EXAMINING THE USE OF A CONTRAFLOW EVACUATION METHOD FOR TROPICAL CYCLONE EVACUATIONS IN NUECES COUNTY, TEXAS

by

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ABSTRACT

Millions of residents along the United States Gulf Coast live with the threat of tropical cyclones. These potentially devastating storms, more commonly referred to as hurricanes in the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and in the eastern or central North Pacific Ocean east of the International Dateline, bring damaging winds, heavy rains, severe flooding, and powerful storm surges that can quickly devastate any area in their path. Due to the dangers of these storms, coastal areas create evacuation plans that allow area residents to safely leave the city before they are impacted. This study examined a contraflow evacuation plan for Corpus Christi, Texas in an attempt to model what a major tropical cyclone evacuation might look like for this region. Using ArcGIS, several potential evacuation routes were created in Nueces County, Texas to simulate an evacuation under “optimal,” “expected,” and “worst case” scenarios. Results of this study show that while a contraflow evacuation plan has the potential to cause severe traffic congestions and extremely long evacuation times, under both “optimal” and “expected” conditions it serves as an effective evacuation method out of the city.

I. INTRODUCTION

The world has begun to see a change in climate that brings with it a need to examine policies and procedures surrounding issues with coastal land use, resource conservation, energy policy, and disaster management. Looking at disaster management, and specifically evacuation policy along the United States Gulf Coast, current strategies must be examined frequently to ensure that they are robust enough to deal with any mass evacuation order that might be given in the future. Gulf Coast state officials also need to be sure that their existing policies ensure the safety of their residents should a major tropical cyclone strike. The scientific community now warns that a warming global climate can bring rising sea levels, changes in storm frequency and intensity, and land degradation, among others, to which the overpopulated coastal regions will be forced to adapt (Frey et al., 2010; Mousavi et al., 2011; Warner and Tissot, 2012). With the potential for storm frequency and intensity changes, city and county emergency managers as well as local government leaders along the Gulf Coast are mandated to put in place evacuation strategies.

In order to provide safe environments for their residents, emergency managers and local government leaders in Gulf Coast cities must examine and evaluate their current disaster policies, including those that focus on evacuation, specifically focusing on evacuation times, potential for traffic congestion and overall effectiveness. If deemed necessary, policy reviews should be conducted to determine the best practices for conducting mass evacuations from natural disasters, particularly from tropical cyclones. Additionally, these areas might benefit from examining evacuation experiences of other coastal areas, to determine the best possible ways to evacuate a populated area.

Additionally, local officials might observe how information is disseminated to residents to ensure that they are able to evacuate as quickly and safely as possible. The Gulf Coast is an area that experiences landfall from several tropical cyclones each year. Should these systems increase in intensity, the region needs to be as prepared as possible to handle the mass evacuations that will occur (Fonseca et al., 2009; Dixit and Wolshon, 2014). By examining policies from other regions, policymakers can determine what may or may not work in their area, in an effort to develop strategies more capable of dealing with mass evacuations.

City planners, local government officials, and emergency managers are constantly working to develop and implement the most effective evacuation strategies as possible for their particular jurisdictions. It was the goal of this study to evaluate the contraflow evacuation plans in Corpus Christi, Texas (Figure 1), looking specifically at its potential implications including evacuation times, effects on traffic congestion, and overall plan effectiveness.

Figure 1. Location of Nueces County, Texas on the Gulf Coast. (Google Maps – www.maps.google.com)

II. BACKGROUND AND LITERATURE REVIEW

It is generally agreed upon that the global climate is changing which will likely alter the weather and storm patterns in several ways (Church and White, 2006; IPCC, 2015; Irish et al., 2010; Mousavi et al., 2011; Yang et al., 2014). Along the United States Gulf Coast, sea level rise and a change in tropical cyclone frequency and intensity are two of the major issues that the area may face in the future (Frey et al., 2010; Mousavi et al., 2011; Warner and Tissot, 2012). A warming planet means warmer waters, which many researchers believe will produce stronger storms (Mousavi et al., 2011). When these storms combine with higher sea levels, the consequences are likely to be disastrous (Mousavi et al., 2011).

Using prediction models such as the Model for the Assessment of Greenhouse-gas Induced Climate Change/a regional climate SCENario GENerator (MAGICC/SCENGEN), which measures and predicts air temperature at the sea surface, researchers have predicted a steady rise in sea surface temperatures through 2080 (Frey et al., 2010). The warmer temperatures are a problem for this area because as the water warms it expands, and in turn increases sea level (Frey et al., 2010; Irish et al., 2010; Mousavi et al., 2011). Using MAGICC/SCENGEN, Frey predicts an increase of 0.36-1.38°C in sea surface temperature by the 2030s and 0.096-5.02°C by the 2080s, which could translate into a 7.5-14.4 centimeters (cm) and 20.9-58.4 cm increase in Gulf Coast sea levels respectively (Frey et al., 2010). This increased sea level would cause higher storm surges and thus a need to evacuate even more people during tropical cyclones. It is unclear how much sea levels will actually rise in the future, but coastal areas need to be prepared for any changes that may occur.

Tropical cyclone strength is also closely tied to sea surface temperature, with warmer waters tending to produce lower pressure storms meaning more powerful tropical cyclones (Frey et al., 2010). Lower pressure in a storm will greatly increase its overall intensity, with studies showing that a 10 to15 percent increase in storm surge is possible for every 10 millibar (mb) drop in pressure (Mousavi et al., 2011). When stronger tropical cyclones combine with potentially higher sea levels, there is a much greater potential for damage, and an increased need for evacuations in Gulf Coastal areas.

Local Policies

Due to these predictions, it is generally agreed upon that existing disaster plans must be regularly evaluated to ensure the safety of area residents (Warner and Tissot, 2012). These plans should consider possible future sea level rise and its implications for coastal communities, the management of utilities and other emergency services, as well as evacuation strategies for when major tropical cyclones do impact an area (Fonseca et al., 2009; Warner and Tissot, 2012; Yang et al., 2014).

The U.S. Gulf Coast is an area of high vulnerability due to an increasing population, which puts more people at risk from tropical cyclones and flooding (Chen et al., 2007; Thatcher, Brock, and Pendleton, 2013). Additionally, rising sea levels compound the impacts from tropical cyclone storm surges and land subsidence, putting the population at an even greater risk for loss of life and land (Thatcher, Brock, and Pendleton, 2013). Several plans are currently in place in Gulf Coast communities that focus on the need to restore services such as electricity, phone, and wastewater as quickly as possible, however, more work needs to be done to ensure the safety of citizens during an emergency (Scharfenaker, 2006).

Over the last few years, existing policies have begun to shift away from focusing on mitigation to those that look more at adapting to changes seen throughout the area (Boswell, Deyle, and Smith, 1999; Cigler, 2009). As the focus of these new plans shift, so must the plans themselves, in order to better provide protection for the local population. Many cities such as Corpus Christi do currently have plans in place to assist them during natural disasters. These plans consist of strategies for evacuation, utility management, economic preparations, and sea level rise among others (Boswell, Deyle, and Smith, 1999; Scharfenaker, 2006; Chen et al., 2007; Thatcher, Brock, and Pendleton, 2013). However, even their published plan states that it will not be sufficient to evacuate all area residents, which will certainly be a problem when evacuation orders are issued (Texas Department of Transportation, 2015).

Tropical Cyclones

Tropical cyclones are large, cyclonic storms that form over warm tropical and subtropical waters (National Hurricane Center, 2016). This study focused on tropical cyclones that form in the North Atlantic Ocean, as they are the storms that impact the United States Gulf Coast. These storms tend to form between 5 and 30 degrees North Latitude and can originate anywhere in the North Atlantic Ocean (National Hurricane Center, 2016) (Figure 2). Tropical cyclones need warm most air in order to form, and tend to occur from late Spring to early Fall, with the actual hurricane (tropical cyclones are referred to as hurricanes in the Atlantic Basin) season spanning from June 1st through November 30th (National Hurricane Center, 2016).

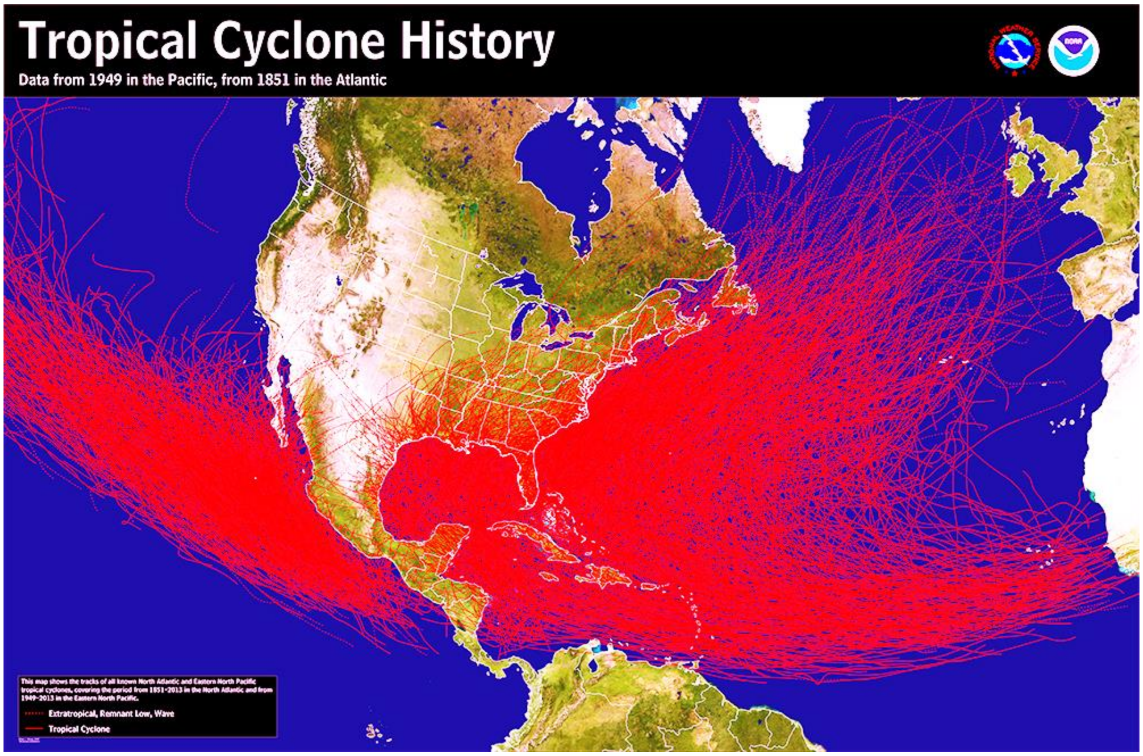

Figure 2. Atlantic Basin tropical cyclone paths. (National Hurricane Center - http://www.nhc.noaa.gov/climo/)

Storm intensity is classified on the Saffir-Simpson Hurricane Wind Scale, which ranks storms based on sustained wind speeds. The scale categorizes storms using five main categories and ranges from Category 1 which is the weakest with sustained winds of 119-153 kilometers per hour (kph), (74-95 miles per hour (mph), to Category 5 having the strongest winds with sustained speeds of greater than 252 kph (greater than 157 mph) (National Weather Service, 2012) (Table 1). A tropical cyclone receives a classification of "major" when it reaches Category 3 status (178-208 kmh, 111-130 mph) because at that point it has the potential to cause extreme structural damage, tree uprooting from powerful winds, and flooding from heavy rains and storm surges that can be devastating to coastal residents (Chen, 2007; Cigler, 2009; National Hurricane Center, 2016).

Table 1. Saffir-Simpson hurricane wind scale

Storm Category	km/h	mph
1	119-153 km/h	74-95 mph
2	154-177 km/h	96-110 mph
3 (major)	179-208 km/h	111-129 mph
4 (major)	209-251 km/h	130-156 mph
5 (major)	> 252 km/h	> 157 mph

As stated above, the official hurricane season for the Atlantic Basin runs from June 1st through November 30th, but storms can, and occasionally do occur outside of these bounds. Peak storm activity is generally seen from mid to late August, extending into October as water temperatures are warmest and will feed these massive storms (National Hurricane Center, 2016).

Tropical cyclones are named to provide easy identification and reference based on a list from the United Nations World Meteorological Organization. The naming lists are set for six years at a time and repeat on the seventh. Names repeat unless there is a particularly devastating tropical cyclone such as Andrew in 1992 or Katrina in 2005 (National Hurricane Center, 2015). When a devastating storm such as these strike, the name is retired and not used again.

A typical season includes many storms of differing categories. Between 1968 and 2014 there has been an average of 11.8 named storms (including tropical depressions and tropical storms) originating in the Atlantic Basin (NOAA, 2015). Of these, 6.2 are strong enough to be classified as a Category 1 storm, and 2.4 reach Category 3, or “major” storm level (NOAA, 2015). Storms originate in the Atlantic Basin, so they do not always move into the Gulf or impact Texas, but a large portion do. From 1851 to 2014, the Texas coast was struck directly by 63 tropical cyclones, 19 of which were classified as

Category 3 or higher (NOAA, 2016). This is second only to Florida, which is impacted by 40 percent of all Atlantic tropical cyclones (NOAA, 2016). Of the storms to strike Texas since 1900, fourteen of them have directly impacted Nueces County and the Corpus Christi area (National Hurricane Center, 2016) (Figure 3). With the potential of storms to impact Texas, and particularly the Nueces County area, it is clear that these areas need effective policies to protect the lives and properties of area residents during the storms, and to manage their damaging effects in the aftermath.

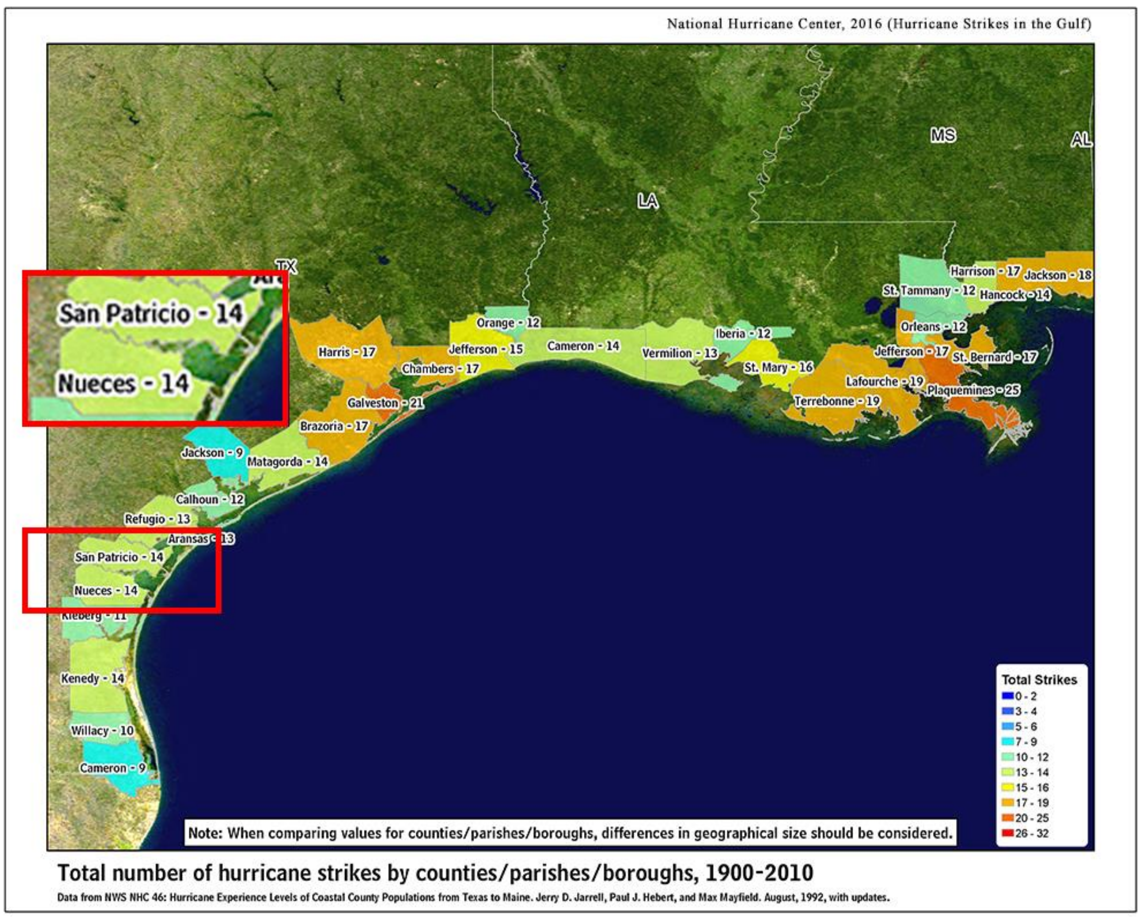

Figure 3. Tropical cyclone strikes on the Gulf Coast, 1900-2010.
(National Hurricane Center - http://www.nhc.noaa.gov/climo/)

Contraflow

When looking at evacuation strategies, several regions have begun implementing contraflow methods in their evacuation plans in an attempt to evacuate as many people as possible from areas threatened by tropical cyclones (Fonseca et al., 2009; Dixit and Wolshon, 2014). In most cases, contraflow is only implemented during large tropical cyclones, Categories 4 or 5, because so much planning and labor is required to initiate it. Because of this, only a few studies are available which have actual contraflow evacuation data and do not use computer-generated models (Wolshon, 2007).

Contraflow evacuations employ methods to reverse the flow of traffic on major roadways to move the maximum number of people out of an area in the shortest amount of time (Fonseca et al., 2009; Dixit and Wolshon, 2014). While these plans do allow more people to leave an area, one study has shown that they have the potential to significantly decrease traffic flow, which could leave a larger number of people stranded on the roadway as the storm approaches (Dixit and Wolshon, 2014). Contraflow plans are clearly not perfect, but have been proven to be effective in the past when used for evacuations (Wolshon, 2001; Dixit and Wolshon, 2014).

There are three primary types of contraflow plans that may be used for varying degrees of evacuation needs. All plans typical focus on federal or state highways with two or more adjacent lanes flowing towards an area (inbound) and two or more adjacent lanes flowing away from an area (outbound). The first type of contraflow plan calls for the reversal of one of the inbound lanes into an outbound lane, thus moving the traffic out of an area (Wolshon, 2001) (Figure 4B-One Contraflow Lane). This plan increases traffic flow by opening another lane to motorists, while still allowing inbound access to the city or to the event that traffic is heading away from. The next method opens the shoulder or shoulders of the existing outbound lane to use for evacuation (Wolshon, 2001) (Figure 1C – Shoulder Lane Evacuation). Depending on whether one or both shoulders are opened, this method may add up to two additional lanes to the evacuation route. However, shoulder lanes are not always constructed to the same standards as main travel lanes and often will not allow for travel at the same speed as normal travel lanes (Wolshon, 2001). The final method is a full reversal of all inbound lanes, sometimes referred to as "One-Way-Out," so that all lanes of traffic are moving in one direction away from an area (Wolshon, 2001) (Figure 1D – Two Contraflow Lanes). This plan allows for the maximum number of people to be evacuated from an area, generally in the shortest amount of time. Despite being one of the most effective means of mass evacuation, issues can and do arise when implementing this type of evacuation. These issues will be discussed later in this section.

The main benefit of contraflow, and the reason it is often used for evacuations, is that it increases the maximum traffic output from an area. Traffic flow is generally reduced during an evacuation under normal conditions as motorists tend to drive slower and face congestions from an excess of vehicles on the roadways (Wolshon, 2001). Each lane that is opened for contraflow, however, increases this output and allows for more people to leave an area. Contraflow lanes will not have the same capacity as the lanes moving in the normal direction under non-evacuation conditions, but adding one contraflow lane has shown to increase overall traffic flow by up to 30 percent, and up to 67 percent when adding two contraflow lanes (Wolshon, 2001; Wolshon, 2007; Fonseca et al., 2009; Fries et al., 2011). This type of increase can make a tremendous difference when an area is facing an approaching tropical cyclone or other disaster.

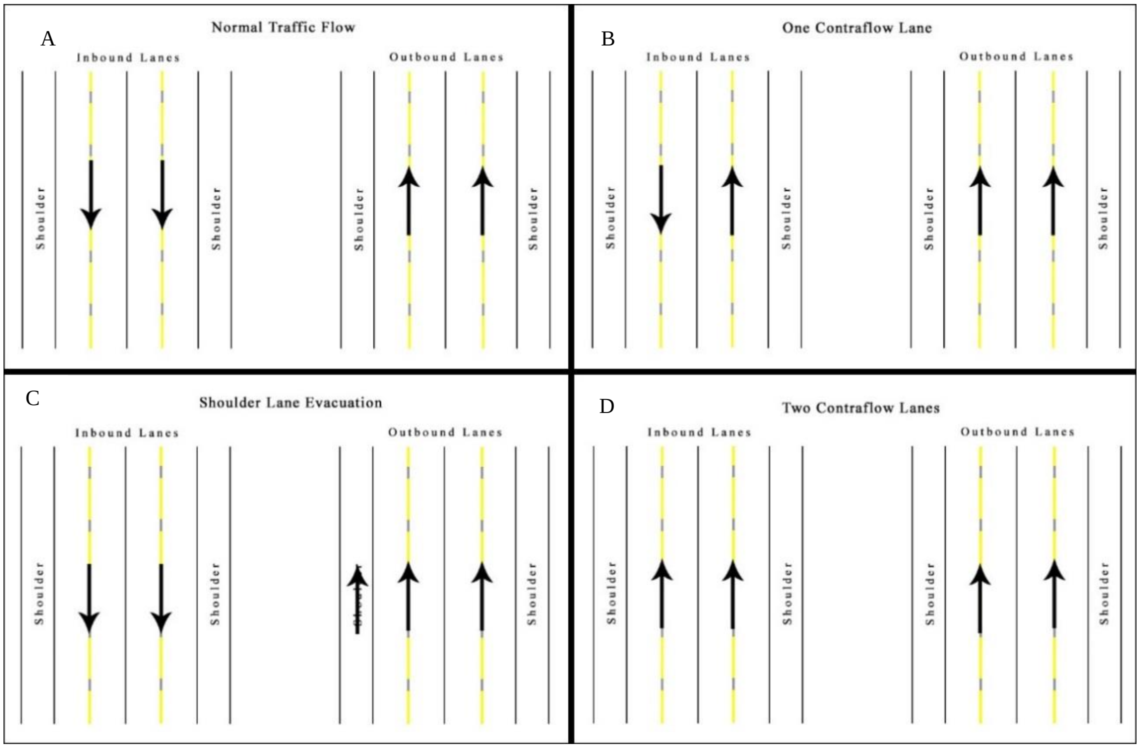

Figure 4. Three primary types of contraflow evacuation strategies.

Despite the benefits of increased traffic flow, and the additional people who are able to evacuate safely from an area, contraflow has several drawbacks to be considered. One major problem with contraflow is signage and facility access for those using the contraflow lanes. Entrance and exit ramps are designed to be used from one particular direction making it very hard to find suitable exits for those using the reversed lanes. This causes problems when people need to exit for food, gas, restroom facilities, or other needs (Wolshon, 2001).

Another major issue with contraflow is motorist safety during the evacuation itself. Traffic accidents tend to occur at higher rates on contraflow lanes due to a lack of signage and safety measures designed for normal flowing traffic (Wolshon, 2001; Fries et al., 2011). Local officials must ensure that all entrances are blocked and that all other vehicles are removed from the lanes that are going to be reversed before implementing contraflow or they face the dangers of head on collisions (Wolshon, 2001). Exits on the contraflow lane itself must be closely monitored as well to ensure drivers do not exit an incorrect place into oncoming traffic.

Access for emergency vehicles is another obstacle, particularly in situations where all lanes are reversed. In these situations, there is no way for emergency personal to get back into the city. If this happens, people may be left stranded in their homes or vehicles, communications might be lost with no way to fix services, while crimes might be committed with no police to assist (Wolshon, 2001).

Finally, cost and implementation must be considered with contraflow evacuations. In most cases, a large force is required to get contraflow started, which may be extremely expensive (Wolshon, 2001). Additionally, the creation of the plan itself as well as the necessary infrastructure improvements are likely to be quite costly to local governments, particularly for infrastructure that may never actually be put to use (Wolshon, 2001). To have a truly effective plan, a great amount of research and testing must be done, which is generally expensive to conduct. This is certainly not an exhaustive list of all problems that can arise, but does highlight several major issues that communities need to consider before designing or implementing contraflow plans.

Contraflow History

Contraflow is not a new concept in traffic management; it has been used for a long time to alleviate congestion and control traffic flow. It has been successfully implemented to manage commuter flow over bridges and arterial roads during rush hour commutes, and to help clear venue parking lots during special events (Wolshon, 2001). Washington, D.C., for example, has implemented contraflow on Connecticut Avenue during rush hour periods to facilitate traffic flow and reduce local congestion (Wolshon, 2001). These instances, however, are conducted on a much smaller scale than interstate contraflow is for evacuations. Because of this, contraflow for traffic control is often easier to implement, manage, and are generally safer due to slower speeds and drivers being familiar with the process (Wolshon, 2001). However, using contraflow on interstate highways introduces numerous factors that can make the process much more dangerous and difficult to implement (Wolshon, 2001).

Contraflow was first used for a tropical cyclone evacuation on Interstate Highway (IH-16) near Savannah, Georgia, as well as Interstate Highway (IH-26) outside of Charleston, South Carolina in 1999 during Hurricane Floyd (Wolshon, 2001). While it did allow for more people to get out of the area quickly, due to the nearly 67 percent increase in traffic flow, it also brought to light some of the potential problems that may be caused by contraflow (Wolshon, 2001; Wolshon, 2007).

Contraflow was ordered by Texas Governor, Rick Perry for the evacuation of Galveston County, Texas during Hurricane Rita in 2005, which led to one of the largest evacuations in U.S. history (Chiu et al., 2008). This particular evacuation, while ultimately effective, led to serious problems with traffic congestion and shed light on some of the potential hazards of traffic congestion that may be experienced during a contraflow evacuation (Chiu et al., 2008; Joh et al., 2014; Medium.com, 2016) (Figure 5).

Contraflow was also ordered in 2005 for the evacuation of the New Orleans, Louisiana are during Hurricane Katrina. This evacuation posed the unique challenge of being the first time the entirety of a major urban center needed to be completely evacuated (Boyd, Wolshon, and Van Heerden, 2009). In addition to the massive scale of the evacuation, it was also incredibly effective, nearly cutting the expected time predicted by city officials in half, due in large part to excellent planning and the implementation of both phased evacuations and contraflow operations (Wolshon, 2007; Boyd, Wolshon, and Van Heerden, 2009).

Figure 5. Traffic congestion during the evacuation of Hurricane Rita.
(Medium.com - https://medium.com/the-weather-channel/evacuate-or-stay-1f1c87b1d62c#.55quovo0z)

Contraflow has been used for other evacuations as well, including Hurricane Ivan in 2004 and Hurricane Gustav in 2008, both of which called for the evacuation of New Orleans, and both conducted with varying degrees of success. The early stages of the Hurricane Ivan evacuation saw reduced traffic flow for several hours with a steady climb towards normal traffic flow (Dixit and Wolshon, 2014). During Hurricane Gustave, however, the evacuation was ordered when traffic was already nearly at a standstill, but greatly improved flow after roughly six hours (Dixit and Wolshon, 2014). Contraflow plans have been established for many other areas aside New Orleans, however, these incidents provide excellent examples of the variation that can be seen when using contraflow, particularly when they are all being used in the same area. Multiple plans have also been established in Georgia, Texas, Mississippi, South Carolina, and Florida (Wolshon 2001). In addition to these cases, traffic models have been created to simulate contraflow evacuations using various storm categories, and across multiples locations along the Gulf Coast. Results show that contraflow proved to be more effective at evacuating large numbers of people than standard methods (Fonseca et al., 2009; Fries et al., 2011). This suggests that, despite the potential drawbacks of contraflow, it is clearly a viable option when it comes to mass evacuation.

Risk Perception Theory

Risk perception theory was examined to understand the reasons that influence individuals' decisions to evacuate, and ultimately influence the efficiency of the evacuation itself. This theory attempts to weigh the various factors that influence both individual and group decisions to act during an event, in this case a tropical cyclone evacuation. Several factors including demographics, age, number of dependents, income level, physical condition, proximity to the storm, animal responsibility, and experience with past storms influence decisions to evacuate or shelter in place (Stein, Dueñas-Osorio, and Subramanian, 2010). It is often the case that those in the same area will not perceive the dangers from an approaching storm in the same way as others, and thus, behave differently towards the threat. When this happens, some residents may choose to stay when they should be evacuating, or, they may evacuate when they should be staying in place. Those that evacuate with no actual need to are sometimes referred to as “shadow evacuees” because they follow those that are evacuating regardless of the need (Stein, Dueñas-Osorio, and Subramanian, 2010). These individuals perceive the storm to be a far greater threat than it might actually be, causing them to react in a way they feel is going to keep them safe. Often, however, this results in additional people on the roadways and further exacerbates the already heavy traffic congestion generally seen during a mass evacuation (Stein, Dueñas-Osorio, and Subramanian, 2010).

Shadow evacuations and unnecessary high levels of risk perception occur in part because of the way evacuation orders are issued. Evacuation orders are given to ensure that those at the greatest risk from the storm are kept safe when the storm strikes. In the case of tropical cyclones, evacuation orders are often given to those that are threatened by storm surge because it is one of the most devastating aspects of a storm (Stein, Dueñas-Osorio, and Subramanian, 2010). These orders, however, only look at the science of the storm and do not account for the perceptions of those in the storm’s path. Some individuals can feel more threatened due to the previously stated reasons and try to escape to safety even though they may live in an area that is not technically in an evacuation zone or in danger of flooding. The opposite can also be true. Residents who have lived through storms in the past may believe they are not in danger despite the evacuation orders and decide to shelter in place rather than evacuate. They perceive that there is not enough danger to evacuate and choose to stay. Both decisions are likely to prove to be dangerous, even deadly, not only to those making the decisions to stay or leave, but to those that are either evacuating with the additional people, or to the emergency responders who may have to rescue those who stay and become trapped.

Since everyone evaluates conditions based on their own experiences and perceptions, it becomes impossible to know exactly how people will react during an evacuation.

Aside from personal perceptions, some people tend to look at their neighborhood holistically when ultimately deciding to evacuate, particularly if they are not directly in an evacuation zone. It is often the case that those who are unsure about evacuating will look at those around them for guidance. If their close neighbors are deciding to leave, they too may decide to do so. Alternately, if their neighbors are staying they may choose to shelter in place as well (Stein, Dueñas-Osorio, and Subramanian, 2010). Along with those around them, the media often plays a very large part in evacuation decisions (Stein, Dueñas-Osorio, and Subramanian, 2010; Dow and Cutter, 1998). Individuals tend to trust media sources more than they do their local government (Dow and Cutter, 1998). For instance, if their local weather channel tells them to evacuate they are generally more inclined to do so (Dow and Cutter, 1998).

It is clear then that the ultimate decision to evacuate is a very complex one. Several different issues, ranging from age, health, family, storm trajectory, neighborhood evacuations, and intensity of past experience factor in to a person's decision to evacuate (Stein, Dueñas-Osorio, and Subramanian, 2010; Dow and Cutter, 1998). Everyone will handle these decisions differently, and what causes a resident or one area to feel the need to evacuate may not cause others in the same situation to behave similarly (Stein, Dueñas-Osorio, and Subramanian, 2010). It is impossible to know exactly how people will behave during a crisis, which is why risk perception plays such an important role in evacuation planning. Human behavior must be considered when planning a mass evacuation, particularly one that requires as much planning as contraflow. The plans must be adaptable to account for any extra evacuees who decide to leave their homes, but must also allow for the reentry of emergency responders to rescue those who may decide to stay. Thus, risk perception plays a very important role in disaster planning should be considered before any evacuation plan is finalized.

Overall, existing disaster management strategies, specifically evacuation plans, should be examined to ensure they are the most effective option for an area faced with an emergency evacuation. It is clear that no single strategy will work for every scenario during a tropical cyclone, but a plan with proven results and a good foundation has the potential to be easily be adapted to fit other scenarios throughout the region. The best plans must be adaptable to manage the unpredictability of storms, however, emergency managers and local government leaders in coastal communities need to have a general idea of what will or will not work when making initial plans.

III. RESEARCH METHODS

Site and Situation

This research was conducted along the United States Gulf Coast, focusing particularly on Nueces County, Texas and the City of Corpus Christi. Corpus Christi is located in Nueces County and situated on the western Gulf Coast, making it susceptible to tropical cyclones from both direct strikes and effects of nearby storms. This area was selected as it is located in an area that has in the past, and could again, face a direct hit from a tropical cyclone, making it extremely important to have effective evacuation policies. Based on historical accounts, this area has been impacted by numerous tropical cyclones, making it safe to assume that it will be again in the future (Roth, 2010). Even without a direct strike, Corpus Christi still faces dangers from tropical cyclones in the area and must be prepared for the future.

Nueces County is a largely populated area, having an estimated population of 324,074 in 2015, with the majority of these residing in the City of Corpus Christi (U.S. Census Bureau, 2016). As with many coastal areas, Corpus Christi continues to grow, seeing roughly 6.2 percent increase in population from 2010-2015 (U.S. Census Bureau, 2015). Additionally, around 17 percent of the population was predicted to be living at or under the poverty level in 2015, causing additional problems of inadequate shelter and/or lack of access to reliable transportation should the need to evacuate arise (U.S. Census Bureau, 2015). Having a large and diverse population located this close to the coast makes the area extremely vulnerable to the effects of tropical cyclones.

The large population also means there are numerous vehicles on the road. As of 2014, there was an estimated 125,352 vehicles in the Corpus Christi area (City Data, 2016). This does not include tourists, individuals who may be in town for work, or truckers passing through the area. This leaves the potential for increased numbers of vehicles attempting to use the same evacuation routes and causing severe traffic congestion.

The Corpus Christi area is a generally low lying area with most of the city residing below 12 meters in elevation (USGS, 2016) (Figure 6). Most of the city is also located on or near the Gulf Coast itself, or close to either Corpus Christi Bay, or Nueces Bay. This puts most of the city's population, particularly those living in proximity to coastal and bay areas, at risk of flooding from tropical cyclone storm surges.

Since 1900, Nueces County has experienced fourteen direct impacts from tropical cyclones (National Weather Service, 2010; National Hurricane Center, 2016). Tropical cyclones forming in the North Atlantic Ocean tend to take a westward trajectory due to the prevailing easterly winds throughout this region, and depending on their origin and path through the Gulf, frequently steer towards the Texas coast (NOAA, 2014). While the Texas coast is a very large area, and storms will not always strike the same place, Nueces County is in an area that faces the potential of both direct and indirect impacts from tropical cyclones.

The most recent and severe storm to impact the Corpus Christi area was Hurricane Celia in 1970. Celia made landfall near Corpus Christi on August 3rd, 1970, as a strong Category 3 storm with sustained winds of 201 kmh (125 mph), having gusts up to 259 kmh (161 mph) (National Weather Service, 2010). Damage from Celia was severe and up to 70 percent of Corpus Christi residents were affected in some way.

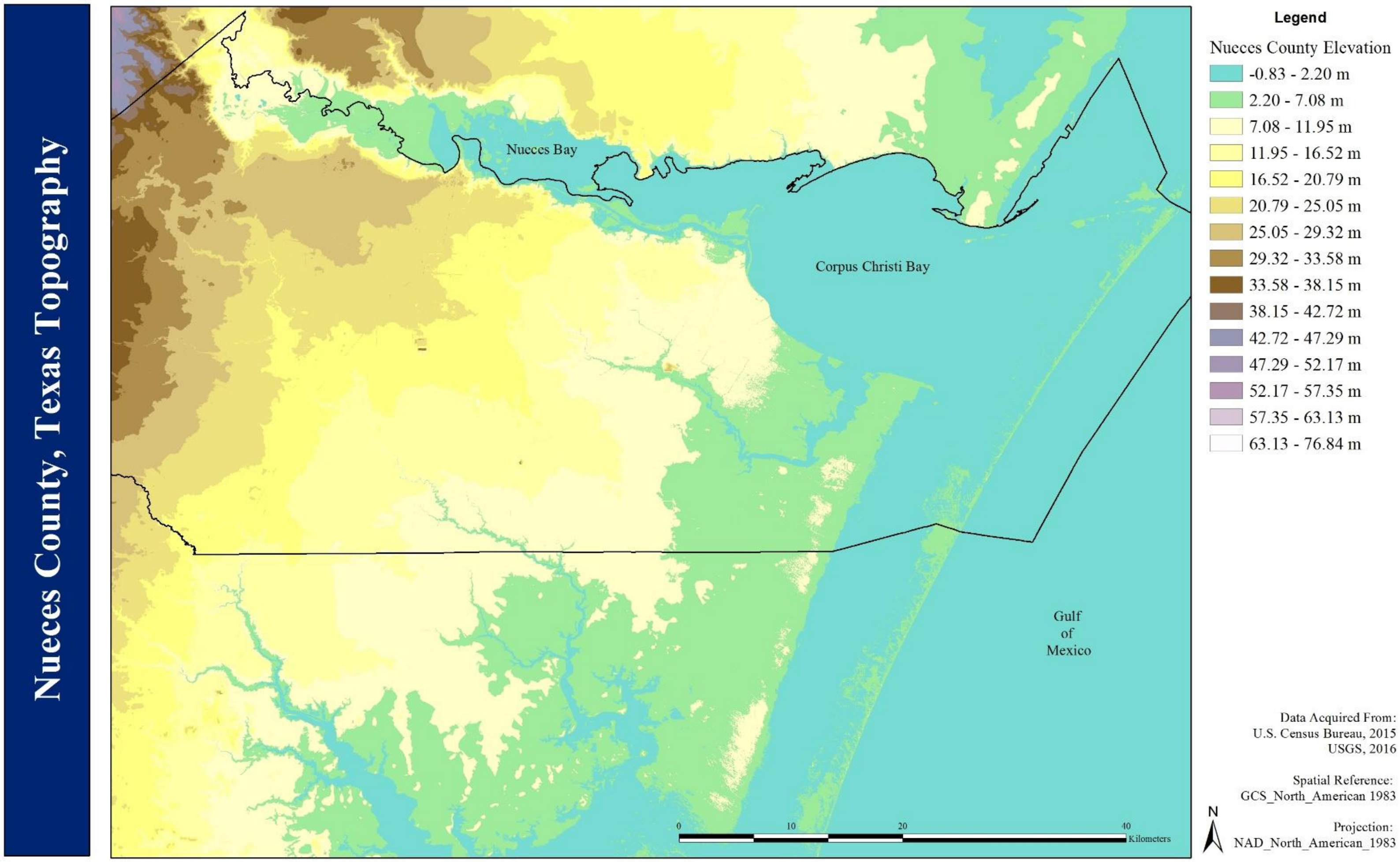

Figure 6. Nueces County, Texas topography.

Celia caused fifteen deaths, destroyed 8,950 homes and damaged thousands more. The storm destroyed 252 businesses, 331 boats, numerous mobile homes, and caused utility shortages to much of the area (National Weather Service, 2010) (Figure 7). Along with the severe winds, Celia brought a storm surge of nearly 1.5 meters (m)(approximately 4.5 feet) to Corpus Christi and around 2.7 m (approximately 8.3 feet) at Port Aransas Beach to the northeast. At least eight tornadoes developed, and from five to seven inches of rain fell over the affected area (National Weather Service, 2010). Storms like Celia are not typical to the area, but it serves as a reminder that they can and do occur, emphasizing the importance of proper planning to ensure the safety of area residents.

Figure 7. Damage from Hurricane Celia. (National Hurricane Center - http://www.weather.gov/crp/?n=celia1970)

Although there is great potential for a major storm to strike this area, Corpus Christi has never actually had to implement its contraflow plan this, it remains untested. The current contraflow evacuation plan for Corpus Christi designates Interstate Highway 37 (IH-37) as the evacuation route for residents from the area. The southbound lanes of IH-37 are planned to be reversed, forcing all traffic northbound towards San Antonio (TxDOT, 2016) (Figure 8). Actual contraflow operations will begin at the junction of IH-69E/US Highway 77 (IH-69E/US-77) and IH-37. At this juncture, motorists traveling along Interstate Highway 69E-US 77 will be forced onto the southbound lane of IH-37, which will be reversed and flowing northward (TxDOT, 2016) (Figure 8). All traffic will then flow north out of Corpus Christi until the termination of contraflow at the junction of State Highway 97 (SH-97) and FM 3006 near Pleasanton (TxDOT, 2015; TxDOT, 2016). North of this junction, traffic on southbound IH-37 will resume its normal flow so all vehicles heading north must exit. To alleviate the potential of traffic congestion at the termination of contraflow, additional exits are located at the junctions of State Highway 359 (SH-359) near Mathis, and US Highway 59 (US-59) near George West (TxDOT, 2016) (Figure 9). These additional exits allow for the dispersion of motorists along the route and help control traffic congestion along the route.

Figure 8. Junction of IH-37 and SH-77 and the start of the contraflow evacuation route. (Google Maps – www.maps.google.com)

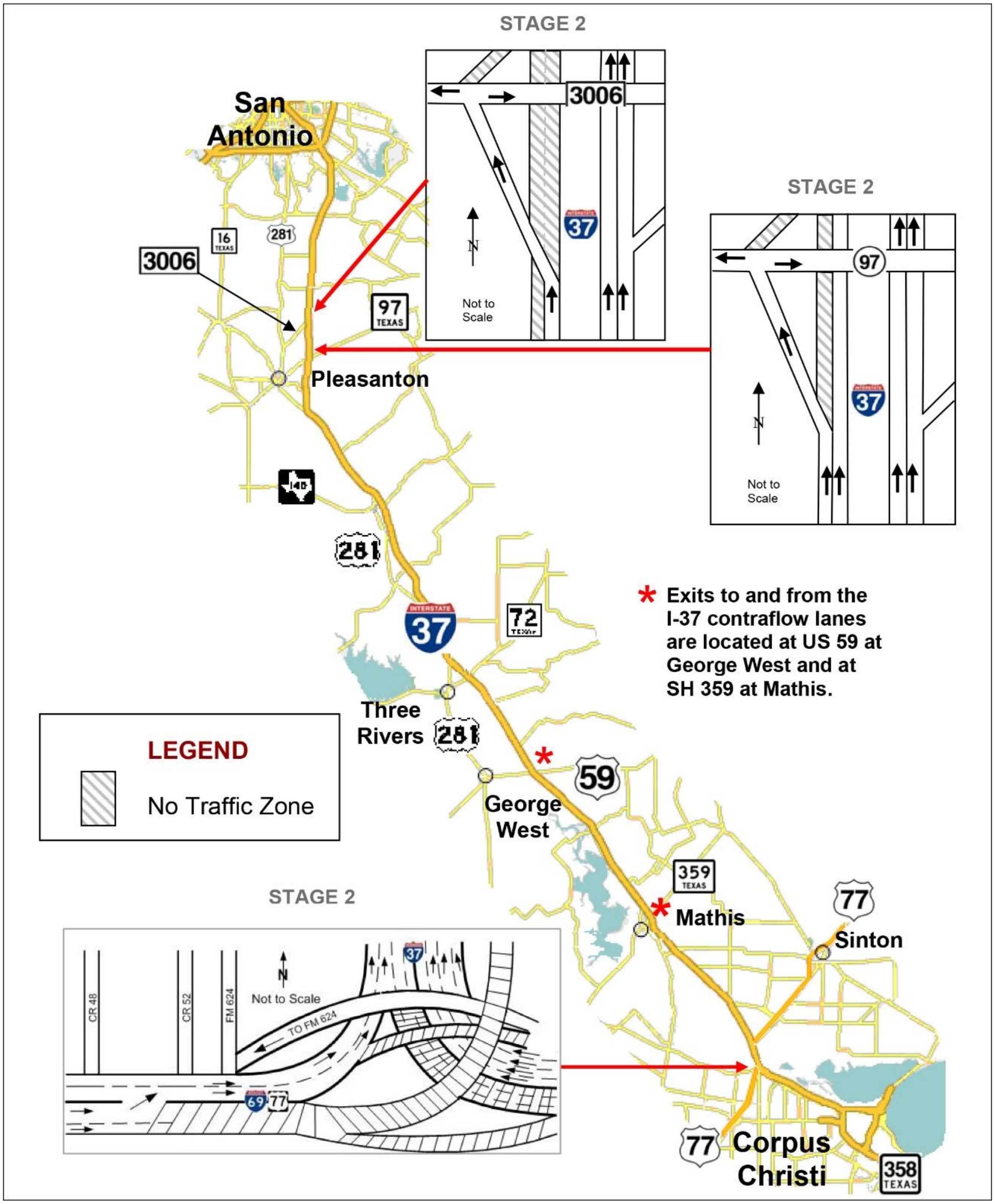

Figure 9. Corpus Christi contraflow evacuation map.
(TxDOT - http://ftp.dot.state.tx.us/pub/txdot-info/trv/hurricane/i37_contraflow.pdf)

Corpus Christi also employs evacuation zones for phased evacuations, and has additional evacuation routes for certain areas of the city. These routes, however, are not part of their overall contraflow plan and are not set up to be reversed, and as such, are not examined in this study. The routes are planned to be used for smaller scale evacuations from weaker tropical systems, or in the early of the evacuation process before contraflow is enacted. It should be noted, however, that the combination of phased evacuations and additional evacuation routes will greatly improve the overall effectiveness of an evacuation from Corpus Christi should a major tropical cyclone impact the area.

Data

The officially published contraflow evacuation plan for Corpus Christi issued by the Texas Department of Transportation (TxDOT) serves as a primary data source for this research (TxDOT, 2016) (Figure 9). Available through the City of Corpus Christi website, this plan lays out the evacuation routes for the area, including the origins, termination, and additional exits along the route.

Texas Partnership Shapefiles were obtained from the United States Census Bureau for the four counties where the full route passes though and includes, Nueces, San Patricia, Live Oak, and Atascosa Counties (U.S. Census Bureau, 2016). These files contained the necessary block level population data and road network data for the analysis. The block level population data was used for Nueces County to create a population density map using hot spot analysis (Figure 10). This map showed the zones of dense population in Nueces County that will ultimately serve as the starting points for the various evacuation routes.

Also contained in the Partnership Shape Files were the road network datasets needed to create a functional road network that spanned the four counties along the evacuation route (U.S. Census Bureau, 2016). Road networks for each of the four individual

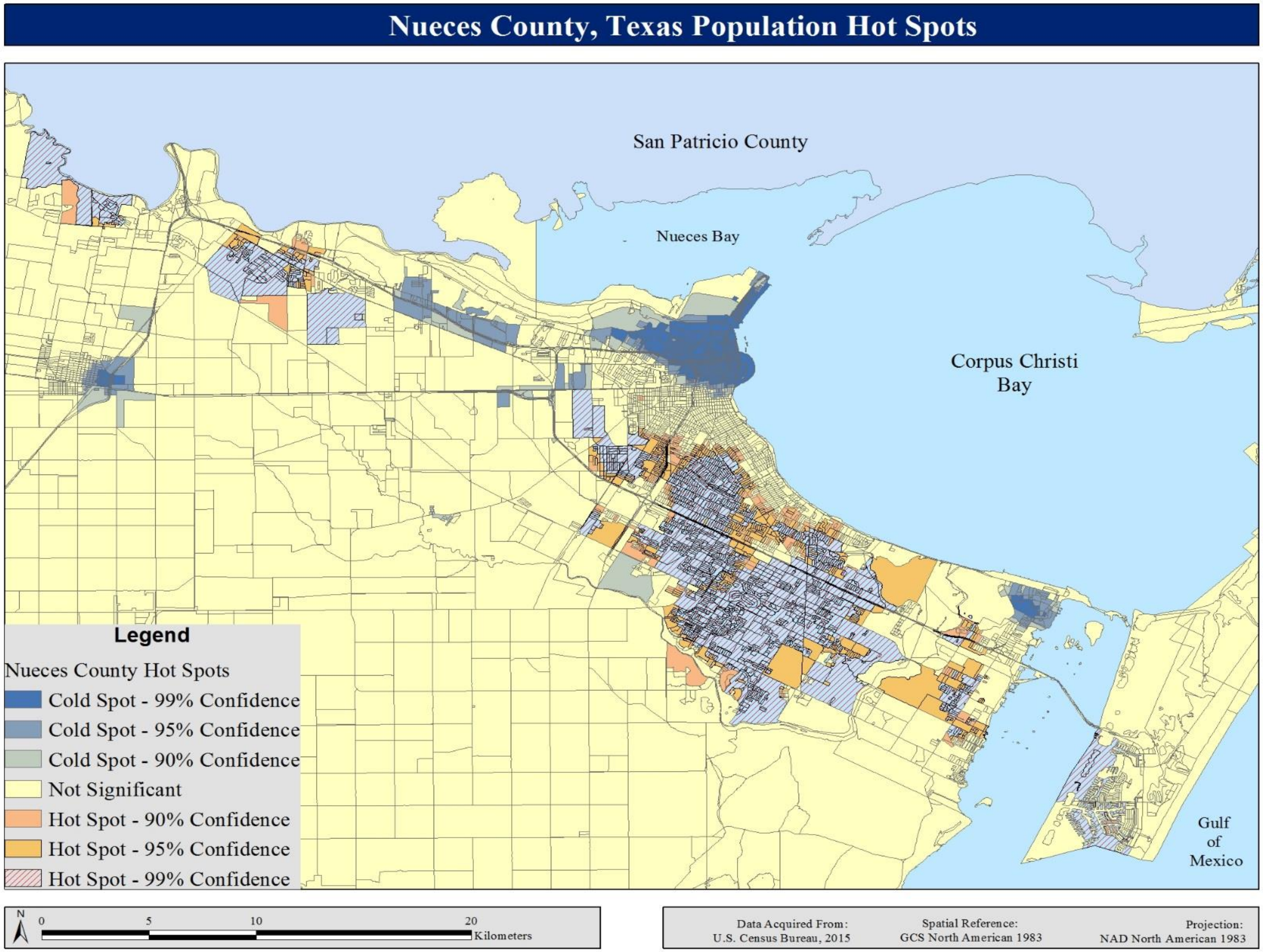

Figure 10. Nueces County, Texas population hot spots.

counties were combined in ArcGIS to create a master road network that allowed for a network analysis to be performed along the entire evacuation route to determine total distance for each of the selected routes.

Additionally, data was obtained from TxDOT containing average annual daily traffic (AADT), hourly traffic volumes, average speeds, and both daily and hourly vehicle counts along major roadways in Corpus Christi (TxDOT, 1/2016; TxDOT, 8/2016). This data allowed for a more accurate estimation of normal daily traffic flow, including average speeds, and serves as a starting point for the examination into the effects of contraflow on traffic during a major evacuation.

Further, a digital elevation model (DEM) of the Nueces County area was obtained from the U.S. Geological Survey (USGS) to examine the local topography (USGS, 2016). This DEM was used to examine the local area relief to gain an understanding of which areas of Corpus Christi appear to be in the greatest danger of flooding from a tropical cyclone (Figure 11).

GIS Setup

Analysis was performed using ESRI's ArcGIS. To begin, block level population data from Nueces County was used to create a population density map using the "Optimized Hot Spot Analysis: function. Hot spot analysis was only done for Nueces County because it is the starting point for all the evacuation routes. Population density is not necessary for the other counties in this study because their evacuation plans are not being examined. They are included in the overall analysis only because the evacuation route for Corpus Christi passes through them.

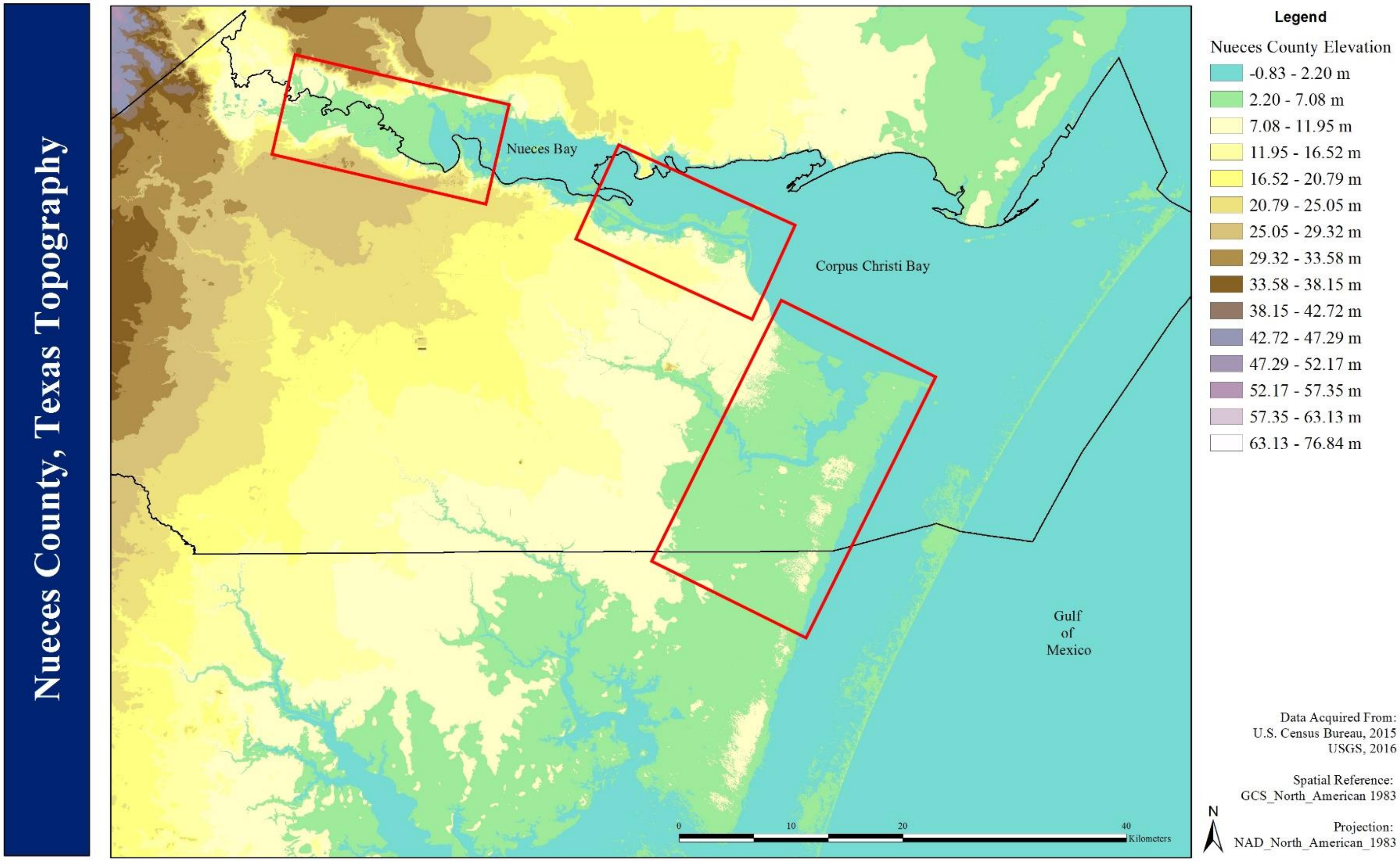

Figure 11. Nueces County, Texas topographic map with potential flood zones.

To begin the mapping process, the “Editor” function was used to remove the water in Nueces Bay and along the shoreline. This ensured that any interior bodies of water would not be displayed on the map to eliminate any confusion over which areas needed to be evacuated. Some water areas around Mustang Island and Padre Island were left so as not to remove any of the road networks associated with area bridges.

The various evacuation routes were selected based on block level population data associated with Nueces County. This data, obtained from the Census Bureau, was the foundation of the analysis. Nueces Country block level population data, was used to see how the population was distributed around the city. The “POP 10” field in the attribute table contained the populations for various census blocks, and thus used to determine the starting locations (U.S. Census Bureau, 2016). The dataset was classified using Natural Breaks (Jenks) and divided into seven categories so that it would have a similar distribution to the population Hot Spot Analysis output. This returned groups ranging from 0-25 to 1031-2135 (Table 2) (Figure 12).

Table 2. Population categories using Jenks Natural Breaks

Category	Population Range
1	0-25
2	26-73
3	74-149
4	150-301
5	302-528
6	583-1030
7	1031-2135

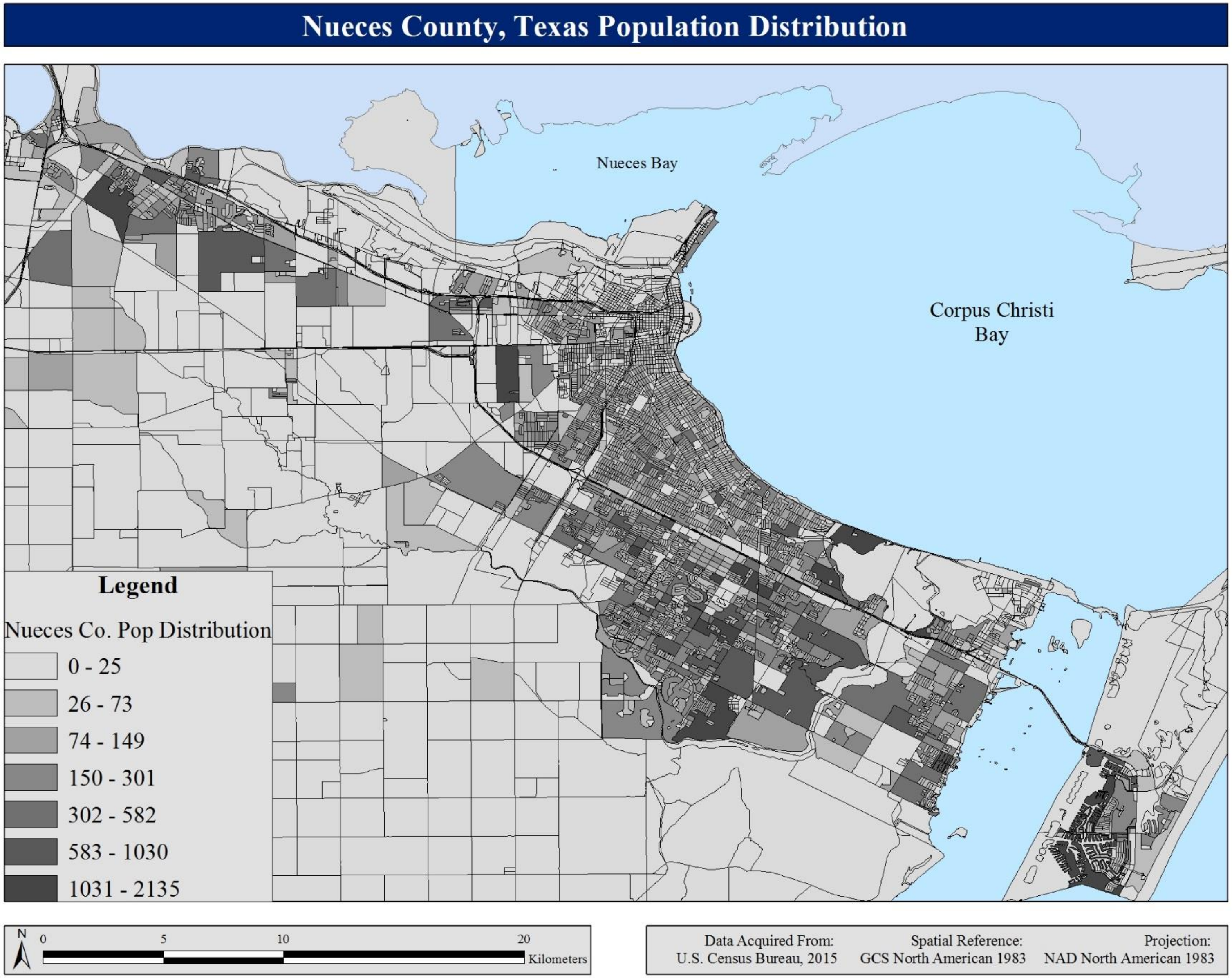

Figure 12. Nueces County, Texas population distribution.

Hot Spot Analysis

To ensure that the areas of high population actually had significance across the area, a hot spot analysis was performed using the "Optimized Hot Spot Analysis" function in ArcGIS. The Nueces County Population layer was used as the input and the hot spot analysis was run on the same "POP 10" field used for the previous population map. This analysis displayed areas that had both a large population in relation to the rest of the area, as well as where this large population was significant. This analysis returned a large area with significant population in one central location of the city so further analysis was necessary to ensure that the areas chosen for the start of evacuation had a large population that was statically significant (Figure 10).

To determine what areas met the criteria for the route starting points, the "Select" tool was used to pull the upper two categories of population from the original population layer. These layers had populations of 583-1030 and 1031-2135. The upper two population categories were used because employing only the top category returned very few locations to serve as potential evacuation starting points. By using the top two it ensured there were at least fifteen potential routes that could be analyzed. This same process was used with the hot spot analysis layer to select only those areas with a 99 percent confidence of being a population hot spot. The two upper categories of population were then overlaid on the hot spot layer using the Select function. This gave an output map that shows only those locations with at least 583 residents that are also statistically significant population hot spots. These areas would serve as the evacuation route starting points because they indicate where people are concentrated in Nueces County (Figure 13).

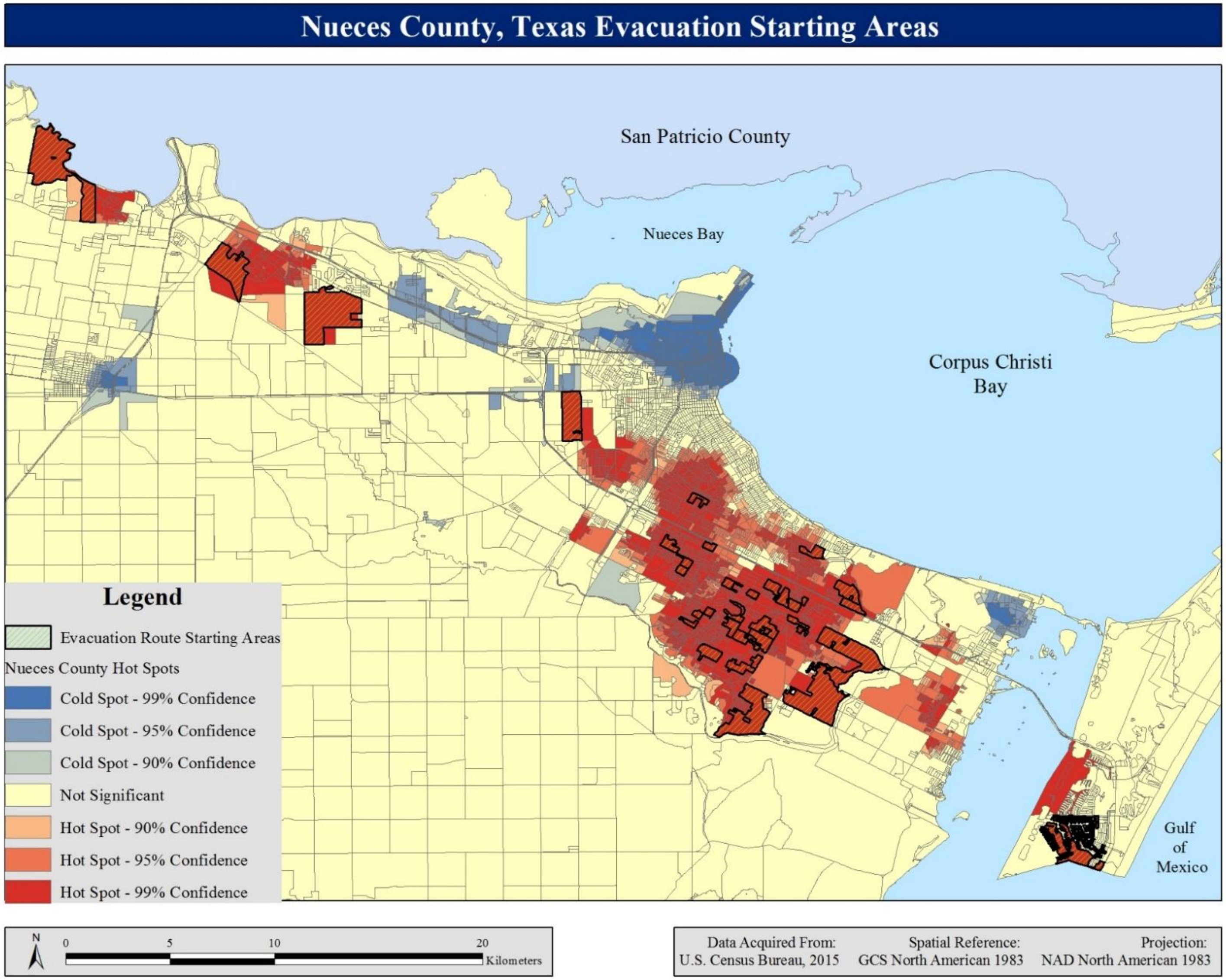

Figure 13. Nueces County, Texas evacuation route starting points

Road Networks

Next the road network was established to begin routing. A road network layer was obtained from each of the four counties, as well as, a county boundary layer to better show the locations of the roads. These layers were merged using the “Merge” tool so they would form one cohesive network allowing routes to cross county boundaries (Figure 14)

To begin the process of creating the road network to run the network analysis, a New Feature Dataset was established within the Corpus Christi Evacuation “CC_Evac” geodatabase. The coordinate system was chosen to match all the previous layers included in the map so that the layers would all work in conjunction with each other. The coordinate system used for this analysis was GCS North American 1983. The XY, and Z coordinate system were left as the default, NAD 1983, so that it, too, would match the rest of the layers already include in the map.

Since no historical traffic data was available this was the only layer included in the analysis. Elevation fields were used to model the elevation of network features and units were set to miles (later converted to kilometers (km)). Once this road network was created it was added to the map and the route starting points could be added.

Setting Route Starting Points

The ”Evac Route Start Points” layer was used to locate the starting location of each of the routes. All routes needed to begin in one of the sections of this layer, and preferably one that had both the highest population level, 1031-2135 and had a 99 percent

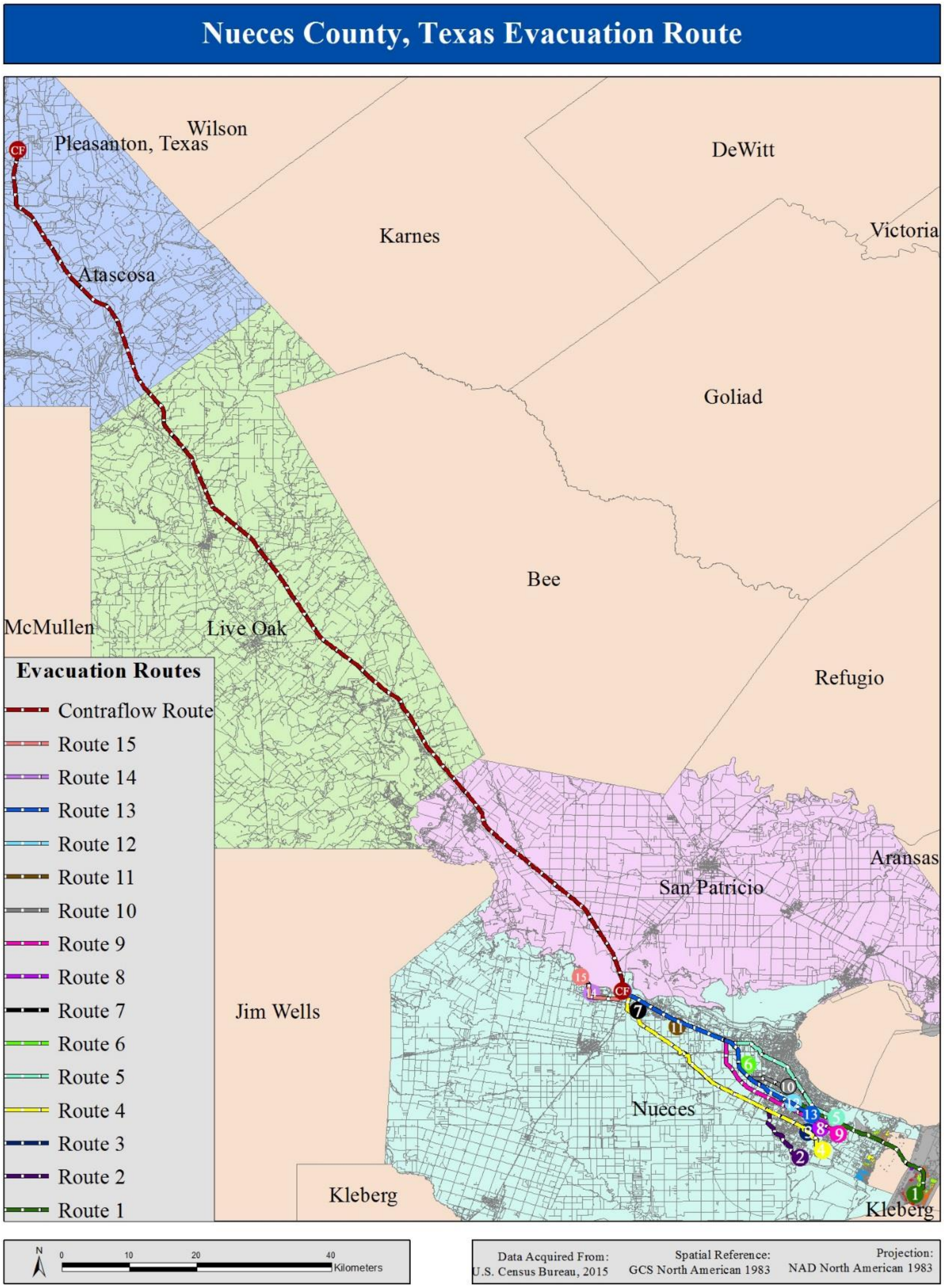

Figure 14. Nueces County, Texas contraflow evacuation route

confidence as a hot spot. To obtain at least fifteen route starting points, however, a few locations were selected from the Category 6 population level, 538-1030.

Starting route locations were chosen by selecting a point within the "Evac Route Start Point" boundary that also had a named road so that the "Find Address" tool could be used. The route starting point was placed near the center of each area while still maintaining access to the rest of the road network. Fifteen locations were ultimately chosen to serve as route starting points for the analysis (Table 3) (Figure 15).

Table 3. Nueces County, Texas selected evacuation route names

Route Number	Route Name	Route Number	Route Name
1	Mingo Cay CT	9	Chachalaca Dr.
2	Radial Ct.	10	Kay St.
3	Dunbarton Oak Dr.	11	Oregon Trl.
4	Freds Folly Dr.	12	Oakhurst Dr.
5	Townhouse Ln	13	Curtis Clark Dr.
6	Green Acre Dr.	14	Riverview Dr.
7	Devils Creek Dr.	15	Rock Island Dr. (Robstown, TX)
8	Amanda St.	16	Contraflow Route

Network Analysis

Once these locations were chosen, the "New Route" function within the Network Analysis tool was used to create each route. A centralized street was used to ensure that it could be located with the ArcGIS database. If the road was detected, then a new route start point could be added to the map. Each starting point was labeled in the following manner "Route # Start, Street Name". For example, the starting point of the first route was

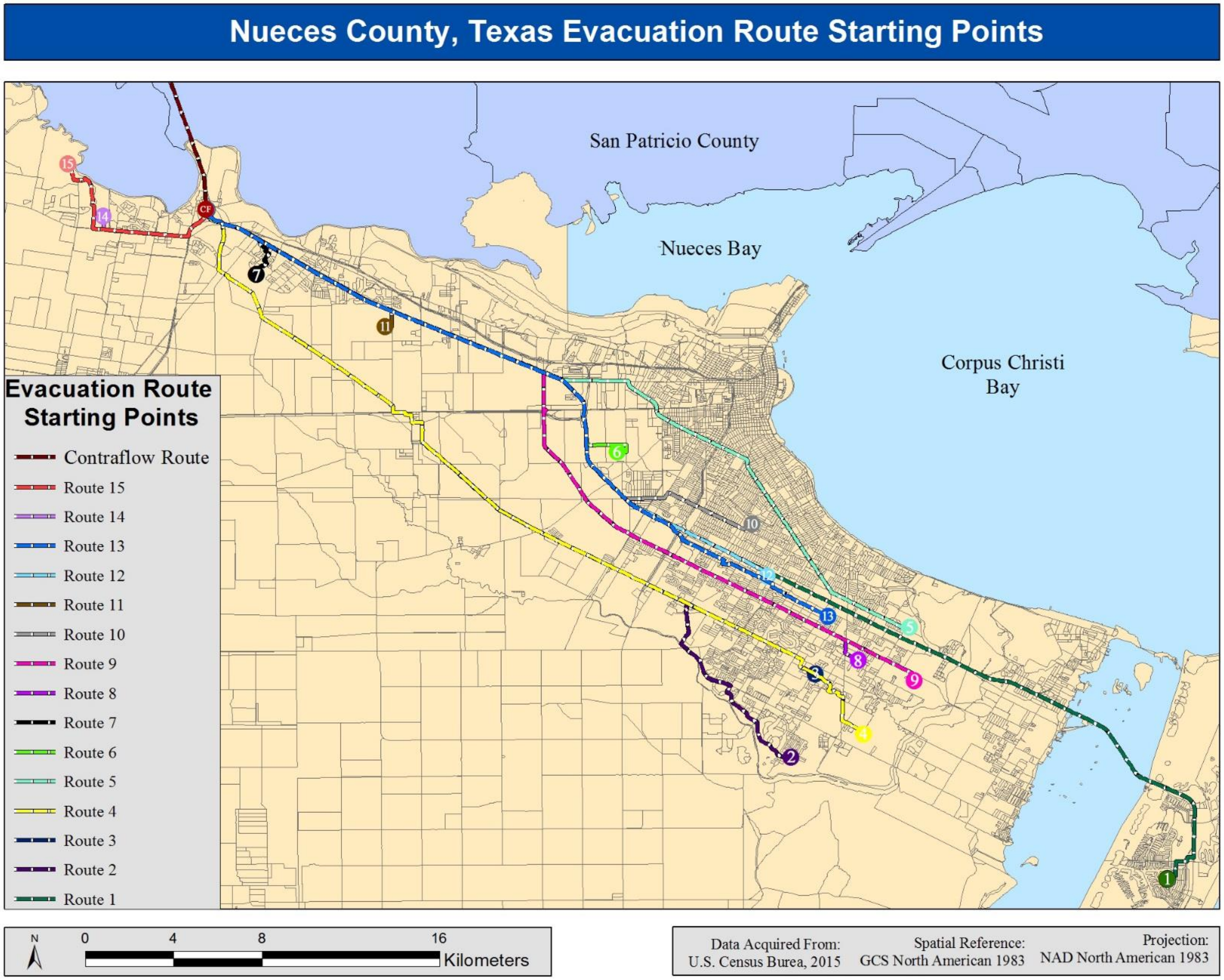

Figure 15. Nueces County, Texas selected evacuation routes

labeled “Route 1, Mingo Cay Ct”. Since there were two sections of the contraflow route to analyze - the “to contraflow” section and the “through contraflow” section - these routes all needed to terminate at the same location to serve as the start of the “through contraflow” section. The contraflow plan for Corpus Christi begans at the junction of IH-69/US-77 and IH-37, this a second marker was placed at this junction for each route and named “Route # End”. Finally, once the route was calculated with the “Network Analysis” tool, each route was labeled and color coded for easy analysis. This process was repeated for all fifteen of the route starting points, enabling the calculation of all distances from the evacuation route origins to the start of contraflow, including the calculation of the effects traffic congestion would have on the route to determine the overall speed of the evacuation under various traffic conditions.

Area Relief

To get a sense of area relief, an elevation map was created using a digital elevation model (DEM) obtained from the USGS (USGS, 2016). The map was created using ArcGIS, and set up using defined intervals of three meters. The resulting map showed the elevation throughout the Nueces County area, and gave a sense of the elevation for most of the population. When combined with the map displaying the evacuation route starting points, it became evident that most of the population of Nueces County resides at relatively low elevation. Most starting points originated between zero to six meters above sea level, while some of the more western areas ranging from 12-21 meters above sea level. The highest origin was Route 7 with a starting point between 21-24 m (Figure 16).

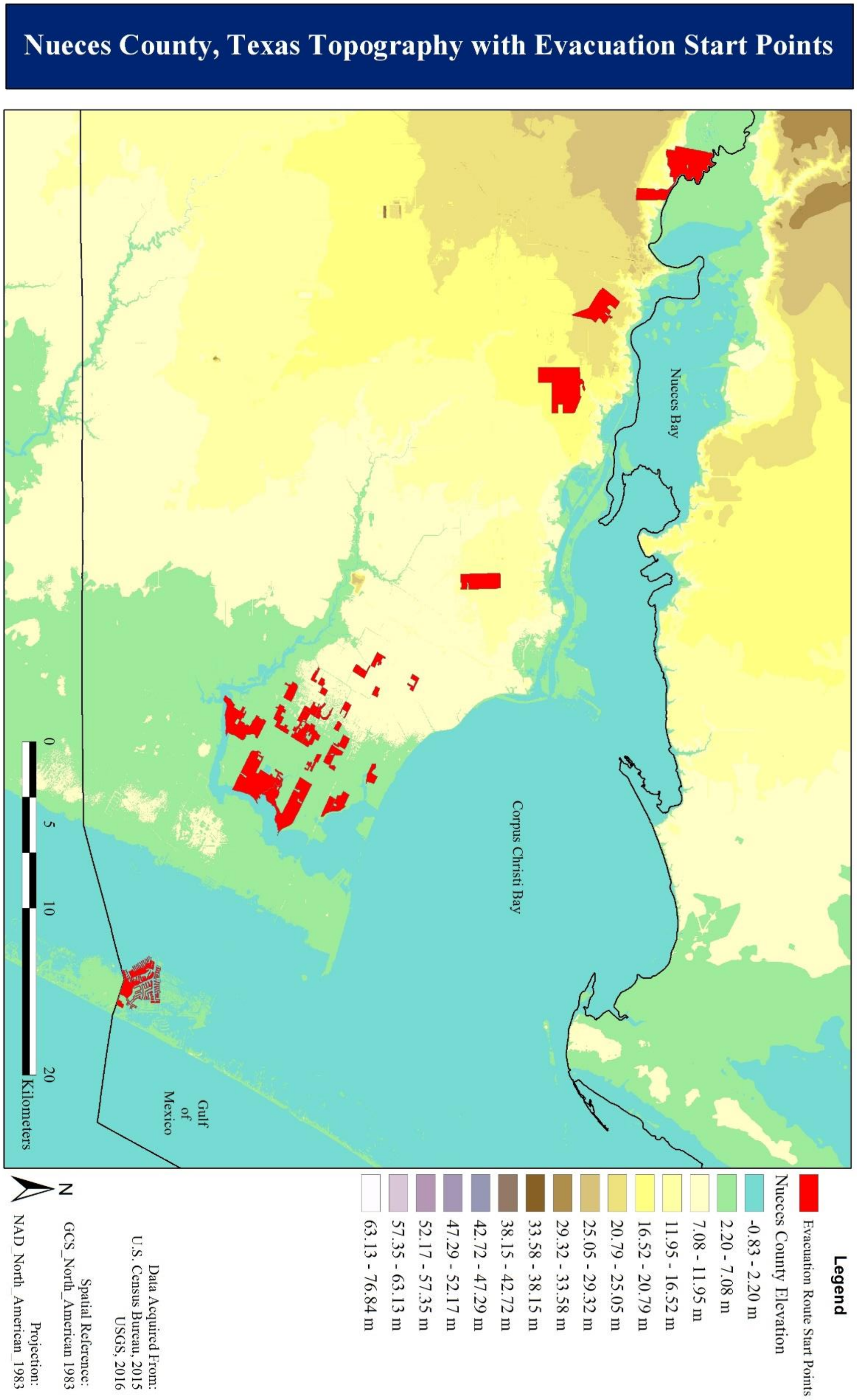

Figure 16. Nueces County, Texas topographic map with evacuation route starting points.

Assumptions for Analysis

A historic traffic dataset was not used in this analysis because it would show travel speeds based on actual speed limits not actual travel speeds. To account for this, data showing actual average travel speeds of IH-37 and various other routes were obtained from TXDOT. This gave a more accurate representation of how fast traffic actually flows during normal conditions, and served as a better baseline for the analysis of traffic congestion (TxDOT, 1/2016). This average traffic speed was not available for every route in the study, however, so average travel times were assigned based on estimated speed limits for the "to contraflow" route sections. In all, the analysis used three assumptions to factor route speed and traffic congestion during a contraflow evacuation.

The first assumption was that travel will be constant throughout the entire route. This means that once a vehicle left the starting point they were in constant motion until reaching the terminus of the route near Pleasanton, Texas. Stops for traffic signals, accidents, facility use or other purposes were not be factored into the analysis.

The second assumption was that traffic will be traveling at a constant speed during the evacuation. Travel speed were be split into two categories, speed "to contraflow" and speed "through contraflow". Since the entire section of contraflow is contained on IH-37, the speed of the "through contraflow" section was held at a constant 125.4 kilometers per hour (kph) (77.9 mph). While this is faster than the posted speed limit of 70 mph, this is the actual average speed of traffic on IH-37 as obtained from TxDOT (TxDOT, 1/2016). The "to contraflow" sections consist of a combination of residential areas, state highways, and access roads and was thus set at 80.5 kph (50 mph) since no average speed from TxDOT could be obtained due to the wide variety of roads included in this section. This speed was chosen to serve as an average speed that should account for the slower residential areas and the faster highways and access roads.

The final assumption was used to account for a decrease in traffic flow, and in turn traffic speed, caused by congestion and the other previously stated issues associated with contraflow. Traffic speeds were decreased by 8.9 kph (5.5 mph) for an optimal evacuation, 15 percent of non-evacuation free flow speed for a "worst case" scenario evacuation, and the median of the two to model and expected evacuation. These numbers were chosen based on research by Dixit and Wolshon (2014) showing how contraflow impacted traffic flow during the evacuations of Hurricane Ivan in 2004, Katrina in 2005, and Gustav in 2008 (Dixit and Wolshon, 2014). These three intervals will create "optimal", "expected", and "worst case" scenarios for examining traffic congestion when using a contraflow evacuation during a tropical cyclone.

Calculation of Travel Speeds

Based on research done by Dixit and Wolshon (2014), the denser traffic becomes the slower traffic flows. The maximum flow rate of contraflow evacuation traffic was found to be roughly 30 percent less than normal flowing traffic (Dixit and Wolshon, 2014). Additionally, free flow speeds during an evacuation were found to be roughly 8-10 kph (5-6 mph) less than during normal commuter traffic. This means that fewer cars will be able to traverse the same section of road as they would during non-evacuation travel due to the decreased capacity, and that those cars will be traveling slower than normal due to the 8-10 kph (5-6 mph) reduction in speed. This is all under maximum flow conditions where each lane has not exceeded capacity and traffic can freely flow out of the area. This of course does not happen through the duration of an evacuation, particularly a contraflow evacuation, because of bottlenecks where lanes drop off, slowdown for onramps to get on IH-37, accidents, stalled vehicles, and many other traffic hinderances associated with heavy traffic flow. Based on data gathered during the evacuation of Hurricane Katrina, there can be several hour periods, approximately six to seven hours in this case, where traffic flows at less than 16 kph (10 mph) or completely comes to a standstill (Dixit and Wolshon, 2014). The same can be said for the evacuation of Hurricane Ivan. During the first twelve hours of contraflow, speeds ranged from approximately 8-56 kph (5-35 mph), less than half of the normal flow speed at its highest point (Dixit and Wolshon, 2014). The evacuation during Hurricane Gustav also has the same results. The first several hours of contraflow saw traffic speeds of less than 32 kph (20 mph) until vehicles began to clear out and traffic could return to normal flow speeds during the latter stages of the evacuation (Dixit and Wolshon, 2014).

For this research, evacuation times were based on approximated travel speeds, not relying strictly on traffic volumes as other studies have done in the past in the hopes of determining how long a contraflow evacuation out of Corpus Christi may take under “optimal”, “expected”, and “worst case” conditions. Since traffic flow is shown to decrease by at least 8-10 kph (5-6 mph) during a contraflow evacuation, the speeds for the “optimal” conditions will be set at 8.9 kph (5.5 mph) lower than the normal non-evacuation free flow speeds. The free flow speed for non-evacuation interstate sections will be set at 116.5 kph (72.4 mph) based on data collected by TxDOT, showing that the average observed speed through sections of the IH-37 evacuation route is 125.4 kph (77.9

mph) (TxDOT, 1/2016). Average speed data was not available for the free flow speed of the non-interstate sections so it was approximated. Since these sections of the route consist of both interstate axis roads, as well as residential areas, it was assumed that the average non-evacuation free flow speed of these sections is 80.5 kph (50 mph). This took into account the higher speed limits on the axis roads as well as the much slower speed limits leaving the various residential areas. These starting speeds equated to an evacuation free flow speed of 116.5 kph (72.4 mph) on the sections of IH-37, and 71.6 kph (44.5 mph) on non-interstate sections of the route (Table 4).

It is clear from the work of Dixit and Wolshon (2014) that traffic does not always flow at optimal levels during an evacuation so more than just the maximum free flow speed must be examined to accurately predict evacuation times. It was observed in the evacuations of Hurricanes, Ivan, Gustav, and Katrina that traffic flow slowed to less than 16 kph (10 mph) for several hours during and evacuation (Dixit and Wolshon, 2014). With the normal free flow speed of each of those evacuations reaching roughly 112.7 kph (70 mph), and using 16 kph (10 mph) minimum as a baseline, it can then be said that traffic speeds slowed to approximately 15 percent of their normal free flow speed for several hours during the contraflow evacuation (Dixit and Wolshon, 2014). This 15 percent decrease in traffic speed was then be applied to the non-evacuation free flow speeds of 125.4 kph (77.9 mph) on IH-37 and the assumed 80.5 kph (50 mph) for the residential sections, making the worst case evacuation speeds 18.8 kph (11.7 mph) and 12 kph (7.5 mph) respectively (Table 4).

Based again on the evacuation during Hurricane Ivan, Gustav, and Katrina it is clear that no evacuation remains at the optimal or worst case scenario through the duration of the evacuation (Dixit and Wolshon, 2014). In the case of Hurricane Katrina, traffic speeds were at near optimal conditions for the first several hours of contraflow then dropped to nearly a standstill during the late stages (Dixit and Wolshon, 2014). Hurricane Gustav saw the exact opposite, where contraflow was initiated when traffic was at a standstill then reach optimal conditions during the late stages of the evacuation (Dixit and Wolshon, 2014). In the case of Hurricane Ivan, travel speeds remained steady at a speed between the optimal and worst case for the first several hours before picking up and eventually reaching optimal conditions through the latter parts of the evacuation (Dixit and Wolshon, 2014). A scenario was then needed that would factor in both the optimal and worst case conditions and give more of an expected scenario for the evacuation. This scenario takes into account periods of free flowing traffic, as well as periods of extreme congestion where vehicles may be moving along at the worst case speeds for a time. The median speed from the already calculated "optimal" and "worst case" scenarios was used as the travel speed for this "expected" evacuation scenario, making the travel speed for the interstate sections 67.6 kph (42 mph) and the travel speed for the non-interstate sections 41.8 kph (26 mph) respectively (Table 4).

Table 4. Evacuation route speeds

Optimal Conditions					
Routes	**Base Speed kph**	**Base Speed mph**	**Speed Reduction**	**Study Speed in kmh**	**Study Speed in mph**
IH 37	125.4	77.9 mph	5.5mph	116.5	72.4
Non-Highways	80.5	50 mph	5.5mph	71.6	44.5

Expected Conditions					
Routes	**Base Speed kph**	**Base Speed mph**	**Speed Reduction**	**Study Speed in kmh**	**Study Speed in mph**
IH 37	125.4	77.9 mph	Median Speed	67.6	42
Non-Highways	80.5	50 mph	Median Speed	41.8	26

Worst Case Conditions					
Routes	**Base Speed kph**	**Base Speed mph**	**Speed Reduction**	**Study Speed in kmh**	**Study Speed in mph**
IH 37	125.4	77.9 mph	15% of max	18.8	11.7
Non-Highways	80.5	50 mph	15% of max	12	7.5

Calculation of Route Distances and Travel Times

Several steps were taken to determine the total distance, total travel time and average speed for each route at each of the three traffic flow reduction intervals. The total distance for each route was determined by adding various “to contraflow” distances to the “through contraflow” section, a constant 152.4 kilometer (km) (94.7 miles). Distances of the “to contraflow” sections ranged from 5 – 54 km (3.1 – 33.5 miles), making the total evacuation routes 157.4 – 206.4 km (97.8 – 128.2 miles), with an average distance of 180.2 km (111.96 miles) (Table 5).

Total travel time for each route was found by calculating the travel time from the route origin to the beginning of contraflow and combining it with the travel time through contraflow. Travel time to the contraflow section varied depending on how long the route was, whereas the travel time through contraflow was held constant for each route based on the reduction in traffic flow being applied. Travel speeds for the through contraflow section were 116.5, 67.6, 18.8 kph (72.4, 42, and 11.7 mph) based on their respective speed reductions off the 125.4kph (77.9 mph) baseline speed on I-37 (Table 4). Travel times for the “to contraflow” sections will be discussed along with the results for the corresponding traffic flow reduction intervals. Finally, the average speed for each route was calculated by taking the total travel time in minutes and dividing by the total distance of the route. This gave an approximate speed per mile which was then divided by 60 to determine the average speed for the route. As with total travel time, the average speed was dependent on the total length of the route, the percentage of traffic flow reduction, and the use of the previously stated assumptions.

Table 5. Evacuation route distances

Route Number	Route Name	Route Distance to Contraflow in Kilometers (km)	Route Distance to Contraflow in Miles	Distance through Contraflow in Kilometers (km)	Distance through Contraflow in Miles	Total Route Distance in Kilometers (km)	Total Route Distance in Miles
1	Mingo Cay CT	54	33.5	152.4	94.7	206.4	128.2
2	Radial Ct.	38.2	23.7	152.4	94.7	190.6	118.4
3	Dunbarton Oak Dr.	34.6	21.5	152.4	94.7	187	116.2
4	Freds Folly Dr.	38.8	24.1	152.4	94.7	191.2	118.8
5	Townhouse Ln	35.7	22.2	152.4	94.7	188.1	116.9
6	Green Acre Dr.	21.9	13.6	152.4	94.7	174.3	108.3
7	Devils Creek Dr.	5	3.1	152.4	94.7	157.4	97.8
8	Amanda St.	35.6	22.1	152.4	94.7	188	116.8
9	Chachalaca Dr.	37.7	23.4	152.4	94.7	190.1	118.1
10	Kay St.	28.5	17.7	152.4	94.7	180.9	112.4
11	Oregon Trl.	9.8	6.1	152.4	94.7	162.2	100.8
12	Oakhurst Dr.	29.5	18.3	152.4	94.7	181.9	113
13	Curtis Clark Dr.	32.8	20.4	152.4	94.7	185.2	115.1
14	Riverview Dr.	5.5	3.4	152.4	94.7	157.9	98.1
15	Rock Island Dr. (Robstown, TX)	9.3	5.8	152.4	94.7	161.7	100.5

Calculation of Clearance Times

Once individual route evacuation times were calculated, it was then possible to approximate the time it will take to fully evacuate all vehicles from the city. In order to calculate this, it was first necessary to find out how many vehicles could be on the road simultaneously during an evacuation. According to the Texas Transportation Institute (TTI), there is a maximum theoretical capacity of 1,400 vehicles per hour (vph) on IH-37 in Corpus Christi during an evacuation (Ballard, et at., 2008). Using this number as a starting point, it was possible to determine a theoretical lane capacity for each of the possible scenarios in the study. The vehicle capacities were determined in a way that mirrored the speeds of each route. The “optimal” scenario uses the 1,400 vph figure found by the TTI, since under this scenario traffic will be moving at free flow evacuation speed. When taking into account all four available lanes, two in each direction, along the contraflow route, it can then be assumed that about 5,600 total vehicles will be able to traverse a given section of road in an hour (Table 6). Using data from 2014, there are 125,352 vehicles registered in Nueces Country meaning that 22.38 groups of 5,600 vehicles would be needed to clear the city (City Data, 2016). This same process was then used to determine the number of evacuation groups for the other two scenarios.

Mirroring the traffic speed calculation method, the approximate vehicle flow rate of the “worst case” scenario was 15 percent of the theoretical maximum flow rate of 1,400 vph, or 210 vph. That means 840 total vehicles per hour could evacuate a section of the county, which would require 149.23 groups to fully evacuate the 125,352 cars in the county (Table65). Finally, the “expected” evacuation scenario again used the median of the two figures and found that 805 vph could be evacuated, or 3220 total vehicles across all four lanes. This evacuation would then require 38.93 groups to clear all the vehicles in the area (Table 6).

Table 6. Approximate clearance rimes for each evacuation scenario.

Optimal Conditions

Vehicles per lane per hour	Number of Vehicles evacuated per hour	Average Route Travel Time (minutes)	Number of Groups	Approximate Total Evacuation Time
1400	5600	101.8	22.38	23 Hours 20 Minutes

Expected Conditions

Vehicles per lane per hour	Number of Vehicles evacuated per hour	Average Route Travel Time (minutes)	Number of Groups	Approximate Total Evacuation Time
805	3220	175.1	38.93	41 Hours 22 Minutes

Worst Case Conditions

Vehicles per lane per hour	Number of Vehicles evacuated per hour	Average Route Travel Time (minutes)	Number of Groups	Approximate Total Evacuation Time
210	840	624.6	149.23	158 Hours 43 Minutes

Limitations of Proposed Methods

While data containing average travel speed was obtained for IH-37, it was not available for every road in the county. This made it impossible to tell the actual average travel speeds for all parts of each route. This was easily mitigated using averaged speed limits, but having this actual data would have made the rout times more accurate. Results would have also be more accurate if stops for traffic signals, accidents, rest stops, and other factors could have be calculated. This could have been accomplished using more sophisticated traffic modeling software such as the Traffic Software Integrated System - Corridor Simulation (CORSIM), but this software package was not available due to financial constraints.

The assumptions behind modeling were also a potential limitation to the study. All figures were based on assumptions and approximations, not actual collected data along points of the route. To accurately predict how long a real evacuation would take, monitoring stations would need to be set up along the entire route to collect speed and flow data. This data could then predict peak traffic times and how fast travel actually moved during those periods. If observed speeds and traffic volumes were used, the actual route durations could be more accurately predicted. These results will give a general approximation of how long an evacuation would take per person per hour, and for the whole city, but they are ultimately assumptions and could vary widely under an actual tropical cyclone evacuation scenario.

Even with accurate traffic data, route modeling, and effective evacuation routes, there is no way to predict exactly how a storm will behave. Storm trajectories can change quickly and even the best planning cannot predict exactly how strong a tropical cyclone will be or what sort of damage it will inflict. That makes research such as this critically important. There is no way to know exactly what may happen, so it is essential to have the best possible plans to ensure the safety of coastal residents. Additionally, simply giving evacuation orders does mean they will be followed or executed as intended. People introduce a level of uncertainty in evacuation situations. Even the most comprehensive plans can break down if they are not followed appropriately. Emphasis must be placed on public education so local populations know and understand these emergency plans before a disaster is upon them.

IV. RESULTS

As expected, the results showed a wide range of evacuation times and speeds depending the level of traffic congestion and the ultimate speed of traffic flow. Since the duration and speed of each evacuation route ultimately depended on the proximity to the start of contraflow, those routes closest to its origin always had shorter times and faster speeds, while those furthest away always had longer times and slower speeds. Results for average evacuation times and speeds will be given for each evacuation scenario, “optimal”, “worst case”, and “expected”. Minimum and maximum evacuation times and speeds will also be given for each of the different scenarios to show variation from different sections of the city. Since the same routes were used for each scenario, results from the same two routes will be used throughout this section to represent the minimum and maximum evacuation times and speeds. Times and speeds will vary depending on the scenario, but distances will be held constant. They will be given here to avoid unnecessary repetition. The route closet to the start of contraflow, and thus having the shortest time and fastest overall speed was the route Devils Creek Dr. (route 7). This route was located 5 km (3.1 miles) southeast of the start of contraflow and has a total distance of 157.4 km (97.8 miles) (Table 5). The longest overall route, Mingo Cay Ct. (route 1), was located on Mustang Island, 54 km (33.5 miles) from the start of contraflow, making the total route distance 206.4 km (128.2 miles) (Table 5). Finally, the average distance of all routes to the start of contraflow is 27.8 km (17.26 miles), and the distance through the contraflow section was held at a constant 156.8 km (97.4 miles) (Table 5).

Under "optimal" conditions with free flowing traffic along the entire route, the average evacuation time per vehicle was 101.8 minutes or roughly 1 hour and 32 minutes, with an average travel speed of 106.7 kph (66.3 mph) (Table 7). At these speeds, an evacuation at optimal conditions should be able to fully evacuate the city in approximately 23 hours and 20 minutes (Table 6). Actual evacuation times and speeds will vary depending on the starting point of the evacuation route. Times ranged from a minimum evacuation time of 82.7 minutes, just under 1.5 hours, at a speed of 101.2 kph (71 mph) for individuals evacuating from the Devils Creek Dr. area, to a maximum of 123.7 minutes, roughly 2 hours and 4 minutes, at 101.2 kph (62.2 mph) from the south eastern portion of the county near Mingo Cay Ct. on Mustang Island (Table 7).

Looking next to the "worst case" scenario with heavy traffic congestion and speeds at 15% of free flowing traffic, it is clear that having only one contraflow route may not be enough to safely evacuate everyone from the area. Under worst case conditions, it would take an average of roughly 624.6 minutes or about 10 hours and 24 minutes per vehicle at an average speed of 17.4 kph (10.8 mph) to evacuate the area (Table 6). This would translate into roughly 158 hours and 43 minutes, or about six days, to evacuate the entire area (Table 6). Again, this figure is with constant traffic congestion and speeds of around 16 kph (10 mph) for the entire evacuation route, making it extremely unlikely that it would ever resemble an actual evacuation. As with all evacuation routes, the routes closest to the start of contraflow had faster evacuation times than those furthest away. This means that the shortest evacuation time under "worst case" conditions was again those evacuating from the Devils Creek Dr. area. Motorists leaving from this area can expect an overall evacuation time of 511.3 minutes, about 8 hours and 31 minutes, at an average speed of 18.5 kph (11.5 mph) (Table 8). For evacuees leaving the Mingo Cay Ct. area on Mustang Island, they can expect an evacuation time of approximately 754.5 minutes, or 12 hours 34 minutes, at an average speed of 16.4 kph (10.2 mph) under worst case conditions (Table 8).

Finally, data gathered from previous evacuations has shown that an evacuation is unlikely to fully occur at either “optimal” or “worst cases” levels, an “expected” evacuation scenario was calculated. The median evacuation speed from the other two scenarios was used to determine the speed for the “expected” scenario. Under expected conditions, a contraflow evacuation should take an average of 175 minutes (2 hours and 55 minutes), at an average speed of 62 kph (35.7 mph) for the duration of the route (Table 9). These times will took into account periods of travel at free flow speeds seen in the “optimal” scenario, as well as periods of traffic congestion seen in the “worst case” scenario, and represented a good estimate of the total time it would take an individual to evacuate from the Corpus Christi area. Under these conditions, a total evacuation of the area should take approximately 41 hours and 22 minutes (Table 6). Those leaving from the Devils Creek Dr. had shorter times of 156.3 minutes (2 hour and 36 minutes) at an average speed of 60.4 kph (37.5 mph), where those evacuating from the Mingo Cay Ct. area had longer times of 226.5 minutes (3 hours and 46 minutes) at an average speed of 54.7 kph (34 mph) (Table 9).

Table 7. “Optimal” evacuation scenario.

Route Number	Route Name	Distance to Contraflow (km / miles)	Average Speed to Contraflow (kph / mph)	Distance Through Contraflow (km / miles)	Average Speed Through Contraflow (kph / mph)	Total Route Distance (km / miles)	Total Travel Time (minutes)	Average Total Route Speed (kph / mph)
1	Mingo Cay CT	54 / 33.5	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	206.4 / 128.2	123.6	100.2 / 62.2
2	Radial Ct.	38.2 / 23.7	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	190.6 / 118.4	110.4	103.6 / 64.3
3	Dunbarton Oak Dr.	34.6 / 21.5	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	187.0 / 116.2	107.5	104.4 / 64.9
4	Freds Folly Dr.	38.8 / 24.1	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	191.2 / 118.8	111	103.4 / 64.2
5	Townhouse Ln	35.7 / 22.2	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	188.1 / 116.9	108.4	104.1 / 64.7
6	Green Acre Dr.	21.9 / 13.6	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	174.3 / 108.3	96.8	108.0 / 67.1
7	Devils Creek Dr.	5 / 3.1	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	157.4 / 97.8	82.7	114.3 / 71
8	Amanda St.	35.6 / 22.1	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	188.0 / 116.8	108.3	104.2 / 64.7
9	Chachalaca Dr.	37.7 / 23.4	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	190.1 / 118.1	110	103.7 / 64.4
10	Kay St.	25.8 / 17.7	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	180.9 / 112.4	102.3	106.1 / 65.9
11	Oregon Trl.	9.8 / 6.1	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	162.2 / 100.8	86.7	112.2 / 69.8
12	Oakhurst Dr.	29.5 / 18.3	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	181.9 / 113	103.2	105.8 / 65.7
13	Curtis Clark Dr.	32.8 / 20.4	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	185.2 / 115.1	106	104.8 / 65.2
14	Riverview Dr.	5.5 / 3.4	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	157.9 / 98.1	83.1	114.1 / 70.9
15	Rock Island Dr. (Robstown, TX)	9.3 / 5.8	56.3 / 44.5	152.4 / 94.7	103.8 / 72.4	161.7 / 100.5	86.3	112.4 / 69.9

Table 8. "Worst Case" evacuation scenario.

Route Number	Route Name	Distance to Contraflow (km / miles)	Average Speed to Contraflow (kph / mph)	Distance Through Contraflow (km / miles)	Average Speed Through Contraflow (kph / mph)	Total Route Distance (km / miles)	Total Travel Time (minutes)	Average Total Route Speed (kph / mph)
1	Mingo Cay CT	54 / 33.5	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	206.4 / 128.2	754.5	16.4 / 10.2
2	Radial Ct.	38.2 / 23.7	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	190.6 / 118.4	676.1	16.9 / 10.5
3	Dunbarton Oak Dr.	34.7 / 21.5	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	187.1 / 116.2	658.5	17.0 / 10.6
4	Freds Folly Dr.	38.8 / 24.1	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	191.2 / 118.8	679.3	16.9 / 10.5
5	Townhouse Ln	35.7 / 22.2	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	188.1 / 116.9	664.1	17.0 / 10.6
6	Green Acre Dr.	21.9 / 13.6	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	174.3 / 108.3	595.3	17.6 / 10.9
7	Devils Creek Dr.	5.0 / 3.1	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	157.4 / 11.8	511.3	18.5 / 10.5
8	Amanda St.	35.5 / 22.1	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	187.9 / 116.8	663.3	17.0 / 10.6
9	Chachalaca Dr.	37.7 / 23.4	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	190.1 / 118.1	673.7	16.9 / 10.5
10	Kay St.	28.5 / 17.7	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	180.9 / 112.4	628.1	17.3 / 10.7
11	Oregon Trl.	9.8 / 6.1	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	162.2 / 100.8	535.3	18.2 / 11.3
12	Oakhurst Dr.	29.5 / 18.3	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	181.9 / 113	632.9	17.2 / 10.7
13	Curtis Clark Dr.	32.8 / 20.4	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	185.2 / 115.1	649.7	17.1 / 10.6
14	Riverview Dr.	5.5 / 3.4	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	157.9 / 98.1	513.7	18.4 / 11.5
15	Rock Island Dr. (Robstown, TX)	9.3 / 5.8	12.1 / 7.5	152.4 / 94.7	18.78 / 11.68	161.7 / 100.5	532.9	18.2 / 11.3

Table 9. "Expected" evacuation scenario.

Route Number	Route Name	Distance to Contraflow (km / miles)	Average Speed to Contraflow (kph / mph)	Distance Through Contraflow (km / miles)	Average Speed Through Contraflow (kph / mph)	Total Route Distance (km / miles)	Total Travel Time (minutes)	Average Total Route Speed (kph / mph)
1	Mingo Cay CT	54 / 33.5	41.8 / 26	152.4 / 94.7	61.3 / 38.1	206.4 / 128.2	226.5	54.7 / 34
2	Radial Ct.	38.2 / 23.7	41.8 / 26	152.4 / 94.7	61.3 / 38.1	190.6 / 118.4	203.9	56.1 / 34.8
3	Dunbarton Oak Dr.	34.7 / 21.5	41.8 / 26	152.4 / 94.7	61.3 / 38.1	187.1 / 116.2	198.8	56.5 / 35.1
4	Freds Folly Dr.	38.8 / 24.1	41.8 / 26	152.4 / 94.7	61.3 / 38.1	191.2 / 118.8	204.8	56 / 34.8
5	Townhouse Ln	35.7 / 22.2	41.8 / 26	152.4 / 94.7	61.3 / 38.1	188.1 / 116.9	200.4	56.3 / 35
6	Green Acre Dr.	21.9 / 13.6	41.8 / 26	152.4 / 94.7	61.3 / 38.1	174.3 / 108.3	180.6	57.9 / 36
7	Devils Creek Dr.	5.0 / 3.1	41.8 / 26	152.4 / 94.7	61.3 / 38.1	157.4 / 11.8	156.3	60.4 / 37.5
8	Amanda St.	35.5 / 22.1	41.8 / 26	152.4 / 94.7	61.3 / 38.1	187.9 / 116.8	200.2	56.3 / 35
9	Chachalaca Dr.	37.7 / 23.4	41.8 / 26	152.4 / 94.7	61.3 / 38.1	190.1 / 118.1	203.2	56.1 / 34.9
10	Kay St.	28.5 / 17.7	41.8 / 26	152.4 / 94.7	61.3 / 38.1	180.9 / 112.4	190.0	57.1 / 35.5
11	Oregon Trl.	9.8 / 6.1	41.8 / 26	152.4 / 94.7	61.3 / 38.1	162.2 / 100.8	163.2	59.6 / 37
12	Oakhurst Dr.	29.5 / 18.3	41.8 / 26	152.4 / 94.7	61.3 / 38.1	181.9 / 113	191.4	57 / 35.4
13	Curtis Clark Dr.	32.8 / 20.4	41.8 / 26	152.4 / 94.7	61.3 / 38.1	185.2 / 115.1	196.2	56.6 / 35.2
14	Riverview Dr.	5.5 / 3.4	41.8 / 26	152.4 / 94.7	61.3 / 38.1	157.9 / 98.1	157.0	60.3 / 37.5
15	Rock Island Dr. (Robstown, TX)	9.3 / 5.8	41.8 / 26	152.4 / 94.7	61.3 / 38.1	161.7 / 100.5	162.6	59.7 / 37.1

V. DISCUSSION

The results of this study show the wide range of possible evacuation times when using the contraflow evacuation plan for the Nueces County, Texas area. This study focused only on the contraflow plan itself, and did not take into account any alternative evacuation routes that motorists may use. However, this route is the main method prescribed by Nueces County and the City of Corpus Christi, so it will likely be the most used by evacuees.

Beginning with the "optimal" scenario, it was clear how effective a contraflow evacuation plan could be for Nueces County. A method to fully evacuate the area in just over 23 hours would be an incredible lifesaving tool in the event of a major tropical cyclone. Being able to move that many people out of an area in such a short time would ensure that most everyone who tried to evacuate would be able to safely get out of the storm's path before they were in any major danger. A plan this effective would also allow the city to delay issuing evacuation orders and ensure that the storm was in fact going to directly strike the area before even attempting to evacuate. Generally speaking, the sooner an evacuation can be started the better, however, if a county knows that it will take under 24 hours to evacuate the entire area they have the luxury of waiting to ensure the evacuation is actually needed. Storms can change paths which can lead to unnecessary evacuation orders, costing the city a great deal of money, along with frustration and mistrust of the government from area residents (Dow and Cutter, 1998).

While this scenario would accurately represent some phases of the evacuation, particularly the late stages of the evacuation as vehicles approach the route terminus at Pleasanton, it is not a fully accurate representation of what would actually occur during an evacuation. In the early parts of the route, vehicles are going to be backed up due to bottlenecks created by onramps to IH-37, traffic congestion along the residential areas near the route starting points, accidents along the route, or any number of the previously stated issues that often accompany a contraflow evacuation. Examining day-to-day vehicle counts makes it is clear that traffic will never be able to fully flow at the maximum flow rate during an entire evacuation. Under normal rush hour conditions, traffic volumes can reach greater than 3000 vph across sections of IH-37 (TxDOT, 8/2016). This means that normal evening traffic can surpass the maximum theoretical lane capacity of 1400 vehicles per lane per hour. It is true that density of traffic only occurs for an hour or two then tapers off, but there is a large difference from normal commuter traffic to mass evacuation traffic. It is clear then that under evacuation circumstances, traffic will never be able to flow at the maximum velocity for the duration of the route. This "optimal" scenario is a great goal to strive for, but a very difficult one to achieve.

To help with this however, the City of Corpus Christi does employ phased evacuations and other, more limited evacuation routes that were not part of this study (City of Corpus Christi, 2016). These additional evacuation strategies could greatly help reduce the overall traffic volume during an evacuation and help ensure that traffic can flow near its maximum flow rate through as much of the evacuation as possible. It will never be perfect, but when combining proper planning, infrastructure, warning systems, and evacuation education, an evacuation that approaches this level of effectiveness could likely be achieved.

If the potential is there through phased evacuation and alternate routes to approach the times seen under the "optimal" scenario, then the "expected" scenario should be a fairly accurate representation of what an actual evacuation of Nueces County would be. This plan combined aspects of both the "optimal" and "worst case" scenarios, and provided a more realistic view of an evacuation than either of the other two scenarios can. This scenario took into account the free flowing traffic that would occur near the terminus of the evacuation route as vehicles started to exit enabling more space on the road for higher speeds. It also took into account the extremely slow conditions that would be seen near the start of the routes as evacuees attempt to begin their evacuation that would move very slowly due to heavy traffic congestion. As previously stated, individual evacuation times for this scenario were just over three hours, making the total clearance time of the city about 41 hours. While still a significant amount of time, as long as timely evacuation orders were given, it would still plenty of time to safely evacuate the area. This sort of a clearance time would ensure that everyone who chose to evacuate should be able to do so safely and in a reasonable amount of time.

As previously stated, the "worst case" scenario is very unlikely to every occur during an actual evacuation. There is no doubt that traffic will flow at speeds of 16 kph (10 mph) or slower during many sections of the evacuation route, but highly unlikely that it would ever occur for the full 156 km (97 miles) from Corpus Christi to Pleasanton. Bottlenecks within the city itself will be the locations most susceptible to heavy congestion, and are thus the areas that city planners should focus more attention on in an effort to ensure that these kinds of slowdowns are avoided during an actual evacuation. Under these sorts of conditions, motorists would be trapped in their vehicles as the storm passed through the city potentially stranding and or injuring thousands of evacuees. A situation like this would be an absolute disaster and exactly the sort of thing that evacuation plans hope to avoid. Methods such as phased evacuations, alternate routes, proper traffic controls, sufficient warning and education, and emergency management services are a just a few of the methods in place to ensure a situation like this would never occur during an actual evacuation.

Despite the unlikelihood of this scenario ever materializing, it gives a glimpse into the sobering reality of just how bad things could potentially go for the city should their evacuation plan fail. Many parts of Corpus Christi's highway infrastructure are located very close to the water, and should those roads become inundated with rain or storm surge, the exit points from the city could actually be shut down, trapping everyone inside the city. Sections of the highway leaving Mustang Island reside nearly at sea level, and would flood very easily should a storm pass through the area (Figure 17). Other

Figure 17. John F. Kennedy Causeway traveling from Mustang Island to Corpus Christi. (Photo by Adam Clark)

areas along IH-37 on the Northwestern section of Corpus Christi are dotted with industrial facilities that could become flooded or damaged in a storm and again have the potential to shut down section of the only major route out of the area (Figure 18). Low

Figure 18. Existing roadside infrastructure and construction along IH-37 in Corpus Christi. (Photos by Adam Clark)

bridges along the evacuation route could also become inundated or completely washed away if enough water were to pass through the area, effectively shutting down the evacuation route and stranding everyone on IH-37 (Figure 19). Other problems could

Figure 19. Labonte Park bridge along IH-37 evacuation route in Corpus Christi. (Photos by Adam Clark)

arise from the poor road quality along the evacuation route, particularly if a shoulder lane were opened up along the way (Figure 20). Vehicles cannot safely travel at higher speeds with poor road conditions, forcing traffic to slow down, and ultimately hindering the evacuation efforts. So, while a worst case scenario situation is unlikely to ever actually occur for the duration of an evacuation, if a powerful enough storm hit the area, the evacuation infrastructure could potential fail with disastrous consequences.

Figure 20. Conditions of evaculane in Live Oak County, Texas. (Photo by Adam Clark)

When examined together, these results certainly show that contraflow is not a perfect solution, but it is still a feasible evacuation method and should certainly be employed during a major tropical cyclone that calls for the evacuation of Nueces County. No evacuation is ever going to function perfectly or fully as planned, but with plans such as this in place, evacuations can be very effective and ensure the safety of thousands of people. Problems will arise with traffic congestion, the evacuation will slow to a standstill at times, but overall, everyone should be able to get to safety in a reasonable amount of time. When used in conjunction with other methods such as phased evacuations, and alternative evacuation routes, there should be no problem fully and safely evacuating the City of Corpus Christi and the larger Nueces County area if the need arose.

VI. CONCLUSION

Evacuation plans are a tool. They are not perfect, they will never be followed exactly as written, they will never be obeyed by everyone, and they can have potentially disastrous consequences if they fail. Despite all of this, they are the best defense coastal residents have against the devastating power of tropical cyclones. There is nothing that can be done to prevent an area from being struck by a one of these storms. Little can be done to prevent the damage that will be caused by the rains, winds, and storm surge, and there is no way to tell when the next storm will strike. All coastal communities, local governments, and city managers can do is be as prepared as possible so when the next storm does strike, and when evacuation orders are given, they know what to do, where to go, and have a cohesive and adaptable plan to follow.

Residents of Nueces County, Texas have not been struck by a major tropical storm in many years. Nonetheless, city planners and engineers have developed plans to ensure that when the time comes, they will be able to protect their local residents and get everyone to safety. This research examined one of those plans and attempted to determine what an evacuation of Nueces County would look like under the currently established contraflow evacuation plan. After determining the areas of the county with the potential to have the greatest number evacuees, evacuation routes were plotted using ArcGIS to determine the approximate length and speed of an evacuation from various areas of the city. The results of this study show that, in a "worst case" scenario, a contraflow evacuation has the potential to take several days to fully evacuate the area, under an 'expected' scenario with normal conditions, it will be a successful means of safely evacuating the area. By using individual evacuation times, along with the theoretical vehicular flow during an evacuation, it has been predicted that a full evacuation of Nueces County would take approximately 41 hours to conduct (Table 6). While this is still nearly two days of evacuation, when coupled with advanced warning and timely orders to evacuate, this should be plenty of time to safely evacuate all who choose to do so.

In any disaster situation there will always be variables that are impossible to account for. Storms may change paths, evacuation routes may flood, individuals may unnecessarily decide to leave their homes, while some may choose to remain despite being told to flee the area. It is because of these unknown variables that thorough and adaptable plans must be put in place well in advance of the need to implement them. Government officials must collect all the data they can regarding the dangers their particular communities face from all sorts of natural and manmade disasters, and have plans in place to ensure the safety of their residents. Future studies must continue examining the dangers coastal locations face from sea level rise, changing storm patterns, coastal degradation, and rising local populations. These studies will becomes extremely important in the future as these areas continue seeing incredible amounts of growth year after year. Since tropical cyclones do not generally strike the same area on a yearly basis, it is easy for area residents to gain a false sense of security which can lead to disastrous consequences if the areas themselves are not prepared to manage a hazardous situation. Work must continue being done on infrastructure improvements, utilities management, emergency services, and evacuation plans, to ensure that people are safe when a crisis strikes.

Until the day comes when people stop living along the coast, we will never truly be safe from the dangers of tropical cyclones. Since that is unlikely to ever happen, it is up to us to be prepared for whatever the future may bring. This research, as well as research like it, has laid a foundation for future studies on the subject in the hopes of ensuring the continued safety of everyone along the coast. No plan will ever be perfect, but through continued work and dedication, plans can be established to help those in need when disaster does strike.

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