Effects of the Uncertainty of Hurricane Tracks on Coastal Hazards and Evacuations

Jieya Yang
Department of Civil Engineering, Florida State University, Tallahassee, USA
Email: jy19j@fsu.edu

Linoj Vijayan
Department of Civil Engineering, Florida A&M University, Tallahassee, USA
Email: linoj1.rugminiamma@famu.edu

Mahyar Ghorbanzadeh
HNTB Corporation, 1276 Metropolitan Blvd., Suite 304, Tallahassee, USA
Email: ghorbanzaeh.mahyar@gmail.com

Onur Alisan
Department of Civil Engineering, Florida State University, Tallahassee, USA
Email: oalisan@fsu.edu

Wenrui Huang and Eren Erman Ozguven
Department of Civil Engineering, Florida A&M University, Tallahassee, USA
Email: {whuang, eozguven}@eng.famu.fsu.edu

Simone Burns
Kimley-Horn, 189 South Orange Avenue Suite 1000, Orlando, USA
Email: simone.burns@kimley-horn.com

***Abstract*—Hurricanes cause devastating amounts of damage to structures and infrastructure. It harms especially those coastal residents along its track. Over the last couple of years, evacuation planning for populated coastal regions has been challenging and time-consuming due to the uncertainty of the hurricane's track. As such, with a focus on Northwest Florida, this research aims to focus on the development of evacuation scenarios for coastal communities that combines hurricane inundation and strong wind forecast and evacuation modeling. The proposed approach integrates storm surge simulation models (ADCIRC and SWAN modeling) and traffic evacuation models (Cube and TIME) by using hurricane forecasting datasets to explore the designation of evacuation zones and the calculation of evacuation clearance times in different counties. This approach was applied to three distinct scenarios with a focus on possible populated coastal cities that Hurricane Michael would have hit in 2018. Selected cities are Pensacola, Destin, and Panama City. This type of approach has the potential to help agencies make more informed decisions on evacuations using the accuracy and timeliness of forecasts and provide safer evacuations in coastal areas by avoiding the traffic jams on evacuation routes.**

***Index Terms*—hurricane uncertainty, storm surge, evacuation modeling, hurricane evacuations**

Manuscript received May 26, 2022; revised July 28, 2022; accepted August 26, 2022.

I. Introduction

Hurricane, one of the severe natural disasters commonly appearing in coastal areas, is usually accompanied by strong winds and heavy rains, posing a serious threat to people's lives, and property. They greatly impact people's livelihood, agriculture, and economy. Due to Florida's unique location surrounded by the ocean on three sides and its long coastline, this state is extremely vulnerable to hurricanes. This is particularly dangerous since Florida has a very high coastal population. Florida is home to about 15.8 million people in coastal areas, ranking only behind California and New York in terms of population density [1]. During the hurricane season, residents must evacuate under mandatory evacuation orders or voluntarily move to other safer places against hurricanes, depending on the predicted track and intensity of the hurricane's impact. Such seasonal mass evacuations often clog and paralyze transportation systems in a short period, making it impossible to evacuate residents in areas expected to be at high risk.

Florida Department of Transportation's (FDOT) maps of evacuation traffic congestion during past hurricanes Irma (2017) and Michael (2018) indicate that different hurricane track predictions have a significant impact on the number of people who want to evacuate through

doi: 10.18178/ijscer.11.4.99-107

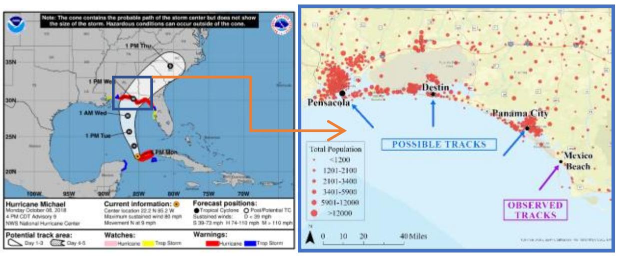
evacuation routes and the traffic evacuation conditions [1]. Therefore, how to properly plan for evacuations based on possible hurricane paths and provide timely emergency plans to avoid excessive evacuation have been a challenging issue. Looking back at the existing research literature, hurricanes in recent years have made transportation agencies and policymakers concerned about finding better evacuation strategies, such as Hurricane Irma, which forced the evacuation of some 6.5 million residents and caused massive delays due to severe congestion, increasing the risk of highway crashes [2]. Therefore, prior to planning evacuation, the best defense against a hurricane is to be able to know and identify the wind and storm surge impacts it would bring to a region [3], which is the focus of this paper.

As the pressure inside a hurricane drops, air from the surrounding atmosphere rushes into the eye to form strong winds, one of the first conditions for a hurricane's progress. Tropical storm winds can extend about 300 miles from the center of the storm. Sustained winds provide enough force to cause structural damage and carry loose air debris to damage the area they cover [4] Storm surge is another hazard based on strong winds: Hurricanes have the ability, low pressure, to push water onto land while out at sea. By the time the hurricane approaches the coast at its high tide, water "piles up" with high tides hundreds of miles wide and up to 12 meters high. Then the surge will cover coastlines, erode beaches, and flood roads. It is also a major cause of loss of life in hurricanes.

In general, forecasts of storm surge levels and precipitation can determine the availability of various routes for coastal evacuation traffic, while strong winds can determine the overall size and schedule of evacuation in terms of traffic safety. However, planning for a hurricane that has already changed its trajectory is a very challenging task to address, which is especially critical for developing efficient evacuation plans. Combining the hurricane inundation and spot models with evacuation models is a possible solution, which is an area still to be studied.

A. Case Study of Hurricane Michael

Hurricane Michael made landfall near Mexico Beach, Florida, on October 10, 2018. It was one of the strongest storms ever recorded to hit the continental United States. Hurricane Michael wreaked havoc across the Florida Panhandle with fearsome winds, heavy rain, and storm surge that threatened residents and transportation systems [5]. Mexico Beach, located on a sandy barrier island in the Florida Panhandle, was damaged heavily due to flooding surf and strong wind along the coast [6]. The hurricane originated from a low-pressure system that embedded itself in a large cyclone circulation in the northwestern Caribbean Sea on October 6, 2018. At 6:00 a.m. local time on October 7, 2018, Michael became a tropical depression 130 nautical miles south of Cozumel, Mexico, with an initial trajectory northward into the Gulf of Mexico [7]. Despite adverse atmospheric conditions and persistent southwesterly wind shear, Michael maintained rapid growth and quickly became a tropical storm and then a hurricane on 12 UCT on October 8. The damage caused by Hurricane Michael not only meant flooding of low-lying coastal areas and blocked coastal roads, but also damaged extensive homes [8] and caused 50 deaths (7 direct and 43 indirect). It caused many residential streets to remain impassable until six days after the hurricane due to downed trees and power lines from Panama City to Mexico Beach and Apalachicola. Existing reports state that there were collapsed bridges in Mexico Beach, destroyed highway signs, and other widespread problems such as the vast majority of damage to traffic lights. Gasoline was in short supply and most gas stations remained closed a week later [9].



(a) (b)

Figure 1. (a) Uncertainty tracks within the hurricane cone (white area) forecasted by National Hurricane Center on Oct 8, 2018, 4 PM CDT [10]; (b) Coastal population density in Northwest Florida and selected hurricane track scenarios with blue arrows and the purple arrow shows the observed landfall of Hurricane Michael.

The worst damage from Hurricane Michael occurred in Bay County, Florida, where more than 46,000 buildings were damaged or destroyed, including two hospitals. In Gulf County, more than 3,200 structures were damaged, and 985 structures were destroyed. Another 80 buildings were destroyed in Franklin County [8]. As shown in Fig. 1a, Hurricane Michael moved north in a direction almost perpendicular to Florida's panhandle coast. Fig. 1b shows the total population of high-density cities along the coast of the Florida Panhandle which was vulnerable to hurricane impact. Especially in these highly populated coastal areas, the uncertainty in forecasts and shift of hurricane track would have significant effects on evacuation decision-making. Therefore, it is important to consider the uncertainty of hurricane tracks in hurricane emergency evacuation planning dynamically.

Mandatory evacuations serve as one of the strategies to ensure minimal casualties in disaster-impacted areas. For example, Hurricane Katrina in 2005 (one of the most powerful hurricanes in the history of the Atlantic Basin) [11] rapidly intensified to a Category 5 on August 28, 2005, entered the Gulf of Mexico, and gradually curved southwest to the north over the next 3 days. The National Hurricane Center (NHC) issued a hurricane warning at 11:00 p.m. CDT on Saturday, August 27 when the storm was a Category 3 and intensifying. The final storm surge from the hurricane was 2.4-6.7 meters [12]. Compared with the previous research results, it is reasonable to consider that Hurricane Michael was more terrifying compared to Hurricane Katrina. If Hurricane Michael had shifted to hit a coastal city, the region should have early warnings of evacuation to have a more efficient evacuation. In historical news records, mandatory evacuation orders for Hurricane Michael were issued to the three affected counties, including the Bay County - issued at 6 a.m. on October 9, Gulf County - issued at 8 a.m. on October 8, and Wakulla County - issued at 8 p.m. on October 8 Click publish [13].

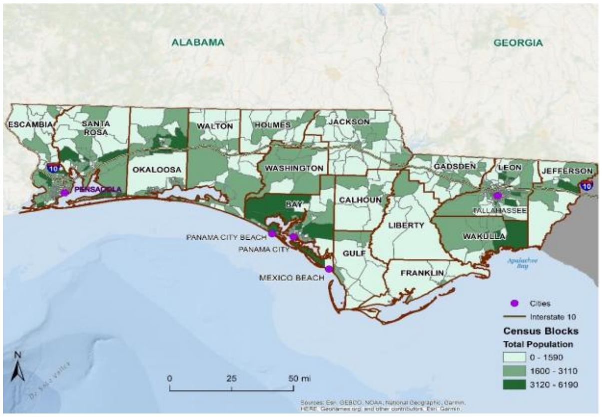
In this study, we propose to establish a certain model that can integrate storm surge simulation and evacuation scenario simulation, which improves the calculation efficiency of evacuation time to help government agencies understand the potential impact area and trajectory of hurricanes in the context of a large-scale hurricane evacuation. To achieve this, we focus on three populated regions in Northwest Florida: Pensacola, Destin, and Panama City. Firstly, hurricane forecast data from National Hurricane Center (NHC) [14]-[15] was downloaded and applied for simulation preparation. Secondly, datasets were applied to Advanced Circulation (ADCIRC) and Simulating Waves Nearshore (SWAN) surge modeling [16] to simulate storm surge elevation and inundation areas. Thirdly, a nested inundation model was developed for different locations. Finally, these results were integrated with Cube Voyager and Transportation Interface for Modeling Evacuations (TIME), the transportation evacuation model established by the Florida Division of Emergency Management (FDEM), and the Florida Department of Transportation (FDOT). Evacuation data of three populated regions in Northwest Florida contains population [17], traffic [18], and maps of designated high-risk areas [19].

II. Methodology

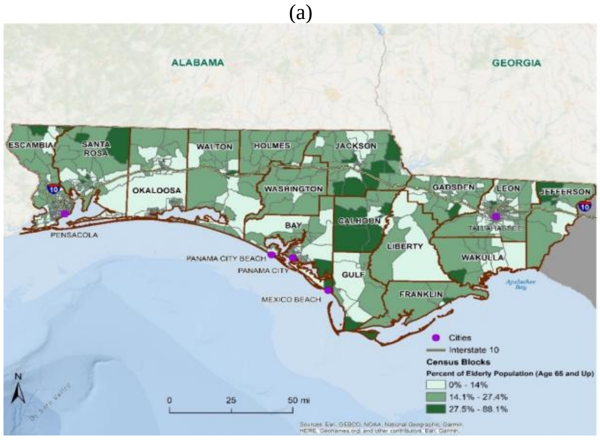
A. Study Area and Data Processing

As a Category 5 hurricane with a maximum wind speed higher than 149 kt, Hurricane Michael was the third strongest storm to make landfall in the continental United States. Around October 10, 2018, persistent heavy precipitation and strong winds occurred near Tyndall Air Force Base on Florida's northwest coast, which led to heaps of debris due to fallen trees mostly [8]. The Federal Emergency Management Agency has approved a $9.8 million grant to the State of Florida to reimburse the cost of removing debris in Jackson County after Hurricane Michael [20]. After the storm in October 2018, the Florida Department of Transportation was responsible for debris collection, disposal, and site management in nine counties including Washington as reported in [20]. The full actual impact of Hurricane Michael on the coastal shoreline and its community is not clear still and needs more research and time to ultimately achieve an accurate and reasonable estimate [4]. One of the difficulties is that hurricanes can change their trajectory at any time, making forecasts requiring constant updates of operations and real-time results. The different landing points resulting from changing tracks would need the areas to provide distinct evacuation plans for different situations combined with their unique characteristics. Following the catastrophic and devastating Atlantic hurricane season of 2004-2005, there has been an increased focus on developing planning directives and policies designed to minimize the impact of uncertain coastal hazards on society [21]. In the transportation domain specifically, researchers focus on methods to better understand evacuation issues [22].

Ref. [17] provides the dataset from which we produced a series of maps that show the population distribution in Northwest Florida (Fig. 2). We converted the ratio of the elderly population (i.e., the elderly age group referenced in this study is 65 years old and above) to the total population of the corresponding county and displayed it as a percentage. As shown in Fig. 2a, each county in Northwest Florida has a high senior total population. We specifically included population numbers and percentages to get a sense of where the highest elderly populations are and where the highest percentages of elderly populations are. In the studied area, as shown in Fig. 2b, the elderly population is very high in Santa Rosa and Bay counties, followed by Okaloosa and south of Walton counties near Destin. Additionally, many census tracts with high proportions of older populations are located near the Florida coastline, particularly in Bay County. This is also important since many of these areas are also vulnerable to storm surges during hurricanes. These two maps can help identify and validate vulnerable communities in the affected areas that were most affected by Hurricane Michael with a focus on the population distribution of older adults.



(a)



(b)

Figure 2. Florida Panhandle (a) Total Population Counts by Census Blocks, and (b) Percent Elderly Population by Census Blocks.

When a hurricane occurs, the judgment and status of evacuation personnel are affected due to untimely information dissemination and guidance [23]. Especially in more densely populated areas, this phenomenon is more obvious. People's lives are not only directly threatened by the hurricane itself - for example, rising water levels can lead to drowning. On the other hand, with the arrival of a hurricane, it is surprising to find that the death toll may increase over time after it hits. Some people may be trapped since they do not have a means of evacuation or access to medical supplies. This accounts for another proportion of the number of deaths in a hurricane [24]. Some people do not pay enough attention to the seriousness of these hurricanes [23]-[24]. On the other hand, because of their low levels of mobility, the elderly population often needs more time to evacuate [25]. Therefore, combined with the population distributions shown in Fig. 2, we selected the three cities shown in Fig. 3 with high population density (i.e., more elderly population) and high disaster probability. We tried to answer a potentially threatening question: What if Hurricane Michael made landfall at any of these highly populated areas? The corresponding counties of Escambia, Santa Rosa, Okaloosa, Walton, and Bay were selected as the counties to be evacuated.

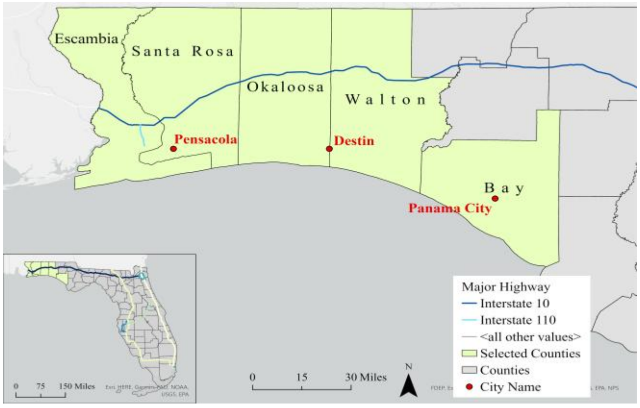


Figure 3. Selected study areas.

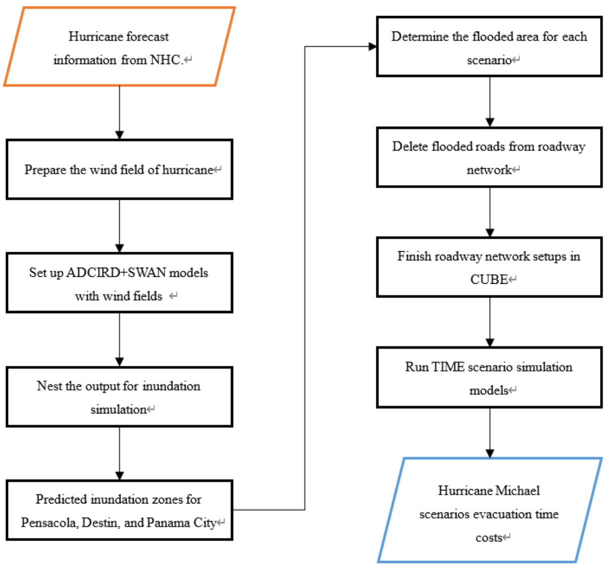


Figure 4. Flowchart of Data Processing and Results Analysis.

As shown in Fig. 4, in the beginning, we imported the forecast information data of Hurricane Michael into a storm surge simulation. At the same time, we needed to predict the wind field for five days as the hurricane approached various locations, and then coupled it with a water level simulation model. Next, we combined inundation results budgeted with the ADCRIC + SWAN model with traffic information. The following step was to set different parameters in the TIME software. Ultimately, we output the clearance time of scenario calculations and analyzed the results.

B. Evacuation Scenario Generation

One of the goals of developing the Transportation Interface for Modeling Evacuations (TIME) software was to allow practitioners of the non-travel demand modeling or non-transportation modeling software CUBE to personally set up, manage, and execute evacuation modeling scenarios. This software will be based on the operation mode of ArcGIS software and is well compatible with the Windows GUI work environment [26]. TIME draws from multiple data sources to run its scenarios: 1) small area data from the U.S. Census and American Community Survey; 2) storm surge data development and evacuation zone map from the National Hurricane Center; 3) Florida counties and regions shelter location and socioeconomic data provided by the Planning Commission; 4) roadway network interface-compatible with Florida Department of Transportation information [27]. After the model operation is completed, the evacuation clearance time is generated as the resulting output. This is a crucial component of the findings of this study since it would help inform emergency planners about how long it will take for governments in disaster-stricken areas to get people out of dangerous areas. The model can also estimate public shelter needs, helping planners and citizens' safety protection groups understand where the most vulnerable will be most quickly secured during a massive hurricane evacuation. The most convenient point of this model is that the settings can be updated at any time, which is convenient for dealing with hurricane disasters that can change.

When setting up scenarios in the TIME software, various evacuation conditions need to be accurately defined, including evacuation counties, year of analysis of socioeconomic data and transportation networks, floating population, shelter availability, and evacuation behavior detail assumptions. In this study, population projections and transportation networks for 2025 were used. The study area network is from the Florida Standard Urban Transportation Modeling System (FSUTMS). Since Hurricane Michael occurred in early October 2018, there were no major holidays, and there was no significant tourist population movement. The hurricane coincides with the universities' fall semester, and all resident populations need to consider the university population, which means 100% in residence. Other detailed assumptions on parameters are given as follows including Table I:

- Assumptions:
    - The evacuation region on TIME is set as '10 – Emerald Coast'

  - Both network and population periods should be concurrent.
  - Only the shelters in the evacuated counties are considered open. This is due to our consideration of using predicted data for evacuations before the hurricane makes landfall and requires a minimum clearance time. Only three models were run, each involving shelters in county towns with a larger capacity than coastal evacuation.
  - Flooded roads are deleted in CUBE based on the inundation maps obtained from storm surge modeling.
  - A 6-hr response curve is used.
- Counties of evacuation level E:
  - Pensacola: Escambia, Santa Rosa
  - Destin: Okaloosa, Walton
  - Panama City: Bay

TABLE I. SCENARIO PARAMETER

Region	Emerald Coast
Network Period	2025
Network Updated	2025
One-Way Operations	None
University Population	Fall/Spring Session
Tourist Rate	Not include
Shelters	Primary Open
Response Curve	6-hour S-curve Loading
Behavioral Response	100% Response
Evacuation Level	Level E for Category 5
Tourist Override Rates	0 %
Counties Evacuating	Escambia, Santa Rosa, Okaloosa, Walton, Bay
Regional Destination Rates	31.03907

The inundation model allowed us to locate the areas that had to be evacuated due to rising water levels (i.e., evacuation zones). Combining the flooded areas with the network on CUBE software made it possible to focus on how and where needed to be evacuated clearly. As stated previously, the first step in this study was to accurately model the storm surge and subsequent inland flooding. The category 5 hurricane hypothetically hitting Pensacola, Destin, and Panama City was modeled using the coupled ADCIRC+SWAN model. In debugging the model, we found that the 6-hour response curve in evacuation scenarios might be closer to a real hurricane than the conventional 12-hour response curve. This is because the National Hurricane Center's forecasts are generally updated every six hours when the hurricane is not yet close inland [15]. Results in the next section indicate that the storm surge water levels on the coast were as high as 5.2 meters, which was augmented by the waves in the model. But there was no apparent need for a countywide evacuation just because of storm surge water levels. What determined that an evacuation had to be enforced should be the impact of strong winds from the hurricane.

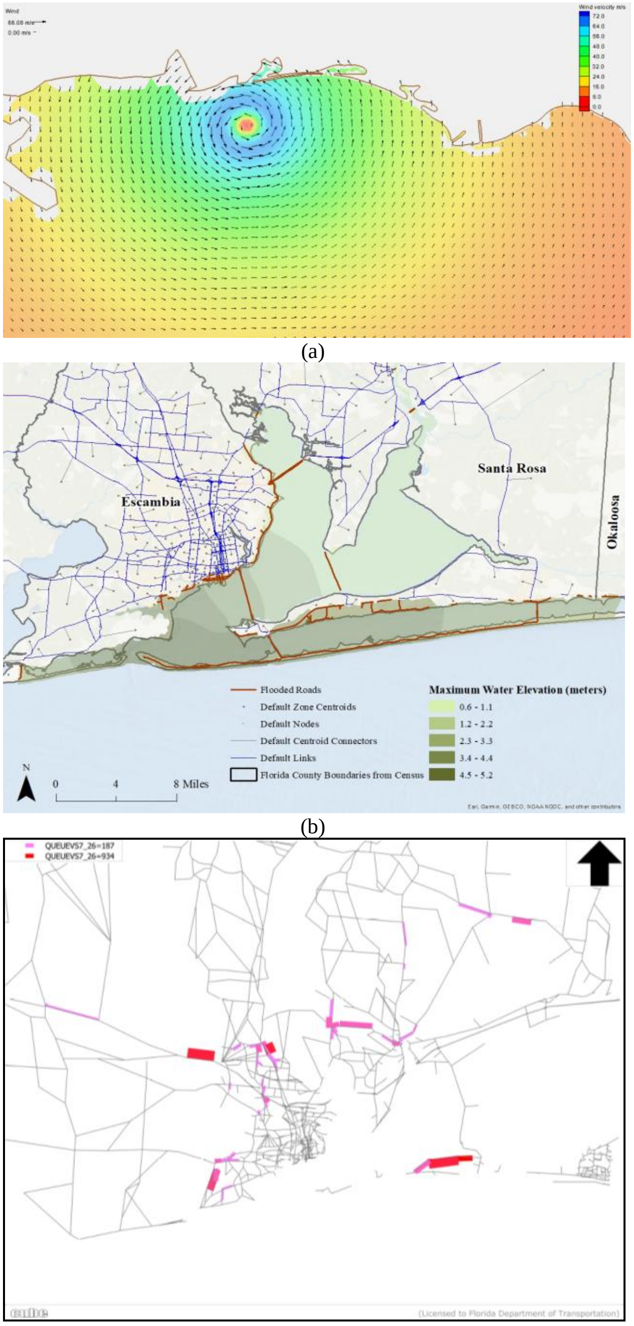
III. RESULTS

Using storm surge models, we simulated the effects of Hurricane Michael for Pensacola, Destin, and Panama City if it hit these areas. All three regions are densely populated cases, such as 305,410 in the Pensacola scenario, 238,772 in the Destin scenario, and 156,378 in the Panama City scenario. We calculated the 5-day wind field coverage of hurricanes before and after they landed on those areas in Northwest Florida. We output maps of water elevation increase and determined the flooded roads in the three regions, and the evacuation levels corresponding to the selected county towns. The following three series of results show that more and more roadways, which may have very low elevation, became unavailable as the hurricane approached due to the surge level rise. Additionally, the damage to the cities from strong winds became more severe. The evacuation time required for the selected disaster-stricken counties has also increased to varying degrees.

A. Pensacola

The impact of the hurricane on the Pensacola area is shown in Fig. 5a and 5b. First, the center of the storm would drive northward from the Gulf of Mexico, approaching the western junction of Gulf Breeze and Villa Sabine, the estuary that Pensacola Bay must pass southward. It is evident from Fig. 5a that the wind speed of the hurricane on the coastline is above 64m/s, which is 143mph. In wind speeds like these, even well-installed high-quality infrastructure will start taking off at 80 mph. This wind damage intensified as time got closer to the hurricane's landfall. According to our calculations, people had to evacuate possibly 1-2 days before the hurricane made landfall - 1-2 days before more precipitation and high tides. Otherwise, strong winds can cause serious travel disruptions. It also increases the probability of dangerous conditions on the roadways.

Fig. 5b shows another hurricane hazard: inundation or rising water levels. On the day of the simulated attack in Pensacola, water levels on the southern coast of Escambia County reached a maximum of 5.2m. According to the geographic information provided by [6], several roadways in the area, such as the Gulf Beach Highway, have low-lying sections close to 26ft (7.9m) below the southwest and southeast sections. There are also some branches of national highways, which usually do not have the additional padding like highways. When storm surges are at their highest levels, accompanied by continuous strong winds and heavy rainfall, these roadways are closed for safety reasons. Using these roadways also means being trapped in the danger of being submerged or blown over. As shown in red in Fig. 5b, including Pensacola Bay Bridge (National Highway 98), Garcon Point Bridge, and National Highway 90 in the eastern coastal section of Escambia County, as well as part of the maritime Interstate 10 will be flooded or damaged by wind.



(a)

(b)

(c)

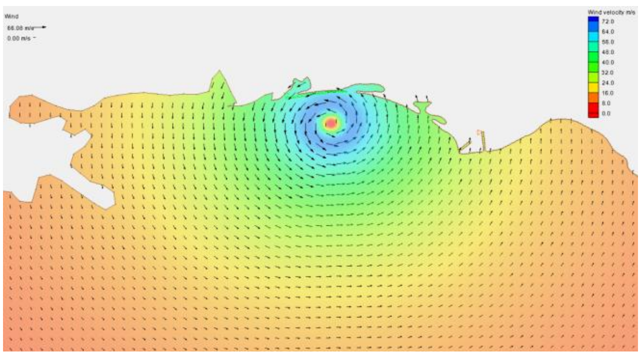
Figure 5. Hurricane Impact Simulation of Pensacola Area – Counties: Escambia, Santa Rosa. (a) Storm Surge with Wind Field Results, (b) Integration of Inundation Results and Transportation Network, and (c) Congested Roads of Pensacola Scenario.

Fig. 5c shows the queue of vehicles on the roadway network 3.5 hours after the start of the evacuation. Due to the closure of the Pensacola Bay Bridge and Garcon Point Bridge, the only roadway available to the north from the southern Narrows Bay was Highway 87. People could only escape the hurricane by converging on Highway 98 Eastbound and then continue northward. That's the reason we had seen congestion on this roadway due to the evacuating vehicles passing at the south end of Fig. 5c. Other congested roadway sections such as Interstate 10 Westbound, on the top left of Fig. 5c, were all traffic situations that could be predicted. This is because the directions available to the disaster victims were within our consideration. Such congestion results are currently reasonable.

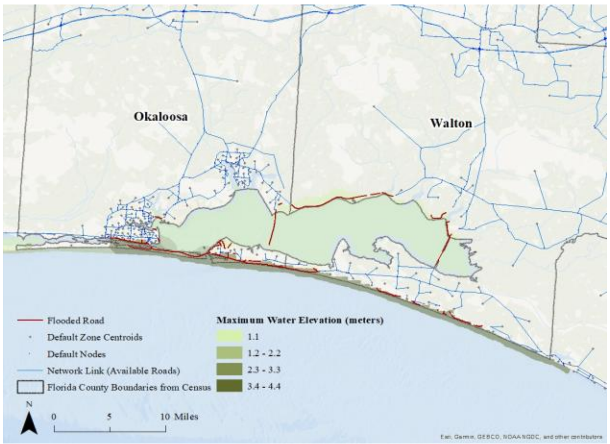
B. Destin

As the hurricane approached Destin Harbor, strong winds swept across the narrow southern island section, bringing rising waters across Choctawhatchee Bay. Fig. 6a and 6b show the simulation results. The eye of the hurricane was located 4 to 5 miles south of Fort Walton Beach. Both southeastern Okaloosa County and southern Walton County experienced winds of 55 to 64 m/s at the time of the hurricane's arrival. The water elevation of the storm surge was 4.4 meters at the highest and 1.1 meters at the lowest. As seen in Fig. 6b, the superimposed 1.1 m storm surge elevation almost completely covered Choctawhatchee Bay. The closer to the eye of the wind, the further south the coastline was, the more rapid and strong winds and higher water levels surrounded it. According to the inundation model output, the following sections of State Highway 98: Miracle Strip Pkwy, East Pass Brg, and Emerald Coast Pkwy, would be unavailable for at least 3 days after the hurricane arrives. The important Mid-Bay Bridge was also facing closure. The impact of the hurricane on the roadways in the Destin area was concentrated on the bridges from the island to the inland areas. It took longer for Destin's victims to evacuate from the coastal areas to the inland. They also faced a greater risk of being trapped. Therefore, it was very important to simulate the inundation data that would provide information on evacuation in advance and therefore make a timely evacuation response for areas such as Destin with large islands and many low-elevation areas and coastal roadways. The timeliness of disaster simulation can significantly improve the evacuation efficiency of such coastal cities.

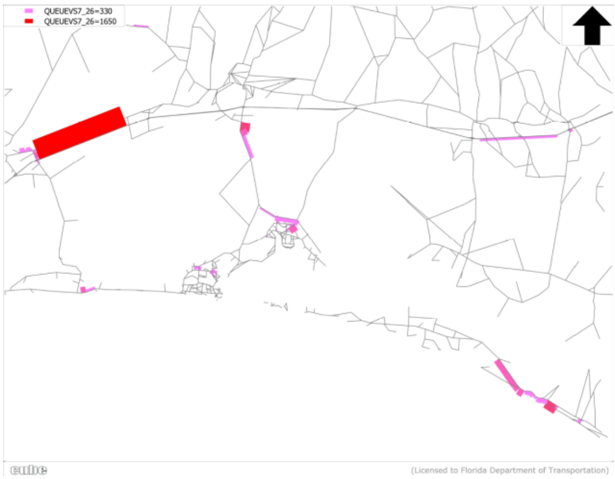
In each scenario, people could only flee to a nearby county or a primary open shelter. As seen in Fig. 6c, the evacuation congestion occurred mainly on the westbound section of Interstate 10, the exit section of the highway where people were evacuated to the nearby county, with queues of more than 10,000 vehicles per hour. This also helps us see why the evacuation times for Destin shown in Fig. 8 are higher than other areas studied. There was only one highway to the west side of the county available, which limited the options for evacuating people to the west.



(a)



(b)



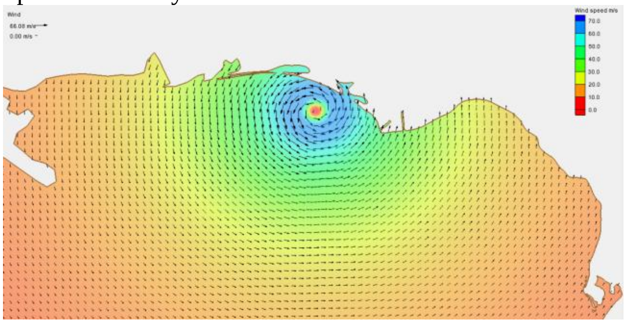
(c)

Figure 6. Hurricane Impact Simulation of Destin – Counties: Okaloosa, Walton. (a) Storm Surge with Wind Field Results, (b) Integration of Inundation Results and Transportation Network, and (c) Congested Roadways of Destin Scenario.

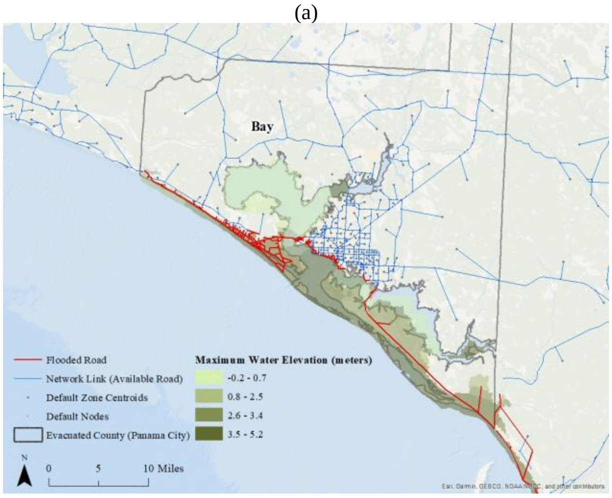
C. *Panama City*

Bay County, where Panama City is located, has a high density of population, as shown in Fig. 2a. But its main roadways are concentrated in Panama City as shown in Fig. 7b, and its main highways, such as Florida 77 and National Highway 231, show a northeastward extension, and the ground surface is not at a low-level elevation. What determines the length of evacuation in the region is whether the evacuation of Panama City Beach, the beach just south of Bay County, can be handled in time.

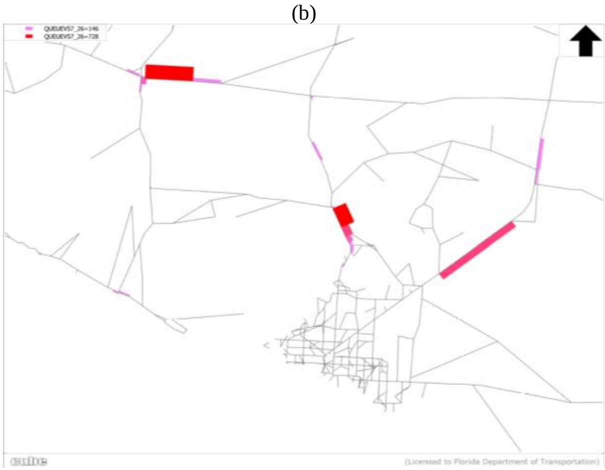
As shown in Fig. 7a and 7b, the winds in Panama City had reached more than 50m/s before the hurricane made landfall. In St. Andrew Bay, the water can reach 5.2 meters above sea level. The backflow of seawater from the estuary into the farthest point of the inland sea area south of Panama City could cause a water level rise of 0.7 meters. Strong winds and heavy rainfall would halt transportation on almost all the coastline of Bay County. For example, the Tyndall Pkwy section of State Highway 98 and all sections of Panama City Beach were within the inundation zone. But fortunately, because the main urban area was sufficiently inland, and there was a wide estuary around its coast as a buffer, most urban roadways would operate normally.



(a)



(b)



(c)

Figure 7. Hurricane Impact Simulation of Panama City – County: Bay. (a) Storm Surge with Wind Field Results, (b) Integration of Inundation Results and Transportation Network, and (c) Congested Roadways of Panama City Scenario.

According to Fig. 7b, it can be recognized that the East Bay area, located in the south, was all within the inundation area, so we closed the Highway 98. This caused the victims in the South Bay area to be able to evacuate only to the northwest or southeast, wait for an opportunity to find a roadway leading to the northern inland areas. For example, most citizens in the main city of Panama City would evacuate first to the northeast via Highway 231 and then waited for an opportunity to evacuate further to the north - for example, via the Fishing Bridge along Highway 77. So as expected, there was a brief queue of 200 vehicles per mile on Highway 231 coming out of the city during the initial evacuation. Congestion still occurred in the east-west direction. This is because some people needed to evacuate to the east or west towards the northbound roadways. Fig. 7c shows that there was a queue on the last westbound leg of Highway 20 out of Bay County to the north, indicating that people trying to escape west or north out of Bay County inevitably faced traffic congestion out of the city before they were slowly diverted to their destinations.

D. Findings

TABLE II. SUMMARY OF EVACUATION SCENARIO RESULTS

Region	City Name	Pensacola		Destin		Panama City
	County Name	Escambia	Santa Rosa	Okaloosa	Walton	Bay
Shelter	Sheltering Demand	11,379	7,487	7,757	4,281	8,886
	Shelter Capacity	76,054		73,906		73,906
Population	Site-Built Population	157,009	107,104	134,653	49,324	119,808
	Mobile Home Population	20,207	16,358	10,397	13,477	24,290
	University Population	218	0	0	0	0
	Tourist Population	3,414	1,100	9,591	21,329	12,280
	Evacuating Population per County	180,847	124,563	154,641	84,131	156,378
	Evacuating Population per Region	305,410		238,772		156,378
Vehicles	Site-Built Evacuating Vehicles	73,515	53,173	74,053	27,074	61,848
	Mobile Home Evacuating Vehicles	11,530	9,077	6,383	8,384	13,933
	University Evacuating Vehicles	218	0	0	0	0
	Tourist Evacuating Vehicles	1,707	550	4,796	10,665	6,140
	Total Evacuating Vehicles	86,969	62,800	85,231	46,123	81,922

Based on combining hurricane inundation simulations and identifying roadway closures, all results from the evacuation scenario calculations are shown in Fig. 8 and Table II. We observe that if two counties with larger tourist populations are simulated together, such as the Destin scenario, the evacuation time is significantly longer than Pensacola, which has a smaller tourist population, and Panama City, which has only one evacuation county. In addition, the number of evacuated vehicles may also lead to increased clearance times. All three regions are densely populated cases, such as 305,410 in the Pensacola scenario, 238,772 in the Destin scenario, and 156,378 in the Panama City scenario. This resulted in a significantly less clearance time in Bay County than in the other scenarios. Therefore, the uncertainty of hurricane tracks during Hurricane Michael may result in the evacuations in different coastal counties, which is similar to the Hurricane Irma evacuation in south Florida in 2017 [6].

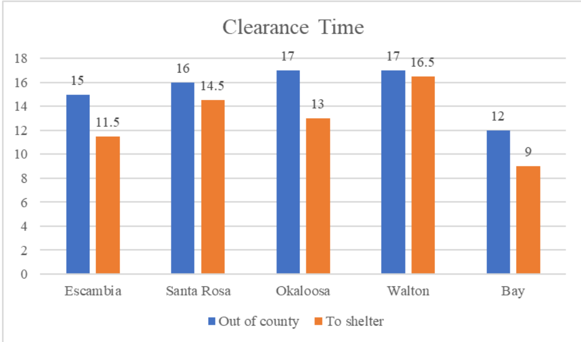


Figure 8. Clearance Time Summary Graph (Unit: Hour).

IV. CONCLUSION

The research aimed to develop a methodology to integrate storm surge models with evacuation scenarios with a focus on Hurricane Michael hitting three populated areas in Northwest Florida. A storm surge and wave model (ADCIRC+SWAN) was used to identify flood areas with a high risk of inundation in the area and roadways that were impassable due to rising water levels. Flooded roadways were entered into the settings of the TIME software scenario using CUBE to estimate area clearing times and shelter availability in selected counties. Our evacuation planning process by simulating storm surge and wind field of uncertain hurricane tracks and integrating the water level and wind-affected zone into evacuation scenarios has the potential to increase the accuracy and efficiency of hurricane emergency response. The findings of this research will help emergency response officers understand the impact of a potential hurricane trajectory bounded by the hurricane cone and its uncertainty over the area of potential hurricane impact.

AUTHOR CONTRIBUTIONS

Jieya Yang and Mahyar Ghorbanzadeh finished evacuation modeling work. Linoj Vijayan and Wenrui Huang conducted storm surge modeling. Onur Alisan and Eren Erman Ozguven provided helps in manuscript preparation. Jieya Yang and Simone Burns generated figures for this research. All authors have approved the final manuscript.

ACKNOWLEDGMENT

This study is supported by National Science Foundation Grant # # 1832068.

REFERENCES

[1] M. Ghorbanzadeh *et al.*, "Integrating evacuation and storm surge modeling considering potential hurricane tracks: The case of hurricane Irma in Southeast Florida," *ISPRS Int. J. Geo-Inf.*, vol. 10, no. 10, p. 661, 2021.

[2] J. K. Lazo, A. Bostrom, R. E. Morss, J. L. Demuth, and H. Lazrus, "Factors affecting hurricane evacuation intentions," *Risk Anal.*, vol. 35, no. 10, pp. 1837–1857, 2015.

[3] S. A. Braun, M. T. Montgomery, K. J. Mallen, and P. D. Reasor, "Simulation and interpretation of the genesis of tropical storm gert (2005) as part of the NASA tropical cloud systems and processes experiment," *J. Atmospheric Sci.*, vol. 67, no. 4, pp. 999–1025, Apr. 2010.

[4] E. Rodriguez, C. Duclos, J. Joiner, M. Jordan, K. Reid, and K. W. Kintziger, "Community Assessment for Public Health Emergency Response (CASPER) following hurricane Michael, bay and gulf counties, Florida, 2019," *J. Public Health Manag. Pract.*, vol. 28, no. 2, p. E542, Apr. 2022.

[5] L. Vijayan, W. Huang, K. Yin, E. Ozguven, S. Burns, and M. Ghorbanzadeh, "Evaluation of parametric wind models for more accurate modeling of storm surge: A case study of hurricane michael," *Nat. Hazards*, vol. 106, no. 3, pp. 2003–2024, Apr. 2021.

[6] A. Green, S. G. Gopalakrishnan, and G. J. AlakaJr, "Understanding the role of mean and eddy momentum transport in the rapid intensification of hurricane Irma (2017) and Hurricane Michael (2018)," *Atmosphere*, vol. 12, no. 4, p. 492, 2021.

[7] J. Beven II, R. Berg, and A. Hagen, "Hurricane Michael (AL142018), national hurricane center tropical cyclone report," p. 86, May 2019.

[8] "Michael graphics archive: Initial wind field and watch/warning graphic," *National Hurricane Center and Central Pacific Hurricane Center*, Oct. 08, 2018. [Online]. Available: https://www.nhc.noaa.gov/archive/2018/MICHAEL_graphics.php (accessed Feb. 25, 2022).

[9] "Tropical Cyclones - August 2005 | National Centers for Environmental Information (NCEI)." [Online]. Available: https://www.ncdc.noaa.gov/sotc/tropical-cyclones/200508 (accessed Mar. 07, 2022).

[10] S. K. Huang, M. K. Lindell, and C. S. Prater, "Multistage model of hurricane evacuation decision: Empirical study of hurricanes Katrina and Rita," *Nat. Hazards Rev.*, 2016.

[11] A. Roberson. Hurricane Michael: First Florida evacuations ordered in gulf county, others in Panhandle. *Tallahassee Democrat*. [Online]. Available: https://www.tallahassee.com/story/news/2018/10/08/hurricane-michael-florida-evacuation-gulf-county-panhandle-wakulla-bay-mandatory/1567904002/ (accessed Feb. 15, 2022).

[12] R. Rahman, T. Bhowmik, N. Eluru, and S. Hasan, "Assessing the crash risks of evacuation: A matched case-control approach applied over data collected during hurricane Irma," *Accid. Anal. Prev.*, vol. 159, p. 106260, Sep. 2021.

[13] Michael cleanup in Florida Panhandle hampered by damaged roads, power outages, *Washington Post*. Accessed: Feb. 15, 2022. [Online]. Available: https://www.washingtonpost.com/transportation/2018/10/16/michael-cleanup-florida-panhandle-hampered-by-damaged-roads-power-outages/

[14] Hurricane MICHAEL Advisory Archive. [Online]. Available: https://www.nhc.noaa.gov/archive/2018/MICHAEL.shtml (accessed Mar. 07, 2022).

[15] NHC Data in GIS Formats. [Online]. Available: https://www.nhc.noaa.gov/gis/ (accessed Mar. 07, 2022).

[16] W. Huang, K. Yin, L. Vijayan, S. D. Xu, M. Ghorbanzadeh, E. Ozguven, "Integrating storm surge modeling with traffic data analysis to evaluate the effectiveness of hurricane evacuation," *Frontiers of Structural and Civil Engineering (FSCE)*, vol. 15, pp. 1301–1316, 2021.

[17] U. C. Bureau, "American Community Survey (ACS)," *Census.gov*, Jan. 13, 2022. [Online]. Available: https://www.census.gov/programs-surveys/acs (accessed Mar. 01, 2022).

[18] "Florida Statewide Network Model (FSUTMS)." [Online]. Available: https://fsutmsonline.net/ (accessed Mar. 06, 2022).

[19] Florida Division of Emergency Management., "Disaster Preparedness Maps," Jul. 31, 2020. [Online]. Available: https://www.floridadisaster.org/planprepare/disaster-preparedness-maps/ (accessed Mar. 01, 2022).

[20] "FEMA Reimburses Department of Transportation $9.8M for Hurricane Michael Expenses," *Targeted News Service*, Targeted News Service, Washington, D.C., United States, Sep. 05, 2019. Accessed: Mar. 11, 2022. [Online]. Available: https://www.proquest.com/docview/2285113058/citation/78C3196B9D0A41F2PQ/1

[21] S. L. Cutter, C. T. Emrich, J. T. Mitchell, B. J. Boruff, and et al, "The long road home: Race, class, and recovery from hurricane Katrina," *Environment*, vol. 48, no. 2, pp. 8-20, 2, Mar. 2006.

[22] M. W. Horner and M. J. Widener, "The effects of transportation network failure on people's accessibility to hurricane disaster relief goods: A modeling approach and application to a Florida case study," *Nat. Hazards*, vol. 59, no. 3, pp. 1619–1634, Dec. 2011.

[23] X. Song, Q. Zhang, Y. Sekimoto, T. Horanont, S. Ueyama, and R. Shibasaki, "Modeling and probabilistic reasoning of population evacuation during large-scale disaster," 2013, pp. 1231–1239.

[24] J. Burlew, "43 and counting: Deconstructing the Florida death toll after Hurricane Michael," *Tallahassee Democrat*. [Online]. Available: https://www.tallahassee.com/story/news/2018/11/29/43-and-counting-deconstructing-death-toll-hurricane-michael/2124902002/ (accessed Mar. 11, 2022).

[25] United States Congress Senate Special Committee on Aging, *Caring for seniors in a national emergency: can we do better? : hearing before the Special Committee on Aging, United States Senate, One Hundred Ninth Congress, second session, Washington, DC, May 18, 2006.* Washington: U.S. G.P.O., 2006.

[26] C. Smith, "Getting to know TIME Version 8.0." Statewide Reginal Evacuation Study Program, Sep. 30, 2015.

[27] FDEM, "Building a robust hurricane evacuation model for Florida." [Online]. Available: https://www.cdmsmith.com/en/Client-Solutions/Projects/Florida-Department-of-Emergency-Management-Hurricane-Evacuation-Model (accessed Feb. 16, 2022).

Jieya Yang Ph.D. candidate of FAMU-FSU College of Engineering, USA. Her main research areas are inundation simulation modeling and coastal hazard evacuation modeling.

Linoj Vijayan Ph.D of FAMU-FSU College of Engineering, USA. His research fields mainly focus on computational fluid dynamics applied to geophysical/environmental systems, ocean circulation modeling and coastal hazard modeling.

Mahyar Ghorbanzadeh Ph.D. Transportation engineer at HNTB Corporation, USA.

Onur Alisan Post-doc of FAMU-FSU College of Engineering, USA. His main research directions are traffic safety, emergency operation management and mathematical modeling.

Wenrui Huang professor in the Department of Civil and Environmental Engineering at FAMU-FSU College of Engineering, USA. His research interests include coastal hazard modeling (storm surge, wave, and storm runoff and flood), impacts of natural hazards and sea-level rise on coastal ecosystems, coastal and estuarine environmental modeling.

Eren Erman Ozguven associate professor in the Department of Civil and Environmental Engineering at FAMU-FSU College of Engineering, USA/director of the RIDER Center, FL, USA. His research interests include emergency transportation operations, hurricane resilience, network modeling, transportation accessibility and safety, connected vehicles, intelligent transportation systems, smart cities, and urban mobility.

Simone Burns civil analyst (Transportation Planning/Traffic Operations) at Kimley-Horn, USA.