THE EFFECT OF HIGH-MAGNITUDE PRECIPITATION EVENTS ON *VIBRIO VULNIFICUS* MORBIDITY CASES IN ESTUARINE ENVIRONMENTS

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THE EFFECT OF HIGH-MAGNITUDE PRECIPITATION EVENTS ON *VIBRIO VULNIFICUS* MORBIDITY CASES IN ESTUARINE ENVIRONMENTS

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ABSTRACT

THE EFFECT OF HIGH-MAGNITUDE PRECIPITATION ON *VIBRIO VULNIFICUS* MORBIDITY CASES IN ESTUARINE ENVIRONMENTS

by

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The geographic origin of infection involving morbidity cases resulting from *Vibrio vulnificus* is difficult to determine. *V. vulnificus* is a halophilic pathogen that exists year-round in the Texas Gulf Coast and requires moderate salinity (5-25 ppt) and water temperatures over 20 degrees Celsius to thrive and reproduce. From 1999-2003, the majority of reported culture-confirmed infections in Texas occurred in Harris, Matagorda, and Galveston counties. These data are recorded by the Texas Department of Health. By analyzing above-normal precipitation (high-magnitude) events in the separate counties and corresponding changes in salinity and temperature in large bay systems, temporal and spatial risk of infection may be inferred.

Precipitation data for the study period from the National Climatic Data Center are compared with NOAA long-term precipitation data for rain gauges in Matagorda and Galveston counties in coastal Texas. Water quality data for the period of study are collected and catalogued by the Texas Parks and Wildlife Department.

Using a Kendall's Tau-b correlation analysis, statistical relationships between water temperature (C°), salinity (0/00), and above normal precipitation events may be determined. The relationship between the occurrence of *Vibrio vulnificus* morbidity cases and above normal precipitation events is tested using a Phi test to determine correlation. The results of this study indicate that salinity levels in both bay systems are correlated with above normal precipitation events at the .05 alpha level, but water temperature is not directly correlated with these events in either system. *Vibrio vulnificus* morbidity cases reported in either bay system does not appear to be related to above normal precipitation events.

CHAPTER 1

INTRODUCTION

The relationship between disease and weather in the field of geography is classified under natural-hazards research. Recorded changes in climate and corresponding variations in weather and the hydrologic cycle allow geographers to create hypotheses about shifting weather systems, droughts, and environmental changes in a system. These changes can then be attributed to shifting levels of naturally occurring bacteria and vectors, which may explain changes in the distribution of disease or morbidity. Climatic changes to an environment can be analyzed to discern new ways for local inhabitants of an ecosystem to adapt and create new measures to ameliorate potentially damaging affects brought about by climate change.

Regional study of weather variability associated with permanent changes in temperature allows researchers to construct models of climate variability extremes in order to provide detail for climate extremes in an ecosystem (Liverman et al. 2003). Recorded variations in normal precipitation levels in sensitive environments and the resulting changes made to an ecosystem have been noted by biogeographers and ecologists as a disturbance mechanism that may change the nature of an ecosystem too rapidly (Liverman et al. 2011). The balance within a system would be upset and natural mechanisms such as fire disturbance would be interrupted, thus disrupting the natural equilibrium.

The human-environment relationship is also disrupted by climate change in the fields of agriculture, urban planning and development, and health. Transformations made to an ecosystem as a result of climate change, particularly in the area of human health have been analyzed statistically at the regional and global scales. With a growing global population and an increase in global warming since the beginning of the industrial era, some interest has been given to the distribution of morbidity cases in urban areas where populations are most dense.

Kalkstein and Davis examined the statistical relationship between morbidity cases and the movement of warm, moist air masses in forty cities across the United States (1989). Research linking morbidity with climate change such as that performed by Kalkstein has often led to the conclusion that an increase in temperature will increase health risks and exacerbate existing health hazards (Liverman et al. 2011). Vector-borne diseases are of especial concern in coastal areas where an increase in high-magnitude precipitation can change the distribution of certain vectors.

Dr. John Snow performed one of the earliest recorded studies on the geography of morbidity during the London cholera outbreak in the mid-19th century. By tracing a large number of confirmed cholera cases to one high-traffic well, Dr. Snow was able to confirm the origin of the majority of cases by identifying which wells were contaminated (Johnson 2006). Cholera is transmitted through water containing *Vibrio cholerae*, a waterborne bacterium that thrives in contaminated water systems. *Vibrio vulnificus* is a pathogen that naturally occurs in estuarine systems. This halophilic pathogen is environmentally sensitive and thrives in locations with moderate salinity and high water temperatures (Kelly 1982). The majority of culture-confirmed morbidity cases in the contiguous United States are reported from the Gulf Coast States each year (CDC 2012). The states with the highest number of cases reported in 2008 are Louisiana, Florida, and Texas (National Enteric Disease Surveillance 2009). The Texas Gulf Coast is of particular interest because of the predicted rise in permanent coastal county populations over the next 40 years (TWDB 2010).

Consistently warm year-round temperatures and an increase in large-scale hydrologic activity, such as high-magnitude precipitation events in the Texas Gulf Coast make the region ideal for *Vibrio vulnificus* growth and reproduction. Environmental requirements for the pathogen itself in the Texas Gulf Coast region have been studied at length (Ramirez et al. 2009), but regional study of reported morbidity cases is limited. Elevated precipitation associated with large-scale storm events often result in coastal flooding on the Texas Gulf Coast. These events decrease salinity levels in estuarine systems and may increase the geographic distribution of *Vibrio vulnificus.* Increased hydrologic events may also be responsible for spikes in reported morbidity cases in this region.

Objectives

The objectives of the proposed research are to answer the following questions:

1) What effects do high-magnitude precipitation events associated with climate variability have on water temperature and salinity levels in estuarine systems in the Matagorda and Galveston Bay region from 1999-2003?
2) How do high-magnitude precipitation events affect the temporal distribution and occurrence of *Vibrio vulnificus* induced morbidity cases in the Matagorda and Galveston Bay region from 1999-2003?

Significance

This research is an examination of the relationship between environmental changes incurred by high-magnitude precipitation events on Texas Gulf Coast estuarine systems and the occurrence of reported *Vibrio vulnificus* morbidity cases. The basic significance of this study is to determine how, if at all, high-magnitude precipitation events affects the occurrence of reported *Vibrio vulnificus* morbidity cases in the Texas Gulf Coast. Analyzing the number of reported cases from 1999 to 2003 and recorded spikes in precipitation and temperature may determine if there is a link between the same parameters thought to be responsible for the presence of the pathogen and the actual reported cases themselves.

Because the majority of morbidity cases in the Texas Gulf Coast region occur in summer tourist destinations, this study will also attempt to determine if the number of cases in this region are seasonally linked to large-scale hydrologic events. Harris, Galveston, and Matagorda County, Texas, are three of the coastal counties with the highest number of culture confirmed morbidity cases between 1999 and 2003 (DOH 2010). The Matagorda Bay system and Galveston Bay system are both productive aquaculture and shellfish harvesting centers in the Gulf Coast. Such coastal industry provides an increased chance for injury and infection if environmental conditions are sufficient for bacterial growth.

CHAPTER 2

THEORETICAL FRAMEWORK

The Geography of Morbidity and Disease

The geography of morbidity and disease has long been a topic of interest because bacteria are a dynamic subject and continuously evolving. In 1854, Dr. John Snow identified a geographic pattern between contaminated well systems in London and reported cases of cholera (Johnson 2006). The geographic clustering of cases is attributed to poor infrastructure in the new industrial metropolis resulting from a large population living in close quarters in a city with amenities that were not evolved and ill-equipped to handle such a large volume of human waste.

By tracking an increase in the number of new cases of cholera emerging from one popular pump, Snow to accurately identified the geographic source of the cholera bacteria responsible for the increase in morbidity cases. *Vibrio cholerae* (cholera) is of the same genus as another water-borne pathogen, *Vibrio vulnificus*. Although each pathogen is dependent on different environmental factors, both are dependent on certain favorable environmental conditions in order to reproduce and thrive. It is possible that morbidity cases from resulting infections can be geographically tracked and traced by analyzing changes in climate and water quality data in a region over space and time.

The definition of health or medical geography has since been re-examined many times to include sociological analysis of patient behavior patterns (Brown and Duncan 2002), or what shapes an individual's vulnerability to health and their susceptibility to disease or an epidemic (Craddock 2000). To further explore the social implications relating health and morbidity, Smith and Easterlow argue that poor health often results from material, social, and cultural inequalities (2005). This is another exploration of human health and migration habits determined by socio-economic status, education and place. Such studies provide valuable insight into the human side of medical geography and morbidity cases.

Extensive research has also been conducted on the biological nature of hazardous bacteria and how such organisms react (or are predicted to react) to changes in climate. An increase or decrease in the amount of precipitation in a region where bacteria naturally occurs may alter the seasonality for that bacterium. Depending on the pathogenicity of the bacterium or whether or not a particular location experiences a high volume of traffic, morbidity case numbers could shift with seasonal change or expansion of populations. This is particularly true for pathogens dependent on warmer temperatures to thrive. A large number of air, water, and vector borne pathogens are dependent on a certain climate to reproduce or find a host. Global temperatures have increased 1° C since 1950, and nighttime and winter temperatures have increased about 2° C in that same time period (Epstein 2002).

With this increase, local climate destabilization and an increase in large-scale storm events such as hurricanes and flash floods may temporally and geographically expand the breeding area for hazardous bacteria, or increase their seasonality. Epstein states that, “the effects of the extreme weather [associated with climate change] that may accompany it may be even more profound [on human health]” (2002:373). However, research focused on climate change or variability resulting in an increase in hazardous bacteria and associated morbidity cases is still being developed.

Environmental changes to coastal systems because of climate variability bring to light not only immediate changes to regional ecological systems, but also possible natural hazards in the form of pathogenic bacteria. Oceanic warming increases heavy precipitation and fewer small hydrologic events that may result in decreased salinity in humid-subtropical and tropical coastal locations. This provides not only a more hospitable environment for *Vibrio vulnificus*, but perhaps other halophilic pathogens for which little adequate geographical information exists. Some assessment may also be made to determine future locations in estuarine systems that are more suitable to the growth of the bacteria because of depth or potential change in seasonality.

Vibrio vulnificus

Vibrio vulnificus is a potentially hazardous halophilic bacterium was first reported in 1970 (Wickbodt and Sanders 1983), and officially recognized by the CDC as “lactose-positive vibrio” in 1976 (Oliver et al. 1982) (Fig. 1).

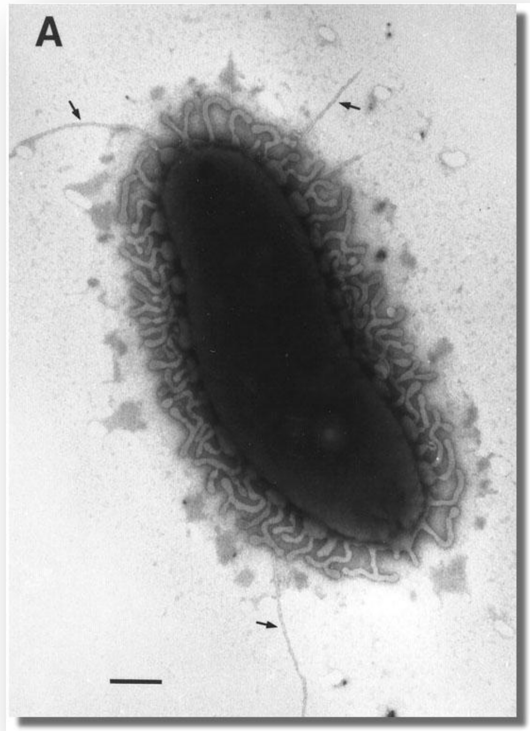

Figure 1: *Vibrio vulnificus* bacteria (Strom and Paranjpye 2001)

Bacteria associated with the *Vibrio* genus are gram-negative, meaning it does not retain crystal violet dye in the staining protocol, independently mobile and halophilic (salt-water thriving) (Vora et al. 2005). The specific bacterium, *V. vulnificus*, can bring about waterborne infection through open wounds, which contribute to the 9 million annual diagnosed cases in the United States (Rose et al. 2001).

Most members of the *Vibrio* genus are nonpathogenic and pose very little threat to humans. Certain strains, like *V. vulnificus*, do have the ability to cause serious harm to humans if ingested or exposed to an open wound (Rose et al. 2001). *V. vulnificus* is associated with two specific clinical syndromes, “primary septicemia and wound infection accompanied by secondary sepsis” (Georgiev 1998: 463). Several different biotypes of *Vibrio vulnificus* exist. The specific biotype associated with human infection is biotype 3, which contains the gene for cytotoxin, making it critical for pathogenicity (Colodner et al. 2002).

Infections resulting from ingestion or contact with *Vibrio vulnificus* differ from those caused by other strains of the genus such as *Vibrio parahaemolyticus* and *Vibrio cholera*, which can cause severe fluid depletion through diarrhea and repeated vomiting. The documented forms of infection resulting from *Vibrio vulnificus* are rapidly progressing infection and fulminating septicemia (Fig. 2) resulting from blood infection, rapidly progressing cellulitis associated with a contaminated wound (Blake et al. 1980), and acute diarrheal symptoms, which are usually a product of raw oyster consumption or handling contaminated seafood (Parker and Parker 2002).

Figure 2: Skin legions resulting from *Vibrio vulnificus* infections (Hsueh et al. 2004)

Any external contact between the bacteria and an open wound in humans can result in aggravated lesions, which progress to cellulitis and myositis (Parker and Parker 2002). *Vibrio vulnificus* is unique in that the major forms of infection produce relatively few diarrheal symptoms compared to other members of the *Vibrio* genus (Blake et al., 1980). West (1989: 13) characterized *Vibrio vulnificus* infection as being:

> "…rapidly onset (often less than 24 h) of fulminating septicemia followed by the appearance of cutaneous lesions. [*Vibrio vulnificus*] has a high mortality rate (more than 50% of persons with primary septicemia die)…"

This number may be skewed depending on the medical history of infected individuals. Among patients with impaired immune systems (specifically chronic hepatic hepatitis, cirrhosis, and impaired iron-storage systems) the elderly, or the very young, these symptoms could lead to amputation or death (Georgiev 1998). Males with underlying defects in liver function, blood disorders, or another form of immunodeficiency are especially at risk although why not apparent (Tacket et al. 1984) is. In persons with hypotension, the mortality rate associated with infection resulting septicemia may reach 100% (Georgiev 1998).

Primary sepsis without a visible wound is usually a result of ingestion of contaminated seafood, or infection of a new or preexisting wound (Parker and Parker 2002). Those who have ingested shellfish containing the bacteria may experience nausea, vomiting, chills and in some cases, septic shock. These symptoms can be worse and even prove fatal if the bacteria have infected an individual with an impaired immune system (Parker and Parker 2002). Many highly toxic strains produce a potent enterotoxin that can cause severe sepsis and aggravated infection (Georgiev 1998). Biological evidence also suggests that *Vibrio vulnificus* produces "extracellular products having…collagenolytic, and elastic activities" (Georgiev 1998 464), that may account for bacteria being able to rapidly attack body tissue (Smith and Merkel 1981).

Outward infections are often exacerbated by severe sepsis and necrotizing of surrounding skin and tissue (Tacket et al. 1984). If exposed to free-floating bacteria through open-wounds, individuals may experience skin disintegration at the site of penetration and ulcerations. Left untreated, body and muscle tissue will continue to breakdown, causing the infected area to rot and become septic (Tacket et al. 1984).

Inland fisheries with relatively shallow pools in warm locations may also provide new habitat for the bacteria in warm locations. A case study in a report by Colodner et al. (2002) in Israel featured a man with a hand infection sustained from bacteria on Tilapia bred in an artificial pond. After handling the fish, the individual had washed his hands and then sustained a puncture wound to his finger 24 hours later. This delay in infection after handling material containing *Vibrio vulnificus* may contribute to a lower rate of diagnoses and case reporting. Inability to establish a geographic origin of the infection may also make accurate diagnosis difficult if the patient does not report immediate symptoms.

In many cases, because the disease can begin as a small infection and be treated quickly with antibiotics, it is believed that the majority of *V. vulnificus* cases go unreported each year (Parker and Parker 2002). This makes quantification and tracking of the bacteria difficult and biased because most cases reported are severe, involving infants, the elderly and those pre-disposed to infection (Rose et al. 2001). Analysis of preferred location and environment of *V. vulnificus* will provide a better idea of where the bacteria thrive, and predict possible locations for high concentrations of bacteria (Rose et al. 2001). In warm, shallow estuarine waters of the Gulf Coast, *Vibrio vulnificus* can live and thrive year-round. However, during the hot summer months, the bacteria breed more efficiently and are more prevalent (Ramirez 2009).

Although the majority of reported cases of infection from *V. vulnificus* come from coastal states, reports exist of infection from contaminated foods shipped inland (Longstreth 1999). Salinity levels and temperature are currently accepted as variables that determine suitable locations for *V. vulnificus* growth and reproduction. Thus, *V. vulnificus* thrives in warm, brackish estuarine waters (Rose et al. 2001) in shallow sections of the coast. Shallow water warming at a faster pace explains why this bacteria thrives closer inland. Effluence may increase the amount of algal growth that can provide a mass of marine material on which *Vibrio* species may grow and multiply (Kelly 1982). Because marine organisms such as oysters, capable of harboring large amounts of *Vibrio vulnificus,* are affected by nutrient levels in estuarine systems, there is reason for future analysis of fluctuations in nitrogen and phosphorus levels in runoff and the relationship between concentrations of the bacteria (Ratner 1987). The bacteria can live independently if temperature and salinity are at sufficiently high levels in an environment, but often colonize shellfish or algae (Ratner 1987).

The Implications for the Geographic Distribution of Vibrio vulnificus Morbidity

The ecological distribution of *Vibrio vulnificus* has been studied in brackish water systems and estuarine environments globally. Oliver et al. determined that *Vibrio vulnificus* colonies present on the southeastern coast of the United States are part of the naturally occurring flora in most brackish water ecosystems (1982). Oysters and other filter-feeding bivalves will often filter water containing *V. vulnificus*, trapping colonies of bacteria and providing a sheltered area for reproduction (Fig. 3).

Figure 3: Oyster colony on a piling in Matagorda Bay, Texas

Although the primary determinants of whether or not *Vibrio vulnificus* thrives in a location are moderate salinity and high temperature, the study performed by Oliver et al. reveals “the number of vibrios in the water column to be positively correlated with turbidity ($P < 0.05$) and total bacterial ($P <0.05$) and fecal coliform” (1982:1406).

These findings suggest that more study is needed to determine how much effluence and turbidity determine the quantity of bacteria in a location. Such a possible connection is noteworthy for future geographic analysis of morbidity cases, particularly considering that according to the NOAA State of the Gulf report in 2010, 58% of the population of the United States has a permanent coastal residence (U.S. Census Bureau 2010). Of the 23 states containing coastal counties, 11 of them, including all of the Gulf Coastal states, have experienced an increase in population from 1960-2008 (U.S. Census Bureau 2011). The American Association of Port Authorities reported 13.3 million Americans employed in 360 commercial ports in 2007 (AAPA 2008). As a result, the national economic impact for this industry alone totaled $212 billion in 2007 and reported customs collections amounting to $20 billion in the 2009 fiscal year (AAPA 2008).

The Center for Disease Control (CDC) Gulf Coast Surveillance System has collected epidemiological data from reported cases of *Vibrio vulnificus* in Texas, Florida, Alabama and Louisiana since 1988 (Shapiro et al. 1998) (CDC 2000). Shapiro et al. conducted a study across those states to assess water temperature and salinity in oyster beds, thereby determining the association between reported infections and water temperature (1998). Such cases are reported to occur in brackish water coastal areas and secondary beaches (Vithanage and Fujioka 2008) where inland river systems and standing water meet the ocean.

Recent studies have shown that the bacteria are able to thrive in temperatures below 10°C in certain locations, such as South Texas, in a “viable but non-culturable state” (Ramirez et al. 2009:2051). Climate variability and change have affected the presence of this organism through longer warm seasons with higher temperatures and an increased number of large storm events. Longer periods of warm weather increase water temperatures in estuaries along the Gulf Coast, making the environment conducive to bacterial growth for greater amounts of time (Rose et al. 2001).

During the El Niño period in Florida, viruses were detected in 75% of locations sampled because of the increase in rainfall (Rose et al. 2001). Oyster harvests in warm months produce high numbers of *V. vulnificus* in any given yield (Osaka et al. 2004). Some research suggests that phytoplankton associated with algal blooms may provide substrate systems on which hazardous bacteria can cluster and breed easily (Hsieh 2007). This finding may provide one explanation of why secondary beaches in tropical and sub-tropical locations are considered to be at higher risk for contamination than primary ones.

The expanding shipping and manufacturing industry and an aging demographic headed to coastal counties means an overall increase in a permanent year-round coastal community. In 2010, the U.S. Census Bureau reported that 4 out of the 5 fastest growing states contained coastal counties (Census 2011). Texas has been reported to have the highest level of population growth (2.10 percent increase in a fifteen month period) since the last census in 2010 (Census 2010). The largest population increases in this state have been along the I-35 corridor linking San Antonio, Austin, and Dallas, and in Harris County where the metropolitan hub Houston is located. Of the ten most populous cities in 2010, Houston was found to be the fastest growing, a 26.1% population increase over a ten-year period (U.S. Census 2011). The 2011 Regional Water Plan produced by the Texas Water Development Board (TWDB) reported the rise in the permanent population of Harris County from 2000-2010 to be over 700,000 (Table 1). In Texas, the U.S. Census Bureau estimated the Houston Metropolitan Area to be the third largest in the state, reporting a permanent population of 5.4 million people.

Table 1: 2011 Regional Water Plan Population Projections for 2000-2060 (TWDB 2010)

2011 REGIONAL WATER PLAN POPULATION PROJECTIONS FOR 2000 - 2060			
YEAR	GALVESTON	HARRIS	MATAGORDA
2000	**250158**	**3367029**	**37957**
2010	**268714**	**4078231**	**40506**
2020	**284731**	**4629335**	**43295**
2030	**294218**	**5180439**	**44991**
2040	**298057**	**5731543**	**45925**
2050	**300915**	**6282647**	**45925**
2060	**302774**	**6833751**	**45925**
Diff.	**52616**	**3466722**	**7968**
% Rise	**17%**	**51%**	**17%**

Each year, the Enteric Diseases Epidemiology Branch of the Center for Disease Control National Surveillance Team publishes a summary of all confirmed cases of *Vibrio vulnificus* nationwide (CDC 2012). Within that reporting system, the Gulf Coast *Vibrio* surveillance system compiles a list of all reported *Vibrio* cases in the five U.S.

states along the Gulf of Mexico. These data are geographically generalized and are made public at the state and regional levels, but the specific geographic information about particular species of *Vibrio* is not released to the public. Nevertheless, when reported to the department of health, some morbidity cases resulting from specific species, such as *Vibrio vulnificus,* can be identified at a finer geographic scale. This means that some reported cases can be traced back to the most likely point (water body or bay system) from where the infection originated.

Texas routinely has the third highest number of reported cases of *Vibrio vulnificus* (National Enteric Disease Surveillance 2009), and so to prevent the sale of contaminated shellfish and an increase in infections, the Gulf Coast Oyster Industry Council (GCOIC) routinely inspects shellfish harvesting operations. According to a 2000 survey conducted by the GCOIC, Texas has no immediate plans to distribute statewide promotional materials warning against the hazard of infection of *Vibrio vulnificus* from ingestion of oysters (Garreis 2000). Oyster beds may provide a system with which *Vibrio vulnificus* breeding "hot spots" can be identified, but several species of marine flora and fauna, including phytoplankton (Hsieh 2007), can provide a substrate system for *V. vulnificus* to congregate and breed. Temperature and salinity have been identified as the key variables that determine where *Vibrio vulnificus* will thrive and so identifying locations with suitable conditions and the most reported geographically accurate morbidity cases may help identify a seasonal pattern of morbidity case distribution (Fig. 4).

Figure 4: Oyster shell barrier island in Matagorda Bay, Texas

Between 1999 and 2003, the state of Texas reported a total of 36 cases of morbidity from 1999-2003 because of *Vibrio vulnificus* that could be geographically traced to water bodies in Harris County (Texas DOH 2010). Although *Vibrio vulnificus* morbidity cases are considered underreported, those that can be diagnosed and linked to a specific water body may identify specific regions at the local level that present potential hot spots for *Vibrio vulnificus* growth.

Climate Variability and Change

Climate change refers to an actual shift in the mean state of climate (Patz et al. 2000). Based on historical data, global surface temperature of the continental United States has increased approximately 0.55˚C in the last 100 years (Patz et al. 2000). Precipitation during incidences of heavy rain has increased more than 5 cm per day during storm events, and occurrence of light rain has decreased (Patz et al. 2000). These observed changes in precipitation as a result of warming of the planet illustrate the dependency of the hydrologic cycle on climate, which is an example of the climate change theory (Patz et al. 2000).

The potential immediate effects of climate change are heat waves, sudden and sporadic precipitation, changes in diurnal temperatures, and seasonal fluctuations in precipitation and temperature. Runoff into water bodies through macropore flow, overland flow, and flood immersion transports nutrient and bacterial particulates downstream and into estuarine ecosystems. Drier summers combined with heavy storm events will result in greater runoff during intense rainfall (Boxall et al. 2009).

Such change in climate can be the catalyst for variations in the ecological processes of an environment and affect the presence and growth of bacteria like *Vibrio* (Chan et al. 1999). The climate of the Gulf Coastal Plain of Texas ranges from humid-subtropical or subtropical near the Texas-Louisiana border, with an annual rainfall of 140 cm, to arid and semiarid near the Rio Grande River with an average annual rainfall of 50 cm (Coffman et al. 2010).

The El Niño winter in 1997-1998 saw elevated levels of *V. vulnificus* in Gulf Coast waters because of higher than normal levels of precipitation and the exacerbating effects of fecal bacteria deposits from runoff (Patz et al. 2000). Increased occurrence of *V. vulnificus* in the United States has been largely attributed to climate variability and climate change (Patz et al. 2000). Climate variability is defined as "short- to medium-term fluctuations around some mean climate state on time scales ranging from less than annual to 30-years plus" (Patz et al. 2000:368). This includes high-magnitude precipitation events that are uncommonly heavy and seasonal. Indicators of coastal climate change are usually linked with multiple stressors, both natural and anthropogenic (Niemi et al. 2004). A corresponding increase in morbidity cases resulting from *Vibrio vulnificus* in coastal states during the warm, summer months has been noted.

Assessments of climate variability on the presence of *V. vulnificus* can be used to roughly predict when and where the bacteria will be most abundant. El Niño and La Niña phenomena are examples of climate variability. Hurricane events can sometimes incur enough change in water temperature and salinity to make a coastal environment ideal for *V. vulnificus* growth and reproduction. A recent study of events following hurricane Katrina in the Gulf coast reported the two most common post-hurricane *Vibrio* illnesses to be *V. vulnificus* and *V. parahaemolyticus* (Bourque et al. 2006). There are 95 reported and confirmed cases nationwide and 35 deaths each year. After Katrina in 2005, 18 cases of *Vibrio vulnificus* were reported during the hurricane season in the Gulf Coast. Each documented case was connected to flood waters contaminated by fecal coliform (Bourque et al. 2006).

It has been suggested that water temperature is the most important factor governing the incidence of *Vibrio vulnificus*, which may explain why estuarine environments with water temperatures exceeding 20°C in summer months in the coastal United States harbor more pathogenic *Vibrio* (Rose et al. 2001). Although the bacteria is able to survive in conditions that are not as favorable, warmer waters and salinity between 5 and 25 ppt have proven to be most conducive to bacterial growth (Kelly 1982).

How high-magnitude precipitation events associated with climate variability will directly affect the rate of infection of *V. vulnificus* in humans is difficult to predict. Temperature is a primary factor dictating the seasonality and geography of the pathogen, which humans work to control. However, *V. vulnificus* can remain virulent outside of its marine habitat for a prolonged period, thus increasing chance of infection despite short-term changes to the environment (Colodner et al. 2002).

Analysis of current changes in seasonal weather patterns will help predict regional weather variability and provide answers to resulting health problems such as increased risk of infection from waterborne diseases (Patz et al. 2000). Even though methods for predicting climate change over time continue to improve, predicting any regional-scale impact accurately is difficult given that conditions vary throughout the country (Patz et al. 2000).

What can be inferred is that a higher number of large storm events in coastal areas could decrease ocean salinity (Klein and Nicholls 1999), thereby making an environment more hospitable to *Vibrio vulnificus* growth and reproduction. This means that cases of *Vibrio vulnificus* morbidity may increase throughout the year in certain coastal industries, such as fishing, aquaculture, and shipping. Variability in weather and length of seasons will affect disease probability for members of a location differently depending upon region and topography (Chan et al. 1999).

Coastal Classification

In order to properly analyze locations of interest, coastal zones are classified according to their geomorphology and geology to determine precisely which coastal areas are conducive to *Vibrio vulnificus* growth and reproduction. Many revisions have been made to Shepard's methodology for coastline classification, which take into account both anthropogenic and physical stressors.

Of particular interest is the primary classification of coastline, which include shallow and dendritic estuaries, as defined by Shepard in 1937. This identification provides a geomorphological framework for this study. Primary coastlines, as defined by Shepard (1937), have not been developed by wave motion, but rather as a result of non-marine agencies, such as erosion and land use change (Finkl 2004). Coastal classification has since been expanded to include more detail such as the *climate province* and the *geotectonic province* (Fairbridge 1992). Finkl incorporates geomorphology and climate theories presented in later studies to define coastal classification as a detailed process while taking the following criteria into consideration:

> "…the shape or form (morphology) of the land surface (above and below sea level), the movement of sea level relative to the land and vice versa (e.g. change in relative sea level, RSL), modifying effects of marine processes, climatic influences on

process and form, and age and durability of coastal materials"
(Finkl 2004).

Under this revised coastal classification, the Texas coast situated on the Texas-Louisiana shelf is classified under Polygenetic (complex) Forms as an Alluvial Landscape, which is further defined as a "submerged landscape feature" (Finkl 2004). The USGS also uses a coastal classification system that uses morphology and human modifications of the coast as a basis for hazard assessment (Morton and Peterson 2005). The USGS classification uses human relationship variables such as density and structural development to determine the combined physical factors that determine erosion.

The Gulf Coast region of the United States is at risk for an increase in *Vibrio*-related illness because of increased temperature and a projected increase in large storm events. The brackish water and subtropical temperatures off of the coast are currently conducive to the growth and multiplication of bacteria year-round. The increase of large-scale hydro-climatic variables such as rainstorms, flooding, and droughts may not only increase the presence of the bacteria in the immediate location, but also expand the environment where the pathogen can thrive (Rose et al. 2001). Natural stressors on coastal climates include water-level fluctuations (floods and droughts), wind events, insect infestation, forest fires, and natural sediment deposition (Niemi et al. 2004). Increased magnitude and frequency of hydrologic events, such as tropical storms and hurricanes, have altered trends in dinoflagellate and chlorophyte abundance in coastal areas, thus affecting nutrient cycling and fishery habitats (Niemi et al. 2004). The coastal geomorphology of the study areas may contribute significantly to the quality of water in the estuary (e.g. turbidity, nutrient levels, temperature, and depth). The presence of *Vibrio vulnificus* in coastal areas such as the East coast region of Texas and the Gulf of Mexico may generate significant risk to both the local and seasonal populations.

Noteworthy anthropogenic environmental forcings, e.g. urbanization and diverted water resources; natural land cover, and geologic features in the study area contribute to the building of sediment transport areas due to overwash fans, dune height (elevation) and continuity, beach width, and presence or absence of emergent sandbars (Morton and Peterson 2005). Overwash fans occur when “storm waters exceed the elevation of the adjacent land and ocean water flows onshore” (Morton and Peterson 2005). These events are extremely likely during large storms when higher than normal amounts of precipitation cause flooding in low-lying coastal areas and marshlands. Large areas of impervious surface in low-elevation coastal areas like those in Houston may also experience increased and prolonged flooding during large-scale hydrologic events associated with climate variability. In low-elevation areas where water may pool in high-traffic areas, stagnant brackish water can heat up over time. Average elevation on the Gulf Coast of Texas is less than 15 meters above sea level (TPWD 2010) (Fig. 5).

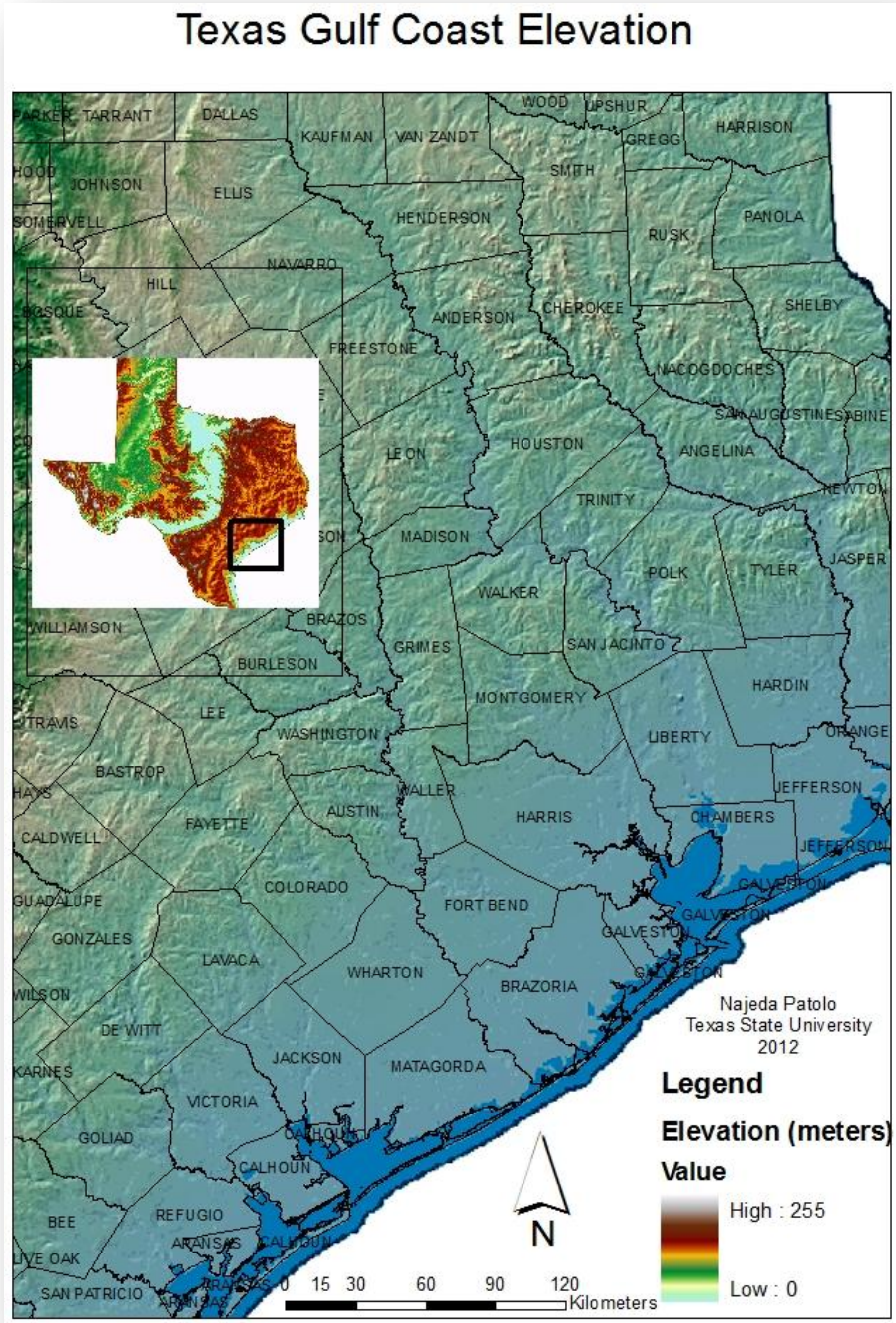

Figure 5: Texas Gulf Coast Elevation (TPWD 2010).

The resulting decrease in salinity combined with inland flooding in low-elevation coastal urban locations provides an ideal location for the temporary and immediate geographical expansion of halophilic bacteria. This is particularly true for coastal urban centers like Houston that have high year-round population numbers. Using elevation above sea-level and flood patterns associated with Hurricane Ike in 2008 to model potential flood inundation for coastal areas with barrier islands, the USGS and NOAA can identify potential coastal areas that are most susceptible to damage in Galveston Bay (Fig 6) and Matagorda Bay area, Texas (Fig. 7).

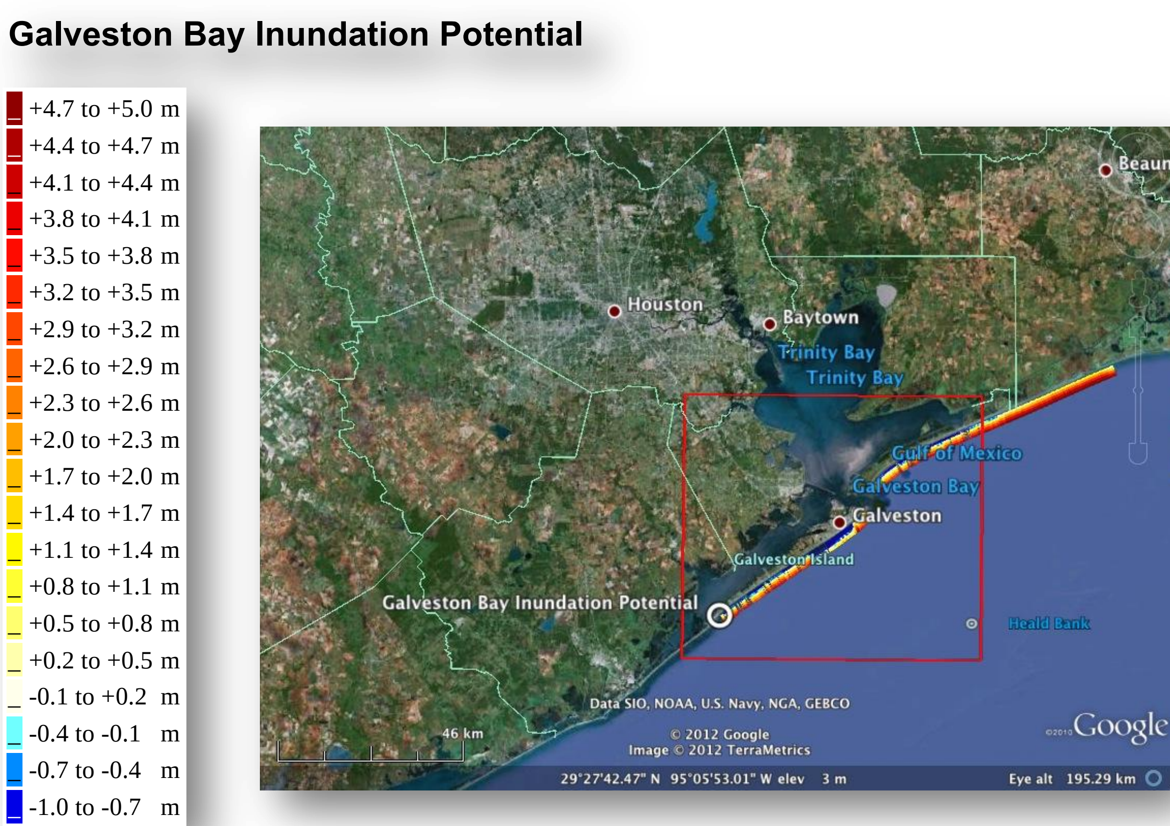

Figure 6: Galveston Bay Inundation Potential (USGS 2008)

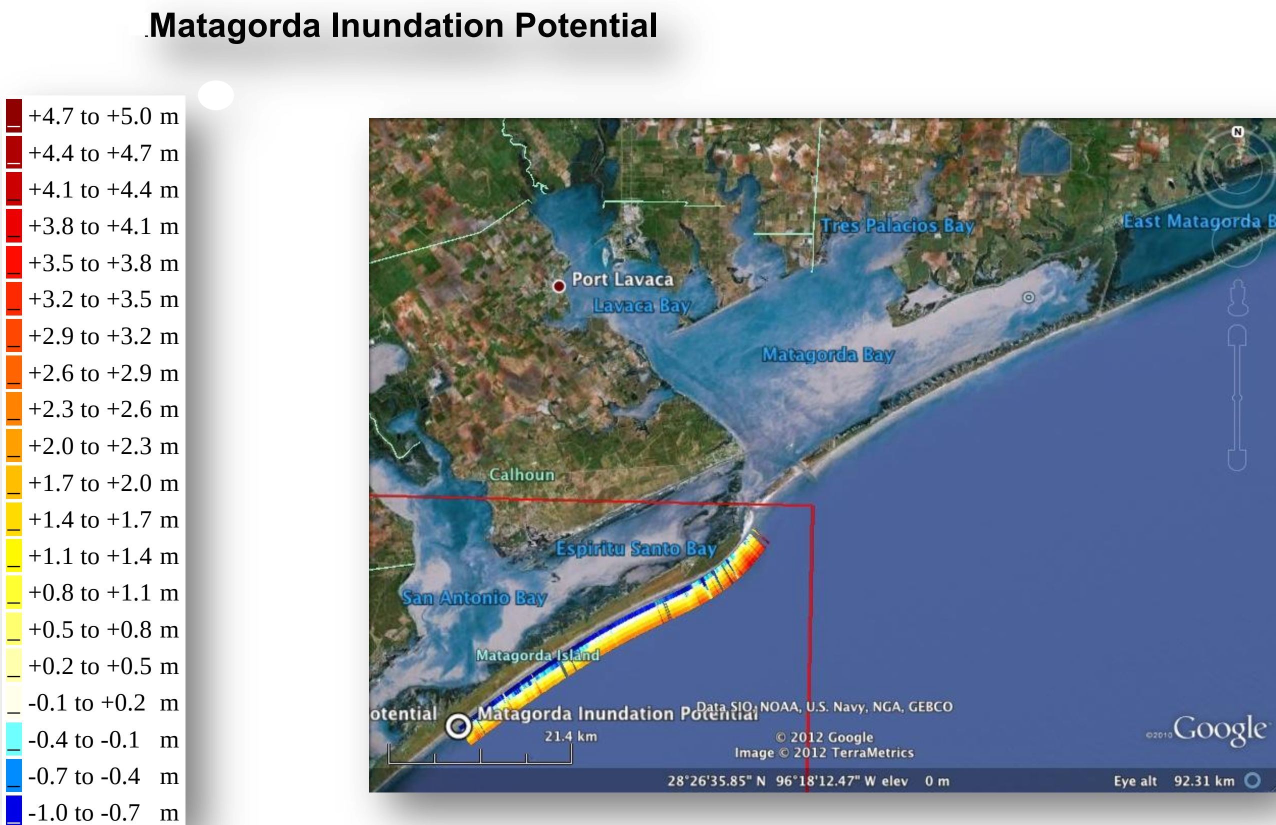

Figure 7: Matagorda Bay Inundation Potential (USGS 2008)

Freshwater runoff produced by on-shore agriculture and aquaculture may also affect salinity and temperature in an estuarine system. Anthropogenic disturbances of coastal areas can include land cover conversion of native plant life into residential, industrial, or agricultural areas (Niemi et al. 2004). These events result in fragmentation of a landscape, increased runoff and nutrient dispersion, increased water temperature, and chemical inputs. Although this possibility will be acknowledged, it is not the primary reason for this study, and will thus not be fully explored. Confirming that an increase of nutrient-rich runoff, specifically from human waste and Concentrated Animal Feeding

Operations (CAFOs), in estuarine systems surrounded by development in tropical and subtropical locations, is directly linked to an increase in *Vibrio vulnificus* morbidity cases may be premature. Studies such as that performed by Ramirez et al. (2009) only expose a possible statistical link between fecal waste and presence of *Vibrio vulnificus*. Enterococcus is not unique to human waste and may therefore affect *Vibrio* in more remote and less densely populated areas.

In urban areas with impenetrable surfaces, storm events cause the transport of nearly 60% of the annual sediment load, which is contaminated with pollutants, waste runoff, and nutrients (Rose et al. 2001). Further studies of urbanization in coastal areas, specifically of sewage and wastewater runoff, may uncover links between specific sites and high levels of *V. vulnificus* in marine animals in surrounding estuarine systems, depending upon proximity and management. *Vibrio* and other bacteria have been found living in sewage systems in concentrations as high as 3000/L (Rose et al. 2001). Recent studies such as that performed by Ramirez et al. (2009) have found significant statistical correlations between high levels of enterococci bacteria and *Vibrio vulnificus* that suggest that nutrient loading may have a significant effect on the presences of *Vibrio vulnificus*. If present, *V. vulnificus* is usually eliminated from wastewater through heating and chlorination during the sewage treatment processes, although treated water often tests positive for viruses because they are heat resistant.

Such findings refute past studies affirming that bacterial levels do not have direct association with effluence or pollution in estuarine systems, and that temperature, salinity levels, pH and dissolved oxygen alone are the primary variables of interest, such as the study performed by Kelly and Avery (1980). It has been suggested that with this connection, new sampling methodology is needed to better determine the distribution of the bacteria (Ramirez et al. 2009).

These implications also require a need for geographical study of morbidity and bacterial cluster distribution to better establish relational links between the distribution of infection and other variables such as climate and land-use in coastal areas. Limited geographical study on *Vibrio vulnificus* morbidity cases exists, perhaps because new methodologies and criteria are required to sample potential variables once considered irrelevant, e.g., effluence and turbidity levels. Given the highly pathogenic nature of this bacteria and the variation in hydro-climatic activity on the Gulf Coast, spatio-temporal relationships involving climatic variables should be analyzed to determine if there is any significance.

If weather variability increases runoff and at the same time decreases salinity in a location such as coastal Texas where the seasonality is fairly constant and the population is highly concentrated in coastal locations, further analysis of such a link may be prudent to discern immediate risk of infection to the surrounding population. In other coastal locations with a greater range in seasonal temperature, weather and climate variability may produce an actual shift in ‘seasonal phenotype’ (Koelle 2005), thereby changing the length of warmer and wetter seasons. This could alter the spatio-temporal diffusion of *Vibrio vulnificus*.

Exploring such data may provide information that can track and predict outbreaks in locations prime for bacteria growth. Most of the current research revolves around the distribution of the pathogen itself in specific coastal regions, or isolated cases in which serious injury or fatalities occur. To better explain when and where morbidity cases are established and determine potential coastal areas at risk, geographical study using statistical analysis may be used to find correlations between large-scale hydrologic events and existing data on reported infections.

Should this study result in a weak relationship or none at all, perhaps further exploration into better methods for cataloguing and identifying the location of infection in morbidity cases will be of use to perform more detailed analysis. Nevertheless, the issue of privacy, private property and the longevity of the bacteria outside of a marine environment may serve to hamper data collection.

CHAPTER 3

STUDY AREA

Matagorda and Galveston Bay Region

For this study, the two areas of interest are located on the Gulf Coastal Plain on the east side of Texas (Coffman et al. 2010). The specific water bodies within this site are the Matagorda Bay system (28°27'6" N, 96°23'18" W) and the Galveston Bay system located at (29° 47' 32.50" N, 94° 41' 06.30" W) (Fig. 8).

To maintain a full record of precipitation data from the National Climatic Data Center (NCDC) between 1999 and 2003 for Harris and Matagorda Counties, the data are from the Houston International Airport, gauge number 414300 (Houston-Bush International Airport) and Palacios Municipal Airport rain gauge number 416750 (NCDC 2011).

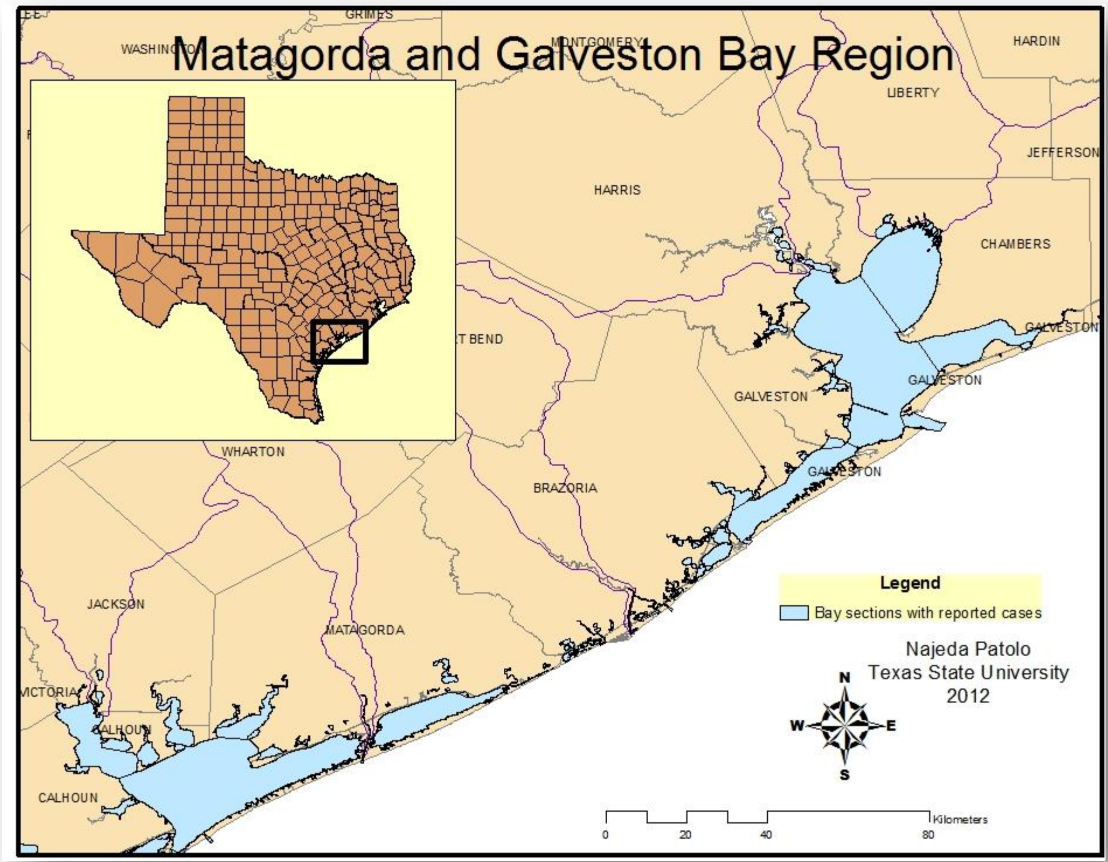

Figure 8: Study site Matagorda Bay and Galveston Bay, Texas

The Houston International Airport rain gauge, which records precipitation levels for Galveston Bay system, is located in the San Jacinto river basin on the Gulf Coastal Plain, which is approximately 14, 503 km^2. Palacios Municipal Airport rain gauge is located in the Lavaca river basin, approximately 5,980 km^2 (Bureau of Economic Geology 1996). Data from this gauge provide recorded precipitation information for the Matagorda Bay system (Fig 9).

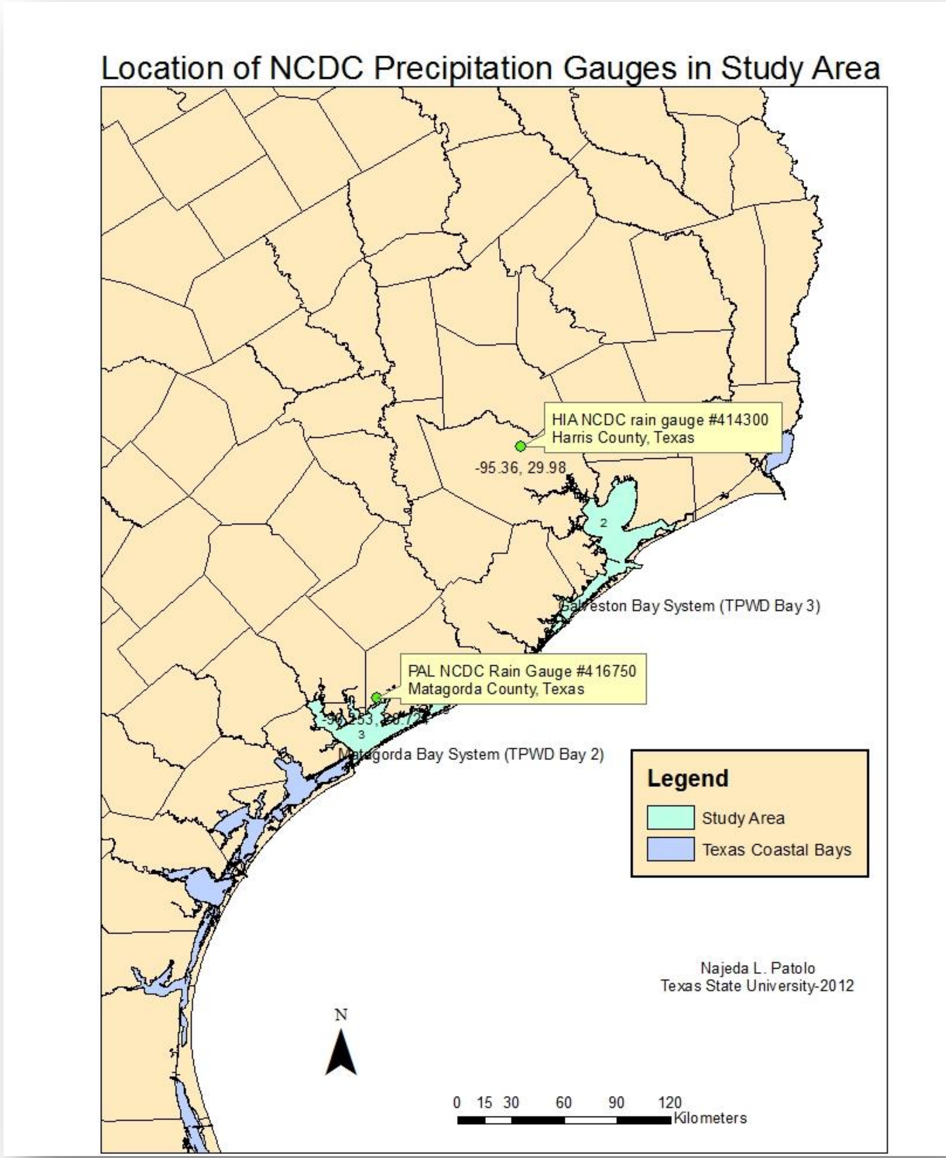

Figure 9: NCDC Precipitation gauges (IHA and PAL) in study area on Texas Gulf Coast.

Long-term precipitation data from the National Oceanic and Atmospheric Administration (NOAA) Online Weather Data provide normal monthly precipitation totals for both rain gauges from 1981-2010 (NOAA 2012). Normal precipitation levels can then be used to identify elevated levels in actual recorded precipitation from both rain gauges (IHA and PAL) between 1999 and 2003 inclusive (Table 2).

Such variation in precipitation over one geomorphic region results in numerous different natural weather hazards from tornadoes, droughts, excessive heat, and funnel clouds to hurricanes, water spouts, and tropical storms (NCDC 2012).

Table 2: Total Monthly Normal Precipitation 1981-2010 (NOAA).

Month	Palacios Municipal (cm)	Houston International (cm)
January	8.56	8.58
February	5.97	8.13
March	7.62	8.66
April	6.60	8.41
May	10.69	12.93
June	11.40	15.06
July	12.09	7.63
August	7.52	7.55
September	13.03	10.46
October	12.65	14.78
November	10.06	11.02
December	7.06	9.5
Annual (total)	**113.5**	**122.7**

In the Texas Gulf Coast region, the warmest months with heavy rainfall are May through October when the average air temperatures are above 22° C and water temperatures are higher than 10° C (TPWD 2011). Between 1999 and 2003, two reported hurricanes affected the Texas Gulf Coast; category 3 Hurricane Bret and category 1 Hurricane Claudette (Roth 2010). Tropical storm Allison is notable in 2001 as being the force behind the three largest rain events between 1999 and 2003 (Roth 2010).

The annual probability of a hurricane strike along an 80 km stretch of the coast of Texas ranges from "31% at Sabine Pass to 41% around Matagorda Bay" (Roth 2010, 4). Tropical storms and hurricanes combined have an average occurrence of 3 out of every 4 years along the Texas Gulf Coast and one of the most devastating effects of these events is extreme flooding (Roth 2010). This is of special concern in highly-populated urban coastal areas like Galveston Bay in Harris County, which are especially susceptible to large flood events because of low-elevation exacerbated by subsidence.

Considered to be the most economically productive of the Texas estuaries, Galveston Bay produced one-third of the fishing income for Central Texas from 1994-1998 and is currently one of the largest oyster producing estuaries in the United States (Thronson and Quigg 2008). At 1,456 km^2, Galveston Bay is the largest estuary in the Texas Gulf Coast, followed by the Lower Laguna Madre (1,308 km^2) and Matagorda Bay (1,115 $k\ m^2$) (Thronson and Quigg 2008, 804). The reasons for selecting Matagorda and Galveston Bay are the similar summer conditions of the estuaries in terms of temperature and salinity; the key variables upon which *Vibrio vulnificus* is dependent for reproduction (Kelly 1982).

Galveston Bay and Matagorda Bay average 13 ppt and 18 ppt salinity levels respectively during the summer season and average roughly 20 ppt year-round (Thronson and Quigg 2008). This level of salinity in a climate with relatively high annual temperatures makes the region ideal for *V. vulnificus*.

Analysis of the geographic nature of Matagorda Bay may influence the distribution of morbidity cases because of the dynamic nature of the system. The

Matagorda system contains two bays, East and West Matagorda Bay. Both are shallow and have moderate salinity, but East Matagorda is more of a “bar-built” estuarine system, meaning that the shallow nature of the system and the virtual separation from the ocean by a barrier island make the estuary more susceptible to variability in temperature and salinity (Bianchi 2007). The paths cut by shrimp trawlers that affect bay depth, turbidity, and salinity levels also affect the muddy bottom of the bay. Large-scale agriculture near the coast also increases runoff, which may affect bay salinity levels, particularly where Tres Palacios River meets West Matagorda Bay.

Morbidity in the Matagorda Bay and Galveston Bay Region

The state of Texas has a reported 69 cases of *Vibrio vulnificus* related morbidity cases from 1999-2003 (U.S. DOH 2010). During that time period, the Texas Department of Health reported a total of 37 morbidity cases resulting from a *Vibrio vulnificus* infection that can be geographically traced to a source in a major bay system (DOH 2010). Of those cases, 30 can be traced to water bodies in Galveston and Harris Counties, and 6 cases can be traced to water bodies in Matagorda County (Table 3). The highlighted reported case in table 3 is not within the study area and is therefore not included in this study.

Table 3: Geographically traceable *Vibrio vulnificus* morbidity cases: 1999-2003.

Geographically traceable *Vibrio vulnificus* morbidity cases: 1999-2003	
Date of Onset	Wound Exposure or Shellfish Site
1/1/1999	Bay Oaks Harbor, Baytown
7/1/1999	Baycliff/Kemah/Texas City
8/6/2002	Bolivar Peninsula
5/1/2001	Brazos River near coast
4/1/1999	E. Galveston Bay
4/1/1999	Galveston Bay
5/1/1999	Galveston Bay
7/1/1999	Galveston Bay
9/1/1999	Galveston Bay
12/1/1999	Galveston Bay
5/1/2000	Galveston Bay
6/1/2000	Galveston Bay
7/1/2000	Galveston Bay
7/1/2000	Galveston Bay
8/1/2000	Galveston Bay
9/1/2000	Galveston Bay
7/1/2001	Galveston Bay

Date of Onset	Wound Exposure or Shellfish Site
8/1/2001	Galveston Bay
8/1/2001	Galveston Bay
6/24/2002	Galveston Bay
7/7/2002	Galveston Bay
10/25/2002	Galveston Bay
8/5/2003	Galveston Bay
10/7/2003	Galveston Bay
10/20/2003	Galveston Bay
11/16/2003	Galveston Bay
7/1/1999	Galveston Beach
6/14/2003	Galveston, West Bay
5/1/2001	Lavaca Bay
7/1/2000	Matagorda Bay
8/3/2002	Matagorda Bay
9/17/2003	Matagorda Bay
5/31/2003	Palacios area on bay
9/1/2001	Port Lavaca
8/11/2002	Port O'Connor
8/1/1999	Trinity Bay
7/1/2000	Trinity Bay

The highlighted case reported in the Brazos River in table 3 is out of the range of the study area. Those cases that have been geographically identified were located on the Gulf Coast on the southeast side of Texas in estuarine environments, clustered around Galveston and Matagorda Bay (Fig. 10). Unfortunately, these cases cannot be identified to specific locations within the bay systems because that information is not available from the Texas Department of Health. Prolonged existence outside of the bacteria outside of a marine system may also delay infection (Colodner et al. 2002), thus preventing positive diagnoses. The geography of these cases was also limited to "shellfish site", which further confines the identification of a specific location of infection (DOH 2010).

Morbidity rates and precipitation data will be statistically analyzed in a primary study to determine spatio-temporal correlation. To visually correlate morbidity cases temporally, graphical analysis is done over the five- year study period to confirm peaks and valleys of reported incidences of infection (Fig. 10).

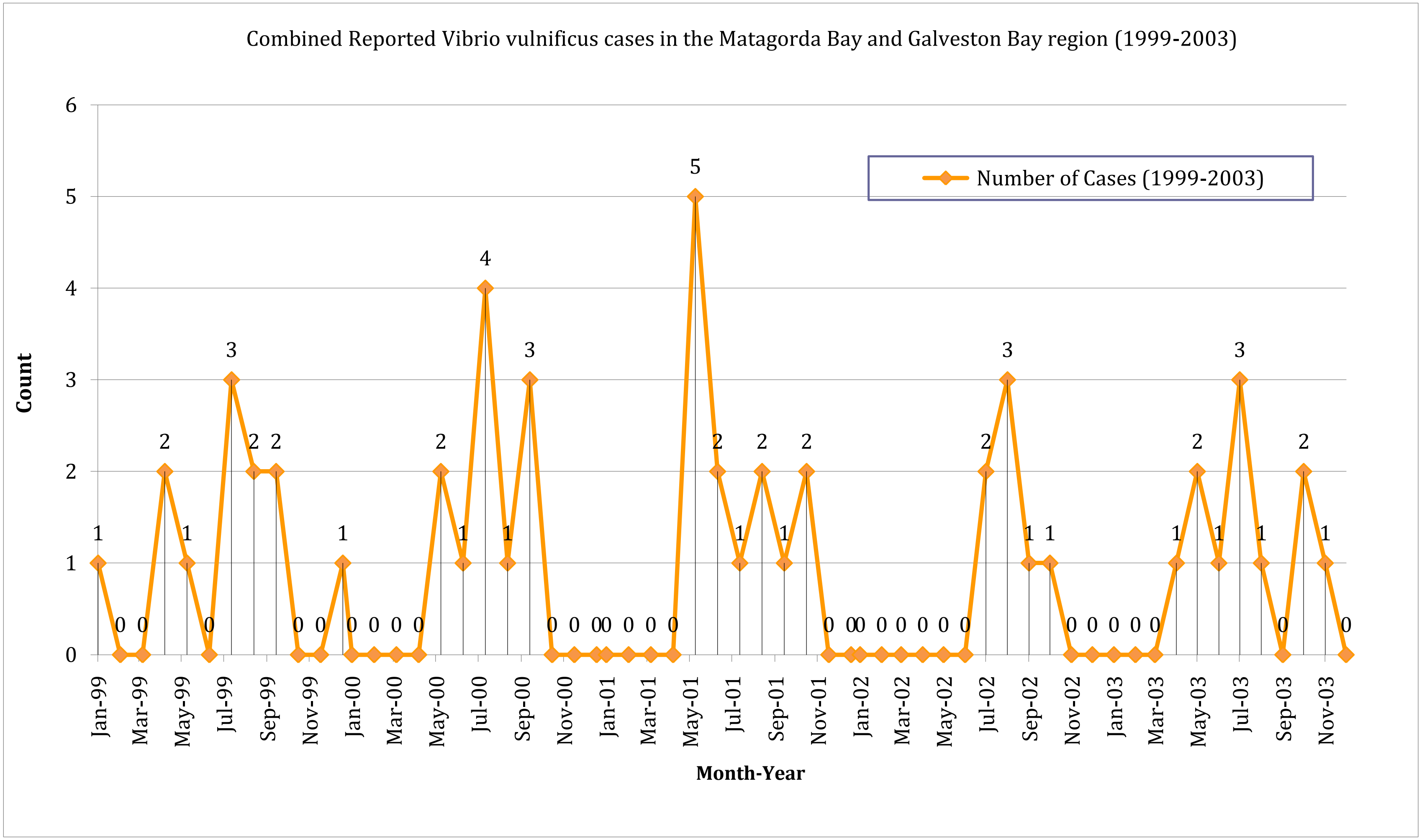

Figure 10: Reported morbidity cases by month from both Matagorda and Galveston (Texas DOH 2010).

CHAPTER 4

DATA AND METHODOLOGY

Research Questions and Analysis

Potential relationships between precipitation, water temperature and salinity, and the relationship between *Vibrio vulnificus* morbidity and precipitation in the study area will be analyzed to determine whether or not there is a statistical correlation. For the purpose of this study, months with high-magnitude rain events are identified as months with higher than normal values, as defined by the official NOAA online weather data (1981-2010). Significant questions leading to the conclusion of these analyses are:

1) What effects do high-magnitude precipitation events associated with climate variability have on water temperature and salinity levels in estuarine systems in the Matagorda and Galveston Bay region from 1999-2003?

2) How do high-magnitude precipitation events affect the temporal distribution and occurrence of *Vibrio vulnificus* induced morbidity cases in the Matagorda and

Galveston Bay region from 1999-2003?

The test variables being analyzed for this study are as follows:

Test Variables	
Independent	**Dependent**
Date (month/year)	Salinity (ppt)
Precipitation (cm)	Temperature (C°)
-----	*Vibrio vulnificus* morbidity cases

Historical data of salinity levels and water temperature changes from the Texas Parks and Wildlife and Department (TPWD 2011) provide base information regarding the nature of the study areas. Of interest are data that track salinity and temperature over the five-year study period (1998-2003). Shapiro et al. provided similar analysis using TPWD data to correlate salinity levels in Texas and four other states with reported *Vibrio vulnificus* morbidity cases (1998). Past records of oyster harvests were correlated with salinity and temperature levels at harvesting sites to determine the source of infection.

This study looks to establish only physical and climatological correlations involving morbidity rates, not those associated with water withdrawal, shellfish harvesting, or other specific anthropogenic disturbances to the estuarine system. Such comparisons will provide statistical information about the relationship between high-magnitude precipitation events and changes in salinity and temperature in counties on the Texas Gulf Coast.

Precipitation Data

Matagorda and Harris County are 2,849 and 4,404 km^2, respectively (U.S. Census 2010) and approximately 149 km apart (Google Earth 2010). Galveston County borders Harris County and is 980 km^2 large. Monthly precipitation data will be analyzed for elevated precipitation levels from 1999-2003 for the Galveston Bay area, which includes both Harris County and Galveston County for this study. For the purpose of this study, a "high-magnitude precipitation event" is defined as having elevated precipitation levels at one standard deviation above the mean amount of monthly precipitation.

For this study, months with higher than normal precipitation levels as defined by NOAA Online Weather Data climate normals will be used as a historical reference when using current precipitation data from both rain gauges determine if there was a large amount of precipitation during that time period (NOAA 2012). These data include sum of monthly precipitation levels Data from this historical record will provide generalized mean numbers of monthly precipitation for Matagorda, Harris, and Galveston Counties with which detailed 1999-2003 precipitation data can be compared (Fig. 11 and Fig. 12).

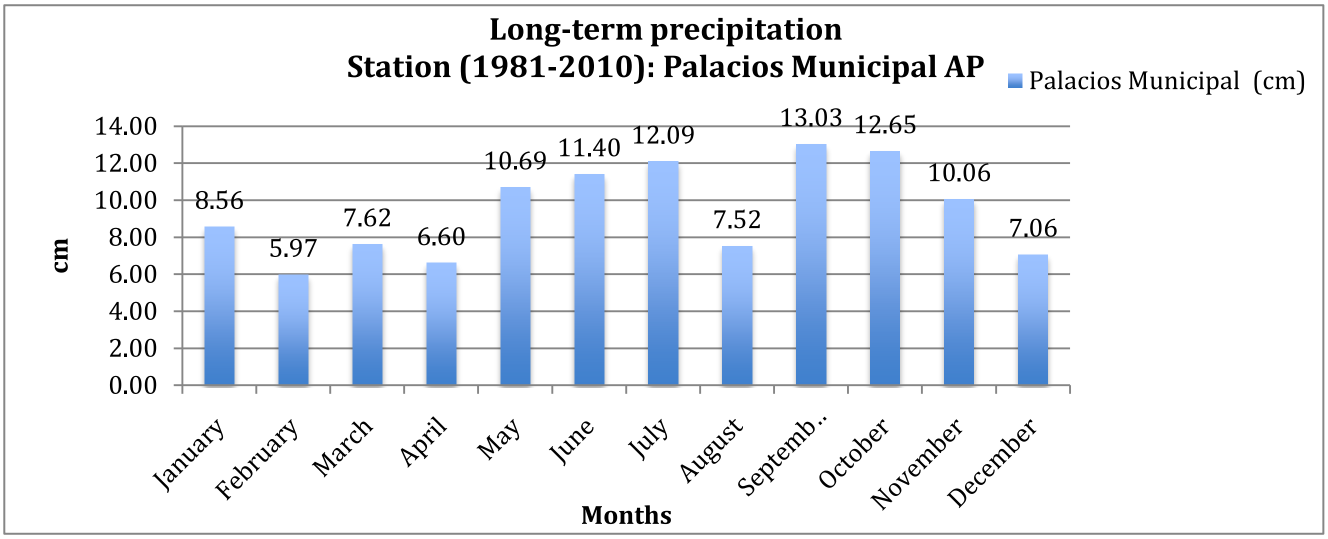

Figure 11: Total monthly precipitation from 1981-2010 for Palacios Municipal Airport rain gauge (Matagorda Bay system) (NOAA 2012).

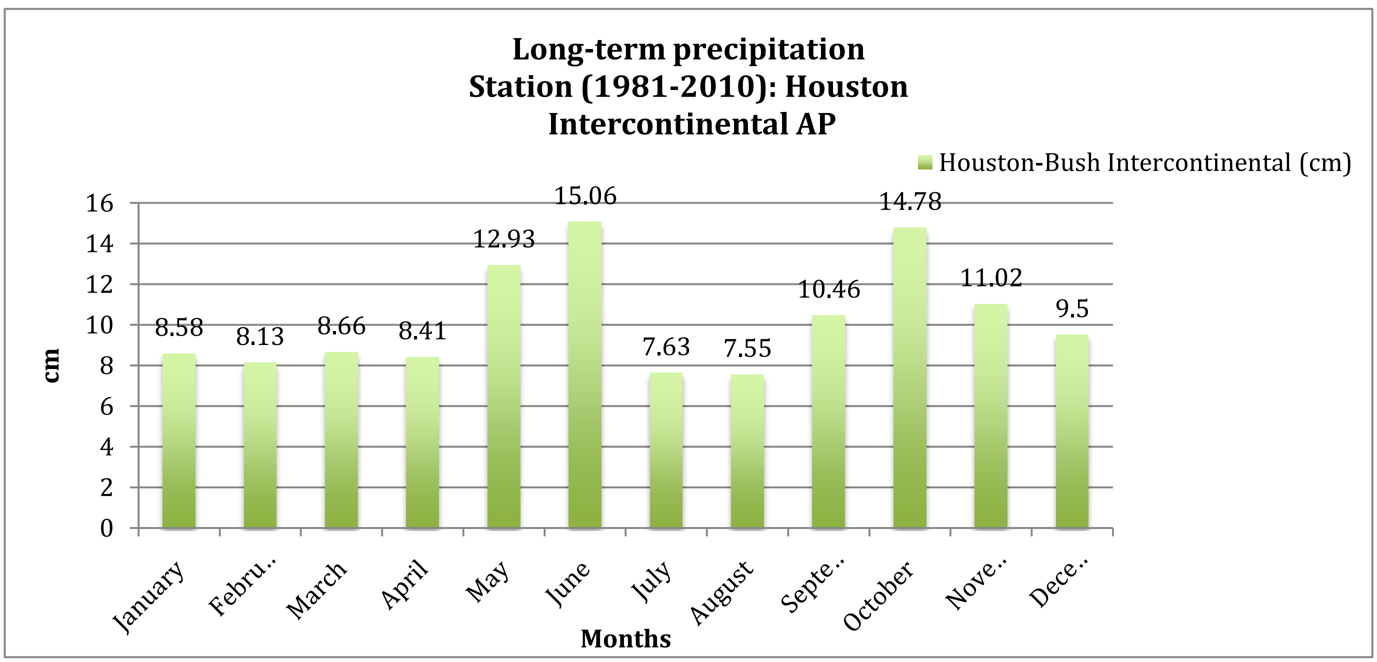

Figure 12: Total monthly precipitation from 1981-2010 for Houston International Airport rain gauge (Matagorda Bay system) (NOAA 2012).

Any month with a higher amount of precipitation than the monthly total from 1981-2010 will be analyzed to determine whether or not a high-magnitude precipitation event occurred in that county as recorded by either Palacios Municipal Airport Precipitation gauge (Fig. 13) or the Houston International Airport Precipitation gauge (Fig.14).

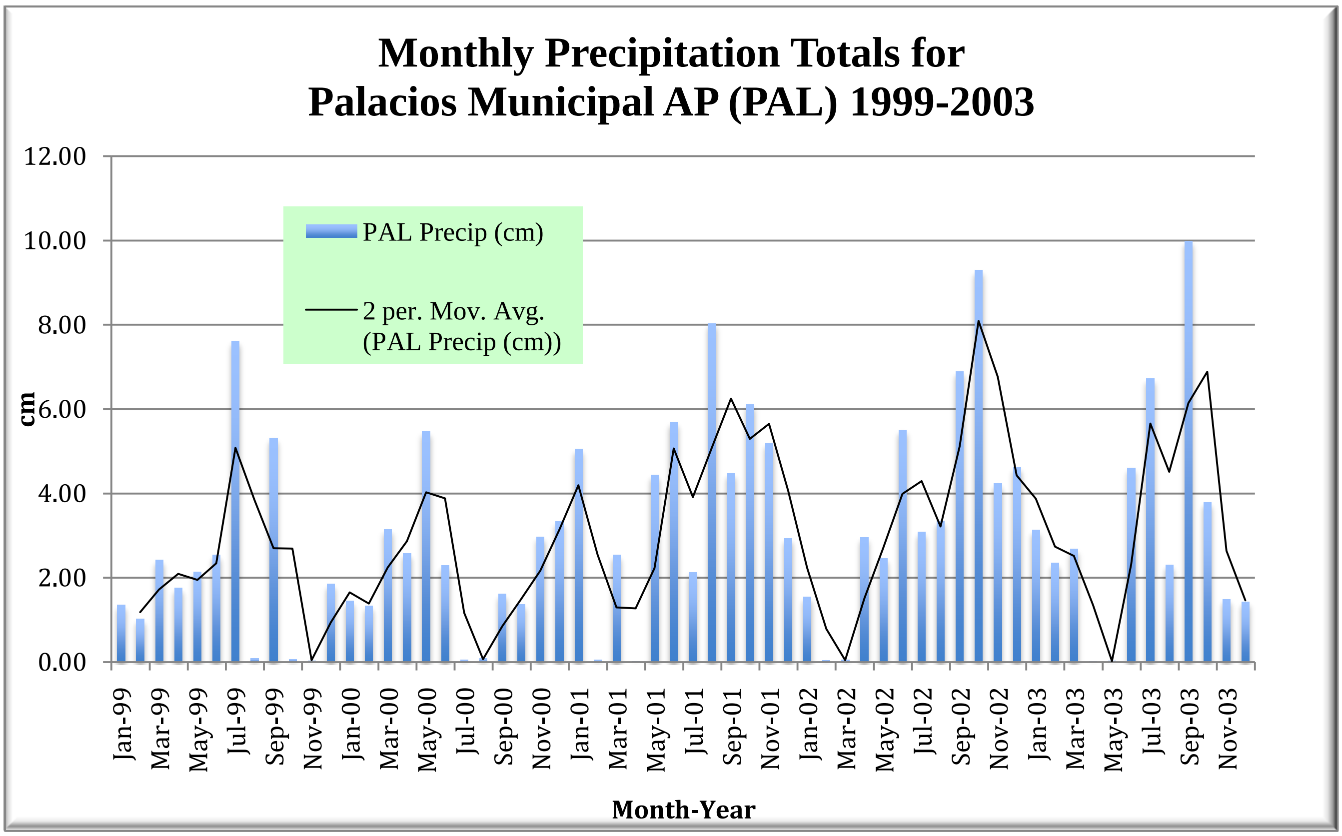

Figure 13: Total monthly precipitation from 1999-2003 for Palacios Municipal Airport rain gauge (Matagorda Bay system) (NOAA 2012).

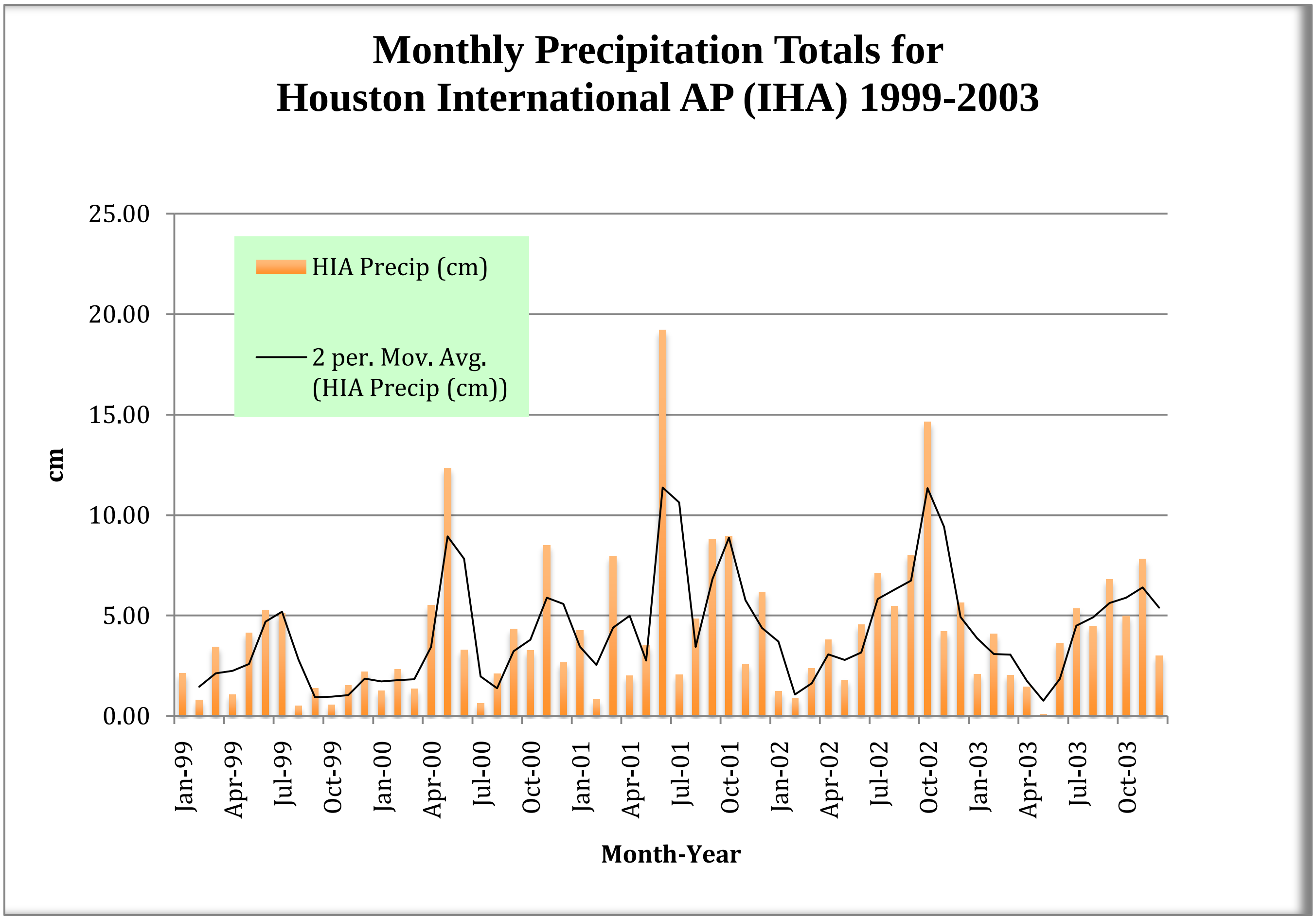

Figure 14: Total monthly precipitation from 1999-2003 for Houston International Airport rain gauge (Galveston Bay system) (NOAA 2012).

Five years of monthly data are statistically analyzed to determine range of precipitation, peak monthly precipitation events for that period and months with lower than normal precipitation. TPWD testing points for salinity and temperature in Matagorda Bay and in Galveston Bay provide the necessary data on salinity and temperature between 1999 and 2003 inclusive for this study.

Additional variables within the tabular TPWD testing point data such as pH are also available, but are not considered necessary for *Vibrio vulnificus* to thrive. Land-use, algal blooms, and technological hazards may affect the biodiversity of the study area and skew the data. These variables are acknowledged, but not tested for directly.

Other analyses have been done for immediate comparison between two locations with similar seasonality and the presence of *Vibrio vulnificus* (Vithanage and Fujioka 2008). Nevertheless, by using such data to define a pattern of behavior for the bacteria using actual morbidity cases and forming projections about the future distribution of hazardous bacteria, studying the climate-driven migration of pathogens becomes more geographically and medically valuable.

Precipitation, water temperature, and salinity

Temperature and salinity levels for these two bay systems are derived from the TPWD water parameter sampling stations. The sampling method employed by TPWD for these parameters is random, so there is no official station for temperature and salinity in either bay system. Between 1999 and 2003 inclusive, there were 5,582 test samples taken for water temperature and salinity in the major Galveston Bay area code and 4,860 in the major Matagorda Bay (TPWD 2011). There appears to be no exact number of tests required each month, so the sampling is spatially and temporally random.

Table 4: TPWD major bays and area codes (TPWD 2011).

Major Bay Codes	**major_area_code**
Sabine Lake	1
Galveston Bay	2
Matagorda Bay	3
San Antonio bay	4
Aransas Bay	5
Corpus Christi bay	6
Upper Laguna Madre	7
Lower Laguna Madre	8
East Matagorda Bay	9
Cedar Lakes	11
off Sabine Lake	17
off Galveston-Freeport	18
off Matagorda-San Antonio-Aransas	19
off Corpus Christi-Upper Laguna Madre	20
off upper Laguna Madre-lower Laguna Madre	21

Besides being random, TPWD water quality testing is also irregularly performed. Some months have recorded tests on every day or multiple times a day. Others show that not every day has recorded testing. In order to obtain the same number of variables for the separate bay systems, testing events for water temperature and salinity are averaged to determine one value for each month for Matagorda Bay (Table 5) and one value for each month for Galveston Bay (Table 6) (60 months per system in total).

Table 5: Gross averages of salinity and water testing from all TPWD testing points in Major Area Code 3 (Matagorda Bay system) and corresponding precipitation.

MONTH	Water temp(C°)	Salinity (0/00)	Precip in (cm)
Jan-99	15.11	20.31	3.43
Feb-99	18.55	20.55	2.59
Mar-99	19.82	25.08	6.15
Apr-99	25.25	21.91	4.47
May-99	27.00	25.22	5.44
Jun-99	29.53	21.14	6.45
Jul-99	30.05	21.35	19.35
Aug-99	30.74	20.95	0.21
Sep-99	29.34	28.26	13.51
Oct-99	23.74	27.09	0.17
Nov-99	21.76	31.35	0.06
Dec-99	14.63	28.33	4.70
Jan-00	18.29	32.32	3.68
Feb-00	18.27	29.23	3.38
Mar-00	21.66	32.50	8.00
Apr-00	24.11	28.64	6.55
May-00	27.93	27.04	13.89
Jun-00	29.37	24.03	5.82
Jul-00	29.94	28.93	0.12
Aug-00	29.94	30.40	0.22
Sep-00	28.58	34.28	4.09
Oct-00	24.30	34.28	3.48
Nov-00	16.48	24.72	7.54
Dec-00	11.91	21.48	8.46
Jan-01	11.90	19.35	12.83
Feb-01	16.42	19.25	0.12
Mar-01	17.05	17.12	6.45
Apr-01	24.95	19.20	0.03
May-01	27.06	19.27	11.28
Jun-01	29.50	22.21	14.45
Jul-01	30.23	26.03	5.41
Aug-01	30.26	27.29	20.40
Sep-01	28.23	11.36	11.35
Oct-01	24.55	15.25	15.52

Table 5 Continued:

MONTH	Water temp(C°)	Salinity (0/00)	Precip in (cm)
Nov-01	21.48	14.54	13.18
Dec-01	16.79	12.95	7.44
Jan-02	14.21	19.20	3.91
Feb-02	14.44	22.80	0.09
Mar-02	16.41	26.28	0.12
Apr-02	24.38	24.71	7.52
May-02	26.09	24.28	6.25
Jun-02	29.61	26.89	14.00
Jul-02	30.51	15.52	7.82
Aug-02	30.72	14.60	8.51
Sep-02	27.42	16.93	17.50
Oct-02	25.74	16.73	23.62
Nov-02	19.13	6.05	10.74
Dec-02	14.83	11.62	11.73
Jan-03	14.44	15.74	7.95
Feb-03	12.92	17.17	5.97
Mar-03	18.84	16.10	6.81
Apr-03	21.25	19.04	0.04
May-03	28.31	22.87	0.07
Jun-03	30.91	22.20	11.68
Jul-03	29.88	19.00	17.07
Aug-03	30.22	22.09	5.84
Sep-03	27.43	19.96	25.37
Oct-03	25.16	15.57	9.63
Nov-03	22.77	18.30	3.78
Dec-03	15.67	20.54	3.63

Table 6: Gross averages of salinity and water testing from all TPWD testing points in Major Area Code 2 (Galveston Bay system) and corresponding precipitation.

MONTH	Water temp(C°)	Salinity (0/00)	Precip in (cm)
Jan-99	14.59	12.63	5.38
Feb-99	18.59	14.40	2.03
Mar-99	19.27	16.57	8.74
Apr-99	23.66	15.96	2.69
May-99	26.85	17.78	10.49
Jun-99	29.35	15.06	13.36
Jul-99	30.30	14.91	12.98
Aug-99	31.29	19.19	1.27
Sep-99	28.80	25.33	3.48
Oct-99	23.37	27.17	1.42
Nov-99	21.36	27.71	3.89
Dec-99	14.35	26.89	5.59
Jan-00	15.82	27.64	3.18
Feb-00	17.36	26.66	5.89
Mar-00	21.66	28.52	3.43
Apr-00	23.41	22.98	14.02
May-00	27.68	19.63	31.37
Jun-00	29.06	20.73	8.36
Jul-00	30.37	23.30	1.63
Aug-00	29.81	24.54	5.36
Sep-00	26.95	27.82	11.02
Oct-00	24.96	27.21	8.31
Nov-00	17.46	20.46	21.59
Dec-00	12.17	16.90	6.78
Jan-01	10.67	13.64	10.80
Feb-01	15.33	12.84	2.08
Mar-01	17.08	10.63	20.24
Apr-01	24.14	8.90	5.08
May-01	26.51	12.37	8.97
Jun-01	29.02	8.67	48.79
Jul-01	30.57	13.50	5.21
Aug-01	29.76	20.79	12.27

Table 6 Continued:

MONTH	Water temp(C°)	Salinity (0/00)	Precip in (cm)
Sep-01	27.91	9.22	22.40
Oct-01	23.21	12.67	22.73
Nov-01	19.37	14.97	6.55
Dec-01	17.37	10.34	15.70
Jan-02	13.75	13.15	3.15
Feb-02	14.07	15.12	2.26
Mar-02	17.47	17.89	5.99
Apr-02	24.33	12.72	9.63
May-02	26.44	11.18	4.55
Jun-02	29.21	13.02	11.53
Jul-02	30.34	13.91	18.06
Aug-02	30.31	14.45	13.89
Sep-02	27.86	12.36	20.37
Oct-02	23.93	12.99	37.21
Nov-02	17.82	6.88	10.67
Dec-02	13.57	9.73	14.35
Jan-03	10.09	13.98	5.31
Feb-03	12.64	13.63	10.36
Mar-03	18.85	9.34	5.18
Apr-03	22.74	14.02	3.71
May-03	27.08	16.49	0.15
Jun-03	30.05	19.56	9.19
Jul-03	29.78	16.17	13.61
Aug-03	30.62	21.84	11.35
Sep-03	27.75	16.43	17.25
Oct-03	24.18	13.03	12.67
Nov-03	22.13	15.65	19.86
Dec-03	13.27	15.70	7.59

Vibrio vulnificus morbidity data

Morbidity data for this study resulting from culture-confirmed cases of *V. vulnificus* are from a de-identified database of recorded cases resulting from shellfish poisoning and wounds recorded by the Texas Department of Health located in Austin, TX (DOH 2010). These data contain specific morbidity details about the type and method of infection and general information about the aquatic origins of infection in coastal Texas (shellfish and wound exposure sites).

As this study is only concerned with the actual occurrence of reported infection and not the specific diagnoses or patient histories, the only data items that will be referenced are:

1. The Onset Date
2. Wound Exposure Site, and
3. Shellfish site and reported shellfish infections

Methodology

Kendall's-tau Correlation: Precipitation and Temperature and Salinity

The first step in this analysis is to determine if there is a statistical correlation between the TPWD water quality parameters of interest and precipitation (Fig. 15). It is hypothesized that because high-magnitude precipitation events may delude the salinity within a shallow estuarine system, precipitation will statistically correlated with salinity.

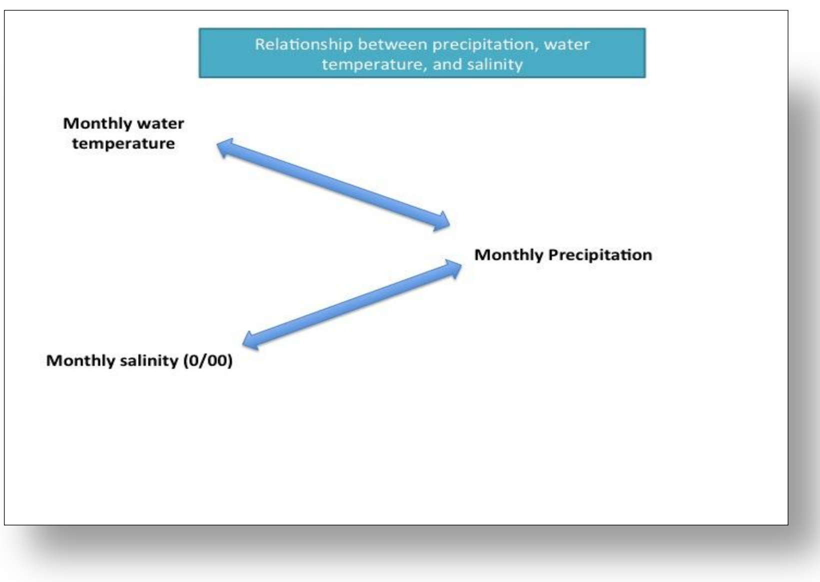

Figure 15: Visual model of potential relationship between precipitation, water temperature, and salinity.

Water temperature may not be directly affected by the occurrence of above-normal precipitation events. Nevertheless, this parameter may be positively correlated to the occurrence of *Vibrio vulnificus* morbidity cases. Warmer temperatures can potentially mean higher populations of people in the study area, which increases the chance for infection and bacterial growth. Water temperatures over 20°C have been proven by Ramirez et al. to be ideal for bacteria to thrive in an estuarine environment (2009).

In a report on the Texas Coastal Bend entitled, *Vibrio vulnificus Monitoring in Recreational Waters*, Mott et al. confirmed that occurrence of the *V. vulnificus* pathogen is more directly related to high water temperatures than to salinity (2008).

The relationship between these two variables may be more directly explored by including seasonality, air temperature, or coastal industry within the drainage basin. In this report, Mott et al., discuss a particular precipitation event, which occurred in a shallow bay area and the resulting sudden drop in salinity (2008). This observation supports the theory that sudden precipitation events directly affect estuarine systems along the Texas Gulf Coast.

A total of four tests are used to determine potential correlation between water quality parameters and precipitation in the two bay systems (Table 7). For this analysis, there are total of four tests (two for each precipitation gauge) will be run to determine:

- The relationship between monthly rainfall at each precipitation gauge and water temperature in the respective bay.

- The relationship between monthly rainfall at each precipitation gauge and salinity levels in the respective bay.

Table 7: Statistical correlative analysis matrix showing tests being performed using Kendall's Tau-b.

Test variables	1999-2003 Monthly Precipitation Rain Gauge: IHA	1999-2003 Monthly Precipitation Rain Gauge: PAL
TPWD Salinity-Matagorda (3)	----	TEST
TPWD Salinity-Galveston (2)	TEST	----
TPWD Water Temp-Matagorda (3)	----	TEST
TPWD Water Temp-Galveston (2)	TEST	----

Non-parametric correlation analysis is used to determine the strength of the correlation between variables. An appropriate statistical test will measure the concordance and discordance between variables to reveal the extent to which one affects the outcome of the other. The test used for analysis of these data is a two-tailed Kendall's Tau-b test for correlation using IBM SPSS software.

Analysis using the Phi Coefficient: *Vibrio vulnificus* morbidity cases and Precipitation

The result of this analysis will determine whether or not high-magnitude precipitation events (rainfall in excess of normal amounts) affect the occurrence of *Vibrio vulnificus* morbidity cases. The variables of interest are:

1. Monthly precipitation (totals) from both Houston International Airport rain gauge and Palacios Municipal Airport rain gauge (NCDC 2012) for calendar years 1999-2003 inclusive.
2. Normal precipitation data from the NOAA online weather data bank from 1981-2010 (NOAA 2012) for IHA and PAL.
3. Reported *Vibrio vulnificus* morbidity cases from 1999-2003 in the Matagorda and Galveston Bay systems.

Kelly et al. have shown that estuarine environments with moderate salinity levels between 5 and 25 ppt provide optimum conditions for *V. vulnificus* bacteria to breed (1982). Though water temperatures are proven to be the variable that has the strongest relationship with the occurrence of the pathogen, salinity is still a factor that determines whether or not a habitat is suitable. If this finding also affects the number of reported morbidity cases, then there is sufficient reason to hypothesize that an increase in precipitation (high-magnitude precipitation events) may result in decreased salinity and even an increase of *Vibrio vulnificus* morbidity cases in Matagorda and Galveston Bay systems.

Normalized long-term precipitation data for both the Houston International Airport rain gauge (HOU) and the Palacios Municipal Airport (PAL) will be used to form to separate tables. To analyze the correlation between precipitation and morbidity, a table is constructed to analyze the cases identified in bay system from where they were reported against precipitation data for that particular bay system. Monthly precipitation data for HOU and PAL analyzed separately against normal long-term precipitation data from NOAA Online Weather Data to determine if morbidity cases occur in months with spikes in precipitation.

To compute the Phi coefficient and determine the statistical correlation between precipitation and morbidity, a matrix is constructed to determine the connection between morbidity and precipitation both rain gauge stations. The idea behind this matrix is to show when recorded morbidity cases are reported during months with increased precipitation (Fig. 16)

(Precipitation gauge name)

Count

		AboveNormPrecip		Total
		N	Y	
VibReport	N	(Number)	(Number)	(Results)
	Y	(Number)	(Number)	
Total				(60 months)

Figure 16: Example of resulting out-put of Phi Table

Each time that an observed precipitation amount from the monthly NCDC data is above the average normal amount, it is recorded as a "Y", and each time a morbidity case occurs in a month with elevated precipitation levels, the result is also be recorded as a "Y" under cases reported. All other results are recorded as "N" (no match). A Phi correlation using Phi and Cramer's V test in SPSS is then used to determine if in fact the occurrence of a *Vibrio vulnificus* case is correlated to months with above-average precipitation events.

CHAPTER 5

RESULTS

Analysis 1: Precipitation and Temperature and Salinity

Galveston Bay System

The results of the Kendall's tau-b correlations test between precipitation (PrecipIHA) and water temperature (WaterTemp) show that the two variables are not significantly correlated at the .05 alpha level (Table 8). Water temperature is not necessarily correlated with precipitation.

Table 8: Results of correlation analysis between IHA above-average precipitation and water temperature in Galveston Bay.

Precip and WaterTemp Correlations Result: Galveston Bay and IHA			Temp	PrecipIHA
Kendall's tau_b	Temp	Correlation Coefficient	1.000	.122
		Sig. (2-tailed)	.	.168
		N	60	60
	PrecipIHA	Correlation Coefficient	.122	1.000
		Sig. (2-tailed)	.168	.
		N	60	60

Results of the Kendall's tau-b correlation two-tailed test between precipitation and salinity show that the statistical relationship between these two variables is significant. Salinity is statistically correlated with precipitation as is shown in the results (Table 9).

Table 9: Results of correlation analysis between IHA above-average precipitation and salinity in Galveston Bay.

Precip and Salinity Correlations Results: Galveston Bay and IHA		PrecipIHA	Salinity
PrecipIHA	Pearson Correlation	1	-.320*
	Sig. (2-tailed)		.013
	N	60	60
Salinity	Pearson Correlation	-.320*	1
	Sig. (2-tailed)	.013	
	N	60	60

*. Correlation is significant at the 0.05 level (2-tailed)

Matagorda Bay System

Results of the correlation analysis in the Matagorda Bay system between precipitation (PrecipPAL) and water temperature (WaterTemp) show the same results as the analysis performed for Galveston. There is no significant correlation between these two variables. Water temperature is not statistically correlated with precipitation (Table 10).

Table 10: Results of correlation analysis between PAL above-average precipitation and water temperature in Matagorda Bay.

Precip and WaterTemp Correlations Result: Matagorda Bay and PAL			PrecipPAL	WaterTemp
Kendall's tau_b	PrecipPAL	Correlation Coefficient	1.000	.122
		Sig. (1-tailed)	.	.084
		N	60	60
	WaterTemp	Correlation Coefficient	.122	1.000
		Sig. (1-tailed)	.084	.
		N	60	60

As hypothesized, test results reveal that salinity is significantly correlated at the .05 alpha level with precipitation events in Matagorda Bay (Table 11). The correlation coefficient of -.206 shows that salinity is significantly correlated with precipitation, which implies that high-magnitude precipitation events affect salinity levels in the Matagorda and Galveston bay systems. For the second test, the null hypothesis is rejected.

Table 11: Results of correlation analysis between PAL above-average precipitation and salinity in Matagorda Bay.

Precip and Salinity Correlations Result: Matagorda Bay and PAL			PrecipPAL	Salinity
Kendall's tau_b	PrecipPAL	Correlation Coefficient	1.000	-.206*
		Sig. (2-tailed)	.	.020
		N	60	60
	Salinity	Correlation Coefficient	-.206*	1.000
		Sig. (2-tailed)	.020	.
		N	60	60

*. Correlation is significant at the 0.05 level (2-tailed).

Analysis 2: Precipitation and Morbidity Cases

Galveston Bay System

The Phi test is completed using a cross tabulation in SPSS. After cross tabulating, the resulting output shows that the occurrence of morbidity cases is not significantly concordant or discordant with above average volume precipitation. The level of significance for the Phi test is -.014. The approximate significance resulting from the test is .914, which shows that there is clearly no link between whether or not precipitation exceeds normal averages and the occurrence of reported cases (Table 12).

Table 12: Cross tabulation between above-normal precipitation and the occurrence of V.v. morbidity cases in the Galveston Bay system.

IHA and Galv VibReport * AboveNormPrecip Crosstabulation		AboveNormPrecip		Total
		N	Y	
VibReport	N	22	15	37
	Y	14	9	23
Total		36	24	60

Table 13: Resulting output showing no significant correlation between above-normal precipitation and morbidity cases in the Galveston Bay system.

Results: IHA and Galv Symmetric Measures		Value	Approx. Sig.
Nominal by Nominal	Phi	-.014	.914
	Cramer's V	.014	.914
N of Valid Cases		60	

Matagorda Bay System

As with the Matagorda data, the Phi test was created in SPSS using the cross-tab command in descriptive statistics (Table 14). Again, the results between above normal levels of precipitation in Matagorda Bay and the occurrence of morbidity do not appear to have a statistical relationship. However the approximate significance is not as high (.567) as it is with the Houston and Galveston Bay data (Table 15).

Table 14: Cross tabulation between above-normal precipitation and the occurrence of V.v. morbidity cases in the Matagorda Bay system.

PAL and Mat VibReport * AboveNormPrecip Crosstabulation		AboveNormPrecip		
		N	Y	Total
VibReport	N	36	20	56
	Y	2	2	4
Total		38	22	60

Table 15: Resulting output showing no significant correlation between above-normal precipitation and morbidity cases in the Matagorda Bay system.

Results: PAL and Mat Symmetric Measures		Value	Approx. Sig.
Nominal by Nominal	Phi	.074	.567
	Cramer's V	.074	.567
N of Valid Cases		60	

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Results from the Kendall's Tau-b correlation analysis show that there is a clear and significantly negative correlation between precipitation and salinity in both bay systems. This result was expected based on evidence presented in past studies (Mott et al., 2008, Ramirez et al., 2008) and is also a logical result. An increase in high-magnitude precipitation events in a shallow estuarine system will cause local salinity levels to temporarily drop.

Correlation analysis between precipitation and water temperature in both bay systems shows no significant relationship. It is expected that seasonality (time of the year) will be a greater determining factor for changes in water temperature. High water temperatures influence the presence of *V. vulnificus,* but changes to that particular variable in the area not directly correlated to precipitation events in the study area.

The relationship results of the Phi test for concordance or discordance between the occurrence of *V. vulnificus* morbidity cases and above-normal precipitation events in both bay systems are not significant. A potential source of error in this analysis is the small sample size of morbidity cases. There are only 30 reported cases identified to the Galveston Bay system and 5 for the Matagorda Bay system over a 5-year period. Perhaps repeating this study at a more coarse scale over a longer time period and using a greater sample of morbidity cases will have a different outcome.

As was previously stated, underreported numbers of infection may also have affected the amount of morbidity data used in this case study. It is hypothesized that analysis of the entire coastal region of Texas and geographically identified morbidity cases may result in a stronger study and possibly different results.

CHAPTER 7

FUTURE IMPLICATIONS AND STUDY

If global and sea surface temperatures continue to rise at the rate predicted (Patz et al. 2000), corresponding changes in the hydrologic cycle can also be expected, especially in humid-subtropical and tropical locations where water temperatures are consistently warm. Warm coastal waters will expand, resulting in sea levels rising, an increase in flood events, and larger hydrologic events in locations with sea temperatures above 26°C (Patz and Olson 2006). This rise in flood events and the resulting decrease in salinity levels may increase the geospatial range of *Vibrio vulnificus*.

Environmental changes to the coastal and estuarine ecosystems of the Texas Gulf Coast may also affect the flora and fauna, which harbor the hazardous bacteria. Future analysis of population clustering in coastal urbanized areas will give the researcher a better idea of where morbidity clusters occur, depending on where the populations are concentrated. In coastal locations where temperatures are high and salinity temperatures are moderated either by a freshwater source inland or high levels of precipitation, such analysis will be useful in determining areas able to support *Vibrio vulnificus* growth and reproduction.

In the 2011 Regional Water Plan for the state of Texas, the Texas Water Development estimated a +50% rise in population for Harris County, +17% for Galveston, and +17% for Matagorda County (Table 1). These increases in the resident population combined with increased weather variability in an already environmentally sensitive ecosystem may very well be a contributing factor to the number of reported water-borne diseases in the Texas Gulf Coast. General knowledge of the bacteria is not always made readily available to the public, and specific water bodies identified that may be potentially hazardous after a heavy precipitation event are not always identifiable.

Over the last four decades, sufficient scientific analysis of *Vibrio vulnificus* has identified the specific environmental needs of the pathogen. Safety measures are taken during shellfish harboring, and information about food poisoning is readily available through the Center for Disease Control and the GCOIC. It appears, however, that those test variables may not determine when and where morbidity cases are reported. More research may need to be performed to determine specific recreational and industrial locations that are high-traffic locations during hurricane season in the study area and in the entire Texas Gulf Coast.

Extensive study is required to determine how much fecal coliform affects the presence of *Vibrio vulnificus* in order to determine potential locations within large bay systems that are ideal for bacterial growth. The general migration patterns of seasonal populations may also be studied to determine if there is a connection between popular recreation locations and reported morbidity cases.

APPENDIX 1

MORBIDITY DATA

Reported *Vibrio vulnificus* Morbidity Cases and Sites Texas Coast (1999-2003)			
ONSET	**SHELLFISH**	**SHELLFISH SITE**	**WOUND EXPOSURE SITE**
Apr-99	1	E. Galveston Bay	N/A
Apr-99	1	Galveston Bay	N/A
May-99	1	Galveston Bay	N/A
May-99	Unknown	Unknown	N/A
Jul-99	0	N/A	Baycliff/Kemah/Texas City
Jul-99	0	N/A	Galveston Beach
Jul-99	0	N/A	Galveston Bay
Aug-99	0	N/A	Aransas Pass
Aug-99	Unknown	Unknown	Unknown
Aug-99	Unknown	Unknown	Unknown
Aug-99	0	N/A	Trinity Bay
Sep-99	0	N/A	Galveston Bay
Sep-99	1	Unknown	N/A
Jan-99	0	N/A	Bay Oaks Harbor, Baytown
Dec-99	1	Galveston Bay	N/A
May-00	1	Galveston Bay	N/A
Jun-00	1	Galveston Bay	N/A
Jul-00	0	N/A	Matagorda Bay
Jul-00	1	Galveston Bay	N/A
Jul-00	1	Galveston Bay	N/A

Table Continued:

Reported *Vibrio vulnificus* Morbidity Cases and Sites Texas Coast (1999-2003)			
ONSET	**SHELLFISH**	**SHELLFISH SITE**	**WOUND EXPOSURE SITE**
Jul-00	0	N/A	Trinity Bay
Sep-00	1	LA	N/A
Sep-00	1	Galveston Bay	N/A
1-May	0	N/A	Brazos River near coast
1-May	1	Lake MacIHAs, LA	N/A
1-May	0	N/A	Lavaca Bay
1-Jun	0	N/A	Galveston Bay
1-Jun	0	N/A	Canal 4 mi. NW of Raymondville
1-Jul	1	Galveston Bay	N/A
1-Aug	1	Galveston Bay	N/A
1-Aug	0	N/A	Galveston Bay
1-Sep	0	N/A	Port Lavaca
1-Sep	1	Unknown	N/A
1-Oct	1	Unknown	N/A
2-Jun	0	N/A	Unknown
2-Jun	1	Galveston Bay	N/A
2-Jul	1	Galveston Bay	N/A
2-Jul	Unknown	Unknown	Unknown
2-Jul	0	N/A	Aransas Bay
2-Jul	0	N/A	Unknown
2-Jul	0	N/A	Unknown
2-Aug	0	N/A	Matagorda Bay
2-Aug	0	N/A	Bolivar Peninsula
2-Aug	0	N/A	Port O'Connor
2-Aug	1	Unknown	N/A
2-Sep	Unknown	Unknown	Unknown
2-Sep	0	N/A	Unknown
2-Oct	1	Unknown	N/A

Table Continued:

Reported *Vibrio vulnificus* Morbidity Cases and Sites Texas Coast (1999-2003)			
ONSET	**SHELLFISH**	**SHELLFISH SITE**	**WOUND EXPOSURE SITE**
2-Oct	1	Galveston Bay	N/A
3-May	0	N/A	Palacios area on bay
3-Jun	0	N/A	Galveston, West Bay
3-Jul	0	N/A	Aransas Pass
3-Jul	0	N/A	
3-Jul	0	N/A	Port Arthur
3-Aug	1	Galveston Bay	N/A
3-Sep	0	N/A	Matagorda Bay
3-Oct	1	Galveston Bay	N/A
3-Oct	1	Galveston Bay	N/A
3-Nov	1	Unknown	N/A
3-Nov	1	Galveston Bay	N/A

APPENDIX 2

PHI TABLE DATA

PHI Table Data: IHA precipitation, normal NOAA data, and V. morbidity cases				
Date	Houston Precip cm	Normal Precip (cm)	Vibrio cases?	Precip above normal?
Jan-99	5.38	8.58	Y	N
Feb-99	2.03	8.13	N	N
Mar-99	8.74	8.66	N	Y
Apr-99	2.69	8.41	Y	N
May-99	10.49	12.93	Y	N
Jun-99	13.36	15.06	N	N
Jul-99	12.98	7.63	Y	Y
Aug-99	1.27	7.55	Y	N
Sep-99	3.48	10.46	Y	N
Oct-99	1.42	14.78	N	N
Nov-99	3.89	11.02	N	N
Dec-99	5.59	9.5	Y	N
Jan-00	3.18	8.58	N	N
Feb-00	5.89	8.13	N	N

Table Continued:

PHI Table Data: IHA precipitation, normal NOAA data, and V. morbidity cases				
Date	Houston Precip cm	Normal Precip (cm)	Vibrio cases?	Precip above normal?
Mar-00	3.43	8.66	N	N
Apr-00	14.02	8.41	N	Y
May-00	31.37	12.93	N	Y
Jun-00	8.36	15.06	Y	N
Jul-00	1.63	7.63	Y	N
Aug-00	5.36	7.55	Y	N
Sep-00	11.02	10.46	Y	Y
Oct-00	8.31	14.78	N	N
Nov-00	21.59	11.02	N	Y
Dec-00	6.78	9.5	N	N
Jan-01	10.8	8.58	N	Y
Feb-01	2.08	8.13	N	N
Mar-01	20.24	8.66	N	Y
Apr-01	5.08	8.41	N	N
May-01	8.97	12.93	Y	N
Jun-01	48.79	15.06	N	Y
Jul-01	5.21	7.63	Y	N
Aug-01	12.27	7.55	Y	Y
Sep-01	22.4	10.46	Y	Y
Oct-01	22.73	14.78	N	Y
Nov-01	6.55	11.02	N	N
Dec-01	15.7	9.5	N	Y
Jan-02	3.15	8.58	N	N

Table Continued:

PHI Table Data: IHA precipitation, normal NOAA data, and V. morbidity cases				
Date	Houston Precip cm	Normal Precip (cm)	Vibrio cases?	Precip above normal?
Feb-02	2.26	8.13	N	N
Mar-02	5.99	8.66	N	N
Apr-02	9.63	8.41	N	Y
May-02	4.55	12.93	N	N
Jun-02	11.53	15.06	Y	N
Jul-02	18.06	7.63	Y	Y
Aug-02	13.89	7.55	Y	Y
Sep-02	20.37	10.46	N	Y
Oct-02	37.21	14.78	Y	Y
Nov-02	10.67	11.02	N	N
Dec-02	14.35	9.5	N	Y
Jan-03	5.31	8.58	N	N
Feb-03	10.36	8.13	N	Y
Mar-03	5.18	8.66	N	N
Apr-03	3.71	8.41	N	N
May-03	0.15	12.93	N	N
Jun-03	9.19	15.06	Y	N
Jul-03	13.61	7.63	N	Y
Aug-03	11.35	7.55	Y	Y
Sep-03	17.25	10.46	N	Y
Oct-03	12.67	14.78	Y	N
Nov-03	19.86	11.02	Y	Y
Dec-03	7.59	9.5	N	N

Table Continued:

PHI Table Data: PAL precipitation, normal NOAA data, and V. morbidity cases				
Date	Palacios Precip cm	Normal Precip cm	Vibrio cases?	Precip above normal?
Jan-99	3.43	8.56	N	N
Feb-99	2.59	5.97	N	N
Mar-99	6.15	7.62	N	N
Apr-99	4.47	6.6	N	N
May-99	5.44	10.69	N	N
Jun-99	6.45	11.4	N	N
Jul-99	19.35	12.09	N	Y
Aug-99	0.21	7.52	N	N
Sep-99	13.51	13.03	N	Y
Oct-99	0.17	12.65	N	N
Nov-99	0.06	10.06	N	N
Dec-99	4.7	7.06	N	N
Jan-00	3.68	8.56	N	N
Feb-00	3.38	5.97	N	N
Mar-00	8	7.62	N	Y
Apr-00	6.55	6.6	N	N
May-00	13.89	10.69	N	Y
Jun-00	5.82	11.4	N	N
Jul-00	0.12	12.09	Y	N
Aug-00	0.22	7.52	N	N
Sep-00	4.09	13.03	N	N
Oct-00	3.48	12.65	N	N

Table Continued:

PHI Table Data: PAL precipitation, normal NOAA data, and V. morbidity cases				
Date	Palacios Precip cm	Normal Precip cm	Vibrio cases?	Precip above normal?
Nov-00	7.54	10.06	N	N
Dec-00	8.46	7.06	N	Y
Jan-01	12.83	8.56	N	Y
Feb-01	0.12	5.97	N	N
Mar-01	6.45	7.62	N	N
Apr-01	0.03	6.6	N	N
May-01	11.28	10.69	N	Y
Jun-01	14.45	11.4	N	Y
Jul-01	5.41	12.09	N	N
Aug-01	20.4	7.52	N	Y
Sep-01	11.35	13.03	N	N
Oct-01	15.52	12.65	N	Y
Nov-01	13.18	10.06	N	Y
Dec-01	7.44	7.06	N	Y
Jan-02	3.91	8.56	N	N
Feb-02	0.09	5.97	N	N
Mar-02	0.12	7.62	N	N
Apr-02	7.52	6.6	N	Y
May-02	6.25	10.69	N	N
Jun-02	14	11.4	N	Y
Jul-02	7.82	12.09	N	N
Aug-02	8.51	7.52	Y	Y

Table Continued:

PHI Table Data: PAL precipitation, normal NOAA data, and V. morbidity cases				
Date	Palacios Precip cm	Normal Precip cm	Vibrio cases?	Precip above normal?
Sep-02	17.5	13.03	N	Y
Oct-02	23.62	12.65	N	Y
Nov-02	10.74	10.06	N	Y
Dec-02	11.73	7.06	N	Y
Jan-03	7.95	8.56	N	N
Feb-03	5.97	5.97	N	N
Mar-03	6.81	7.62	N	N
Apr-03	0.04	6.6	N	N
May-03	0.07	10.69	Y	N
Jun-03	11.68	11.4	N	Y
Jul-03	17.07	12.09	N	Y
Aug-03	5.84	7.52	N	N
Sep-03	25.37	13.03	Y	Y
Oct-03	9.63	12.65	N	N
Nov-03	3.78	10.06	N	N
Dec-03	3.63	7.06	N	N

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