TRB Annual Meeting

Planning for Special Needs Shelters: A Hurricane Track Uncertainty-based Approach Integrating Coastal Inundation and Accessibility

--Manuscript Draft--

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ABSTRACT

Storm surge and evacuation traffic under the observed track of Hurricane Michael (2018) showed clear accessibility/evacuation challenges for Panama City, Florida although the city was not hit directly. This paper tries to answer the following questions: What if Michael hit Panama City directly? How would the special needs populations and their accessibility to Special Needs Shelters (SpNS) be impacted, and what could have been done to alleviate this impact? A previously validated storm surge model was used to predict storm surge inundations under this hurricane track. Based on this, a GIS-based optimization methodology was developed to evaluate the accessibility and siting of SpNS. Results indicate that if Michael shifted to Panama City, most of the coastal region of Panama City would have been inundated, compelling residents to evacuate. The possible landfall of Michael would also lead to a maximum storm surge of 5-6 m, which is above FEMA's 100-year flood elevation. Also, the only evacuation route out of the Panama City area, when the bridges were flooded, was US 231. This would have been life-threatening since there is only one SpNS in the north accessible by this roadway. This paper studies the accessibility of this SpNS shelter and provides a reasonable approach for SpNS shelter siting or repurposing regular shelters for this purpose. Emergency plans can be updated by optimization model findings, which can locate additional sites/shelter locations while minimizing travel costs and integrating the impact of storm surge modeling and accessibility analysis.

Keywords: Storm Surge Modeling, Coastal Inundation, Hurricane Evacuations, Accessibility, Hurricane Michael, Special Needs Shelters

INTRODUCTION

With monstrous wind and storm surges, Hurricane Michael was the first Category 5 hurricane (on the Saffir-Simpson Wind Scale) ever to hit the Florida Panhandle and the first one in the contiguous U.S. since 1992 (*1*). It caused 74 deaths, including 59 in the U.S., and approximately $25.6 billion in total damage (*2*, *3*), making it the eighth-most expensive Atlantic hurricane to affect the U.S. It had maximum sustained winds of 161 mph and peak storm surge inundation of 9 to 14 feet from Mexico Beach to Indian Pass, leaving thousands of residents without housing for weeks up to several months. The damages were primarily due to surge waves, inundation, and strong winds, with watermarks above National Flood Insurance Program (NFIP) VE zone (i.e., highest risk in the 100-year floodplain) (*3*).

Similar to Hurricane Irma (*4*), the uncertainty in hurricane forecasting for Hurricane Michael caused challenges for emergency managers regarding evacuations and sheltering decisions in the Florida Panhandle especially due to the uncertainty associated with the path and strength of the hurricane. Michael became a Category 5 hurricane overnight on October 10, 2018. This strengthening of a hurricane is rare but extremely significant as it became the strongest type of hurricane on the scale and caused catastrophic damage to buildings and infrastructure. Most of the areas impacted were along the border of Bay and Gulf counties; however, Panama City, a medium-sized city in Bay County, was not hit directly. An estimated total of about 375,000 Florida residents evacuated from the Florida Panhandle region due to Hurricane Michael (*5*). Vulnerable communities in the impacted area had additional challenges since very few state roadways would help them reach safety. These roadways were under flooding risk, making their evacuations less timely and more difficult. This was a challenging issue since the elderly and no vehicle access population had over 28% combined representation of the total population in the impacted area (*6*). According to a study, this area was found to be one of the most vulnerable locations to hurricanes in Florida due to the weaker emergency preparedness and evacuation plans than other locations in the state (*7*–*9*).

Evacuation decisions by emergency managers are often affected by hurricane track forecasting provided by the National Hurricane Center (**Figure 1a**). The storm's forecast track is represented by a white "cone" on the graphic. The cone represents the probable track of a tropical cyclone's center and is formed by enclosing the area swept out by a set of circles along the forecast track (at 12, 24, 36 hours, etc.). The size of each circle is set at two-thirds of the historical forecast error over the previous five-year period. Based on those previous forecast errors, the entire track of the tropical cyclone can be expected to remain within the cone about 60 to 70 percent of the time. As shown in **Table 1**, the hurricane forecasting cone becomes wider over time as the forecast uncertainty increases.

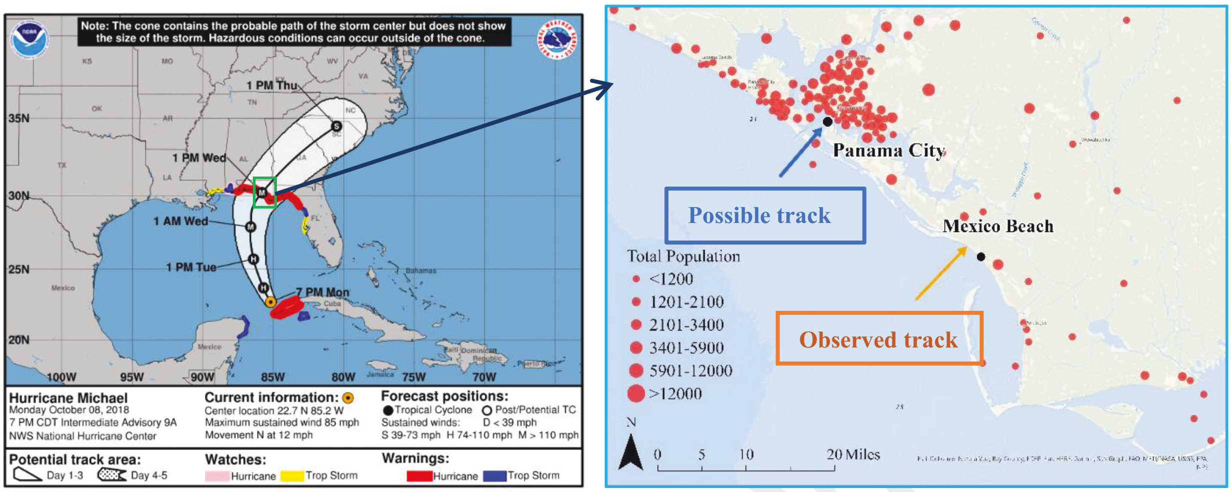
TABLE 1 Radii of possible hurricane track under different forecasting hours

Forecast Period (hours)	24	48	72	96	120
Radii of 2/3 probability circle, Atlantic Basin, (nautical miles)	45	78	107	159	211

Note: data obtained from NHC: https://www.nhc.noaa.gov/aboutcone.shtml

Special needs populations majorly consist of aging, disabled, potentially vulnerable people, and certain young groups of population (*10*). Any extra time needed in reaching safety before the hurricane hit was confounding due to their potential health problems and mobility needs. Providing transportation accessibility to shelters was a huge concern especially due to the uncertainty associated with the track of Hurricane Michael, which made landfall on October 10, 2018, near Mexico Beach, Gulf County, Florida(*1*). From this standpoint, serious challenges were observed while ensuring transportation-based accessibility to specifically designed special needs hurricane shelters (SpNS as named by the State of Florida). To further clarify, SpNS provide medical and assistive services (*10*) compared to the regular shelters that just accommodate general populations without ‘special needs’.

The hurricane's actual path crossed Mexico Beach (**Figure 1a**), a relatively low populated town; however, there was a high possibility (**Figure 1b**) that it could have hit a highly populated area in the region, namely Panama City. A direct hit on this medium-size city would have made evacuation planning and response very challenging, especially for those populations with special needs. Also, please note that the only special needs shelters available are located to the north of Panama City (**Figure 3a**).



(a) (b)

FIGURE 1 (a) Hurricane cone (white area) forecasted by National Hurricane Center (*11*) on October 8, 2018, at 7 PM CDT, and (b) One highly populated city in the Florida Panhandle that would have been hit by Hurricane Michael (blue arrow), and actual landfall (yellow arrow). Red dots show the total population counts for U.S. census block groups.

An efficient strategy to address this problem involves using Geographical Information Systems (GIS)-based tools to evaluate the available transportation network in conjunction with the spatial distribution of people and critical emergency facilities, plus regional traffic characteristics. Many studies in the literature have assessed the transportation-based accessibility to critical facilities. Several examples include healthcare services, supermarkets, libraries, shelters, and mental health facilities (*12–16*). Ghorbanzadeh et al. (*8*) also measured the spatial accessibility of census block groups to mental health facilities in Florida given different age groups, showing that several vulnerable population groups, including older adults, had lower accessibility than others. Results indicated that residents in Northwest counties generally had the lowest level of access to critical facilities.

The optimal location of the service facilities is another significant concern for the decision makers. Discrete location choice models were used to select facility locations by choosing a subset of locations from a finite set of available sites (*17*), and the *p*-median model is a generic version of those models originally formulated by (*18*). The *p*-median model was used as a spatial optimization technique, with various large-scale implementations in different fields such as urban planning by land-use planning (*19*), public health by sensor location selection for water quality (*20*), healthcare by maternal hospital location (*21*), and public services by school allocation (*22*). Within the emergency service systems, *p*-median models were widely employed to solve location problems such as the determination of fire station locations (*23*), ambulance locations (*24*), healthcare centers (*25*), medical service locations (*26*), backup service levels for emergency service systems (*27*), and shelter locations (*10*, *28–30*). The objective function of these types of *p*-median models usually searches for the minimum total cost while assigning population nodes to a subset of the candidate shelters in the affected region. Therefore, those models could be used to decide on optimal shelter locations given the accessibility levels and requirements (demands) within a given study area.

This paper proposes a Geographical Information Systems (GIS)-based methodology to assess the vulnerability of Panama City concerning the possible impacts of Hurricane Michael. Specifically, the paper tries to answer the following questions: What if Hurricane Michael hit Panama City directly? How would the special needs populations and their accessibility to SpNS be impacted, and what could have been done to alleviate this impact? The proposed analysis is twofold. Firstly, it involves investigating the effects of uncertainty of Hurricane Michael's track on coastal inundations by storm surge modeling (i.e., coupled storm surge and wave finite element model (ADCIRC+SWAN)). Secondly, a GIS-based accessibility and optimization methodology was developed focusing on the accessibility of vulnerable populations to SpNS. Integrating coastal hazard modeling with the GIS-based analysis has the potential to help develop more efficient and reliable emergency evacuation plans and the response to hurricanes. The assessment conducted from this study can guide officials on better SpNS planning throughout the Florida Panhandle.

STUDY AREA AND DATA ON HURRICANE MICHAEL

Study Area

In this paper, we aimed to assess the impact of Hurricane Michael if it had directly hit Panama City (**Figure 2**) rather than Mexico Beach. Panama City has a population of 36,284, and Bay County contains approximately 168,852 people based on the 2010 U.S. Census. The region is heavily dominated by tourism, especially during the spring break. 26% of the elderly live alone in the region, and approximately 3% live in nursing homes, group charters, and assisted facilitie(*14*, *16*, *31*). This demographic distribution makes the problem very challenging since the accessibility of these populations to shelters becomes very critical.

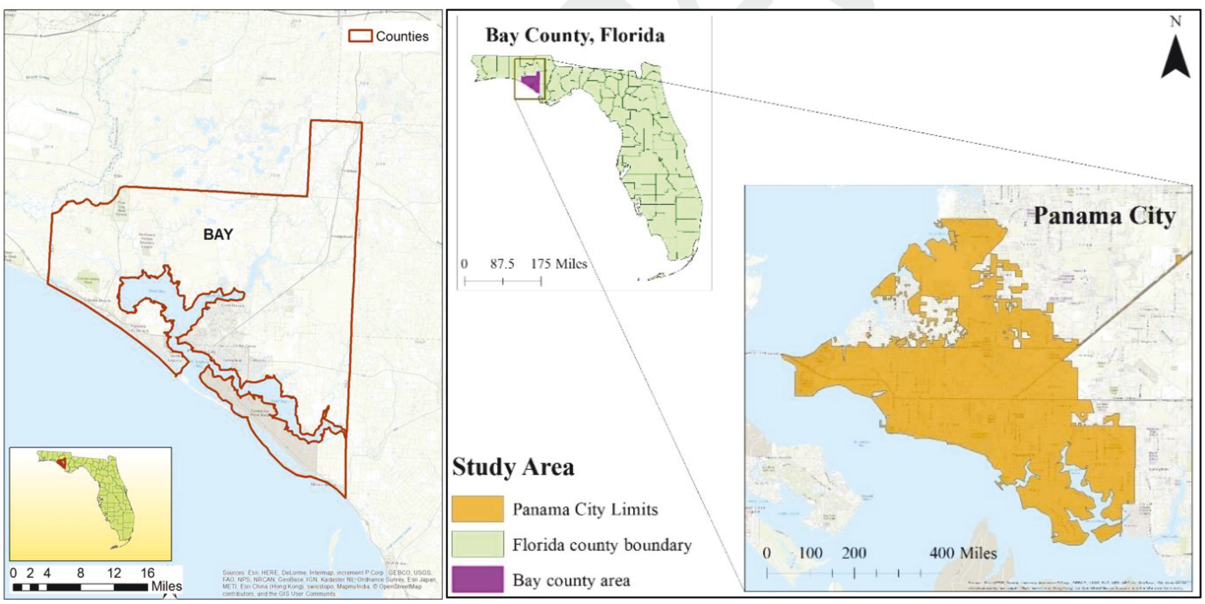
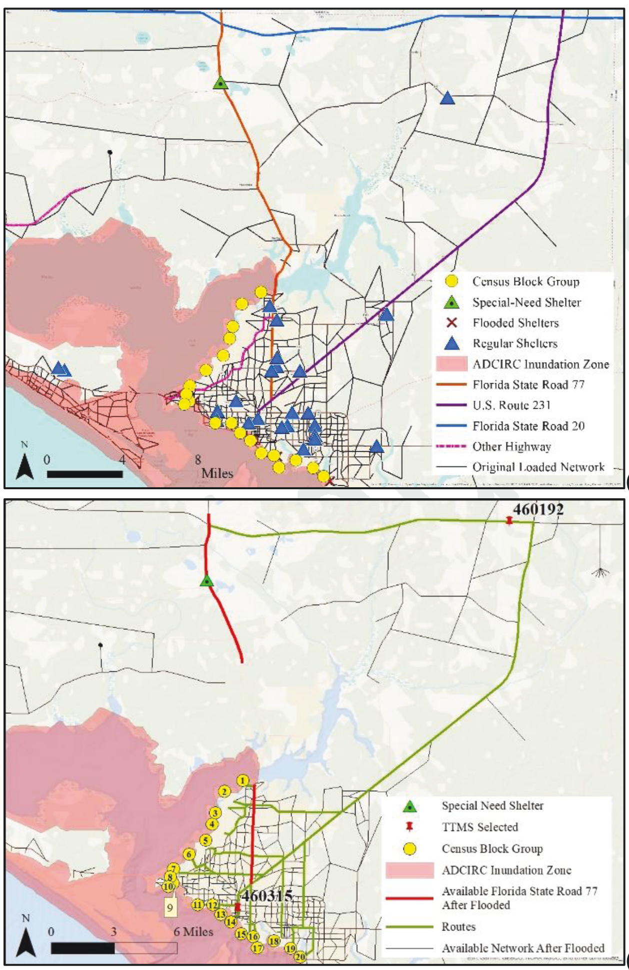


Figure 2 Study area

This study employed different datasets, including U.S. census block groups, Florida roadway network, and shelter locations, to conduct the proposed accessibility and optimization analysis. Population block groups information was acquired using 2014-2018 American Community Survey (ACS) Census estimates (*14*). The shelter dataset was provided by the Statewide Regional Evacuation Study Program (SRESP) (*16*), and the transportation network was obtained from the Florida Standard Urban Transportation Model Structure (FSUTMS) (*32*).

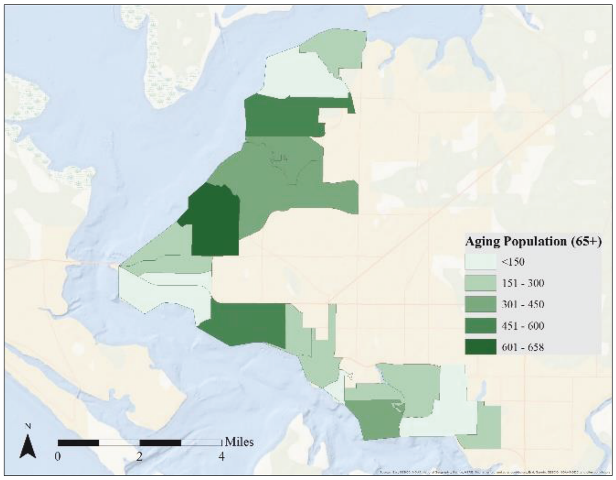
As mentioned before, one of the major groups of people considered by agencies as special needs population is the aging people (65+ will be used in this paper). This is particularly important for Panama City since it has a high percentage of aging population. **Figure 3** shows the 65+ and total population maps as well as the major roadways and available shelters in the region. For traffic data, there were two Telemetered Traffic Monitoring Site (TTMS) locations (*15*) where the Florida Department of Transportation collected real-time data on traffic volumes during evacuation. These TTMS locations (**Figure 3b**) as TTMS 460192 and TTMS 460315. The actual accessibility level of the census block groups to the existing SpNS during the Hurricane Michael evacuation in 2018 was evaluated based on this data.

Based on the developed hypothetical scenario for which Michael hit Panama City, we focused on the 20 U.S. Census block groups selected based on the impact of possible inundation levels as the storm surge modeling analysis identified. Those 20 block groups (**Figure 3b**) were affected directly if Hurricane Michael hit Panama City. Please note that the only SpNS available is located north of Panama City shown in the top left corner of **Figure 3a**. Additionally, with a focus on special needs populations, we analyzed the accessibility of impacted census blocks to shelters, simulating an evacuation scenario for the population with special needs and hypothetically repurposing the capacity of regular shelters along with already used special needs shelters in Panama City. Note that identifying the composition of the evacuee demand is another critical task. In a real-life disaster situation, for example, relying on registries of 65+ people with disabilities may be misleading and underestimate the real demand. Moreover, people with disability or special needs who does not request special care may also be sheltered at a regular shelter.



(a)

(b)



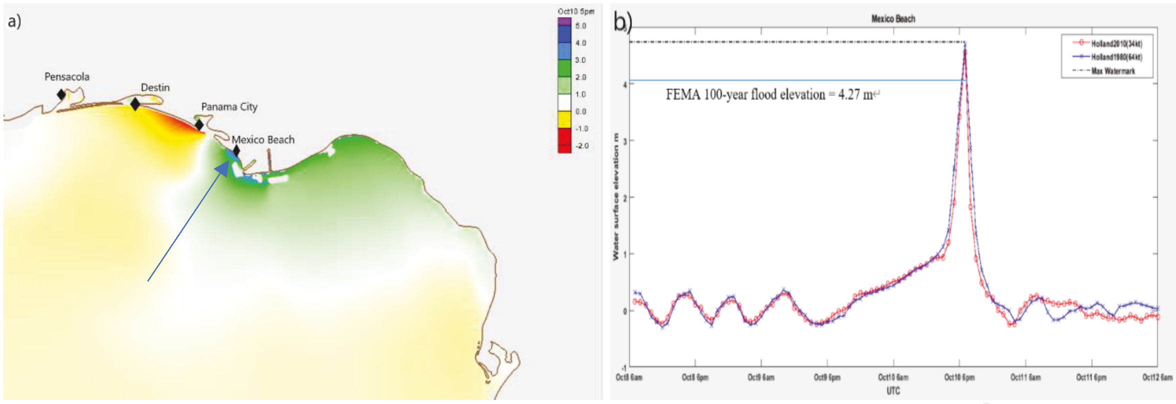
(c)

Figure 3 (a) Roadway network and shelters, (b) Selected census block groups and traffic sensor locations, and (c) 65+ population for the selected census block groups

Storm Surge and Coastal Inundation under Observed Track of Hurricane Michael

The Advanced Circulation (ADCIRC) model developed by Luettich et al. (*9*) was used to simulate the storm surge due to Hurricane Michael. ADCIRC produces reliable results while simulating coastal storm surges, as shown by the number of studies worldwide, including those by Yin et al. (*12*) and Vijayan et al. (*3*). It simulates water levels and velocities by solving the coupled equations of depth-integrated Generalized Wave-Continuity Equation (GWCE) and two-dimensional depth-integrated (2DDI) momentum equations. The circulation model (ADCIRC) was previously validated by numerical simulation of the storm surge and tides for the observed hurricane track during Hurricane Michael in 2018 by Vijayan et al. (*3*) (**Figure 4a**). The hydrodynamic model was forced with tidal constituents at the ocean boundary and wind forcing on the surface. Results indicate that both Holland 1980 and Holland 2010 wind parametrizations produced reasonable accuracy in predicting maximum water level in Mexico Beach, with an error between 1% and 3.7%.

The peak storm surge is above FEMA's 100-year flood risk elevation (**Figure 4b**). Compared to the observed peak water level of 4.74 m in Mexico Beach, Holland 1980 wind model with a radius of 64-knot wind speed for parameter estimation results in the lowest error of 1%. However, wind fields away from the hurricane wall using a radius of 64-knot wind speed for parameter estimation are generally weaker than those using a radius of 34-knot wind speed. As a result, comparing 17 watermark observations along the coast and hourly measurements at NOAA gage in Apalachicola, Holland 2010 wind model using a radius of 34-knot wind speed for parameter estimation shows the minimum average error and root-mean-square error, indicating that Holland 2010 wind model more reasonably describes the wind field outside of the hurricane eyewall.



(a) (b)

FIGURE 4 (a) Model simulated storm surge inundation for observed track of Hurricane Michael landed near Mexico City, and (b) Time series of storm surge at Mexico Beach with maximum water elevation above FEMA's 100-year flood elevation

Accessibility to SpNS under Observed Track of Hurricane Michael

Based on the real-life data collected at the two TTMS locations on the evacuation corridor leading to the available SpNS shelter, this section shows the accessibility of selected Census block groups (**Figure 1b**) to the SpNS that is located to the north of the city. This was performed by retrieving historical hourly continuous counts recorded by two TTMS cameras deployed by FDOT: TTMS 460315 at the start of U.S. 231 south of Panama City, and TTMS 460192 at the junction of S.R. 20 and U.S. 231. Note that Hurricane Michael hit the Mexico Beach area on October 10, and **Table 2** clearly shows that reaching this SpNS shelter was problematic for all selected population block groups. This is since there were two roadways (U.S. 231 and S.R. 20) available for people to use after the bridges were flooded. This is a significant challenge and there is a need to find a solution to this critical problem. One solution is to re-purpose closer regular hurricane shelters into special needs shelters, which will be explored in this study. By 're-purposing', we mean that regular shelters other than the designated ones will be repurposed as a fraction of the total spaces.

TABLE 2 Accessibility of the SpNS shelter to the Census Block Groups

Census Block Group No.	Original Congested Travel Time (min)	Travel Time on 10/7/2018 (min)	Travel Time on 10/8/2018 (min)	Travel Time on 10/9/2018 (min)
1	16.90	>180	>240	>180
2	19.56	>180	>240	>180
3	20.90	>180	>240	>180
4	22.10	>180	>240	>180
5	26.73	>180	>240	>180
6	31.11	>180	>240	>180
7	31.70	>180	>240	>180
8	32.11	>180	>240	>180
9	31.98	>180	>240	>180
10	32.53	>180	>240	>180
11	30.74	>180	>240	>180
12	29.44	>180	>240	>180
13	30.06	>180	>240	>180
14	29.51	>180	>240	>180
15	29.98	>180	>240	>180
16	30.03	>180	>240	>180
17	30.53	>180	>240	>180
18	32.57	>180	>240	>180
19	34.31	>180	>240	>180
20	35.77	>180	>240	>180

METHODOLOGY

This study proposes an integrated methodology that utilizes storm surge modeling, accessibility, and optimization with a case study application of Hurricane Michael in Northwest Florida under the scenario of Hurricane Michael-hypothetical track hitting Panama City. **Figure 5** illustrates the conceptual flowchart of the research methodology. The steps of the methodology are discussed in the following subsections.

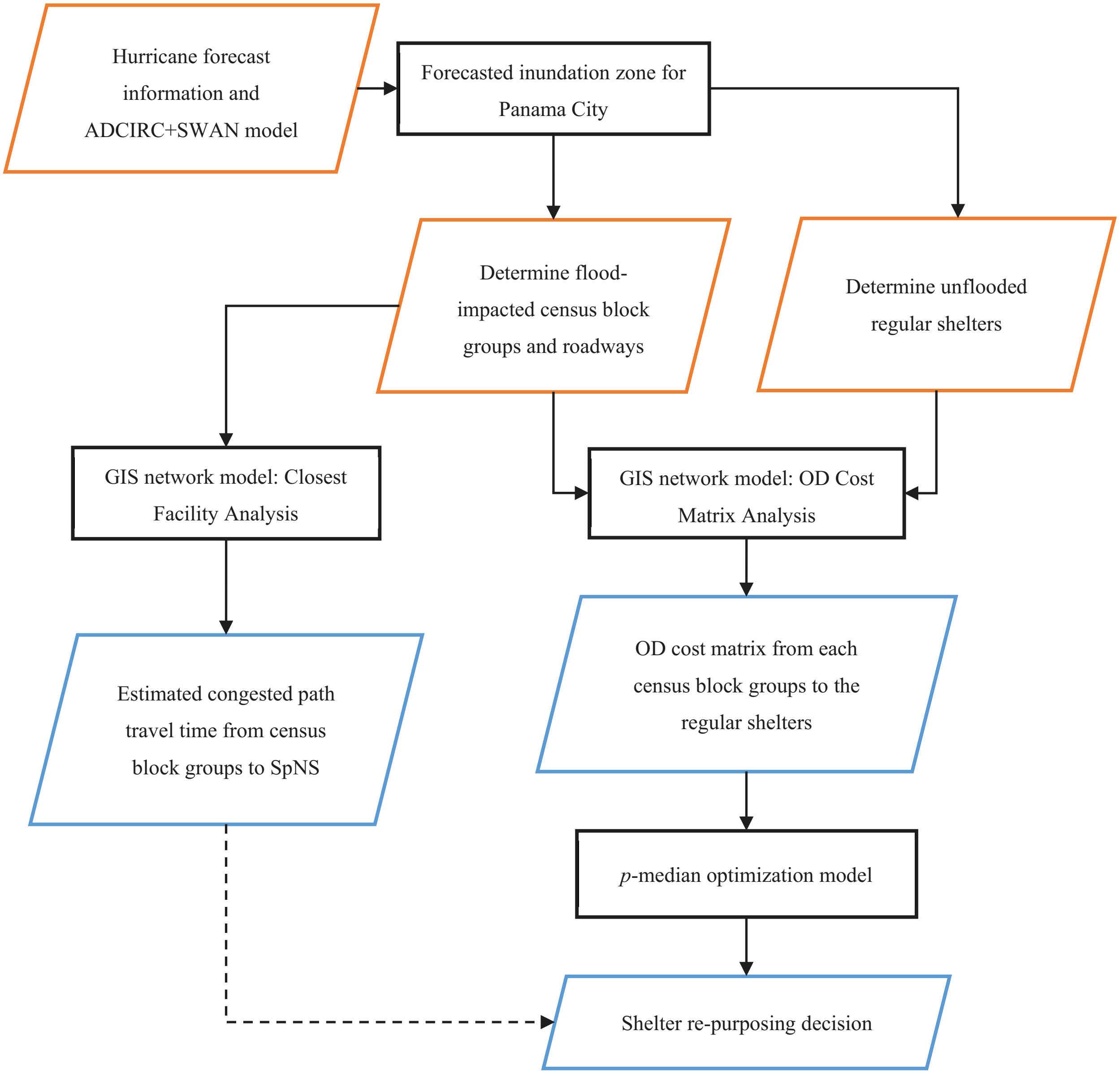


FIGURE 5 Conceptual flowchart of the methodology

Storm Surge and Coastal Inundation based on the Hurricane Forecast Zone

In the case of Hurricane Michael, any potential shift of hurricane track within the hurricane cone could have a huge impact due to storm surge inundation and wind. This, in turn, will affect evacuation planning and responses. Based on the hurricane forecasting cone (**Figure 1**) and the coastal population density within the hurricane cone, the Panama City hurricane track scenario was created. All the data connected with the submerged area were selected as the basis of the study. Since the ADCIRC model is based on mesh calculation, mesh accuracy was considered (**Figure 6**). Here, each cell in the grid was classified as either submerged or unsubmerged according to a specific elevation value. The area adjacent to the flooded area has created a destructive depth. Note that Panama City has accuracy values ranging from 100 meters to 120 meters. The maximum precision value of each model was selected as the additional buffer of the flooded area to ensure the accuracy of evacuation, so the number of evacuation elements was not omitted.

Accessibility to SpNS through Closest Facility Analysis

A scenario was generated to analyze when Hurricane Michael would raise water elevation and how large the evacuee population would have been in Panama City when Hurricane Michael hit Panama City. In **Figure 3**, roadway network, shelters, census block groups, and the inundation zone are presented. In this setting, we assumed that all shelters within flooded areas are not functional since they will not be able to provide safety when inundated (**Figure 3a**). All shelters near flooded areas have been shut down in hurricane scenarios since they would not be able to keep people safe when flooded.

Census block group centroids and shelters were considered as origins and destinations for the accessibility analysis, respectively. Next, the travel times on each roadway in the transportation network were obtained via the FSUMTS model built-in CUBE transportation demand modeling software (*33*). The main research tool for closest facility analysis was the Geographic Information System (GIS), which provided the shortest-path analysis designed with the Dijkstra algorithm. (*34*). The path solvers in the ArcGIS Network Analyst extension include Route, OD (origin-destination) Cost Matrix, and the Closest Facility. Dijkstra algorithm was adapted to calculate the shortest path between the origin nodes and defined destinations. Impedance (cost) is the parameter inputted as edge weights in the network, representing the weight to decide the order of shortest path generation. The cost figures available include free-flow travel time, congested travel time, and distance. In this paper, congested travel times on each roadway were considered as the impedance (cost) of the accessibility model. Ultimately, the Network Analyst module in ArcGIS was used to measure spatial accessibility between census block groups and facilities, particularly the "Closest Facility" parameter.

In determining the census block groups to be evacuated and the unavailable shelters, those that resided in flooded areas obtained from the storm surge analysis were considered. Using the storm surge analysis, census block locations and shelters under risk were identified. Those shelters located in the evacuation zones were not considered destinations. Flooded roadways were also separated into feature layers to provide relief to survivors and assist them in evacuating. The disruption of the roadway network also prevented the impacted people from getting help and delayed evacuations to shelters (*35*). ArcGIS Network Analyst module's OD cost matrix function was used to calculate the travel times between the evacuated population centroids and the shelters closest to them. Travel times in the roadway network were obtained from the FSUTMS model with built-in CUBE software (*36*). These travel times were used in combination with the ADCIRC model.

Selection of Regular Shelters to Repurpose as SpNS

After determining the possibly affected census block groups, the conditions of the shelters (whether they would be inundated or serve the people in need), and the availability of the roadway network, the next step was to decide on the shelter assignments. In Bay County, most shelters serve the general public. There would, however, be dedicated shelters (SpNS) for people with special needs. In this paper, we will tackle the problem of evacuating 65+ residents with special needs to SpNS shelters.

There was significant congestion on the main roadways U.S. Route 231 and State Road 77 (**Figure 3b**) due to the surge in traffic during the evacuation (**Table 2**). According to the FDOT records, from the early morning of October 7 to October 8, 2018, the number of vehicles on the U.S. 231 reached 285 vehicles in each hour where TTME 460192 was located at the junction of the southern end of the roadway in Panama City, causing significant traffic. This route carried an average of 136 vehicles every three hours since U.S. 231 was the major evacuation route for Panama City, and people had to use this roadway to get out of the impacted area. Bridges that connected Panama City to the west were also flooded, therefore U.S. 231 was the only option for evacuation. This roadway also led to S.R. 77 and Interstate 10. Increased travel times were especially problematic to special needs populations such as the elderly and those that are disabled. The situation was even direr for this population group since the region has only one SpNS, which is far away from Panama City in the northwest. Therefore, repurposing regular shelters as SpNS and making those shelters available to coastal populations in the region would be a viable alternative. This alternative scenario, repurposing regular shelters as SpNS, would be salient to timely and conveniently evacuate the people needing special assistance.

For this purpose, a selection algorithm should be applied to evacuate the impacted populations and allocate them to shelters. There are alternative locations such as regular shelters, and the most suitable ones should be selected. Therefore, rather than coverage models, median models are more appropriate for the defined problem. A *p*-median model was proposed for this setting, one of the typical models used to solve facility location problems. Accordingly, among the alternative supply points, *p* facilities were selected to minimize the overall cost of serving all the demand points (*37*), where each demand point must be served, and exactly a single supplier should provide this service. The following notation was used to formulate this generic problem for our shelter repurposing problem:

Sets and parameters:
N: set of demand points (census block groups)
S : set of supply points (regular shelters)
p: the number of regular shelters to be repurposed as SpNS
c_{ij}: travel time between census block group *i* and shelter *j*
D_i: 65+ population at census block group *i*

Decision variables:

$$x_{ij} = \begin{cases} 1 \text{ if block group } i \text{ is served by shelter } j \\ 0 \text{ otherwise} \end{cases}$$

$$y_j = \begin{cases} 1 \text{ if shelter } j \text{ is selected to be repurposed as SpNS} \\ 0 \text{ otherwise} \end{cases}$$

Depending on the above notation, the following formulation is used for the *p*-median problem:

$$Minimize\ \sum_{i\in N}\sum_{j\in S} D_i c_{ij} x_{ij} \qquad (1)$$
Subject to:
$$\sum_{j\in S} x_{ij} = 1 \quad \forall\, i \in N \qquad (2)$$
$$\sum_{j\in S} y_j = p \qquad (3)$$
$$\sum_{i\in N} x_{ij} \le y_j \quad \forall j \in S \qquad (4)$$
$$x_{ij} \in \{0,1\} \quad \forall i \in N, \forall j \in S \qquad (5)$$
$$y_j \in \{0,1\} \quad \forall j \in S \qquad (6)$$

Accordingly, **Equation 1** minimizes the demand weighted travel costs (congested travel times in this setting) between the census block groups and the shelter locations. **Constraint 2** imposes that each block group *i* must exactly be assigned to one shelter *j*. **Constraint 3** ensures that exactly *p* shelters are selected from set S to be repurposed as SpNS. **Constraint 4** ociatesthe decision variables and guarantees that if a block group is assigned to a shelter, that shelter is selected. **Constraints 5, 6** the integrality constraints. The resulting p regular shelters were chosen to be repurposed as SpNS, which minimized overall special needs population-weighted travel time. Moreover, as *p* was defined as a predetermined parameter for the problem, solutions for varying *p* values gave essential information for the decision-making process as a sensitivity analysis.

RESULTS

Storm Surge and Coastal Inundation if Hurricane Michael Hit Panama City

Since Panama City is located near the central line of the hurricane cone as shown in **Figure 1a** (i.e., with a high possibility of hurricane landing), the scenario of hurricane landing at Panama City was selected for this study. The calibrated ADCIRC model by Vijayan et al. (*38*) was used to simulate wind field and storm surge inundation areas in Panama City. For the scenario of a hurricane landing in Panama City, (**Figure 6 a-b**), the maximum storm surge induced by the hurricane is approximately between 5m and 6m along the coast of Panama City Beach, which would inundate a large portion of Panama City Beach. Due to the protection of a barrier island and the location inside St Andrews Bay, the storm surge in Panama City was lower than on other coasts, ranging from 2m to 5m depending on the location. The storm surge decreased to about 4 m along the coast in Mexico Beach. The storm surge inundation maps produced by the ADCIRC model were used to estimate the area and populations that were required to evacuate before the hurricane made its landfall.

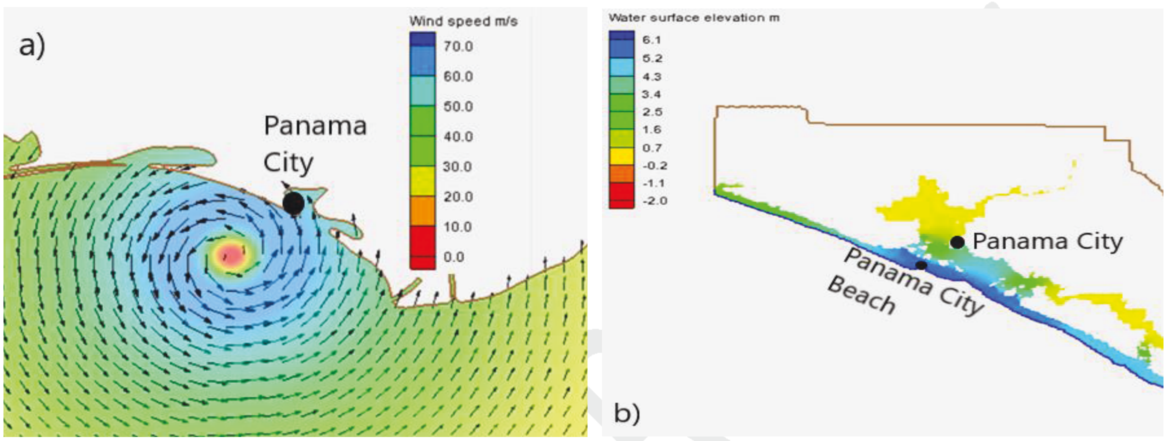


FIGURE 6 Wind field (a) and storm surge elevation in m, and (b) under different hurricane landing scenarios at Panama City

The inundation model allowed us to locate the areas that had to be evacuated due to rising water levels (i.e., evacuation zones) in **Figure 3.** This made it possible to focus on the areas that needed to be evacuated (i.e., the 20 census block groups). Flooded shelters, bridges, and roadways were also determined, and evacuation times were determined for each census block group studied using the ArcGIS OD cost matrix function. Note that these scenarios only consider the problems associated with inundation. The purpose is to provide a dynamic quantitative analysis of the areas to be evacuated, the extent of damage, and the need for disaster emergency evacuation caused by a storm surge during a hurricane. Generally, hurricanes are unique and they usually have a large impact area and evacuation travel in a specific direction. For a strong hurricane to force evacuations in Florida, they can only head north in roughly the same direction (*39*). The results shown in **Figure 6** depict the northward evacuation.

Accessibility to SpNS under the Panama City Inundation Scenario

This section analyzes the accessibility of census blocks to shelters, simulates an evacuation for those with special needs, and hypothetically uses regular shelters along with Panama City's special needs shelter. As a result of the storm surge in Panama City, we selected 20 U.S. census block groups. The regular shelters that were not flooded are our destinations. Congestion on roadway links between origins and destinations was included in travel costs based on the Florida Standard Urban Transportation Model Structure (FSUTMS). Roadways that were flooded since the storm surge were removed from the analysis. Based on these travel time costs, several of the remaining regular shelters will be repurposed to serve the demand based on the outputs of the optimization model.

Shelter Selection for Panama City Depending on the Accessibility Analysis

Since the scenario was based on storm surge impact, coastal areas of Panama City were impacted more than inland locations, which also included downtown Panama City. Those shelters closest to the population blocks affected by the increase in water level due to storm surge (**Figure 7**). Flooded areas, which directly reduced the land that can be used for housing and transportation, needed to be evacuated. This provided us with the impacted census block groups. Those areas with high flooding risks could be evacuated to hurricane shelters via the available roads. Therefore, storm surge analysis identified the coastal areas that were inundated and needed to be evacuated. State evacuation orders would mandate these evacuations prior to the hurricane hitting the coast. However, the hurricane may also cause heavy rainfalls that may bring more risk of roadways being flooded, which was out of scope for this paper.

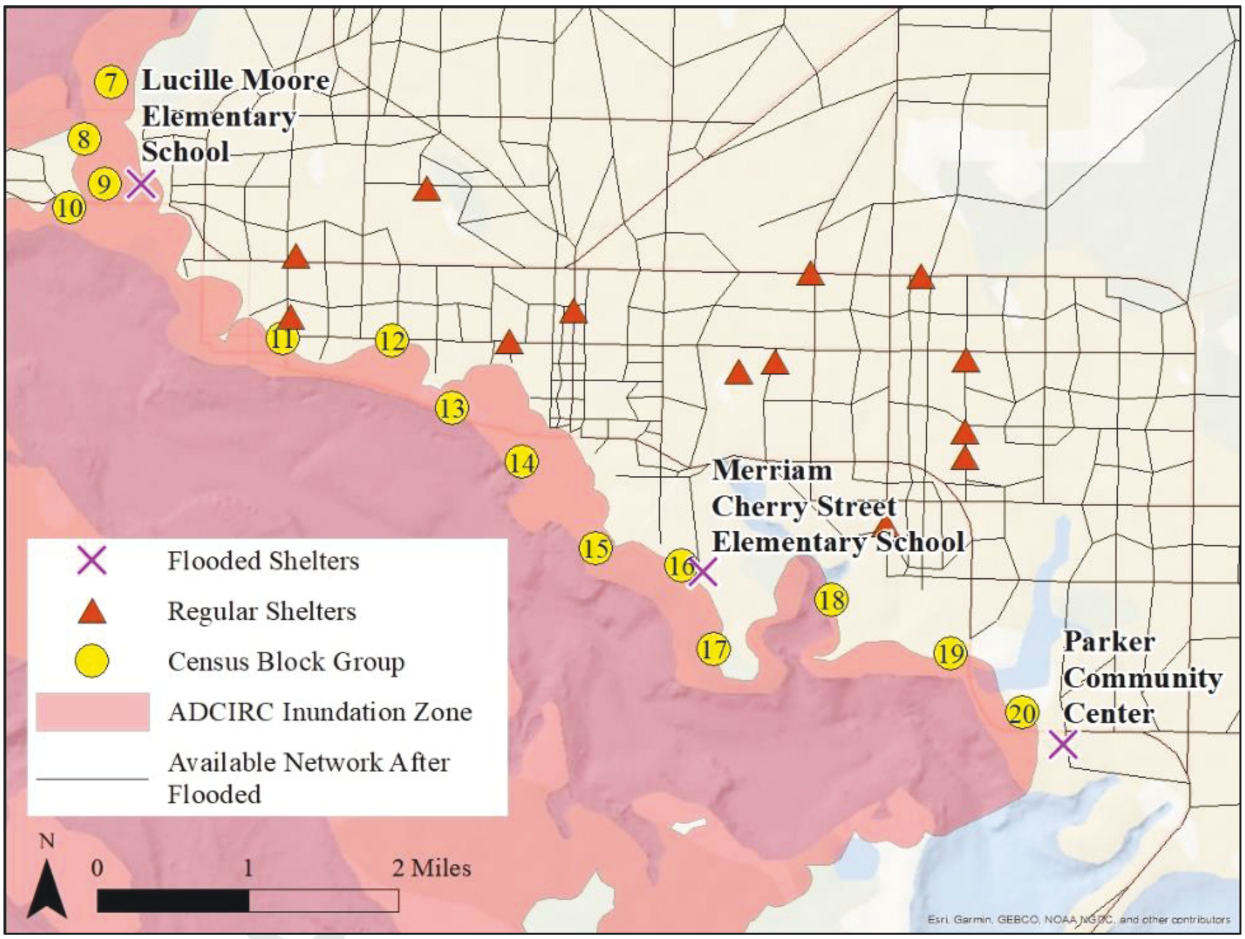


FIGURE 7. Shelters located in the inundation area

According to the inundation model simulations, three regular shelters along the coast of Panama City were inaccessible due to rising water levels and surrounded by the storm surge. They were Lucille Moore Elementary School, Merriam Cherry Street Elementary School, and Parker Community Center (**Figure 7**). Based on the *p*-median optimization model, we aimed to reduce the travel times needed to access the special needs shelter by re-purposing several regular shelters closer to the city. The proposed optimization model is run per the scenario given the shelter and roadway availability as well as the 65+ population demand for each census block group. The number of shelters to be repurposed has been decided by minimizing the total travel time (so the average travel time) and then comparing the maximum travel time needed for each 65+ person in census block groups (**Figure 8, 9**). When *p* was equal to 1 (i.e., there is only one repurposed shelter in the region), the average travel time per person and maximum travel time per person was 7.43 and 13.05 minutes, respectively. In addition, this indicates the need to repurpose a high number of shelters, as census block groups had to travel approximately 13 minutes to reach the closest SpNS on average. When *p* was 3, the average travel time per person and maximum travel time per person was 4.26 and 6.91 minutes, respectively (**Table 3**). Given that the average time for emergency response is around 8 minutes (*40*), this seemed reasonable. According to the result of *p*=4, although the average travel time decreased, the maximum travel time stayed the same. Therefore, the optimization process could be completed with 3 regular shelters being selected. This is because sheltering should also be required for other segments of the population, and repurposing additional shelters could make some citizens to be sacrificed.

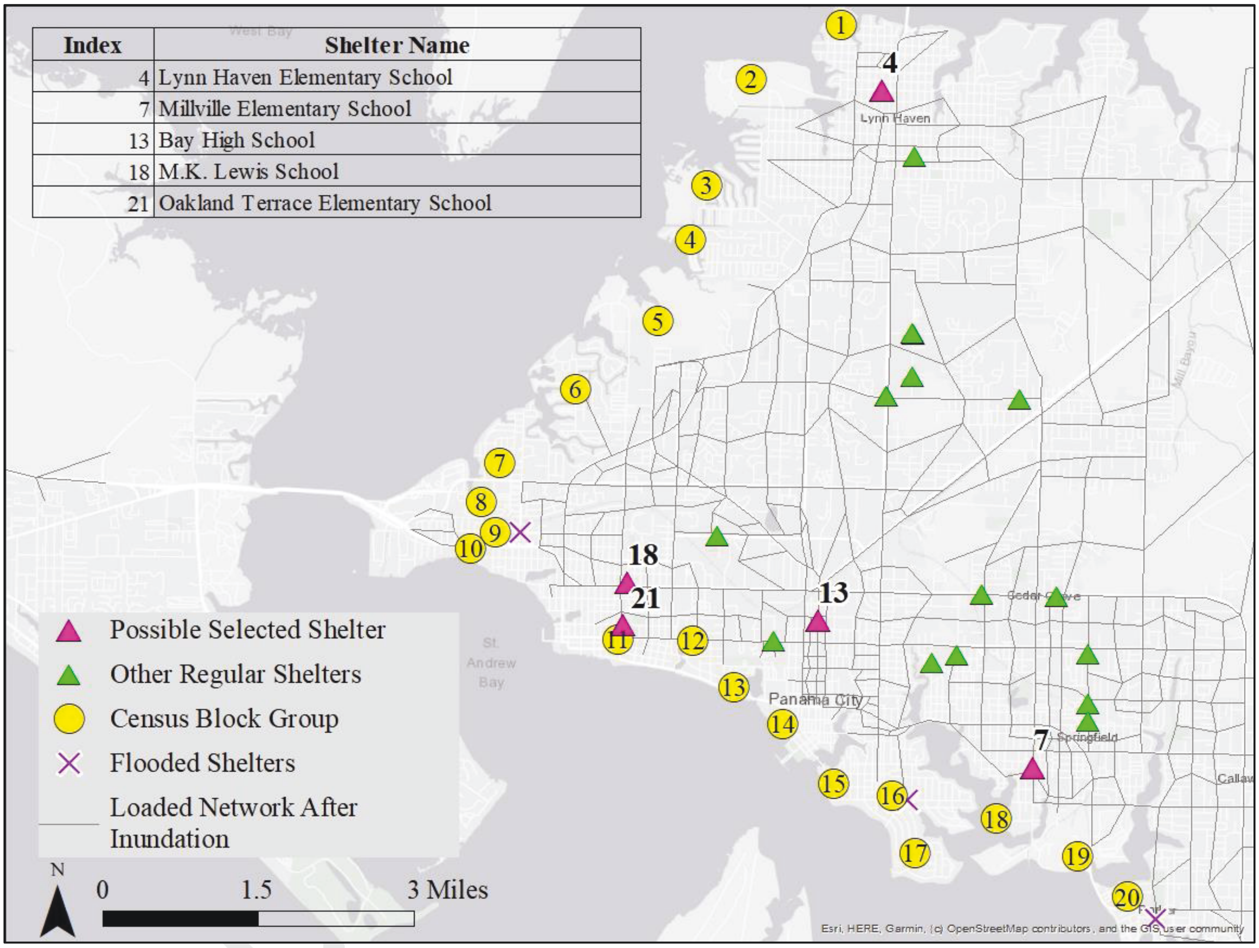


FIGURE 8. Summary of selected shelters after optimization

TABLE 3. Optimization Analysis Results

p	**Selected Shelters**				**Total Travel Time (minute)**	**Average Travel Time (minute/person)**	**Maximum Travel Time (minute/person)**
1	13				42,632.02	7.43	13.05
2	4	21			32,537.86	5.67	16.8
3	4	7	18		24,431.7	4.26	6.91
4	4	7	15	18	22787.77	3.97	6.91
Note: The total of 65+ people in the impacted area is 5,741.							

(a) (b) (c) (d)

FIGURE 9 Results of regular shelter selections when (a) *p*=1, (b) *p*=2, (c) *p*=3, and (d) *p*=4

In general, the analysis provides a reasonable approach for shelter siting or repurposing based on the hypothesized travel time most likely to be experienced on roadway networks based on the impact of Hurricane Michael. This can be helpful for emergency officials who are charged with developing shelter allocation plans.

Roadway disruptions have a vital effect on evacuation times and shelter sitting. For example, when the bridges that connected Panama City to the northern part of Bay County got flooded due to Hurricane Michael, congested travel times were so high for some census block groups to reach the available SpNS in the north. In addition, the only evacuation route out of Panama City area when the bridges were closed was the US-231, which experienced high delays and long queues during evacuations in the real-life Hurricane Michael case. As such, the findings show that there is undeniably a need for alternative routes, which can ease the evacuation operations. Therefore, authorities could invest in plans to expand US-231 or provide alternative routes. Emergency plans should also be updated by the results of optimization models, such as the one presented in this study, which can locate additional sites or shelter locations that are needed to improve shelter allocation while minimizing travel costs.

In addition, hurricane conditions are highly uncertain as shown, and there is always a possibility that shelters will be faced with extra demand due to shadow evacuees or those that have evacuated from other counties. As such, local and state agencies should have concrete emergency plans that clearly indicate which and how regular shelters can be repurposed for people with special needs. The proposed methodology will be helpful to identify those possible locations based on the extensive evaluation of the roadway network, hurricane conditions, and demographics. Although the methodology has been applied with a focus on 65+ populations, it can be extended to other population groups to provide better and more comprehensive emergency plans.

CONCLUSIONS

From an emergency management perspective, it is critical to study the needs of populations with special needs, such as aging adults. Their evacuations can particularly become problematic due to (a) their potential cognitive, physical, and mental limitations, including possible health/medical problems, (b) the possibility that they cannot make quick decisions while driving under contextually and physically demanding environments, and (c) their lack of familiarity with new roadways they may have to drive on. This clearly indicates the importance of an integrated dynamic storm surge, accessibility, and sheltering modeling, which was proposed in this paper. As such, the findings of the proposed model can dynamically change based on the output of the storm surge modeling. For example, inland parts of Panama City were mostly not affected based on the scenario; however, a hurricane with different strengths and profiles can affect the entire city, making the problem even more complicated.

By improving knowledge of the transportation accessibility of different census block groups in Florida in the uncertainty of hurricane tracks, agencies and stakeholders can help increase mobility. Public and/or private agencies can address the needs of evacuees and solve related problems as part of disaster plans. This indicates a clear need for the proposed integrated evacuation and storm surge model that has the potential to provide decision support and emergency assistance to agencies in real-time. The methodology presented in this paper can be extended to other locations in Florida and elsewhere. Qualitatively, however, the methodology's effectiveness in a particular location will be affected by the type, impact area, and strength of a hurricane.

However, this study does have limitations such as a) the exact demand is unknown during an evacuation since only aging population (65+) were assumed to be the representative segment of special needs populations, and b) it is assumed that people could evacuate to the designated shelters, but this may not be possible due to access to vehicles. Those would be a future direction for research that could embrace hurricane modeling, shelter optimization, and vehicle routing. Another simplifying assumption was that the remaining regular shelters were enough for the general population, which may not be the case. Thus, one other future direction would be capacity considerations in modeling.

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AUTHOR CONTRIBUTIONS

The authors have confirmed contributions to the paper as follows: study conception and design: W. Huang and E. Ozguven; analysis and interpretation of results: J. Yang, L. Vijayan, M. Ghorbanzadeh, E. Ozguven, W. Huang, S. Burns, O. Alisan; manuscript preparation: J. Yang, L., Vijayan, M. Ghorbanzadeh, E. Ozguven, W. Huang, S. Burns, E. Huang, and O. Alisan. All authors have reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Beven II, J., R. Berg, and A. Hagen. Hurricane Michael (AL142018), National Hurricane Center Tropical Cyclone Report. 2019, p. 86.

2. NCEI. Assessing the U.S. Climate in 2018. National Centers for Environmental Information (NCEI). http://www.ncei.noaa.gov/news/national-climate-201812. Accessed Mar. 1, 2022.

3. Vijayan, L., 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. Natural Hazards, Vol. 106, No. 3, 2021, pp. 2003–2024. https://doi.org/10.1007/s11069-021-04525-y.

4. Allen, G. Lessons From Hurricane Irma: When To Evacuate And When To Shelter In Place. NPR, Jun 01, 2018.

5. Florida Division of Emergency Management. Disaster Preparedness Maps. https://www.floridadisaster.org/planprepare/disaster-preparedness-maps/. Accessed Mar. 1, 2022.

6. Burns, S. R. Assessing the Vulnerability of Florida Panhandle Communities Impacted by Hurricane Michael Using Geographic Information Systems. M.C.E. Florida Agricultural and Mechanical University, United States -- Florida.

7. Unal, M., and C. Uslu. GIS-Based Accessibility Analysis of Urban Emergency Shelters: The Case of Adana City. International archives of the photogrammetry, remote sensing and spatial information sciences., Vol. XLII-2/W1, 2016, pp. 95–101. https://doi.org/10.5194/isprs-archives-XLII-2-W1-95-2016.

8. Ghorbanzadeh, M., K. Kim, E. E. Ozguven, and M. W. Horner. A Comparative Analysis of Transportation-Based Accessibility to Mental Health Services. Transportation Research Part D: Transport and Environment, Vol. 81, 2020, p. 102278. https://doi.org/10.1016/j.trd.2020.102278.

9. Blain, C., J. Westerink, J. Luettich Richard, and N. Scheffner. ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries. Report 4. Hurricane Storm Surge Modeling Using Large Domains. 1994, p. 68.

10. Horner, M. W., E. E. Ozguven, J. M. Marcelin, and A. Kocatepe. Special Needs Hurricane Shelters and the Ageing Population: Development of a Methodology and a Case Study Application. Disasters, Vol. 42, No. 1, 2018, pp. 169–186. https://doi.org/10.1111/disa.12233.

11. Michael Graphics Archive: Initial Wind Field and Watch/Warning Graphic. National Hurricane Center and Central Pacific Hurricane Center. https://www.nhc.noaa.gov/archive/2018/MICHAEL_graphics.php. Accessed Feb. 25, 2022.

12. Yin, K., S. Xu, W. Huang, and Y. Xie. Effects of Sea Level Rise and Typhoon Intensity on Storm Surge and Waves in Pearl River Estuary. Ocean Engineering, Vol. 136, 2017, pp. 80–93. https://doi.org/10.1016/j.oceaneng.2017.03.016.

13. US Census Bureau. American Community Survey 1-Year Experimental Data Products - Data Profiles. Census.gov. https://www.census.gov/programs-surveys/acs/. Accessed Mar. 6, 2022.

14. Bureau, U. C. American Community Survey (ACS). Census.gov. https://www.census.gov/programs-surveys/acs. Accessed Mar. 1, 2022.

15. Florida Department of Transportation (FDOT). Florida Traffic Online. https://tdaappsprod.dot.state.fl.us/fto/. Accessed Mar. 1, 2022.

16. Statewide Regional Evacuation Study Program (SRESP). Northeast Florida Regional Council (NEFRC). https://www.nefrc.org/sresp. Accessed Mar. 1, 2022.

17. Marín, A., and M. Pelegrín. P-Median Problems. In Location Science (G. Laporte, S. Nickel, and F. Saldanha da Gama, eds.), Springer International Publishing, Cham, pp. 25–50.

18. Farhan, B., and A. T. Murray. Siting Park-and-Ride Facilities Using a Multi-Objective Spatial Optimization Model. Computers & Operations Research, Vol. 35, No. 2, 2008, pp. 445–456. https://doi.org/10.1016/j.cor.2006.03.009.

19. Arentze, T. A., A. W. J. Borgers, L. Ma, and H. J. P. Timmermans. An Agent-Based Heuristic Method for Generating Land-Use Plans in Urban Planning. Environment and planning. B, Planning & design., Vol. 37, No. 3, 2010, pp. 463–482. https://doi.org/10.1068/b35050.

20. Berry, J., W. E. Hart, C. A. Phillips, J. G. Uber, and J.-P. Watson. Sensor Placement in Municipal Water Networks with Temporal Integer Programming Models. Journal of water resources planning and management, Vol. 132, No. 4, 2006, pp. 218–224. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:4(218).

21. Baray, J., and G. Cliquet. Optimizing Locations Through a Maximum Covering/P-Median Hierarchical Model: Maternity Hospitals in France. Journal of business research, Vol. 66, No. 1, 2013, pp. 127–132. https://doi.org/10.1016/j.jbusres.2012.09.003.

22. Ndiaye, F., B. M. Ndiaye, and I. Ly. Application of the P-Median Problem in School Allocation. American journal of operations research, Vol. 2, No. 2, 2012, pp. 253–259. https://doi.org/10.4236/ajor.2012.22030.

23. Serra, D., and V. Marianov. The P-Median Problem in a Changing Network: The Case of Barcelona. Location Science, Vol. 6, No. 1, 1998, pp. 383–394. https://doi.org/10.1016/S0966-8349(98)00049-7.

24. Dzator, M., and J. Dzator. An Effective Heuristic for the P-Median Problem with Application to Ambulance Location. Opsearch, Vol. 50, No. 1, 2012, pp. 60–74. https://doi.org/10.1007/s12597-012-0098-x.

25. Jia, T., H. Tao, K. Qin, Y. Wang, C. Liu, and Q. Gao. Selecting the Optimal Healthcare Centers with a Modified P-Median Model: A Visual Analytic Perspective. International Journal of Health Geographics, Vol. 13, No. 1, 2014, p. 42. https://doi.org/10.1186/1476-072X-13-42.

26. Jia, H., F. Ordóñez, and M. Dessouky. A Modeling Framework for Facility Location of Medical Services for Large-Scale Emergencies. IIE transactions, Vol. 39, No. 1, 2007, pp. 41–55. https://doi.org/10.1080/07408170500539113.

27. Karatas, M., and E. Yakıcı. An Analysis of P-Median Location Problem: Effects of Backup Service Level and Demand Assignment Policy. European Journal of Operational Research, Vol. 272, No. 1, 2019, pp. 207–218. https://doi.org/10.1016/j.ejor.2018.06.017.

28. Bayram, V., B. Ç. Tansel, and H. Yaman. Compromising System and User Interests in Shelter Location and Evacuation Planning. Transportation research. Part B: methodological, Vol. 72, 2015, pp. 146–163. https://doi.org/10.1016/j.trb.2014.11.010.

29. Na Ayudhya, W. S. Flood Shelters Location Using P-Median Model. 2020.

30. Kocatepe, A., E. E. Ozguven, M. W. Horner, and H. Ozel. Study Data from FAMU-FSU College of Engineering Update Knowledge of Disaster Risk Reduction (Pet-and Special Needs-Friendly Shelter Planning in South Florida: A Spatial Capacitated P-Median-Based Approach). Politics & Government Week, 2018, pp. 393–393.

31. Florida Department of Transportation (FDOT). An Introduction to Systems Traffic Modeling in Florida. FDOT. https://www.fdot.gov/planning/fto/stm/modelintro.shtm. Accessed Mar. 1, 2022.

32. FSUTMSOnline : Model Download : Statewide and Regional Models : Florida Statewide Model. https://fsutmsonline.net/index.php?/model_pages/modDS1/index/. Accessed Mar. 1, 2022.

33. Ozguven, E. E., M. W. Horner, A. Kocatepe, J. M. Marcelin, Y. Abdelrazig, T. Sando, and R. Moses. Metadata-Based Needs Assessment for Emergency Transportation Operations with a Focus on an Aging Population: A Case Study in Florida. Transport Reviews, Vol. 36, No. 3, 2016, pp. 383–412. https://doi.org/10.1080/01441647.2015.1082516.

34. Xie, D., H. Zhu, L. Yan, S. Yuan, and J. Zhang. An Improved Dijkstra Algorithm in Gis Application. p. 3.

35. Tuzun Aksu, D., and L. Ozdamar. A Mathematical Model for Post-Disaster Road Restoration: Enabling Accessibility and Evacuation. Transportation Research Part E: Logistics and Transportation Review, Vol. 61, 2014, pp. 56–67. https://doi.org/10.1016/j.tre.2013.10.009.

36. FSUTMSOnline. https://fsutmsonline.net/. Accessed Mar. 1, 2022.

37. Daskin, M. S. Median Problems. In Network and Discrete Location: Models, Algorithms, and Applications, Second Edition, John Wiley & Sons, Ltd, pp. 235–293.

38. Huang, W., K. Yin, M. Ghorbanzadeh, E. Ozguven, S. Xu, and L. Vijayan. Integrating Storm Surge Modeling with Traffic Data Analysis to Evaluate the Effectiveness of Hurricane Evacuation. Frontiers of Structural and Civil Engineering, Vol. 15, No. 6, 2021, pp. 1301–1316. https://doi.org/10.1007/s11709-021-0765-1.

39. Zhu, Y.-J., Y. Hu, and J. M. Collins. Estimating Road Network Accessibility During a Hurricane Evacuation: A Case Study of Hurricane Irma in Florida. Transportation research. Part D, Transport and environment, Vol. 83, 2020, pp. 102334-. https://doi.org/10.1016/j.trd.2020.102334.

40. Ulak, M. B., A. Kocatepe, E. E. Ozguven, M. W. Horner, and L. Spainhour. Geographic Information System–Based Spatial and Statistical Analysis of Severe Crash Hotspot Accessibility to Hospitals. Transportation research record, Vol. 2635, No. 1, 2017, pp. 90–97. https://doi.org/10.3141/2635-11.