scanned to confirm that no definitive duplicates existed. Many of the unknowns had unique DMORT#’s, and those that did not were either from the same source dataset (where they are assumed be listed as unique cases) or had other information (such as age or gender) that indentified them as unique.

A.3 Steps to Compile Unique List of Victims and Associated Data

The “CATALDIE_DB” from April 2006 provided the starting point. This spreadsheet included five worksheets that contained separate lists of victims’ and/or recovery locations. In addition, some of these included a DMORT number, a unique identifier linked to the DMORT Receipt of Remains. Four of these tables provided both a DMORT# and first & last name. Concatenating the four tables, a list of all DMORT#s and names was created, which was then visually scanned to delete duplicates. At this point, a “Find Duplicates” SQL query was conducted to identify and delete any duplicates that were missed in the first round. The result was a single table listing each unique name and/or DMORT#.

From here, other tables were imported into the database and Relationships were defined between the tables. Either the DMORT# or a field called “FirstLast,” which was first and last names concatenated, was used to link the various tables. A find “Unmatched Table” was used to identify and edit cases where some simple discrepancy, such as a misspelling, prevented two identical cases from being linked. With these relationships defined, SQL queries joined the tables and then identified duplicates that needed to be deleted from the joined tables. Additional steps and data reviews were conducted to minimize the possibility of duplicated victims. Once a list of all unique cases (identify by DMORT# and/or FirstLast) was obtained, SQL Join queries added additional victim data to the table. In addition to columns including basic demographic, residence, and recovery information from the victim datasets, a handful of catch all columns that consisted of concatenated miscellaneous data from the original sources were added to the tables (to assist later interpretation of individual cases). A final step Imported and joined the Field Assessment Data.



AllNames

ID
Coroner Case #
FirstLast
Last Name
First Name
Middle Initial
Sex
Race
Age
Data Entry Comments
Residence Address
Residence City
Residence Parish
Residence State
Residence Zip
Recovery Date
Number Recovered
First Discovered By
Recovery Scene
Recovery Structure Type
Recovery Facility Name
Recovery Street
Recovery Cross Street
Recovery City
Recovery State
Recovery Zip
Recovery Parish
Recovery Comments
Recovery Data Comments
Circumstances Comments
vipssite4-21 Comments1
KENYONDB Comments1
KENYONDB Comments2
KENYONDB Comments3
KENYONDB Comments4
KENYONDB Comments5
KENYONDB Comments6
recovery_locations Comments
vip_coronertrack Comments
VIP_Vaddress Comments1
VIP_Vaddress Comments2
Field Assessment ID
Form #
ID_AllNames
Field Address
Field Notes
typo
Clerical Errors
Location
Field Building Type
DHH Item #

DHH_041206

ID
DMORT#
KENYON#
DATE
TYPE
FACILITY NAME
STREET
CROSS STREET

recovery_locations (CATALDIE-DB)

ID
DMORT#
KENYON#
DATE
TRANSPORTED BY
TEAM
CONTACT NAME
CONTACT NUMBER

KENYONDB (CATALDIE - DB)

ID
Report
D-MORT #
Duplicated DMORT#
Number Recovered
Case
Facility Name (Old)
Facility Name

vipssite4-21 (CATALDIE - DB)

ID
Body Bag Numbers
After Processing Location
NUMBER OF SPECIMAN PHOTOS
Date found
Time Found
Place body found

vip_coronertrack_03300...

ID
Dmort #
ID Done
Facility
Coroner #

VIP_Vaddress_0400406_...

ID
Coroner Case #
RM Number
V Last Name
V First Name
V Middle Initial
V Sex

DeceasedReport_022206_D...

ID
Last
First
Gender
Race
Age
Parish of Residence
FirstLast

Jefferson Victims (from Times-Pic...

Age
Cause of Death
Recovery Location
Recovery Date
City
Parish
FirstLast

OUT OF PARISH_Catakdi...

ID
Last Name
First Name
Race
Gender
Age
Home Parish
Reporting Parish
Notes
FirstLast

Field Assessment Data

ID
Form #
ID_AllNames
QC Code
Field Address
Field Notes
typo
Clerical Errors

Figure A.1: Table relationships in the Access database. AllNames is the master table.

Sample SQL Query: this query joined columns from DeceasedReport_022206_DHH to AllNames for cases with identical FirstLast.

```
SELECT

AllNames.ID, AllNames.FirstLast, DeceasedReport_022206_DHH.First,
DeceasedReport_022206_DHH.Last, AllNames.Sex, DeceasedReport_022206_DHH.Gender,
AllNames.Race, DeceasedReport_022206_DHH.Race, AllNames.Age,
DeceasedReport_022206_DHH.Age, AllNames.[Residence Address], AllNames.[Residence
City], DeceasedReport_022206_DHH.[Parish of Residence]

FROM AllNames RIGHT JOIN DeceasedReport_022206_DHH ON AllNames.FirstLast =
DeceasedReport_022206_DHH.FirstLast;
```

A.4 Geocoding and Spatial Joins

Following the creation of the master database, both the residential address and the recovery location were geocoded and entered into a GIS. GIS software was then used will assign to each victim various other data columns including, flood depth, wind speed, distance to nearest levee breach, distance between home and recovery location, along with other possible data related to evacuation, hazard exposure, emergency response, etc.

In turn some of the data generated through GIS steps were then imported back into the master base. At this time, the master table includes columns for the flood hazard conditions for the matched recovery addresses.

A.5 The End Result

The final database included 1572 victims and 120 total columns, of which 70 columns contain pertinent and useful information. The remaining columns are for database management (unique identifiers for joining table) or catch all comments from the original datasets (for verification). Naturally, there are numerous missing data points, and *n* varies by column.

The useful data columns include:

- Victim Data: Name, Age, Race, Gender
- Victim Residence: Street Address, City, Parish, State, Zip
- Recovery Location: Scene, Facility Type, Name, Street, Cross Street, City, Parish State, Zip, Recovery Comments
- Hazard Conditions at Recovery Locations: Maximum Windspeed, Flood Depth (from LSU Grid and from SOBEK), Flood Flow Velocity, Depth x Velocity, Rate of Rise, Arrival Time
- Field Data: Address, GPS Location, Building Type & condition, Stories,

Ceiling Height, Foundation type and elevation, height of watermark, structural damage, evidence of waves or debris, miscellaneous observation regarding the victim, disability, or escape & rescue.

Appendix B: Geocoding Hurricane Katrina Victims Master Database

B.1 Introduction

This appendix describes the steps taken to geocode the victims listed in the victim database (which is described in an accompanying report). The victim database lists approximately 1200 victims related to Hurricane Katrina's impacts on Louisiana, and it includes information on victim's residences, victim's recovery locations, and the location of our field assessment. The last two are essentially the same location, except one the first was recorded as an address while the other was recorded as GPS coordinates. From this data, the geocoding process produced three point locations, one representing the residence and two representing the victim recovery location. Coding the field locations was essentially a trivially task of converting a pair of X and Y columns to a point shapefile. However, geocoding the two sets of addresses, which consisted of typos, misspellings, formatting errors, and incomplete data, was a much more involved task that is described in the next section.

B.2 Automatic Geocoding Based on Street Address Versus Manually Assigning a Location Based on Limited Information

Arcview 9.3 along with an appropriate geolocator (viz. a streets layer in a specific format) provides a robust tool to batch geocode a set of addresses listed and formatted properly in a spreadsheet. For a well specified location in the proper format, such as 1234 Mandeville St, New Orleans, La., 70448, the software gives a point that is typically accurate to within 50 ft. When the information is incomplete, for example Magazine St. or 70117, the software gives the user the option to assign a point at a chosen location .

For this task, geocoding the dataset consisted of a two step process of first automatically coding the addresses for which sufficient information in the proper format is available and then manually assigning locations when the incomplete information. [In the middle are the addresses that were missed the first time by the software, but that can be automatically coded based on the information available through a manual process of inspecting and adjusting the entered address. (In other words, the addresses that describe a specific location but not in a format that is not automatically coded the first go around).] For each set of addresses, these two geocoding processes resulted in the creation of two sets of point shapefiles that different in terms of precision and representativeness.

The automatic geocoding process, which included all addresses with sufficient information to specify a corresponding spot on the map, produced a point layer that is precise. However, this layer is not fully representative of the magnitude or spatial extent of victim's residences and recovery locations. These two shapefiles (residential & recovery) consist of about 800 locations. To clarify, these include addresses where the available information identified a specific point on the earth's surface.

In contrast, the data layers produced by the second manual process are representative of a larger sample but lack some of the precision. To be specific this layer includes the points matched automatically in the previous set, along with points manually assigned based on the incomplete information. This incomplete information may be a street, a zip code, or a neighborhood. In the case of the 272 victims in the “Out Of Parish” spreadsheet the only spatial information included was the parish of residence and parish of recovery. When the available data did not specify a point on the map, a point was manually assigned within the region specified. This could be the center of a length of street, for example if the recovery location was ‘Magazine Street’. It also could be the center of a zip code or a parish.

A couple of basic guidelines where followed when manually assigning points based on incomplete information. One, evacuee deaths tend to cluster around the urban areas. Two, deaths tend be closer to the path of the hurricane. Three, to best represent the magnitude of impacts, is was best to assign points in a manner that fills the voids in areas with a large number of points. Four, when all the above fail, the center of the parish is a good place. Both of these layers contain just over 1,000 points.

The two sets of data layers, termed “Matched” and “Matched+Assigned,” varying in their strengths and weaknesses. The Matched layers strength lay in its precision where is matters most – around Metro New Orleans. This will allow precise model of the direct flood fatalities. However, this data layer fails to accurate portray victims that died post evacuation in places like Shreveport and Monroe, which are depicted in Matched+Assigned. This layer will be used to make general comments about the trends related to evacuee deaths.

B.3 Basic Maps

The following pages contain a few basic maps created from the geocoded locations and other background layers. Each set shows each of the four layers at difference geographical extents.

- Spatial Extent:
Full extent of location data layer (Not that these varying between Matched and Matched+Assigned.
Louisiana,
Metro New Orleans,
Wind Strom (Grid),
Flood Depth (Grid)

- Symbols:
    Triangle represent victims’ residences,
    Circles represent victims’ recovery locations

    Match+assigned locations are colored red,
    Just matched locations in purple.

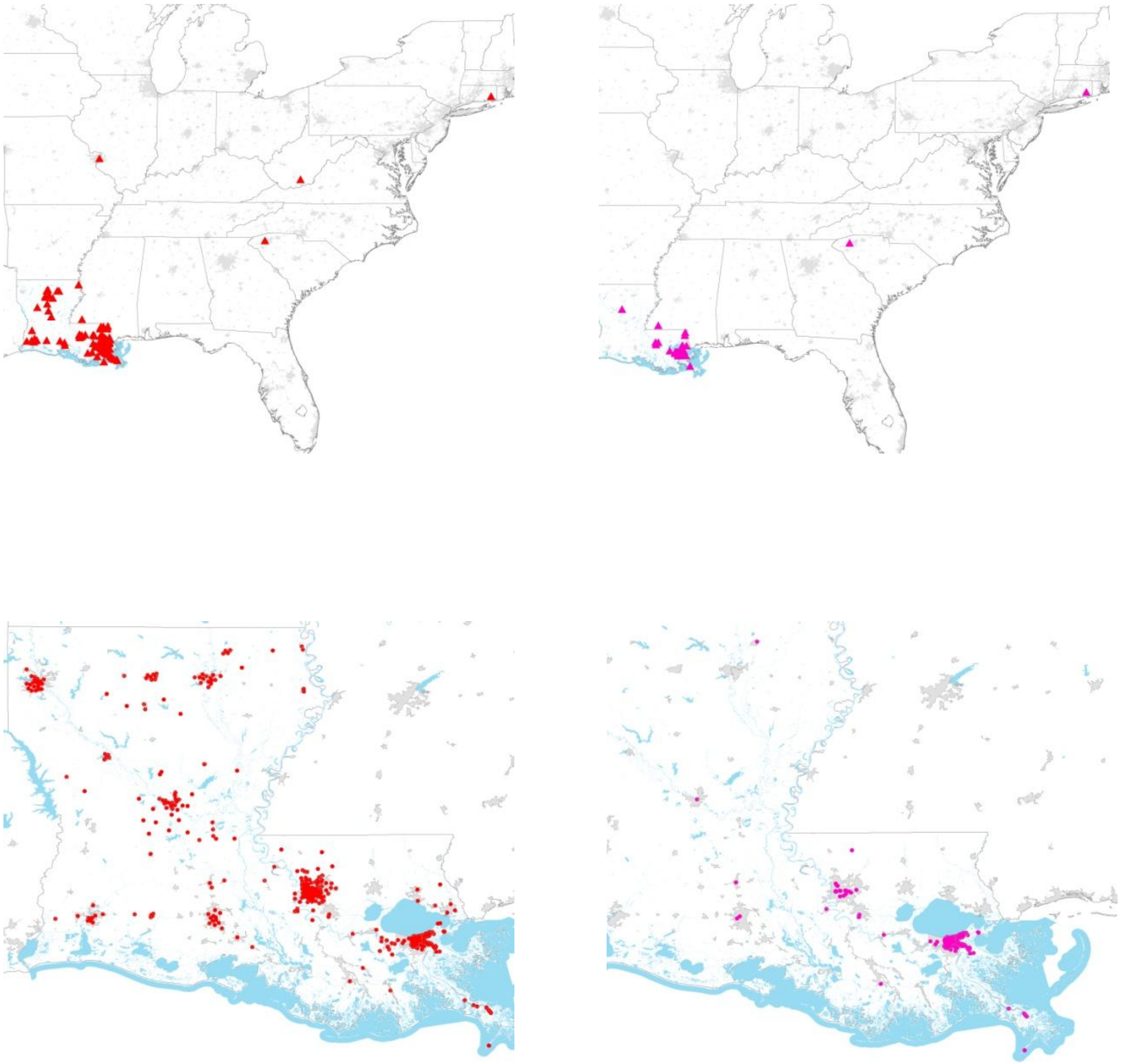


Figure Set B.1: Full extent of the data layer. From top left to bottom right: All Residences, Matched Residences, All Recoveries, Matched Recoveries

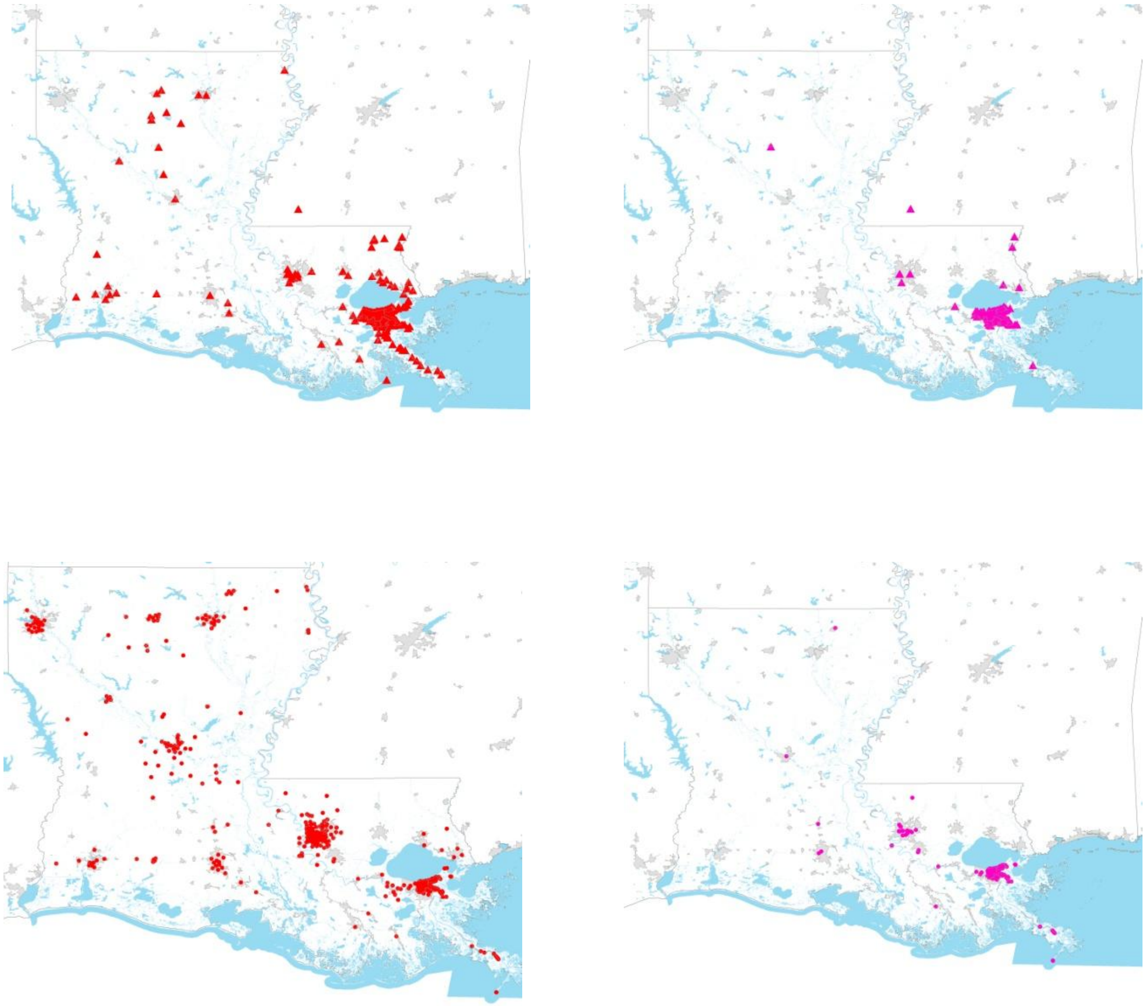


Figure Set B.2: State Extent

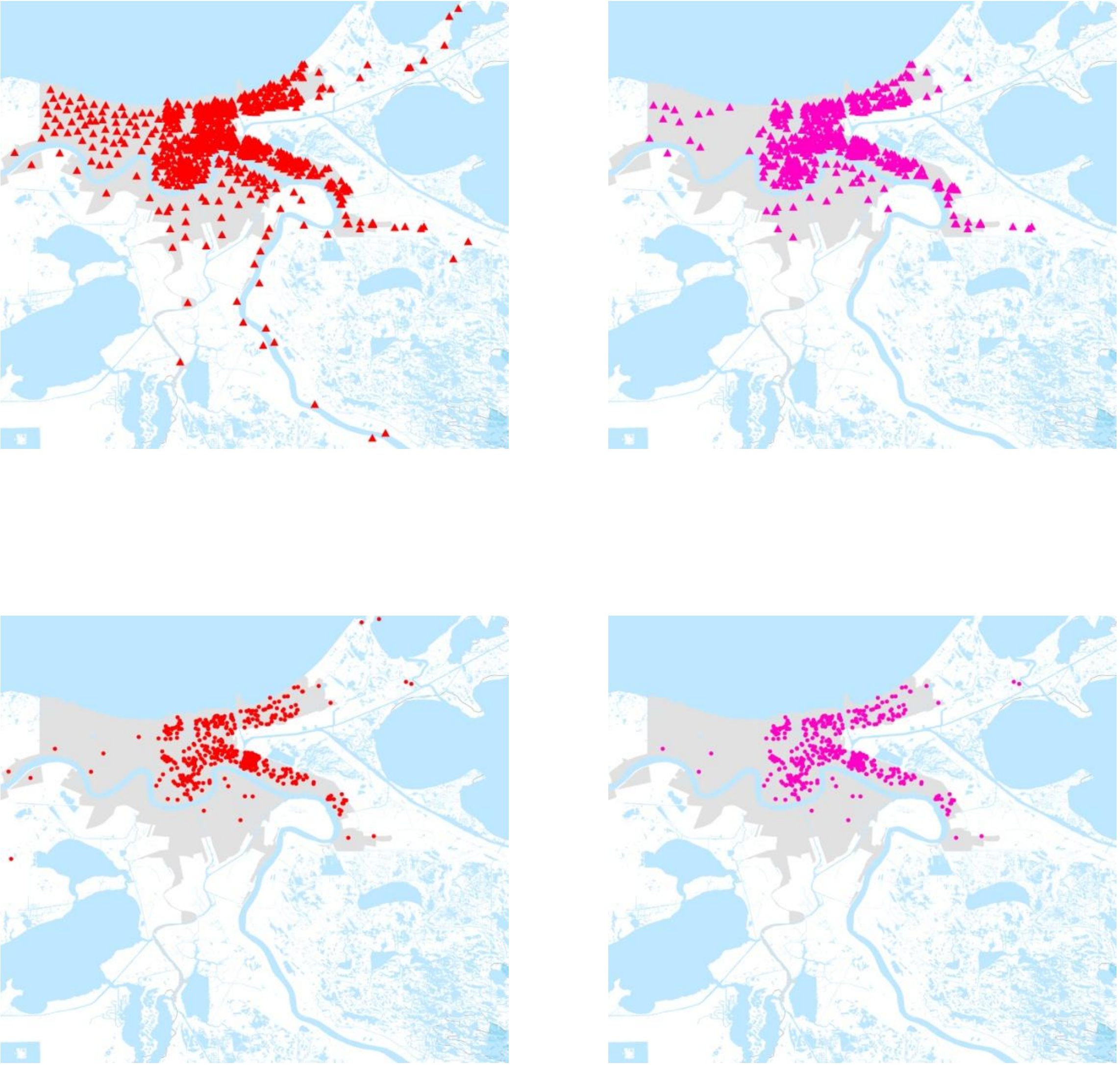


Figure Set B3: Metro New Orleans Extent

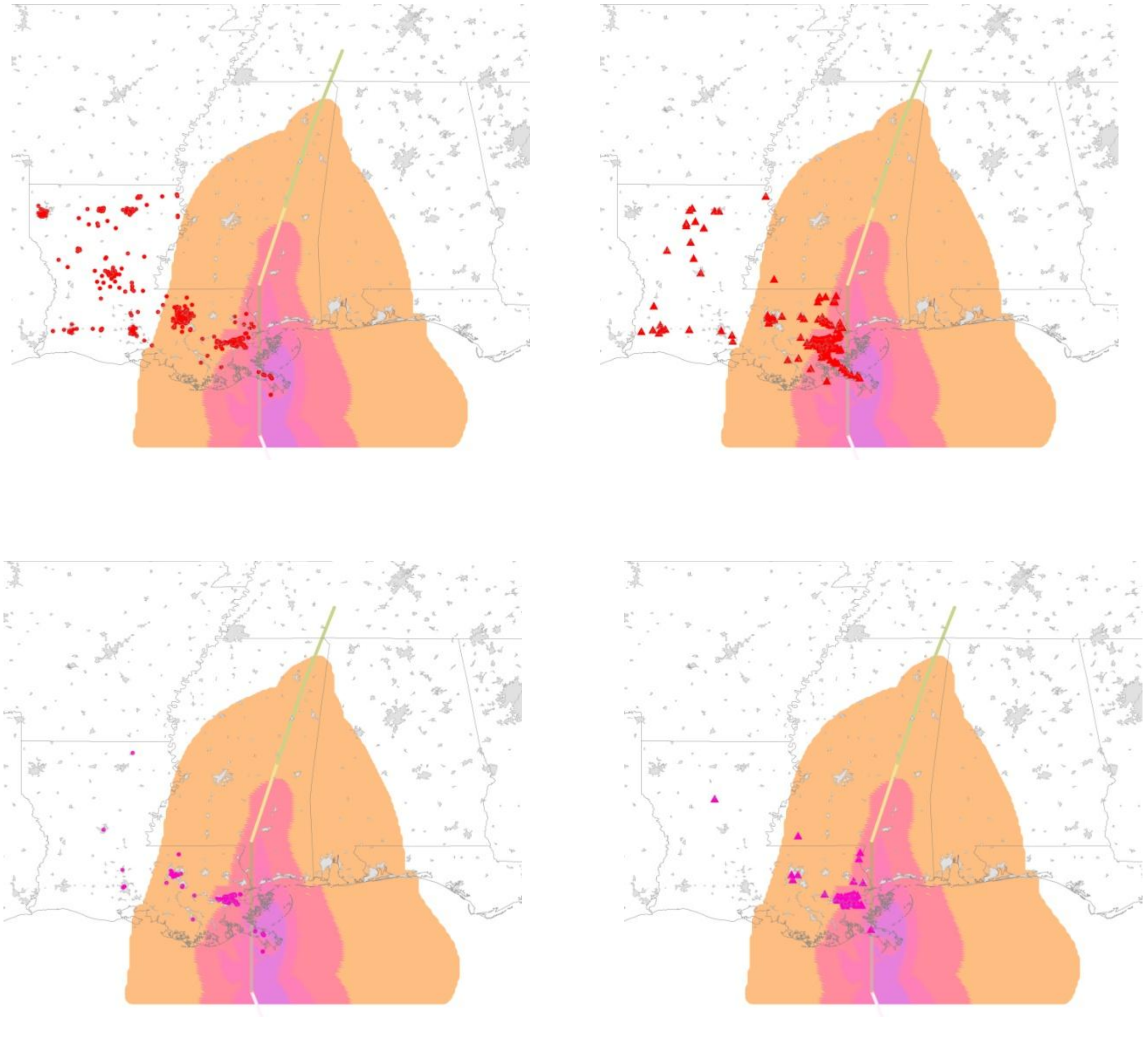


Figure Set B.4: Extent of Wind Grid

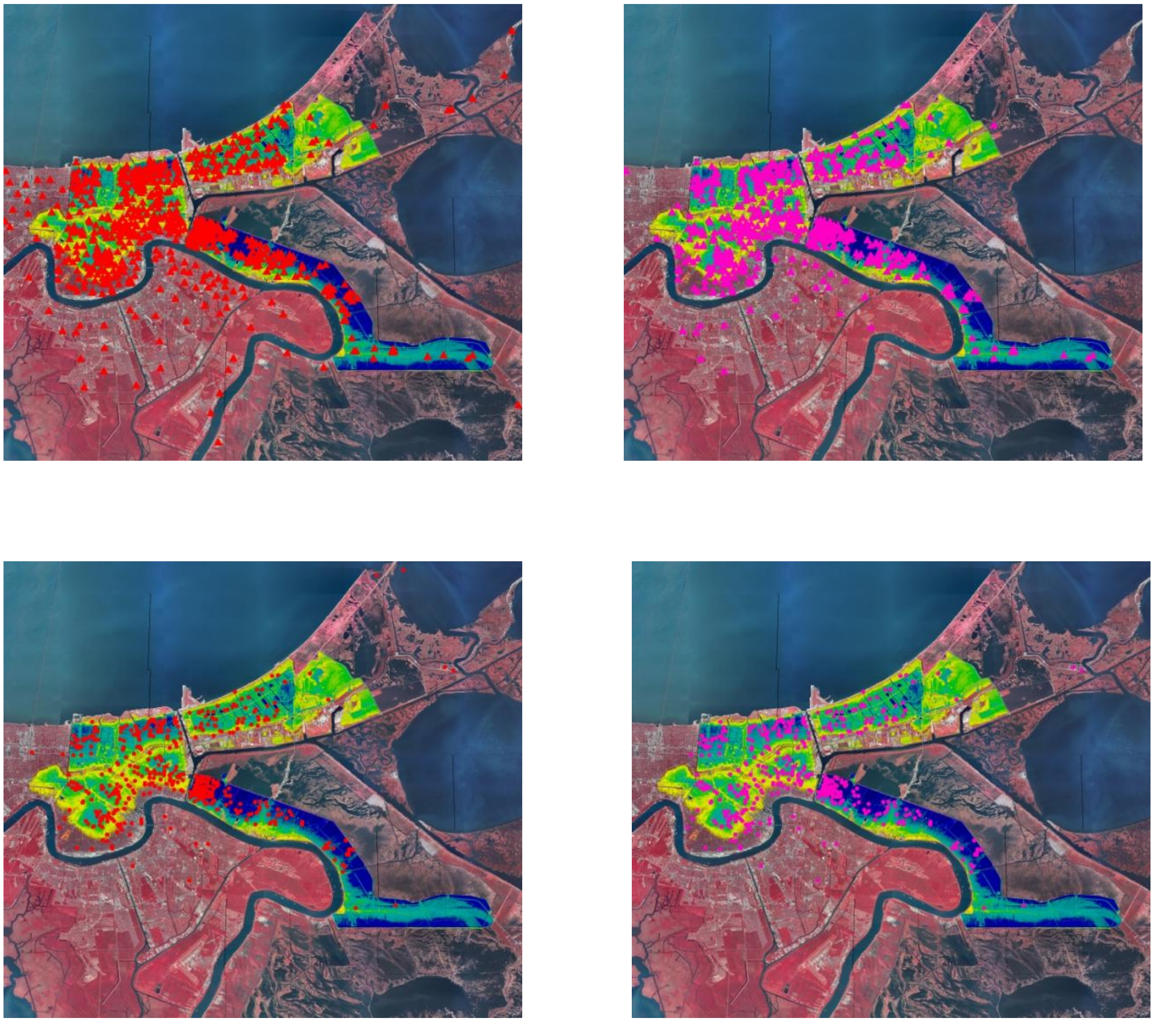


Figure Set B.5: Extent of Flooding

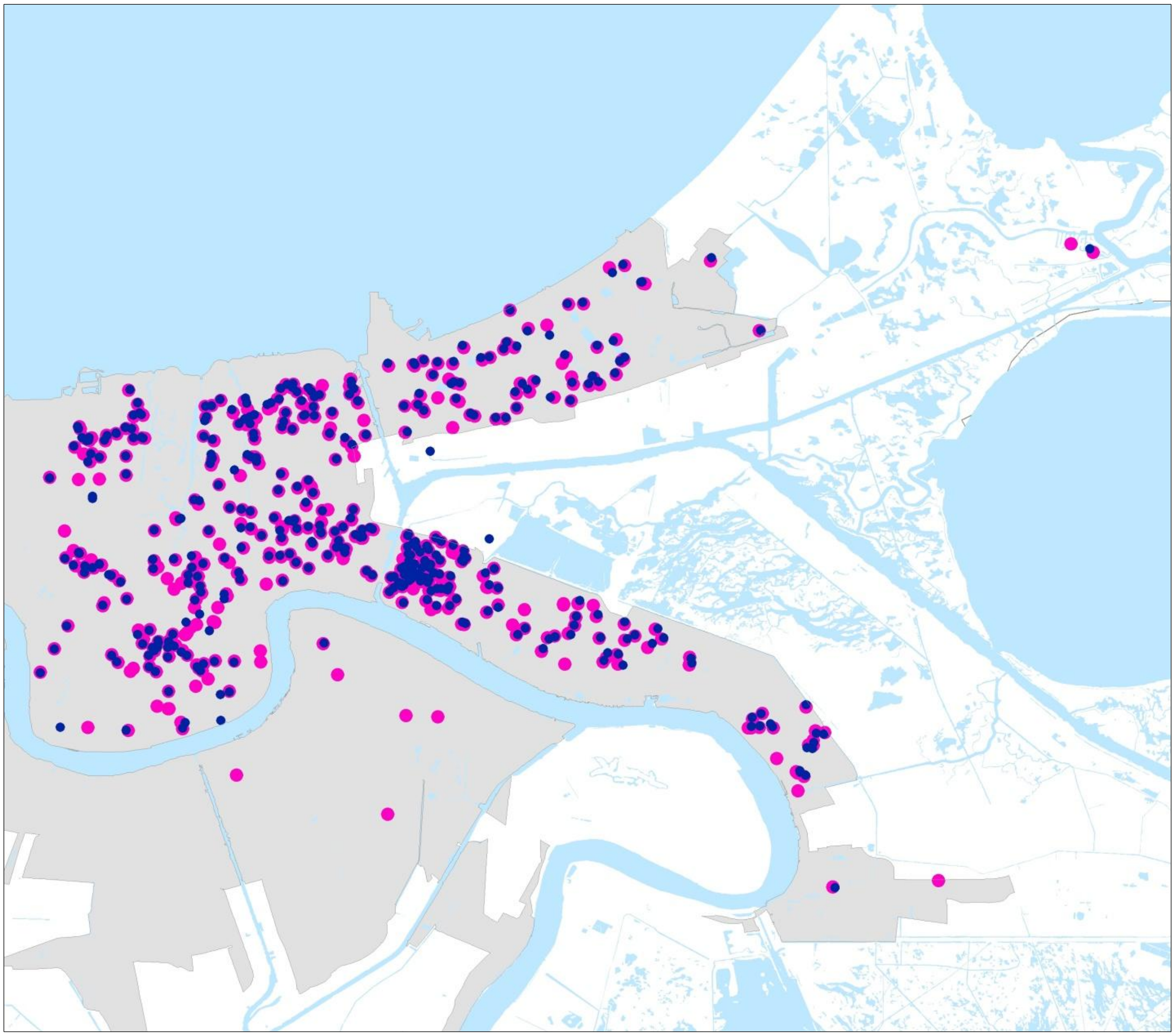


Figure B.6: Comparing the matched recovery locations (purple) and the GPS field locations (blue). The purple dots are large and the smaller blue dots are laid on top of them.

Appendix C: Determining Circumstances of Death

C.1 Introduction

The Louisiana Katrina Victim Database contains 1,573 victims compiled from various sources. This appendix describes the steps used to classify each case according to the circumstances of death as inferred from the available information. In principal, there are three categories: direct flood death, emergency circumstances deaths, and evacuation / displacement deaths. In practice, the uncertainties and ambiguities made it necessary to utilize three more categories: assumed flood death, emergency circumstances / wind, and unclassified. Also, this review indentified one death related to Hurricane Rita, and two persons who died before the storm. What follows is a bare boned description of the filters and steps that were undertaken to complete this task. The first steps involved blanket assignments, such as labeling all out-of-state deaths as evacuation/displacement. Later steps involved a more refined examination of case specific data.

Direct Flood Deaths

- Filtered by WaterDepth to determine all victims recovered from location with Depth > 0.
    => 619

- Filter by Recovery Structure type to remove: Coroner Office, Funeral home, Health care, Hospice, Hospital, Medical, Nursing Home, Superdome, Temp Medical Clinic
    => 471

- Filtered by "Recovery Scene" to remove: Anything that indicate more than 1 story on structure, any type of apt or apt building or multi family, an assisted living complex, a back balcony, interstate on ramp, medical clinic, morgue, parking garage, unknown
    => 442 labeled "Direct Flood Deaths"

- Filtered for Circumstances are blank:
    - Filtered for Facility Name equal St Rita's
    => 34 cases added
    - Filtered for Recovery Scene equal "Out Front of Superdome" (known flood death)
    => 1 case added
    - Filtered for Circumstances Notes listing drowning
    => 2 cases added
    - Filtered for Recovery facility Name equal Lake Pontchartrain
    => 1 case added
    - Filtered for Water Depth > 0
        - Filtered for Recovery Structure Type equal Residence
            - Filtered for Recovery Scene equal 2nd Bed Room
            => 1 case added
            - Filtered for Recovery Scene lists apartment. Reviewed 8 cases.
            => 4 cases added

- Reviewed 18 cases
  - => 9 cases added that indicated flood exposure
- Filtered for Recovery Structure Type equal Medical Clinic, Parking Garage, Interstate Ramp
  - => 1 case because victim recovered from flooding parking lot
- Filtered Recovery that indicates home, public place, in water, field, lot, debris. 24 cases reviewed :
  - => 6 cases added because SOBEK Depth > 0
  - => 6 cases added because Field Inside Depth Above Ceiling & Attic Escape
  - => 7 cases added because recovered from debris/rubble
  - => 1 case added because recovery location in flood zone
- Filtered for SOBEK Depth > 0. Reviewed 5 cases
  - => 3 cases added because no indicate of refuge above flood waters
- Filtered for residence in Orl, StB, Jeff, Plaq. Reviewed Recovery info for 25 cases
  - => 15 cases added. Residence & recovery in Plaquemines
  - => 2 cases added because recovered from flooded nbhd of NO
  - => 4 cases added because NO residence recovered from JP coroner office.
- Filtered for Recovery Parish Orleans or Jefferson. Reviewed 8 cases
  - => 7 cases recovered in Orleans, post-SMEO

- Manual Review of 73 remaining cases
  - => 15 cases added

TOTAL = 561

Assumed Flood

- Filtered Recovery Address equal Unknown
  - => 44 cases labeled

TOTAL = 44

Displacement / Evacuation

- Filtered by Recovery State to exclude all those recovered outside Louisiana. Blanks and Unknowns also filtered out
  - => 343 labeled “Displacement”

- Filtered by Recovery Parish to exclude all parishes outside of SE Louisiana. Excluded parishes are East BR, Jefferson, Lafourche, Livingston, Orleans, Plaquemines, St. Charles, St. John, St. Tammany, St. Bernard, Terrebonne, Unknown
  - => 168 cases added

- Filtered for Circumstances are blank
  - Filter for Recovery Structure Type equal Funeral Home. Noted that all cases recovered

in Terrebonne or EBR. Some comments noted ‘evacuee’
    => 10 cases added
- Filtered for residence in Orl, StB, Jeff, Plaq & recovery not in these parishes
    => 92 cases added
- Filtered for residence in St. Tamm, Tangi, Lafourche, St Charles, Livingston, Washington. Reviewed Recovery Parish for 16 cases
    => 5 cases, mostly recovered in EBR. One St Tammany resident recovery in Livingston.
- Filtered for residence in Orl, StB, Jeff, Plaq. Reviewed Recovery info for 25 cases
    => 1 cases added. Residence in StB, recovered in Jeff. Vipsite comments list “storm evacuee”
    => 1 case added. Residence in Orl, recovered in EBR. Comments note “Evacuated from Memorial Hospital”
- Reviewed other comments
    => 6 cases added based on police shooting or died at collection piont
- Filtered for Morgue, NH, Hospital, Funeral Home
    => 6 cases added because recovered outside of heavily impacted area and/or notes mention “evacuee”
- Filtered for Recovery Parish Orleans or Jefferson. Reviewed 8 cases
    => 1 case added in Jeff, because COD listed as “Natural Causes”
- Filtered for Recovery Parish equal East Baton Rouge. Reviewed 6 cases
    => 1 case added because KenyonDB comments state “Evacuee form NO”

- Manual Review of 73 remaining cases

    => 7 cases added

TOTAL = 641

<u>Emergency Circumstances</u>

- Filtered for Recovery Structure Type equal Airport, Convention Center, Hospital, Hospitaliere, Medical Center, Superdome (excluded flood depth found Out Front of Superdome)
    => 181 labeled as “Emergency Circumstances”

- Filtered for Circumstances are blank
    - Filtered for Circumstances Notes listing Carbon Monoxide, Suicide, Vehicle Accident, Electrocution
    => Added 14 cases
    - Filtered for Recovery Facility Name equal Lafon Nursing Home (based on Washington Post article) + Residence Address equals Lafon NH
    => Added 11 cases + 1
    - Filtered for Water Depth > 0
        - Filtered for Recovery Scene lists apartment. Reviewed 8 cases.
        => 4 case added based on information that indicated refuge above first floor
            - Reviewed 18 cases

=> 7 cases added
- Reviewed 25 cases:
=> 7 cases added from NH with > 1 story
- Filtered for Recovery Structure Type equal Medical Clinic, Parking Garage, Interstate Ramp
=> 1 case because vipssite lists medical emergency
=> 1 case because recovered from interstate on ramp
=> Added 12 cases because 2nd floor of hospital or NH or unflooded NH
- Filtered Recovery that indicates home, public place, in water, field, lot, debris. 24 cases reviewed :
=> 1 case added because comments list suicide and field depth is a few inches
=> 1 case added because comments describe victim recovered from 2nd floor
=> 1 case added because field comments state disease, not flood.
=> 1 case added because no evidence of flooding
=> 1 case because vipssite lists medical emergency
- Filtered for SOBEK Depth > 0. Reviewed 5 cases
=> 2 cases added because victim recovered from 2nd floor
- Filtered for residence in Orl, StB, Jeff, Plaq. Reviewed Recovery info for 25 cases
=> 3 cases added because recovered from 2nd story apts
=> 1 case added because shot by NOPD

- Manual Review of 73 remaining cases
=> 17 cases added

TOTAL = 253

Emergency Circumstances / Wind

- Filtered for Circumstances are blank
- Filtered for residence in St. Tamm, Tangi, Lafourche, St Charles, Livingston, Washington. Reviewed Recovery Parish for 16 cases
=> 11 cases, mostly recovered in residence parish. One Tangipahos resident recovery in Livingston. One Lafourche residence recovered in St. Charles
- Filtered for Recovery Parish equal East Baton Rouge. Reviewed 6 cases
=> 5 cases added because residences in EBR

TOTAL = 16

Pre-Katrina

- Filtered for Recovery Facility and found comment "body in basket"
=> Labeled 1 case

- Manual Review of 73 remaining cases
=> 1 cases added

TOTAL = 2

Rita

- 1 case recovered from LNG Terminal in Calcasieu Parish on 10/4/2005

Unknown

- Filtered for Circumstances are blank
  - Filtered for Recovery Parish equal St. Tammany or St. Charles
    - => 5 added because no other info provided

- Manual Review of 73 remaining cases
  - => 33 cases added

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Figures 2.1b: The standardardized all hazard mortality ratio (Borden and Cutter 2008, Reprinted by permission from BioMed Central under open access license, copyright 2008),

Research

Spatial patterns of natural hazards mortality in the United States

Kevin A Borden and **Susan L Cutter***

* Corresponding author: Susan L Cutter scutter@sc.edu

▸ Author Affiliations

For all author emails, please log on.

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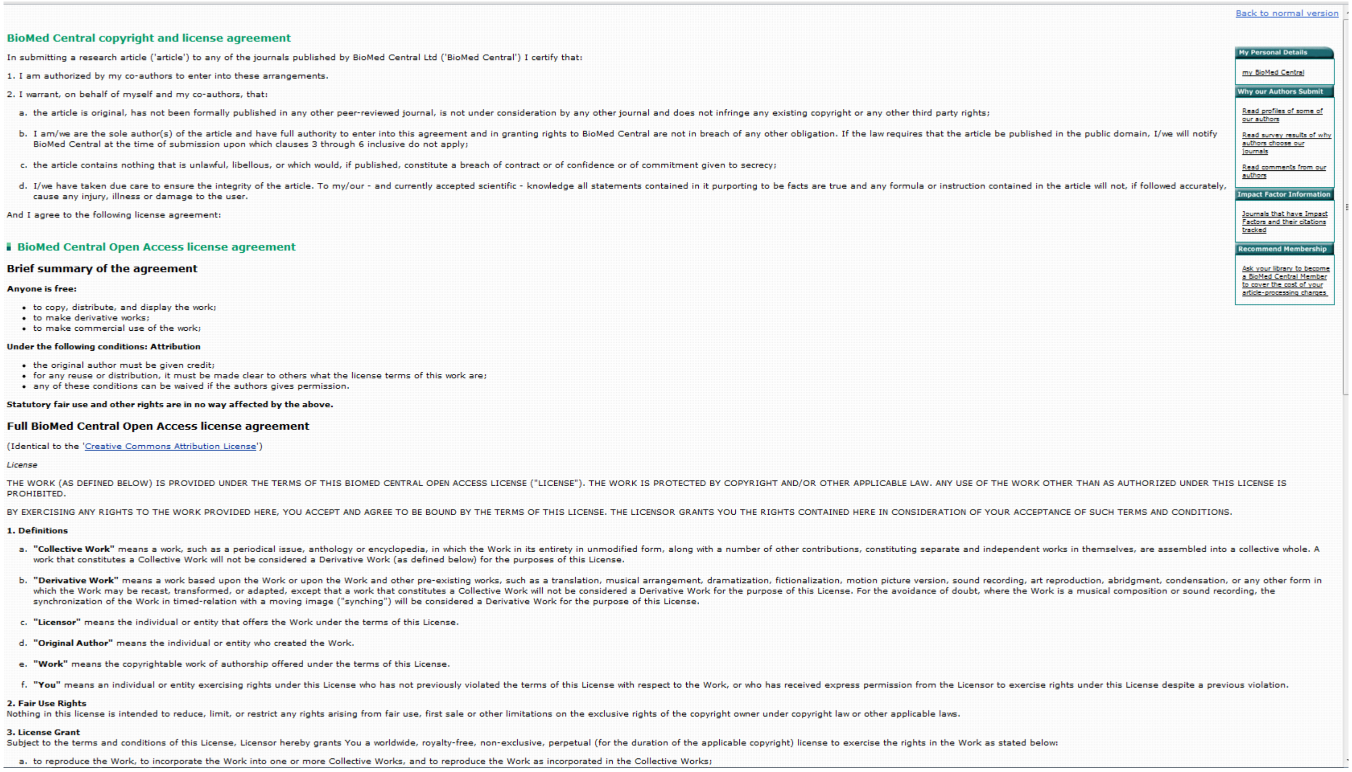
Published: 17 December 2008



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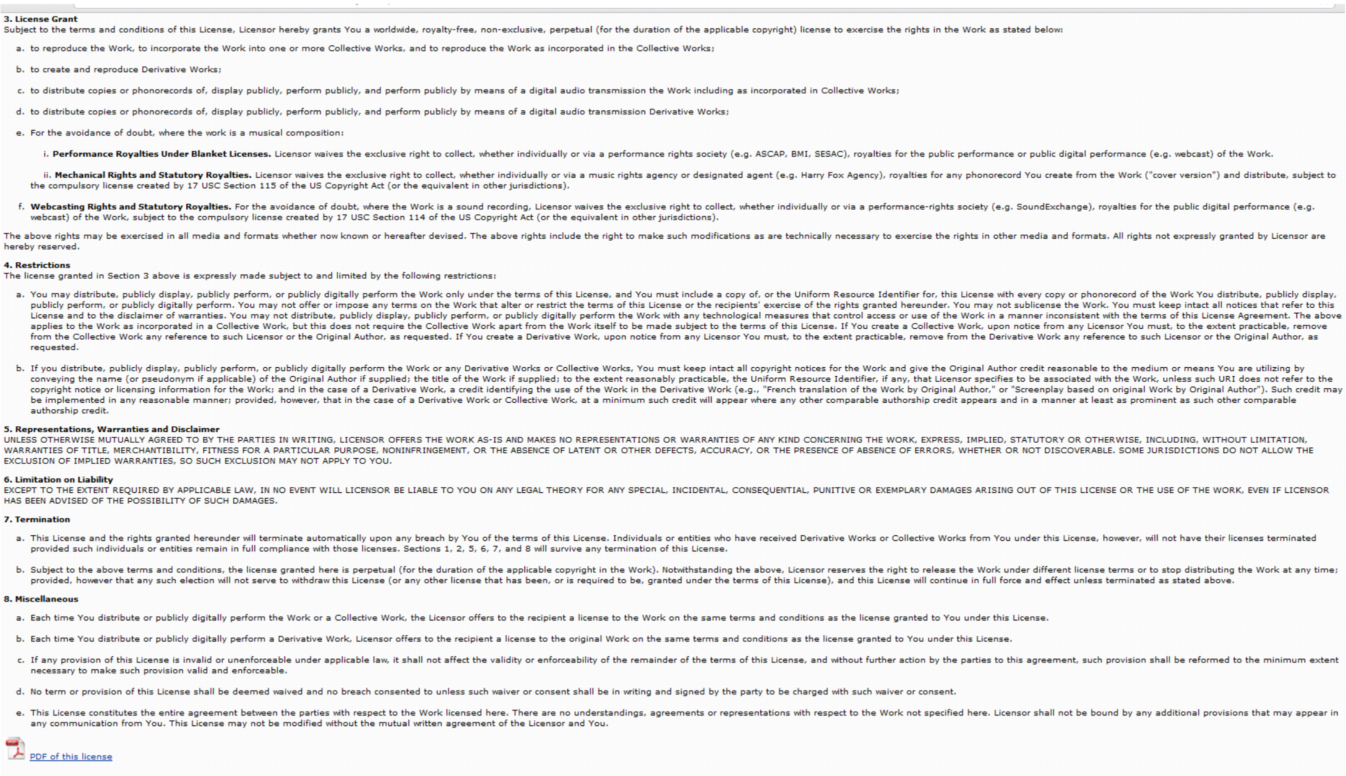

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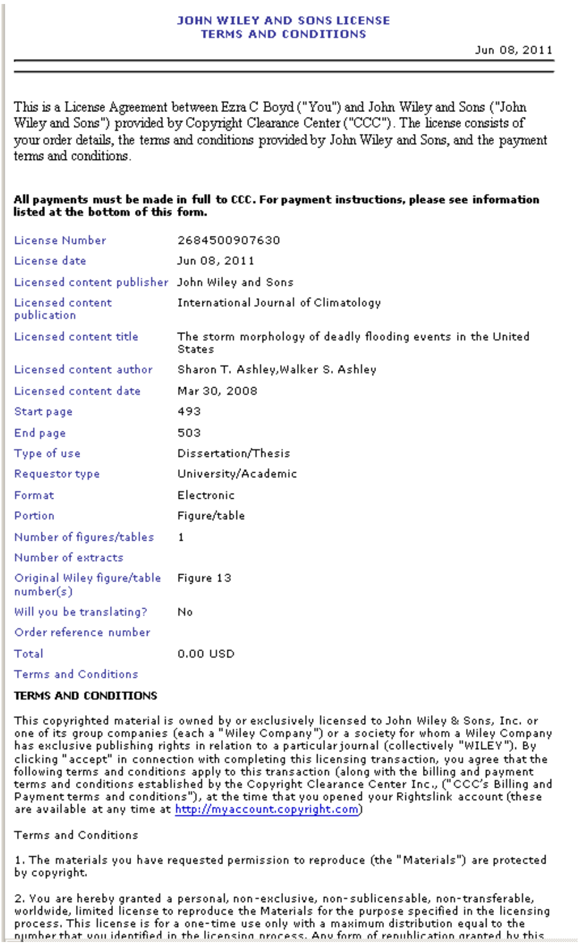

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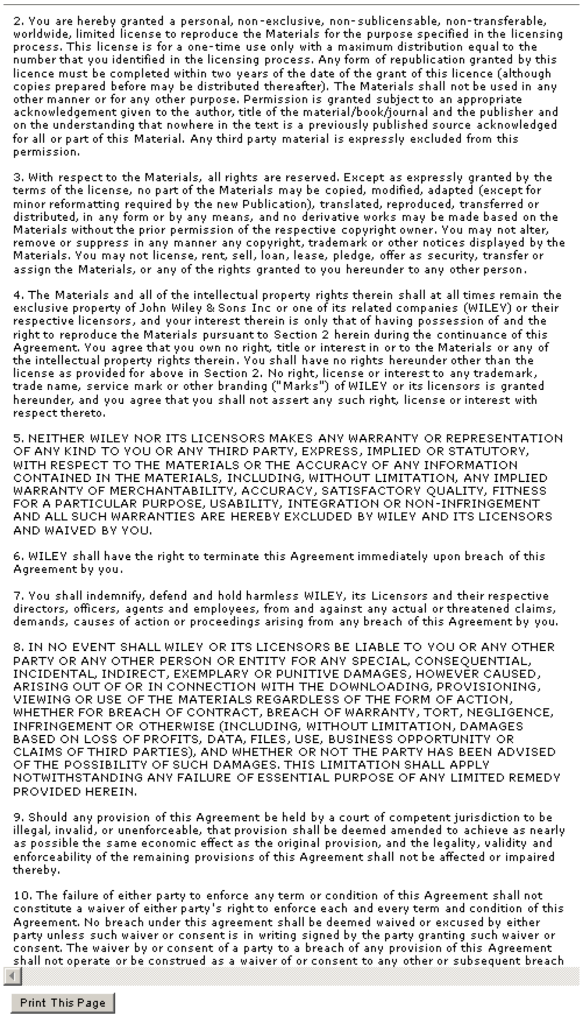

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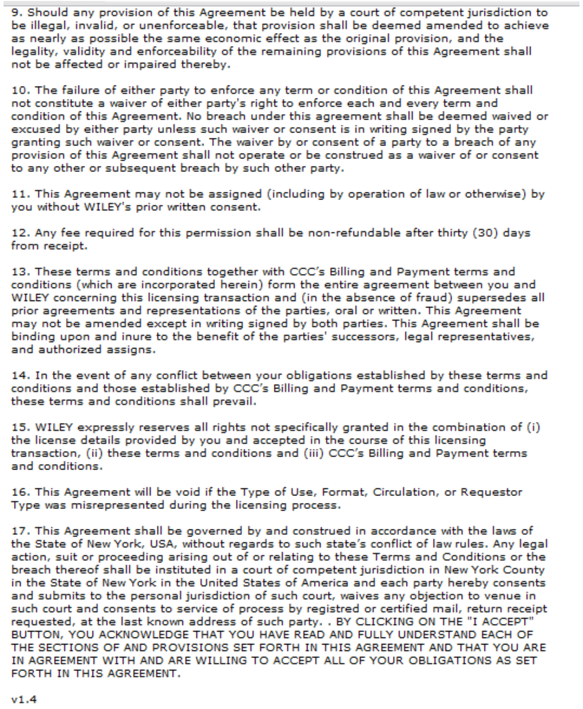

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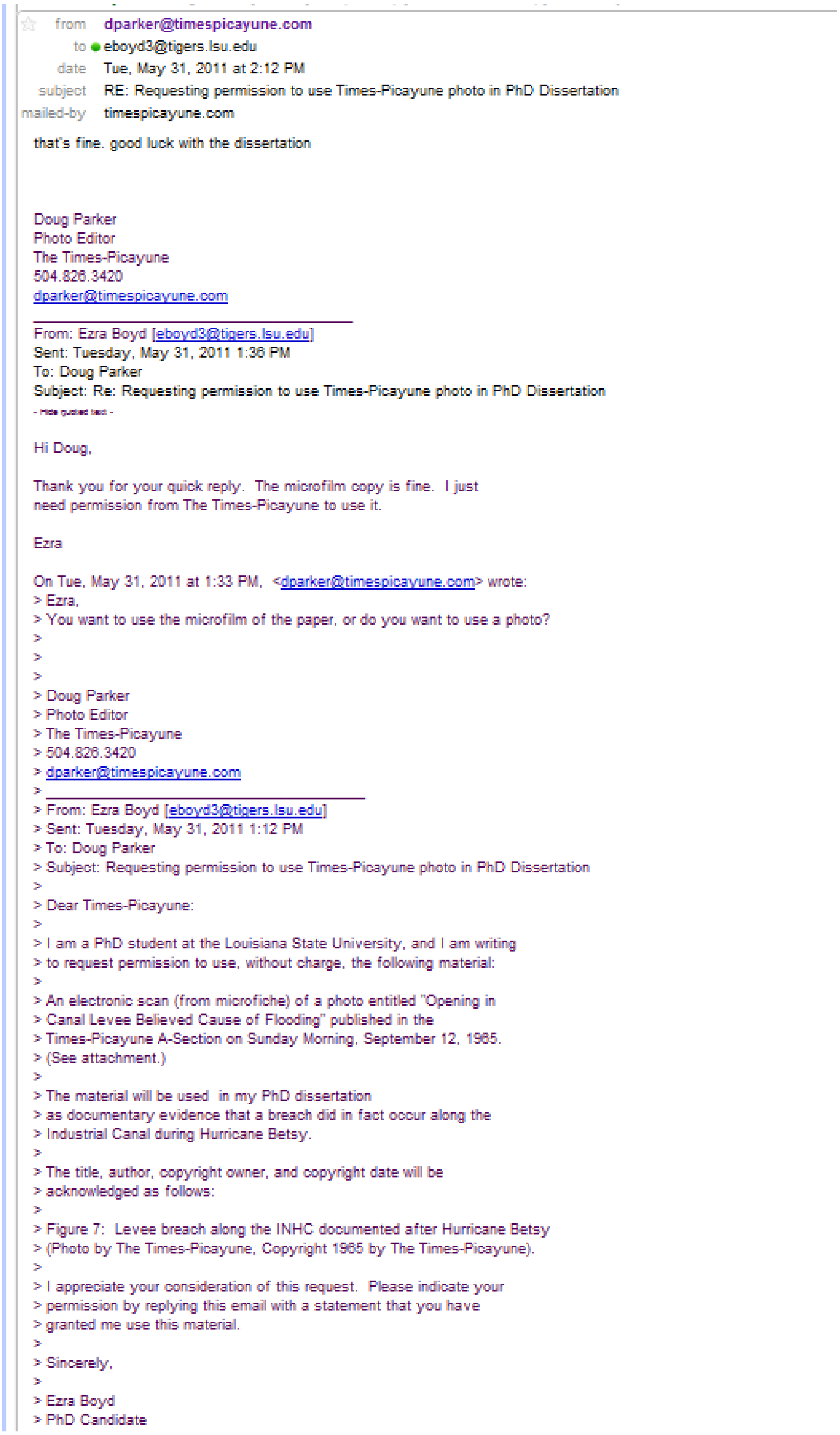
Figure 3.7: Levee breach along the INHC documented after Hurricane Betsy



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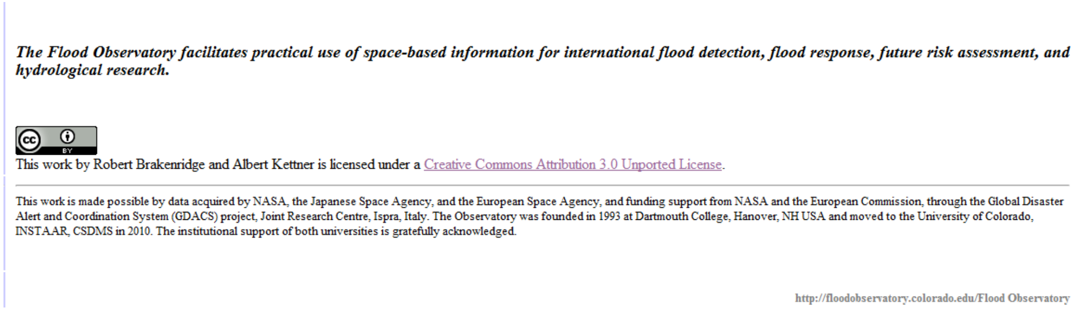

The Flood Observatory facilitates practical use of space-based information for international flood detection, flood response, future risk assessment, and hydrological research.

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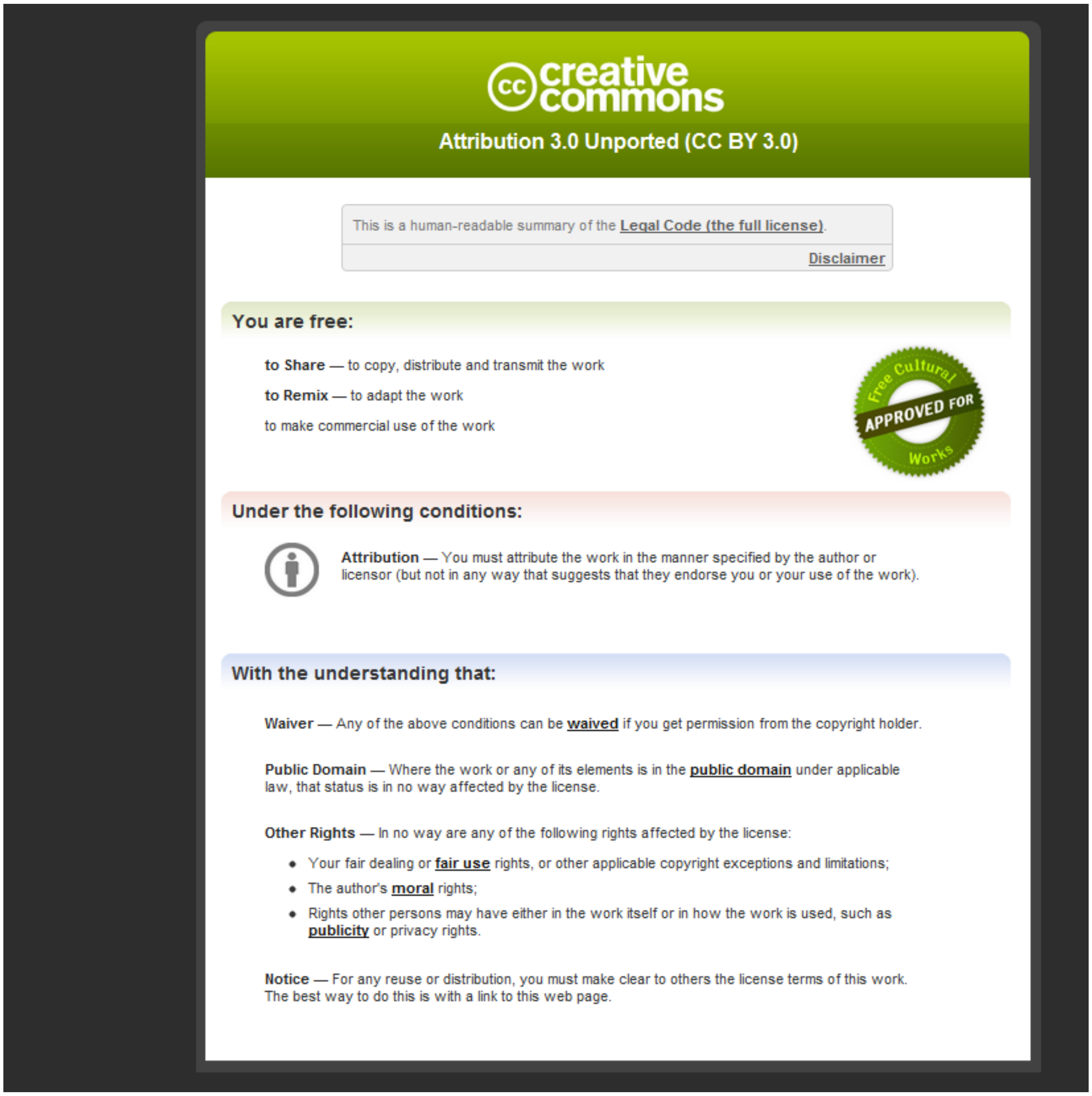
http://floodobservatory.colorado.edu/Flood Observatory



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Chapter 7

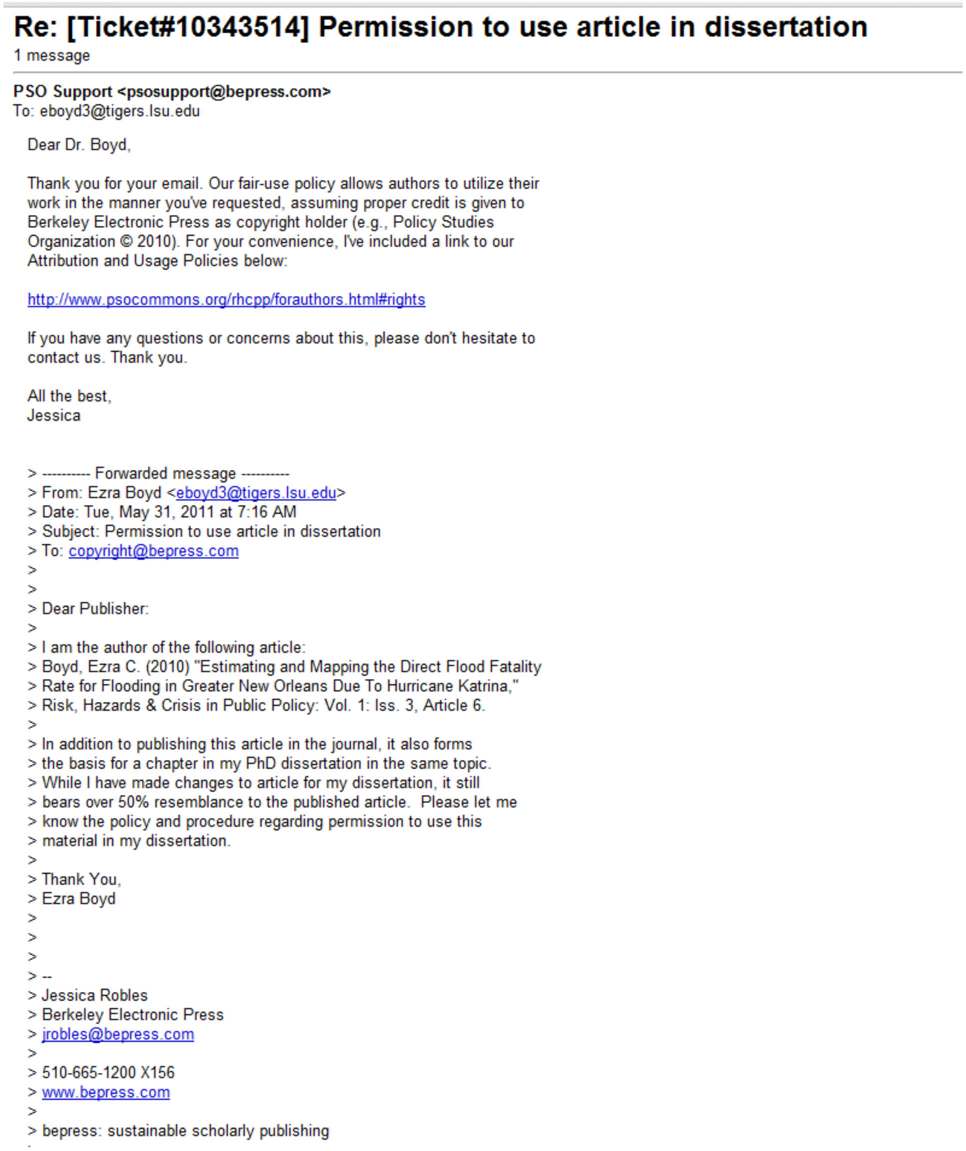

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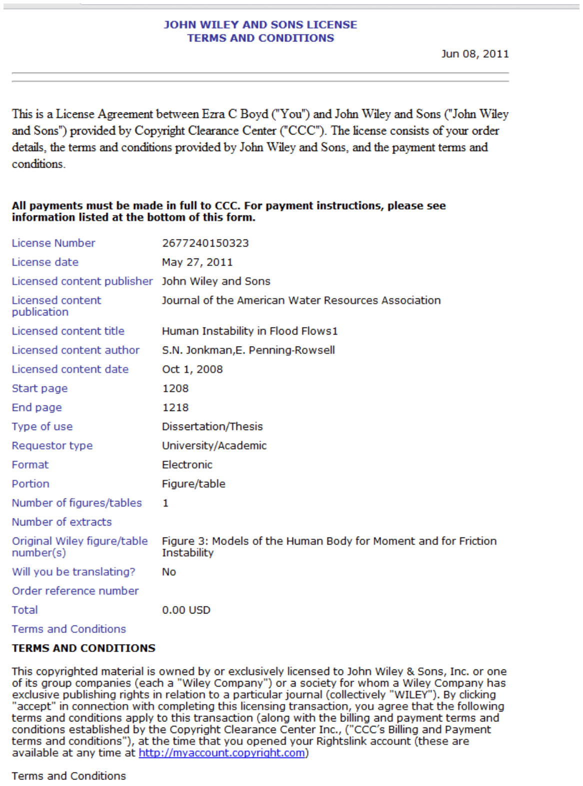
Figure 8.7: Diagrams depicting the moment and friction instabilities for human bodies trapped in flowing floodwaters.



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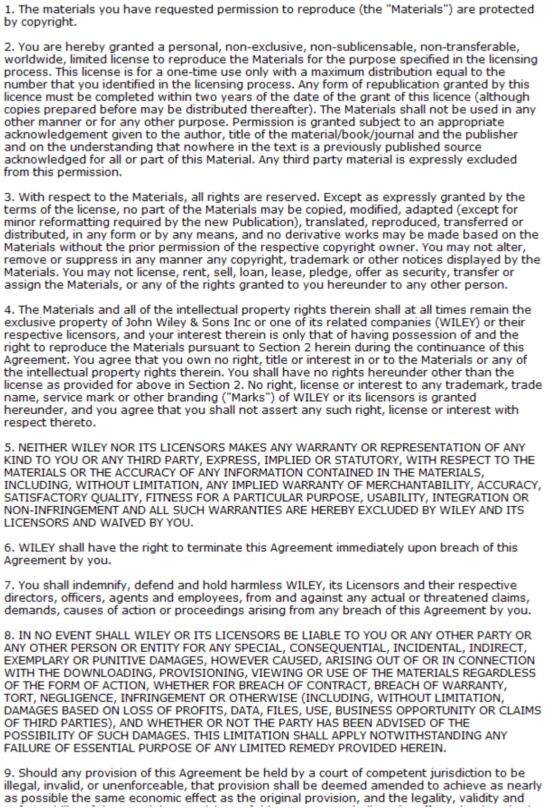

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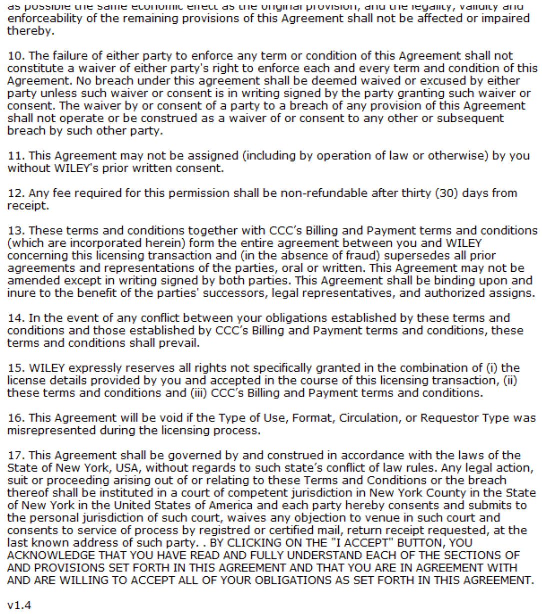

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v1.4

Vita

Ezra Boyd, a native of New Orleans, has been a doctoral student with the Geography and Anthropology Department at Louisiana State University since 2004. While a graduate research assistant with the LSU Hurricane Center, Mr. Boyd worked with Dr. Marc Levitan and Dr. Ivor van Heerden assisting directly with the planning, emergency response, and recovery from the flood catastrophes of 2005. In addition to commissioned reports and conference proceedings, he is lead author of two peer-reviewed journal articles and co-author of another journal article related to the preparation, response, and impacts of Hurricane Katrina and the levee failures in southeast Louisiana. Mr. Boyd earned a Bachelor of Arts degree in physics (with honors) from the University of Chicago and a Master of Arts degree in political science from the University of New Orleans. He currently resides in the Gentilly neighborhood of New Orleans in a house that flooded to the ceiling in 2005. Rebuilding this house largely by himself, he has used many new energy efficient and disaster mitigation technologies. He currently works part time with the Coastal Sustainability Program at the Lake Pontchartrain Basin Foundation as an assistant to the program director and GIS specialist.