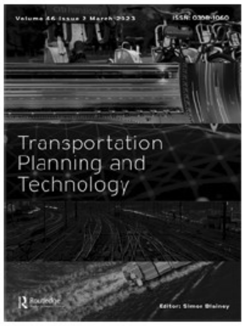

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Integrating storm surge modeling and accessibility analysis for planning of special-needs hurricane shelters in Panama City, Florida

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ABSTRACT
We investigated the transportation accessibility of special needs populations to Special Needs Shelters (SpNS) by incorporating storm surge modeling into hurricane shelter planning in Panama City, a medium-sized city located close to the landfall location of Hurricane Michael. The storm surge model validated for Hurricane Michael was used to predict the coastal inundation. Using this model, A Geographical Information Systems (GIS)-based optimization methodology was developed for evaluating the accessibility to special needs shelters and repurposing existing regular hurricane shelters for special needs populations. With the proposed optimization approach, the average travel time per person-trip decreased from 28.5 minutes to 7.4 minutes after repurposing one regular shelter and to 4.3 minutes when three regular shelters converted to SpNS. Emergency plans can be improved by the proposed methodology, which can estimate the inundation zones by storm surge modeling and allocate the emerging shelter demand by accessibility analysis and location modeling.

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KEYWORDS
Storm surge; accessibility; special needs shelters; hurricane evacuation

1. Introduction

Hurricane Michael, which made landfall on October 10, 2018, near the City of Mexico Beach, Gulf County, Florida (Beven, Berg, and Hagen 2019), was the first Category 5 hurricane ever to hit the Florida Panhandle since 1992 (Chen and Ji 2021; Pathak, Zhang, and Ganapati 2020). It can serve as a good reference for hurricane mitigation and response planning for similar hurricanes affecting the Florida Panhandle in the future (Yang et al. 2022). Hurricane Michael caused 74 deaths, including 59 in the US, and approximately $25.6 billion in total damages (Beven, Berg, and Hagen 2019), making itself the eighth-most cost Atlantic hurricane in the US. The damages were primarily due to high winds and storm surge inundation, with watermarks above National Flood Insurance Program (NFIP) VE zone (i.e. highest risk in the 100-year floodplain)

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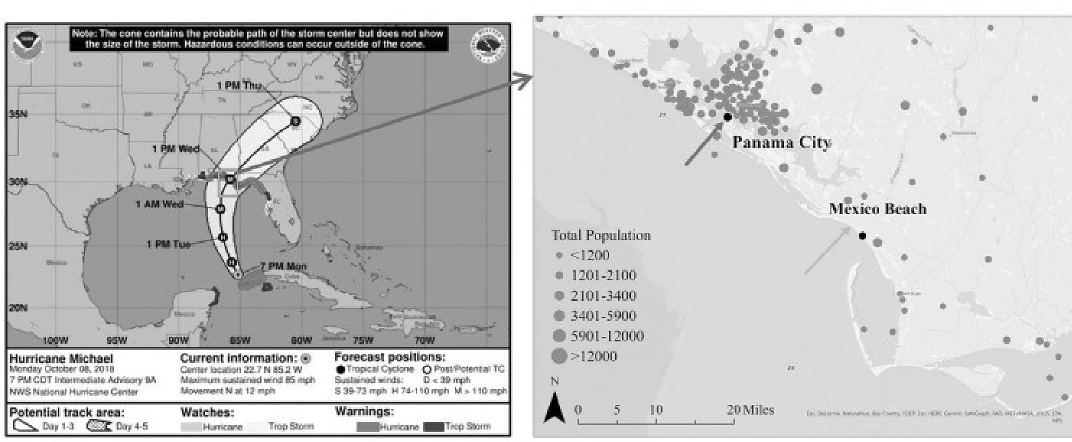
(Vijayan et al. 2021). It had maximum sustained winds of 161 mph and a peak storm surge inundation of 9 to 14 feet from Mexico Beach to Indian Pass, respectively. Approximately 375,000 Florida residents along the border of Bay and Gulf counties were warned to evacuate the Florida Panhandle region (Associated Press 2018).Vulnerable communities in the impacted area had additional challenges since very few state roadways were available for them to reach safety (Fries et al. 2011). These roadways were under high flood risk, making evacuations less timely and difficult.

Evacuation decisions by emergency managers are often affected by hurricane track forecasting provided by the National Hurricane Center. Hurricane tracks are forecasted within the envelope of the hurricane cone. The entire track of the tropical cyclone can be expected to remain within the cone about 60 to 70 percent of the time. Although Hurricane Michael landed in the city of Mexico Beach with a relatively low population density shown in Figure 1(b), there was a high possibility for the hurricane to hit Panama City because it is located near the center of the hurricane cone. A direct hit on this medium-size city would have made evacuation planning and response very challenging, especially for those populations with special needs.

Special needs shelters (SpNS) have been utilized by the State of Florida according to the State of Florida '2022 Statewide Emergency Shelter Plan' (2022), in whole or in part, designated under Chapter 252 and section 381.0303, Florida Statutes. On the contrary to regular shelters that serve the existing general population, SpNS require more space per person (60 sq-ft per victim instead of the 20 sq-ft used for regular shelter spaces), medical assistance from care givers, medical equipment, and standby back-up electric power supporting the air-conditioning. These space requirements are the minimums recommended by the Florida Division, Department of Health and partner agencies for SpNS. They are to minimize deterioration of pre-event levels of health. According to the Statewide Emergency Shelter Plan, 'a statewide deficit of SpNS spaces continues to exist and must rely on either use of local facilities not recognized as meeting minimum hurricane safety criteria or transport to host shelters outside risk



(a) (b)

Figure 1. (a) Hurricane Michael: hurricane cone (white area) forecasted by National Hurricane Center, and (b) Bay County and Panama City are near the center of the hurricane cone for possible landing showing high density population density in Panama City area.

areas.' Similarly, there is only one SpNS that serves the whole county, including Panama City (Figure 3(b)), and this clearly indicates the need to study the accessibility of this shelter as well as the possibility of investigating other solutions to address this SpNS demand in the coastal areas.

With a focus on this critical problem, the contribution of this study is the integration of storm surge modeling with accessibility and location optimization analyses. This would serve as an effective tool for local and state agencies towards efficient and reliable emergency evacuation planning for hurricane response. Hurricane Michael was selected as a case study where we study the impact of the hurricane if it shifted to make landfall in Panama City, which was clearly within the hurricane cone (Figure 1). A validated storm surge model was applied to predict the coastal inundation. This was followed by a GIS-based accessibility and optimization methodology developed to analyze the accessibility of vulnerable populations such as older adults to SpNS. The methodology proposed in this study can provide a guidance to support SpNS planning throughout the Florida Panhandle as well as the entire state of Florida.

2. Literature review

Early in 2010, Svensson (2010) realized that the number of people with disabilities would increase significantly due to the aging population growth. The study applied a GIS model to provide information on the spatial distribution of accessibility and the possibility of independent travel for impaired population in eight Swedish cities. Similarly, another study (Burns 2022) found out that, a Hurricane Michael-impacted area in northwest Florida, where people without vehicles had over 28% combined representation of the total population, 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 (Ulak et al. 2018; Ünal and Uslu 2016). This makes it more important and urgent to focus our research on Panama City, which is the largest city in this area.

Although hurricane shelters are planned to be safe destinations for evacuees (Coulbourne 2002), providing transportation-based accessibility to such emergency facilities has been a critical concern due to extremely destructive wind and flooding impacts of hurricanes (Sanusi et al. 2020). This is more challenging for special needs populations, including elderly (Marcelin et al. 2016), and people with disabilities (Horner et al. 2018). The State of Florida has specifically designed Special Needs Shelters (SpNS) which provide medical and assistive services, being specialized compared to the regular shelters that just accommodate general populations (FDEM 2020). However, during a large-scale evacuation, these shelters in Florida are limited or located far from special needs populations and any extra time needed in ensuring their accessibility to SpNS would be confounding (Horner et al. 2018; Hua et al. 2015).

Former studies have developed effective strategies to help explore the accessibility of communities using Geographical Information Systems (GIS)-based tools by evaluating existing roadway network in conjunction with the spatial distributions of those populations and important facilities including healthcare facilities (Ulak et al. 2017; Islam and Aktar 2011), supermarkets (Niedzielski and Kucharski 2019), libraries (Ghorbanzadeh et al. 2020), shelters (Zhu et al. 2018), and mental health facilities (Ghorbanzadeh et al. 2020). For instance, the spatial accessibility of census block groups in different ages to mental health facilities was measured in Florida (Ghorbanzadeh et al. 2020), showing that several vulnerable population groups including aging residents, had lower accessibility to critical facilities than other population groups. Other relevant GIS-based accessibility analyses include combining probabilistic vulnerability models to study the spatial accessibility of goods and health services during hurricanes (Balomenos et al. 2020), evaluating the accessibility to emergency response facilities (police stations, fire stations, and hospitals) during hurricanes in Tallahassee, Florida (Kocatepe et al. 2019), and utilizing two-step floating catchment area method (Zhou et al. 2021; Li and Wang 2022; Zhu et al. 2018). Ghorbanzadeh et al. (2021) offers another possibility of using storm surge models along the southeast Florida to determine inundation zones and identify roadways with high inundation risk that would make them inaccessible, which are used in evacuation modeling. However, this study did not focus on SpNS planning using optimization analysis.

In addition to the accessibility, the optimal location of the service facilities has been a significant concern for decision makers. In the literature, discrete location choice models were commonly used to select facility locations by choosing a subset of locations from a finite set of available sites (Marín and Pelegrín 2019), and the p-median model is a generic version of those models originally formulated by (Farhan and Murray 2008). 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 (Hua et al. 2015), public health by sensor location selection for water quality (Berry et al. 2006), healthcare by maternal hospital location (Baray and Cliquet 2013), and public services by school allocation (Ndiaye, Ndiaye, and Ly 2012). In particular, within the emergency service systems, p-median models were widely employed to solve location problems such as the determination of fire station locations (Serra and Marianov 1998), ambulance locations (Dzator and Dzator 2012), healthcare centers (Jia et al. 2014), medical service locations (Jia, Ordóñez, and Dessouky 2007), backup service levels for emergency service systems (Karatas and Yakıcı 2019), and shelter locations (Bayram, Tansel, and Yaman 2015; Na Ayudhya 2020; Horner et al. 2018; Kocatepe et al. 2018). Objective functions of these p-median models usually search for the minimum total cost while assigning populations to a subset of the candidate shelters in the affected region. Therefore, those models could be used to decide on optimal shelter location given the traffic characteristics and population demand.

To the authors' knowledge, there has not been a study integrating storm surge modeling with GIS-based accessibility and optimization to address the critical need of serving the SpNS demand. The focus has been on Panama City, Florida, where one SpNS is located to the northwest of the city, and there are no other SpNS in the vicinity of the city. We have also chosen to focus on older adults as our target group as this represents perhaps one of the most challenging cohorts to accommodate during emergencies such as hurricanes.

3. Study area and validated storm surge model

3.1. Study area: Panama City, Florida

We aimed to assess the possible impacts of Hurricane Michael if it had directly hit Panama City, Bay County, Florida (Figure 2) rather than Mexico Beach. Panama City

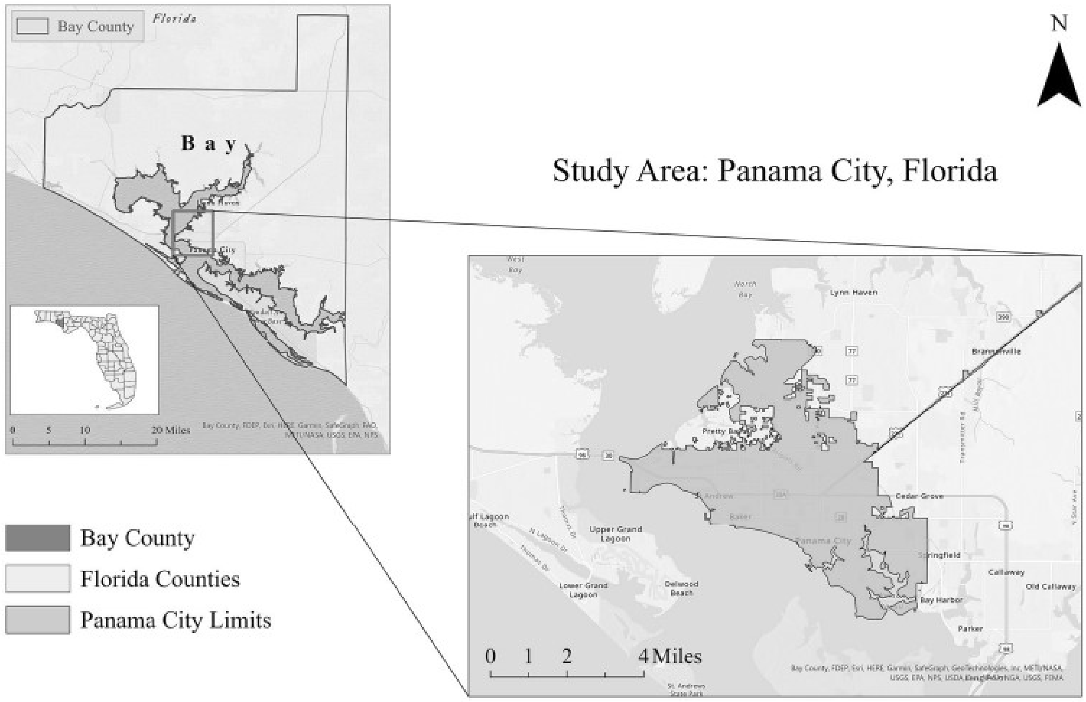


Figure 2. Study area.

has a population of 36,880, and Bay County contains approximately 182,482 people (American Community Survey 2018). The region is heavily dominated by tourism, especially during spring break. 26% of the elderly live alone in the region, and approximately 3% live in nursing homes, group charters, and assisted facilities (Bureau 2022; FDOT 2021; NEFRC 2021). This demographic distribution makes the problem very challenging since the accessibility of these populations to shelters becomes very critical.

Different datasets, including US census block groups, the roadway network, and shelters, were utilized in this study to conduct the accessibility and optimization analysis. Population block group information referred to 2014-2018 American Community Survey (ACS) Census estimates (Bureau 2022). The shelter dataset (NEFRC 2021) and the transportation network (FDOT 2018) were gathered from state official websites.

The major group of evacuees in this study considered as special needs is 65 years and over population. We note the challenge of the identification of SpNS demand due to the fact that we do not have actual evacuation data, if it were obtained, would represent exact information for the number of vehicles on roadways. In the absence of that information, basic census data reflective of the 65+ population seems to be a reasonable proxy and approach for this type of analysis, since older populations' health conditions can potentially deteriorate faster than other population groups during hurricanes due to their access and functional needs, and therefore they may require SpNS (Ozguven et al. 2016). This is particularly important for Panama City, where 65+ population percentage is higher than the nationwide and the county-wide, as shown in Table 1 (American Community Survey 2018).

Based on the developed hypothetical inundation scenario of storm surge modeling analysis for Panama City, we focused on 20 US Census block groups selected in

Table 1. American community surveys (ACS) 5-year population estimates data (2018).

	Estimates		
Region	Total population	65+ Population	65+ Population %
United States	322,903,030	49,238,581	15.2%
Bay County, Florida	182,482	30,160	16.5%
Panama City, Florida	36,880	6,807	18.5%

Figure 3(c). For traffic data, there were two Telemetered Traffic Monitoring Site (TTMS) locations (FDOT 2022) where the Florida Department of Transportation collected real-time data on traffic volumes during Hurricane Michael evacuation. These TTMS locations are shown in Figure 3(b) as TTMS 460192 and TTMS 460315. The accessibility level of census block groups to the existing SpNS during the Hurricane Michael evacuation in 2018 was evaluated based on this data. Please note that the only special needs shelter available is located to the north of Panama City, shown in the top left corner of Figure 3(a), while regular shelters in the region are in closer proximity coastal residents.

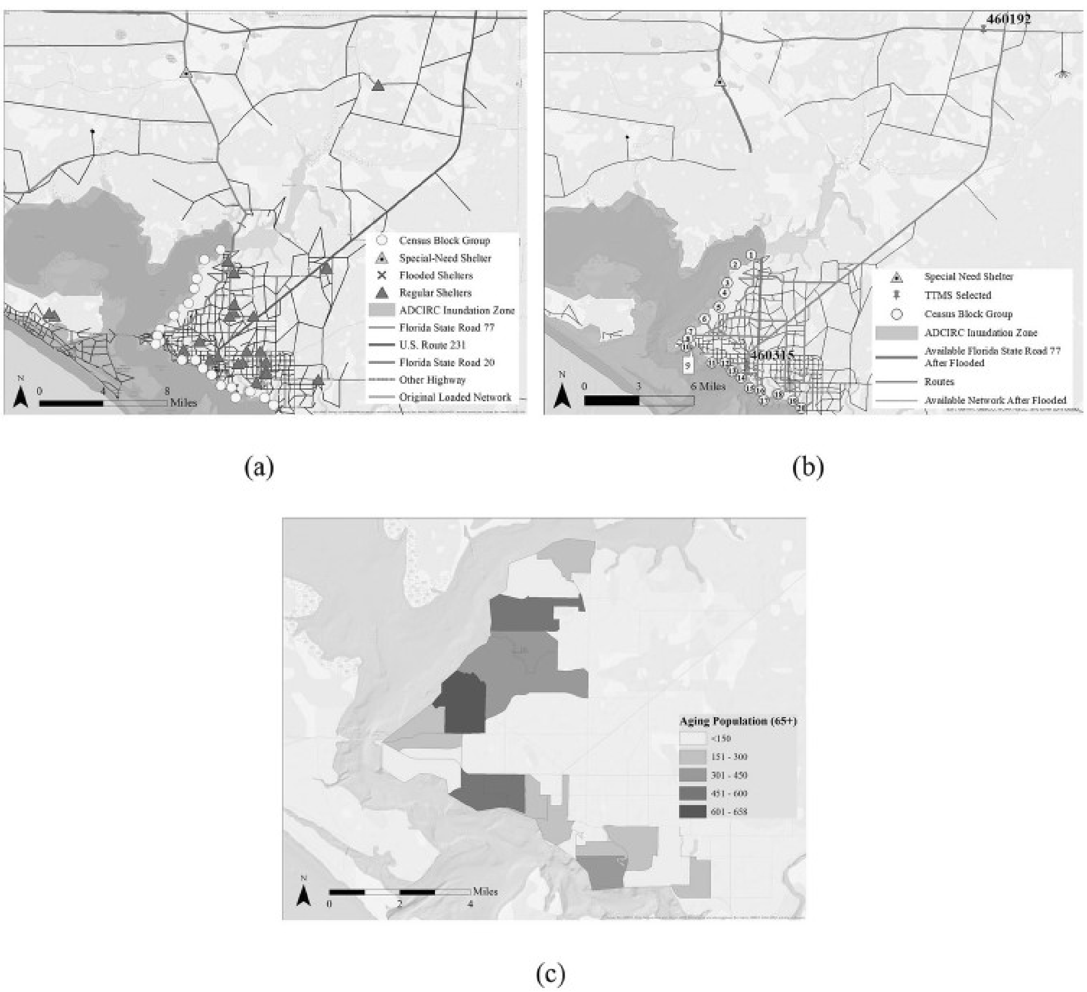


Figure 3. (a) Roadway network and shelters, (b) Selected census block groups and traffic sensor locations, and (c) 65+ population for the selected census block groups.

3.2. Storm surge model validated for Hurricane Michael

The Advanced Circulation (ADCIRC) model (Blain et al. 1994) 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 (Vijayan et al. 2021; Yin et al. 2017). 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 (Vijayan et al. 2021) (Figure 4(a)). 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 4(b)). 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.

4. Methodology

This study integrated storm surge modeling with accessibility analysis and optimization models applied to Panama City during a hypothetical Hurricane Michael landfall. Figure 5 shows a conceptual flowchart of the methodology. The steps of the methodology are discussed in the following subsections, including the following: (a) inundation areas are delineated after the storm surge simulation, (b) affected census

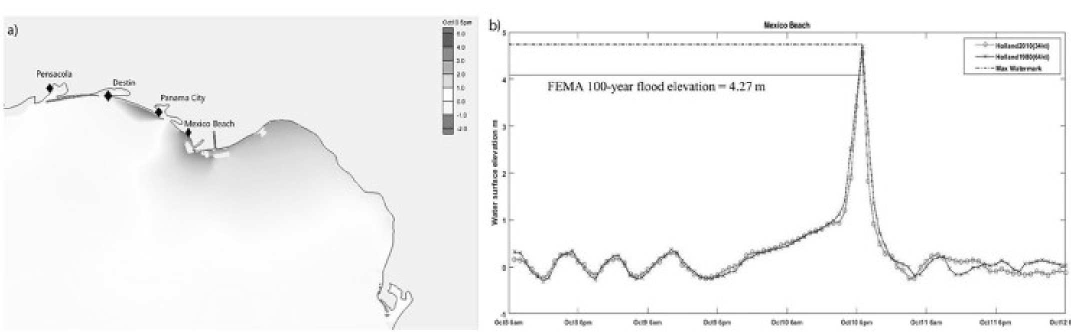


Figure 4. Validated storm surge model for the case study of Hurricane Michael (Vijayan et al. 2021): (a) spatial distribution of storm surge, and (b) time series of storm surge at Mexico Beach.

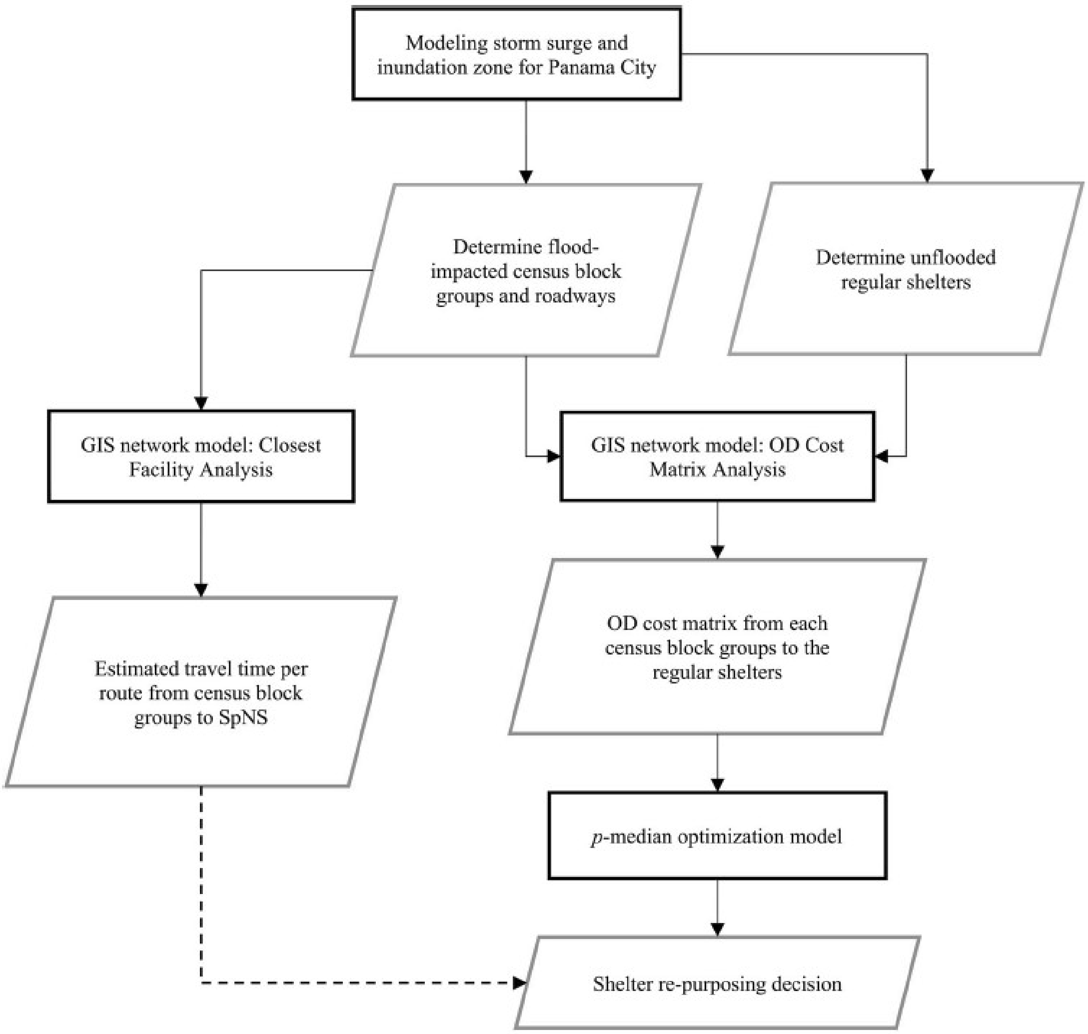


Figure 5. Flowchart of the study methodology.

block groups and roadways are identified based on these inundation areas, (c) estimated evacuation travel times to the SpNS before the optimization are calculated, and (d) most suitable regular shelters are selected for repurposing via optimization with new evacuation time outputs.

4.1. Storm surge modeling for coastal inundation in Panama City

Based on the hurricane forecasting cone as shown in Figure 1, and the coastal population density within the hurricane cone, all the data within the submerged area were selected as the basis for the study. Since the ADCIRC model is based on a mesh calculation, mesh accuracy was considered. 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.

4.2. Estimated evacuation time to SpNS before optimization

In Figure 3(a,b), available and impacted roadways, shelters, and evacuated census block groups are presented combined with the inundation zones. We assumed that shelters intersecting with inundation zone would not be functional since they could not provide safety due to hurricane impacts such as raised water elevation, and high wind. To conduct the accessibility analysis, census block group centroids and shelter locations were considered origins and destinations, respectively. Next, the congested travel time on each roadway segment in the transportation network were obtained via the FSUMTS model built-in CUBE transportation demand modeling software (Ozguven et al. 2016).

In the GIS literature, the main research methodology to find out the shortest-path analysis is the closest facility analysis designed with the Dijkstra algorithm (Xie et al. n.d.). Closest facility solver of the ArcGIS Network Analyst tool adapts the Dijkstra algorithm 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. In this paper, congested travel time per roadway was considered as the impedance (cost) of the accessibility model.

It is important to emphasize that there was not an actual evacuation traffic for Hurricane Michael's direct landfall in Panama City since it hit Mexico Beach. Therefore, after the closest facility analysis, we estimated the 'actual' average travel time per route by applying the Bureau of Public Roads (BPR) function (1) (Tan, Yang, and Zhang 2017) based on the data collected from two TTMS cameras deployed by FDOT: TTMS 460315 at the start of US 231 south of Panama City, and TTMS 460192 at the junction of SR 20 and US 231. They retrieved historical hourly continuous counts on the evacuation corridor leading to the single available SpNS in the region.

$$t = t_i \times \left[1 + \alpha\left(\frac{v_i}{C_i}\right)^{\beta}\right] \tag{1}$$

t_i – the free flow travel time on a roadway section (min), , – the coefficients with widely recommended values of $\alpha = 0.15$, $\beta = 4$, v_i – the vehicle flow on a roadway section recorded by two TTMS cameras, C_i – the actual capacity of a roadway section.

Note that this is just a static estimation of the evacuation traffic that would have occurred if Hurricane Michael hit Panama City. We assumed that t_i was shortest travel time calculated by Closest Facility Analysis from each census block group to the only one SpNS. v_i contained all evacuation vehicles including people drove to SpNS, which restored the actual congestion of the roadways and led BPR function results reach the fast exponential growth interval. When considering roadway capacity, since most roadways used in our scenarios were county roadways, we assume there was no contraflow nor closure when evacuation happened 3 days before hurricane landed.

Calculation of travel time from origins (census block groups) to destination (SpNS) has 4 steps:

- Step 1 Gather travel time and roadway capacity data (FDOT 2018) providing t_i and C per roadway section.

- Step 2 Collect hourly continuous traffic data recorded by two TTMS cameras from Oct 7 to Oct 9 in 2018 before Hurricane Michael's landfall.
- Step 3 Identify the vehicle flow rate v from the first two steps.
- Step 4 Apply the function (1) to calculate travel time per roadway section and sum them for the whole evacuation route.

4.3. Optimized and repurposed regular shelters as SpNS

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. The 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 (Daskin 2013), where each demand point must be served, and exactly a single supplier should provide this service for each demand point. 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:

$$\text{Minimize} \sum_{i \in N} \sum_{j \in S} D_i c_{ij} x_{ij} \tag{2}$$

Subject to:

$$\sum_{j \in S} x_{ij} = 1 \; \forall \; i \in N \tag{3}$$

$$\sum_{j \in S} y_j = p \tag{4}$$

$$\sum_{i \in N} x_{ij} \leq y_j \; \forall j \in S \tag{5}$$

$$x_{ij} \in \{0, 1\} \; \forall i \in N, \forall j \in S \tag{6}$$

$$y_j \in \{0, 1\} \; \forall j \in S \tag{7}$$

Accordingly, the objective function (2) minimizes the demand weighted travel costs (congested travel time in this setting) between the census block groups and the shelter locations. Constraint (3) imposes that each block group i must exactly be assigned to one shelter j. Constraint (4) ensures that exactly p shelters are selected from the set S to be repurposed as SpNS. Constraint (5) associates the decision variables and guarantees that if a block group is assigned to a shelter, that shelter is selected. Constraints (6) and (7) are 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.

5. Results and discussions

5.1. Modeling coastal inundation in Panama City under Hurricane Michael condition

The calibrated ADCIRC model (Huang et al. 2021) was used to simulate wind field and storm surge inundation areas in Panama City. For the proposed case study (Figure 6(a, b)), the maximum storm surge induced by the hurricane is approximately 5 m to 6 m

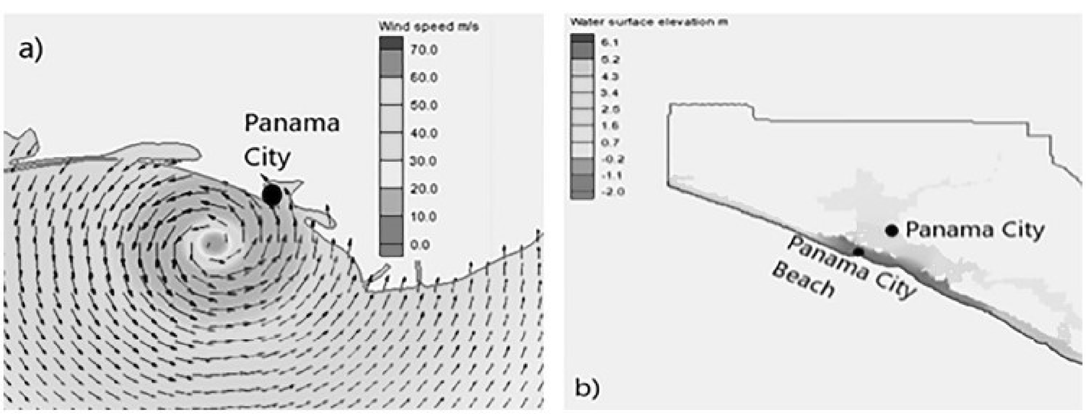


Figure 6. (a) Hurricane wind field, and (b) storm surge when hurricane lands at Panama City.

along the coast of Panama City Beach, which would inundate a substantial 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 2 m to 5 m depending on the location. It decreased to about 4 m along the coast in Mexico Beach. The strong hurricane forced evacuations in Mexico Beach where people majorly headed north to safety (Pathak, Zhang, and Ganapati 2020). Results shown in Figure 6 reflected that northward evacuations were urgent, which paved the impacted area and population estimations that would be required to evacuate before the hurricane's landfall.

5.2. Accessibility to SpNS for Panama City under Hurricane Michael condition

We estimated travel times from impacted coastal census block groups to the only existing SpNS by applying the historical traffic flow recorded by two TTMS (460192 and 460315) in Panama City when Hurricane Michael's landfall was on Mexico Beach in 2018. We derived the time for each selected 20 census block groups evacuated to the SpNS as shown in Table 2. Although these still-accessible evacuation routes are about half an hour away under daily and normal conditions, with the addition of intensive evacuation traffic, the travel time can reach to at least 4 hours or more.

Based on Figure 3(b) and Table 2, during hurricane Michael in 2018, there was significant congestion on the main roadways US Route 231 and State Road 77, for people evacuating towards north where the only existing SpNS is located. According to the FDOT records, from the early morning of October 7 to October 8, 2018, the number of vehicles on the US 231 reached to 285 vehicles at every hour where TTMS 460192 was located at the junction of the southern end of the roadway in Panama City, causing significant

Table 2. Estimated travel times to the existing SpNS in Panama City when Hurricane Michael landed near Mexico Beach, Florida.

Census block group no. (i)	65+ Population (p_i)	Original travel time[a] (t_i/minute)
1	168	16.9
2	118	19.6
3	554	20.9
4	369	22.1
5	446	26.7
6	658	31.1
7	239	31.7
8	209	32.1
9	110	32.0
10	143	32.5
11	489	30.7
12	511	29.4
13	269	30.1
14	221	29.5
15	127	30.0
16	248	30.0
17	339	30.5
18	239	32.6
19	115	34.3
20	169	35.8

[a]The estimated travel times for all census block groups on 10/7/2018 and 10/9/2018 were greater than 180 minutes; and on 10/8/2018 they were greater than 240 minutes.

traffic. This traffic led to more than 3 hours of travel time on October 7 and October 9, and more than 4 hours on October 8. This is critical since US 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 inaccessible since the connecting roadway sections heading to them were flooded due to storm surge. Thus, US 231 was the only option for evacuation. This roadway also led to SR 77 and Interstate 10.

If Hurricane Michael hit Panama City directly, the traffic should be even higher than the ones presented in Table 2. Increased travel time can be especially problematic to special needs populations since they would need to reach the SpNS as soon as possible. The situation will be dire for these population groups since the only existing SpNS is located far away in the northwest of Panama City. For this reason, it would be a viable alternative to repurpose closer regular shelters as SpNS and make those shelters available for the coastal populations in the region.

5.3. 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. Figure 7 shows those shelters closest to the population blocks affected by the increase in water level due to storm surge. We considered evacuating those areas with high flood risk through the available roadways to the open hurricane shelters. Thus, storm surge analysis informed us of the areas that were inundated and needed to be evacuated. These evacuations would have happened before the hurricane hit the land based on the evacuation orders issued by the state.

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. As shown in Figure 7, they were Lucille Moore Elementary School, Merriam Cherry Street Elementary School, and Parker Community Center. Based on the p-median optimization model, we aimed to reduce the travel time needed to access a special needs shelter by repurposing several regular shelters closer to the city. The proposed optimization model is run per p scenario given the shelter and roadway availability as well as the 65+ population demand for each census block group. Figure 8 shows locations of repurposed shelters when $p = 1, 2, 3$, and 4. The results of optimization scenarios are shown in Figure 9 as well as in Table 3.

The number of shelters to be repurposed has been decided by finding the lowest weighted travel time, average, and maximum travel times per trip needed for each 65+ person living in selected census block groups considering the regular congested travel times. For demand weighted travel time, we multiplied the travel time per route and the 65+ population living in the corresponding census block group. Hence, the average travel time per 65+ person was simply the demand-weighted travel time divided by the total of 65+ population living in the impacted areas. In Table 3, firstly, we included results from Table 2, with the first row showing the base case without optimization which can be compared to results after the optimization. Unsurprisingly, the optimized demand-weighted travel time was significantly lower than the estimated case shown in Table 2. Simultaneously, the average travel time per person-trip was decreased from 28.53 minutes to 7.43 minutes. Since the repurposed shelters are already located

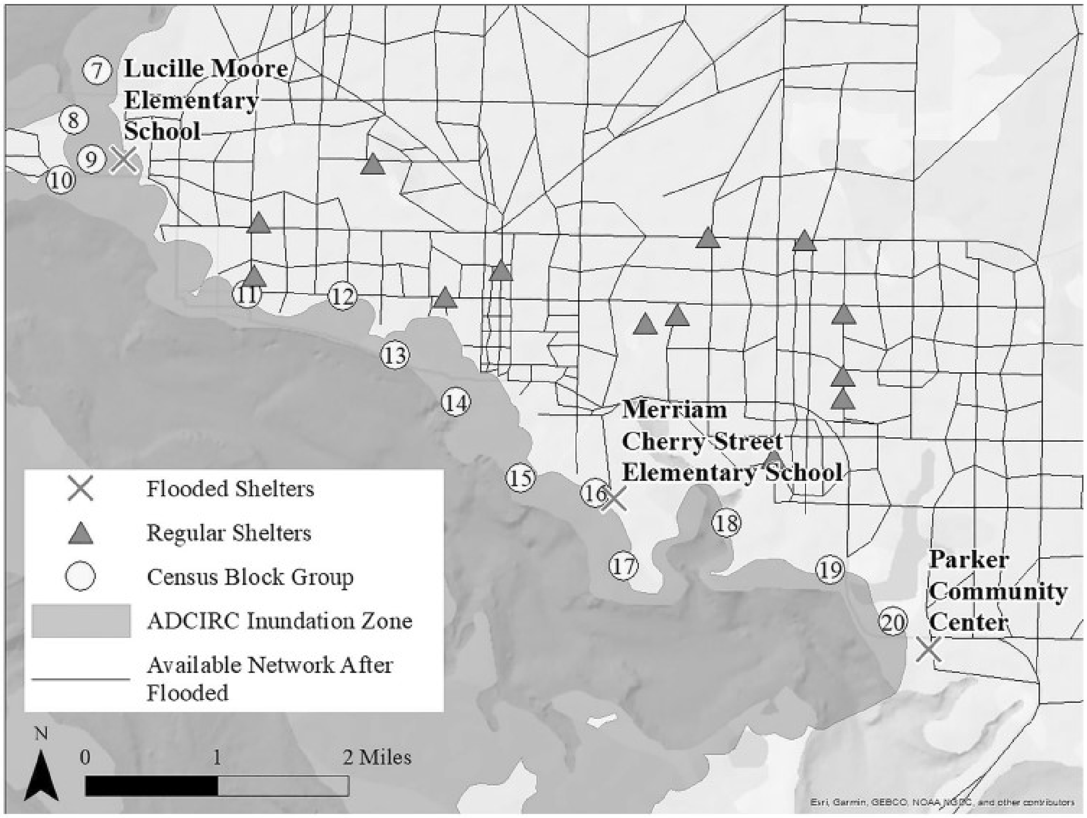


Figure 7. Shelters located in the inundation area.

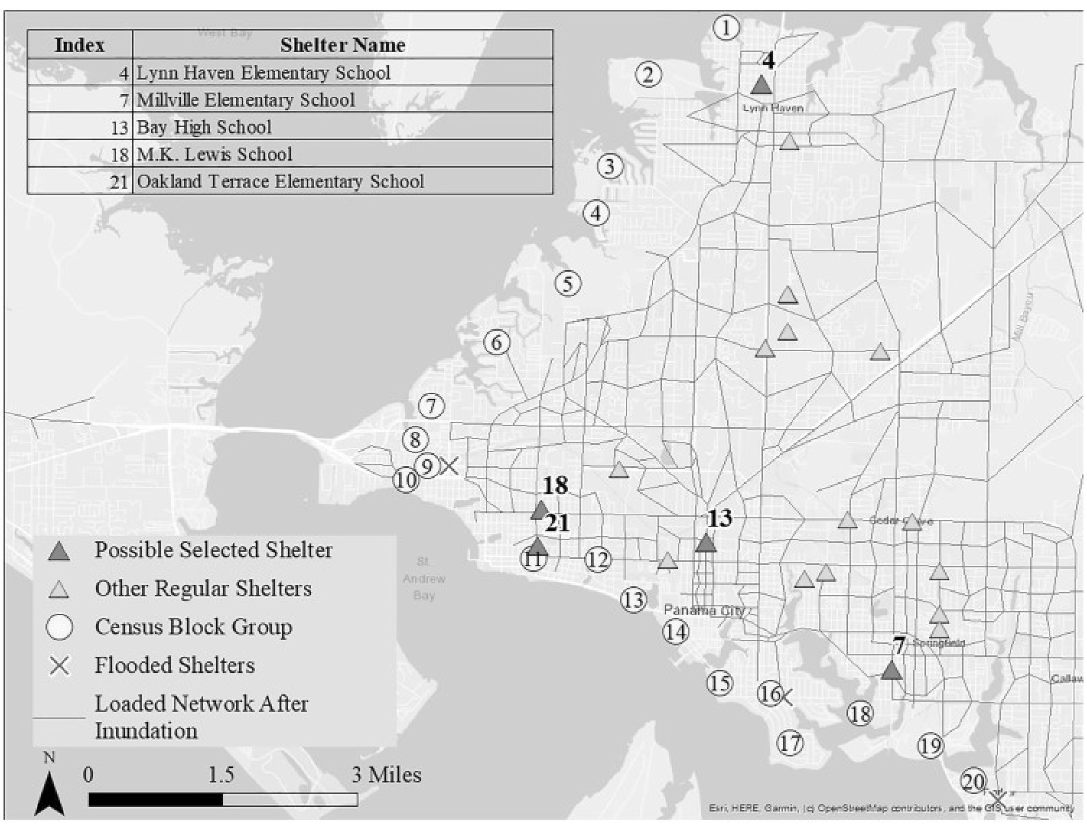


Figure 8. Summary of possible selected shelters after optimization.

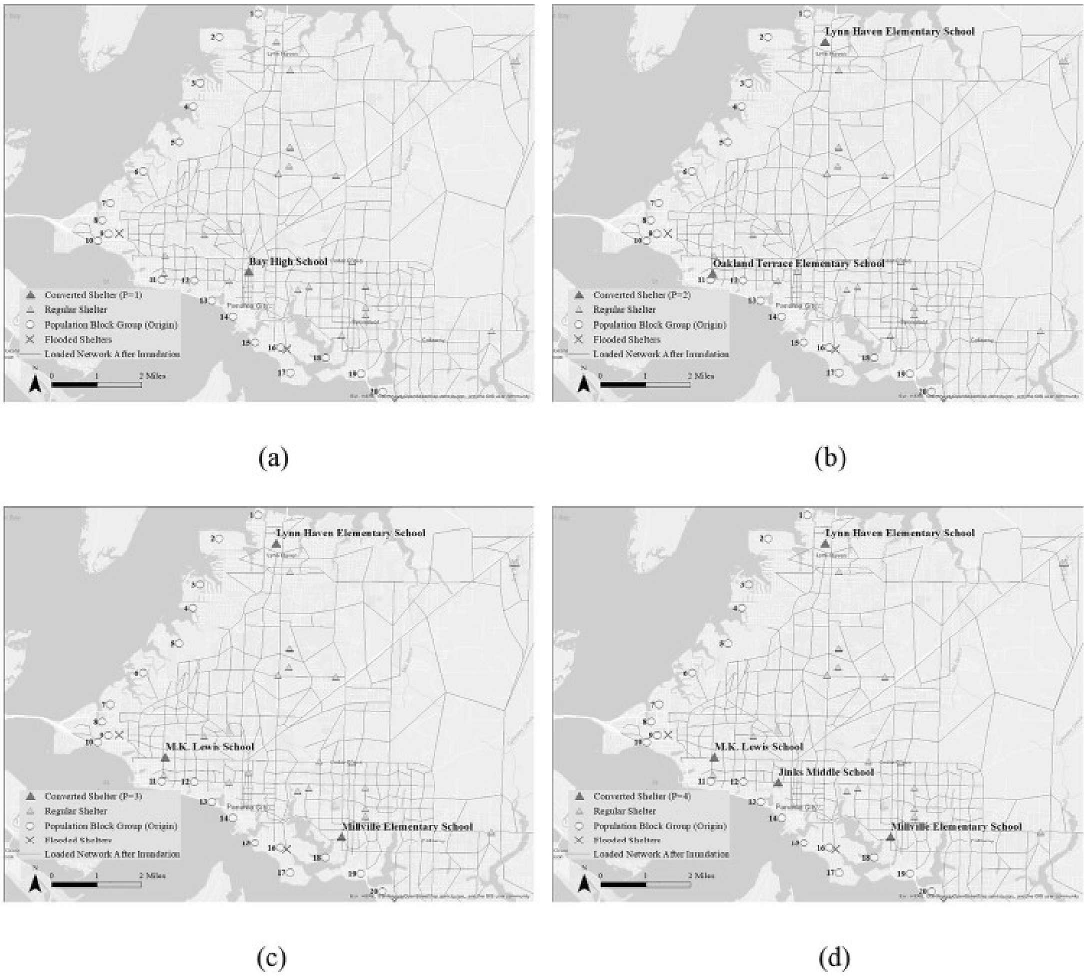


Figure 9. Results of regular shelter selections when (a) $p = 1$, (b) $p = 2$, (c) $p = 3$, and (d) $p = 4$.

Table 3. Travel time improvements after optimization.

Base case

p	Selected shelters	Demand-weighted travel time	Average travel time (minutes per person-trip)	Minimum and maximum travel time (minutes per person-trip)
0		163,792.75	28.53	16.9 & 35.77

Optimization results

p	Selected shelters				Demand-weighted travel time	Average travel time (minutes per person-trip)	Maximum travel time (minutes per person-trip)
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	22,787.77	3.97	6.91

Note: The total population of 65+ people in impacted areas is 5741.

closer to the city, people would not need to travel longer distances to the SpNS located in the northwest, and each census block group needs less time to reach an SpNS than before.

Furthermore, even the Hurricane Michael did not directly hit this region, the only way to reach the former shelter, US 231, was enormously congested and this would be direr in a direct hit situation. As such, the only SpNS would not be within the reach of these people living in the impacted area. Therefore, providing available shelters within the region by considering inundation and roadway closures, which is the purpose of this study, would help special needs populations such as the elderly safely reach an SpNS in a shorter amount of time.

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. The optimized maximum travel time when $p = 1$ was already shorter than the minimum travel time in the original situation. Continue to find the optimal solution; when p was 3, the average travel time per person and maximum travel time per person was 4.26 and 6.91 minutes, respectively. Given that the average time for emergency response is around 8 minutes (Ulak et al. 2017), this seemed reasonable. According to the result of $p = 4$, although the average travel time decreased, the maximum travel time stayed the same. Comparing the weighted demand of $p = 3$ and $p = 4$, it decreased by 1,643.93 only, which was reduced much more slowly than when the number of converted shelters was increased before $p = 3$ as high as 8,000. Therefore, the optimization process could be terminated with 3 regular shelters being selected. This is because sheltering is also required for other segments of the population, and repurposing additional shelters could lead to situations in which some citizens may not find available shelters.

6. Conclusions

This paper presents a GIS-based approach utilizing a validated storm surge model applied to predict the coastal inundation of the densely populated coastal Panama City under a hypothetical hurricane track. Using the results of ADCIRC + SWAN storm surge simulation, we extensively evaluate the accessibility of special needs populations to dedicated hurricane shelters (SpNS) and propose an optimization-based methodology that can help provide better access and shorter travel times to these shelters.

Disruptions such as flooding on roadways have a critical impact on evacuation times and shelter siting. For Panama City, when the bridges that connect Panama City to the north of Bay County get flooded due to Hurricane Michael, congested travel times were very high and the elderly would have to suffer extremely high delays as shown in Table 2. With the addition of intensive evacuation traffic, the travel time can reach to at least 4 hours or more on the only available evacuation route out of Panama City (US 231 when the bridges are closed) as shown in this study. As such, the findings show that there is definitely a need for more SpNS, which can ease the evacuation operations. There is undeniably a need for alternative evacuation destinations, which can help reduce evacuation traffic congestion. Table 3 presented results that clearly indicate how roadway disruptions have a vital effect on evacuation times and how SpNS optimization can help alleviate this problem.

Moreover, to answer the problems mentioned in literature review, this paper can help improve evacuation and sheltering plans focusing on special needs populations with the following advantages:

(1) The models in this study can help provide more effective and reliable emergency evacuation planning and response to hurricanes for special needs populations. As the

hurricane forecast data is updated while it moves closer towards the landfall, we can conduct storm surge previews, delineation of affected areas, roadway accessibility assessments, and better evacuation and shelter planning for special needs populations including the elderly, and disabled. Governments can assist in the evacuation of elderly people who cannot move to special needs shelters on their own due to lack of cars and resources in the areas affected by the hurricane before landfall. Local and state agencies could also update their emergency plans to indicate which and how regular shelters can be repurposed for people with special needs. The proposed methodology will help identify those possible locations based on the extensive evaluation of the roadway network, hurricane conditions, and demographics.

(2) Evacuation destinations can be dynamically shifted and flexibly selected. This will greatly improve the evacuation efficiency in those densely populated areas. Also, '2022 Statewide Emergency Shelter Plan' (2022) states that Bay County shelters will meet the normal standard of 20 sq-ft of floor space per occupant until 2027, and the total shelter space in Bay County will continue to expand from 134,740 sq-ft to 136,620 sq-ft. However, there is only one SpNS located in the north of the city, which is not easily accessible, especially to those living in the coastal areas. This constitutes the motivation for this paper.

(3) The 'Estimate-Situation-Optimize' model provided in this paper provides an effective design for evacuating specific populations and can be applied not only to enhance the accessibility level of special needs shelters, but also to optimize other emergency facilities after timely estimation of the impact of a disaster and existing disruptions on the access routes. For example, evacuation stations can be deployed in advance of a hurricane to help people who cannot drive themselves away from the coast or move residents to nearby settlements when migration of marine pollutants poses a substantial health risk to residents and treating pollutants from multiple preplaced prevention and control stations.

From a disaster management perspective, evacuations of older adults 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 indicates the importance of integrated storm surge, accessibility, and sheltering modeling. 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. 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.

This paper focused on the development of a methodology to identify the best regular shelter locations to repurpose at SpNS integrating storm surge modeling with accessibility and optimization, which was the scope of this paper. In the future work, there is a need to delve into the restrictions of facility locations identified as possible candidates for repurposing.

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