Space-time variation in shelter accessibility in Eastern North Carolina, following Hurricane Florence (2018)

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Introduction

Tropical cyclones are rotating storm systems that can wreak havoc on coastal communities and even areas well inland. These storms generally bring heavy rains, strong winds, storm surges, and spin-up tornadoes that can quickly cause extensive damage to an area's infrastructure. Road infrastructure can quickly become unreliable due to flooding and debris that blocks various roadways. Residents who do not evacuate prior to the storm's arrival can suddenly become trapped until clean-up crews are able to clear roads or floodwaters recede (Cova and Church 1997, Dow and Cutter 2002, Chang and Liao 2015,).

In this paper, we evaluate the impact of the 2018 Hurricane Florence on road network of North Carolina's coastal communities in terms of accessibility to shelters before, during, and after the hurricane. Hurricane Florence was a historic storm due to its slow motion and record rainfall, which caused extensive flooding on the coast and well inland along rivers. This makes it an ideal case study for examining how travel distances from census block groups to designated shelters throughout the coastal region were impacted during the event.

According to the National Weather Service, Hurricane Florence was the wettest tropical cyclone on record in the Carolinas1. At its peak, Hurricane Florence was rated as a Category 4 storm on the Saffir-Simpson scale, which is solely based on sustained wind speed. The hurricane weakened considerably as it approached the Carolina coast and made landfall near Wrightsville Beach, NC as a Category 1 storm on September 14th, 2018. Despite its weakened status and unusual path (see Figure 1A), the storm's large wind field, heavy rain, and storm surge combined with its slow motion caused extensive damage throughout the coastal regions of North Carolina. Many areas received rainfall amounts of 20+ inches, with a few areas receiving around 30 inches of rain, which caused catastrophic and life-threatening flooding. This flooding was the main culprit for crippling the road networks of the effected region, and in some cases, completely trapping whole communities until waters receded.

Our main objective is to determine the impact of road closures on accessibility for residents who are attempting to reach shelters during extreme weather events (Horner et al. 2018). Other, secondary research questions of interest to this study include (1) Whether shelters placed in regions that provide good accessibility to residence, (2) Whether there are specific regions that tend to be more vulnerable to road closures than others, (3) What are the temporal implications of road closures and (4)

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[1] US Department of Commerce and Noaa, "Historical Hurricane Florence, September 12-15, 2018," National Weather Service (NOAA's National Weather Service, January 10, 2019), https://www.weather.gov/mhx/Florence2018)

Whether we can detect space-time variations in shelter accessibility. Answering these questions will help provide a better understanding of how residents who do not initially evacuate are impacted by hurricanes. This study fuses OpenStreetMap (OSM) data linked with road closures information from the North Carolina Department of Transportation and census information (population weighted centroids). Since the road closure data is provided in latitude and longitude, it is critical to ensure that these locations spatially coincide with existing roads from OSM, otherwise routing optimization is biased. We resort to python scripting to ensure proper overlay.

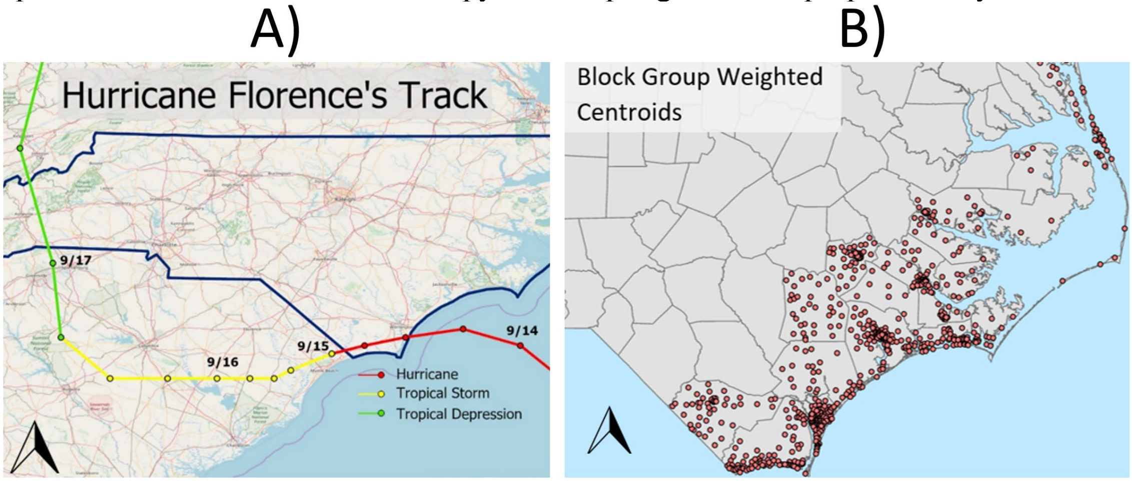

Figure 1. Hurricane Florence's official center track and intensity in A), and block group weighted centroids used as proxies for residents' origins in B).

Methodology

This section focuses on the data, including, (1) the population weighted centroids, (2) shelters locations, (3) road closure data, and the methods used to (4) the construction of an in-house network dataset, and perform (5) the network analysis. The study area used to complete the analysis, shown in Figure 2, consists of the coastal counties for North Carolina and counties inland that had mandatory or voluntary evacuation orders during Hurricane Florence.

Population Weighted Centroids

We use population weighted centroids of block groups from the 2017 American Community Survey (ACS) to represent the residents and their potential starting locations (Figure 1B). Block groups were used so that population estimates from the 2017 ACS could be included, as opposed to census blocks which are only reported upon during the decennial census. To limit the study area (and computational effort), only block groups from counties that had mandatory or voluntary evacuation orders were used. In total, 16 counties had evacuation orders in place[2].

Shelters

Unfortunately, there is not a centralized place where information on shelters is maintained. This is because shelters are generally opened by local municipalities rather

[2] All of North Carolina's barrier islands were under a mandatory evacuation. These orders are more strictly enforced on the islands, but mandatory evacuation orders in other regions are typically loosely enforced. This why block groups in mandatory evacuation areas are included in this study.

than state-run organizations. State officials do work in coordination with those local municipalities, but the dissemination of shelter information is done at a local level. So, to collect information on shelters, news sources were used. An article posted by WXII 12 in Winston-Salem[3] provided a list of all 100 shelters opened throughout the state and their addresses. This list was then cross-referenced with other news sources to confirm accuracy. These 100 shelters were then geocoded using ESRI's World Geocoder.

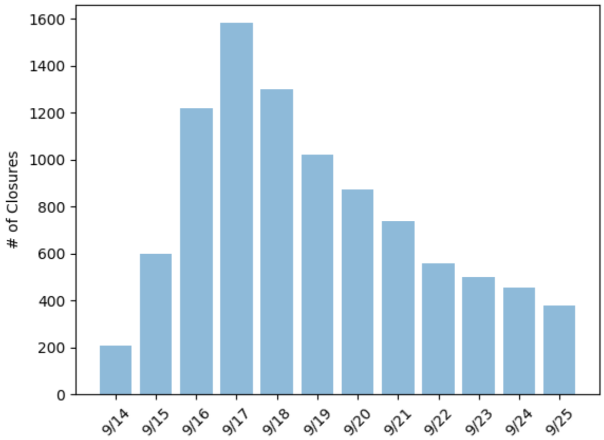

Figure 2. Active road closures from September 14 to September 25, 2018.

Road Closures

Data involving road closures were provided by the North Carolina Department of North Carolina (NCDOT). Approximately 2,500 road closures occurred due to Hurricane Florence according to the NCDOT. Specifically, NCDOT provided a spreadsheet with information that included when (start and end dates) and where (latitude and longitude) these closures took place. These closures began to appear in multitudes on September 14th and reached a peak on September 17th before slowly decreasing for many days thereafter (Figure 2). Since the closure data was provided in latitude and longitude, it is critical to ensure that these locations spatially coincide with existing roads, otherwise the routing optimization will be affected. To ensure this accuracy, a python script was developed to find road closures that had been placed within 10 meters of multiple road segments (Figure 3). The magnitude of 10 meters was chosen because it allowed for the finding of closures that were placed on medians, which are generally only a few meters wide, between two road segments. Closures that occurred on the roads labelled as interstates were inspected and edited, if needed. This was necessary because oftentimes interstates are digitalized as split segments with one-way flow of traffic designated by each polyline. The road closure data, however, would note that both directions were closed, but the point would only be on one of the segments.

In-house Road Network Dataset

An in-house network dataset was created using OpenStreetMap (OSM) data to allow for flexibility and repeatability of analysis (Delmelle et. Al 2019). We followed the approach set forth by Karduni et al. (2016), which details a technical procedure for the creation of a dataset from spatial polyline data. OSM data, which consists of polylines, was extracted from Geofabrik, a website that allows for the download of OSM data. The dataset was then cleaned to remove any segments that were not for

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[3] Jonee' Lewis, "List of Shelters Available for Hurricane Florence Evacuees in North Carolina," WXII, September 14, 2018, https://www.wxii12.com/article/list-of-shelters-available-for-hurricane-florence-evacuees-in-north-carolina/23102046)

meant for vehicle travel (incl. bridleways, cycleways, footways, paths, steps and pedestrian). Due to the existence of bridges and tunnels, connections between road segments may be made where they should not. This is the main topology that exists when using OSM data. To address the topology problems, the steps shown in Figure 4A were followed. The result is a network comprised of edges and nodes that more accurately reflects the real-life road network.

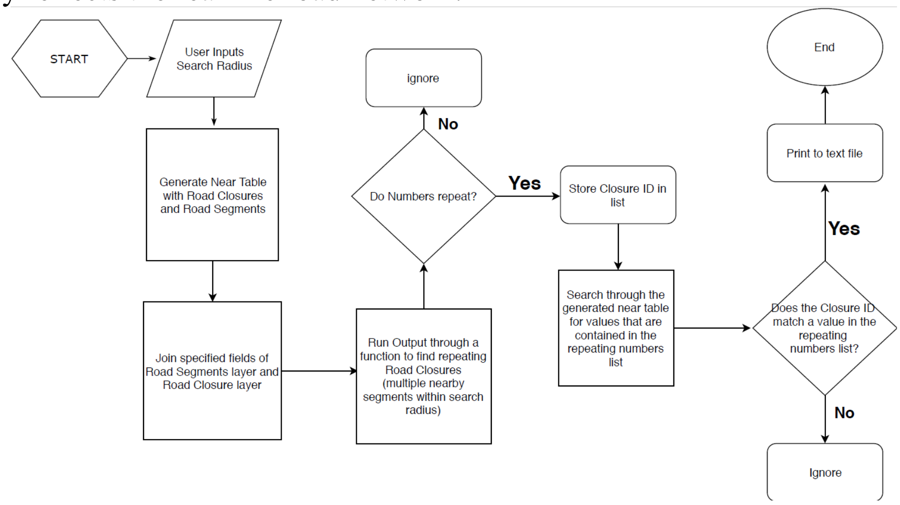

Figure 3. Flowchart to find closures that are near multiple road segments.

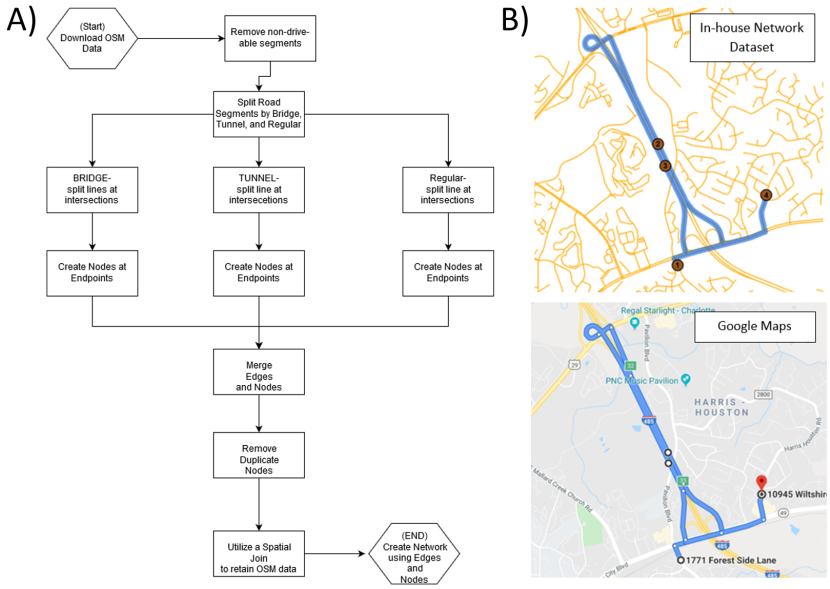

Figure 4. Converting polyline OSM data to create a network dataset in A). Comparison of the routes used to reach identical waypoints in B).

Portions of the network were then tested to determine if the protocol followed successfully created a usable and accurate network (Delmelle et al. 2013). Figure 4B shows a comparison of routes between the in-house network and Google Maps. The waypoints were strategically chosen to force the routes to utilize two complex interchanges and a few bridges. Both networks solved the routes in identical fashion and the route distances were computed as 5.0 miles[4].

[4] Google Maps only reports travel distance to the nearest tenth value. ArcGIS' network solution is more precise and reported a value of 5.03162 miles.

Network Analysis

To calculate distances it would take a resident to reach the nearest shelter, we relied on the 'closest facility' algorithm, which measures the driving distance between incidents and facilities in order to determine which facility is closest. The output includes the shortest route to reach the closest shelter and the distance needed, based on the Dijkstra's algorithm[5]. The algorithm was run with no road closures to provide a base measurement of the initial conditions, and then road closures were inserted into the algorithm as barriers. The algorithm was run 11 times, with only barriers changing based on when the road closures were present[6]. This accounts for the initial conditions and September 14 through September 23. For each of the 11 scenarios, the difference between the initial and actual distances to reach the shortest shelter was estimated.

Results

We report results based on initial and deteriorating conditions between September 14, 2018 and September 23, 2018. Table 1 summarizes the variation in accessibility throughout the time period. The total miles travelled is an aggregate measure of the distances necessary to reach the closest shelter from all the block group centroids, and it is weighted by the population of each block group (Fig 6A). This number is based off all solutions[7], though, so it can be skewed by the number of unsolvable solutions present and the population of those block groups. Another way to explore the trends in the data is by looking at the mean and median values of travel distances throughout the time period (Figure 5), suggesting that (1) the average travel distance is much higher than the median due to the inclusion of outliers[8], and (2) residents were most impacted by road closures on September 16th.

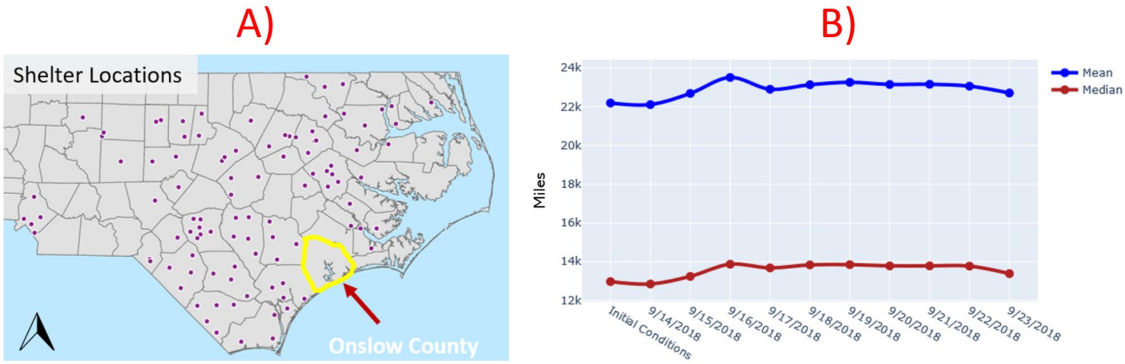

Figure 5. Shelter locations throughout North Carolina in A). Onslow County is highlighted in yellow because no shelters were opened within the county. Mean and median travel distances multiplied by block group populations in B).

Initial Conditions

In order to have a baseline to compare how much residents were impacted by road closures, the network analysis algorithm was run under optimal conditions (Fig 6B,

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5 We used shelters as facilities and the population weighted block group centroids as the incidents (Fig 6A).

6 The option to utilize the barriers was chosen over manually editing the network dataset and creating separate networks for each day because of the way the closure data was presented. The barriers allowed for easy implementation of the closures and quick production of multiple solutions based on the days being analyzed.

7 Some block groups were 'unsolvable' (no routes found that could reach a shelter; trapping people living in these locations)

8 Some of the Outer Banks islands contained block groups that needed to travel between 40 and about 120 miles to reach a shelter under the initial conditions.

showing the distance residents would need to travel in order to reach the nearest shelter). In these conditions, there were 690 block groups with solutions, while 4 block group centroids were unable to be solved (these were all on barrier islands that were only reachable by ferry, so they were ignored for this analysis). Off the 690 solvable block groups, the average distance needed to travel to reach a shelter was 14.92 miles. This number was slightly skewed due to the northern coastal counties where population is sparser, the barrier islands have more limited access to the mainland, and shelters are less present. The first two factors are more permanent in nature, but the lack of shelters may be due to the projected east-southeast path of the storm.

Table 1. The amount of block group centroids that could access a shelter (solvable solutions), unsolvable solutions, the total miles traveled by all residents to shelters, and the average each resident needed to travel reach the nearest shelter.

Date	Frequency	Unsolvable Routes	Total Miles * Population	Average Miles
Initial Conditions	690	0	15,313,158	14.92
9/14/2018	665	25	15,256,891	15.09
9/15/2018	665	25	15,654,300	15.47
9/16/2018	667	23	16,223,333	15.93
9/17/2018	662	28	15,803,265	15.57
9/18/2018	676	14	15,964,415	15.66
9/19/2018	681	9	16,050,186	15.68
9/20/2018	690	0	15,973,389	15.45
9/21/2018	690	0	15,980,455	15.45
9/22/2018	690	0	15,912,178	15.39
9/23/2018	690	0	15,669,778	15.20

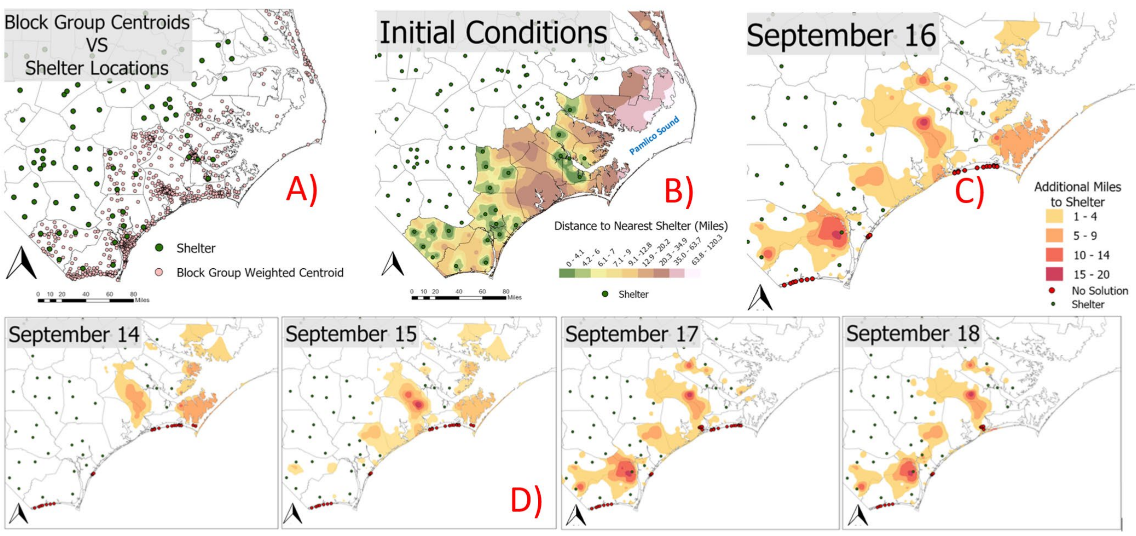

Figure 6. Distribution of shelter locations and block group weighted centroids in A). Approximate distance a resident would need to travel to reach a shelter if all roads are open in B). Additional miles needed to travel to reach the nearest shelter on September 16 in C), and on September 14, 15, 17 and 18 in D).

The initial conditions can give a good idea of how well shelters are spread throughout the region. A county with optimized shelter locations would see an even spread of travel distances throughout much of the county. However, some counties may consider optimizing the location of the shelters as a function of population distribution. Apart from Onslow County (Figure 5A), it seems that much of the coastal counties took this approach of placing shelters in or near the most populated regions (Figure 6A). This pattern makes sense as emergency managers generally take population density into account when configuring their emergency preparedness plans. Figure 6B shows that the four most southern counties of Brunswick, Columbus, New Hanover, and Pender have good spatial coverage because most of the areas in these counties can reach a shelter in 12 miles or less. An exception to that is north-eastern Pender County which looks to be adversely affected by the absence of shelters in Onslow County. Residents within this portion of Pender County would need to drive upwards of 20 miles to reach a shelter. However, it is worth noting that this an area that is sparsely populated.

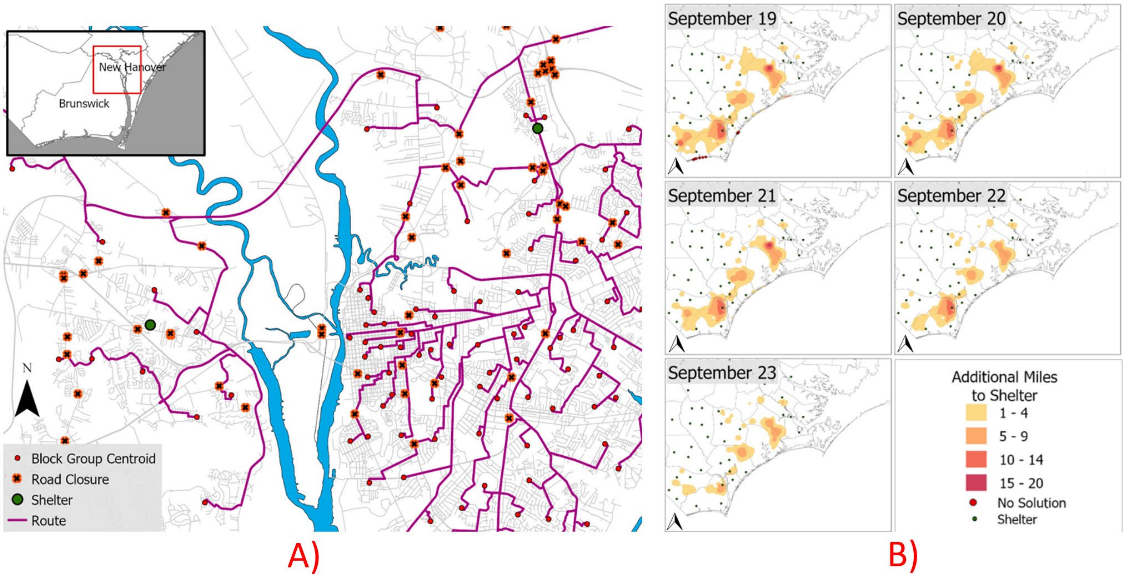

Figure 7. Routes used from block group weighted centroids to reach the nearest accessibly shelter (example of Wilmington, New Hanover county) in A). The shelter in Brunswick County (the eastern most shelter shown in green) could not be accessed due to flooding of the main road used to access it. Additional miles needed to travel to reach the nearest shelter on September 19-23 in B)

The central coastal counties seem to have their shelters situated around the more populated regions such as the New Bern area. This provided decent access to shelters along some of the inlets. Some of the less populated regions found along the Pamlico Sound would need to travel upwards of 60 miles to reach a shelter. The same pattern is observed in the northern coastal counties; however, this could simply be attributed to the lack of shelters in these counties.

September 16, 2018

On the 16th of September, the amount of road closures throughout North Carolina skyrocketed to about 1,200. Despite the system weakening to a tropical storm by that point, the center of circulation was in South Carolina and still bringing rainfall to much of the Carolinas. This led to inland flooding of low-lying areas as well as near rivers and other waterways. In terms of average miles needed to reach a shelter, it peaked to 15.93 miles. The area most affected by the road closures on the 16th, as shown in Figure 6C, was in northeast Brunswick County. Residents within this region needed to travel an extra 7.3 to 19.2 miles to reach the nearest shelter. At first glance, this was surprising to see as there is a shelter located right in the middle of this region. However, a closer look at the road closures in this region shows that the roads to access that shelter were flooded. These closures essentially cut-off that shelter from any potential residents. Figure 7A shows the routes that would need to be taken to reach the next nearest shelter, which is in New Hanover County. In order to reach this other shelter, the residents would need to cross the Cape Fear and Brunswick River. Flooding of the rivers and the low-lying areas near them caused some closures of bridges that cross the rivers and some main roads that access these bridges. This caused residents in eastern Brunswick County to have to travel north and use I-140 to cross these rivers and eventually reach the other shelter. This caused the total travel distance of much of these block groups to increase to 17 - 20 miles. This is significant because under normal conditions, the residents in this area would only need to travel a few miles. If a resident here assumed they could easily reach the nearest shelter, they may feel comfortable with waiting out the storm for as long as possible.

September 17, 2018 – September 18, 2018

The same general pattern shown on the 16th continued into the 17th. The shelter in northeast Brunswick County continued to be inaccessible, eastern Pender County was still being slightly affected, and residents of central Jones County were still needing to travel an extra 16.6 miles to reach their nearest shelter. The biggest additional impact shown on the 17th is in eastern Onslow County where a pocket of "no solutions" are present (Figure 6D), suggesting that residents within that region would be unable to reach any shelter.

September 19, 2018 – September 23, 2018

On September 19, block groups in eastern Onslow County were once again able to access shelters as two of the three access points reopened. In general, much of the other study area remained within the same conditions apart from a slight decrease in magnitude of the region in eastern Brunswick County (Figure 7C). This decrease can be attributed to the opening of roads that provided a more direct access across the Cape Fear and Brunswick rivers. The shelter in eastern Brunswick County, though, remained inaccessible. On the 20th, all block groups were able to access shelters as bridges to barrier islands opened and the total amount of road closures dropped to around 900. This is still a significant amount of closures, so many areas remained impacted. The same general areas that have been previously affected continued to be an issue. The 21st displayed the same conditions with only minor improvement in isolated spots. The most significantly affected regions remained in central Jones County and eastern Brunswick County. On the 22nd, areas that previously exhibited 15-20 additional miles began to decrease to lower values. This is seen in Jones County where conditions improved to only needing to travel an extra 8 miles, at most, to reach the nearest shelter. Still though, the eastern section of Brunswick County would need to travel 10-14 additional miles to reach the nearest shelter. September 23, 2018 marks the ninth day since the Hurricane Florence made landfall and impacts on shelter accessibility were still present. The biggest improvement is seen in eastern Brunswick County where the shelter was finally accessible to nearby block groups.

Discussion and Conclusion

Road closures showed a clear impact on the ability of residents in the study area to reach their nearest shelter. This increase in travel distance was sometimes attributed to the routes being adversely affected by road closures. Other times, it was attributed to closures that prevented access to a shelter. In the most extreme case within Jones County, residents would have needed to travel an additional 23 miles to reach a shelter. This increased their total travel distance to 40.29 miles and would have affected approximately 2,203 residents. The block groups of eastern Brunswick County also experienced similar issues as their typical shelter became inaccessible due to road closure. This study shows that the worst affect from road closures occur when residents must resort to their second option of shelter. In this scenario, the travel distance will naturally inflate, but road closures along the new route may also increase mileage. This combination of affects presents a unique situation that often isn't considered when designing emergency preparedness plans.

The worst-case scenario is for residents to become trapped due to road closures that surround their area. This occurred in a small area region near the coast of Onslow County where the three roads that could be used to access this area were blocked due to flooding. Identifying regions that are susceptible to becoming trapped is a difficult, but important endeavour that should be further explored. Coastal communities are at an increased risk of being trapped due to the limited access points and the likelihood of these access points being blocked by damage or flooding. With the information gathered from this study, emergency management officials can better warn these communities of the dangers of not evacuating.

Overall, this study shows that the potential for road closures should be taken into consideration when designing a comprehensive evacuation and emergency preparedness plan. The closure of roads can have an adverse effect on residents who are trying to reach a place of safety. These affects are exacerbated when shelters are spread out or completely devoid in a region. Roads that provide a direct access to shelters are of utmost importance as their vulnerability can affect a large portion of residents. To help limit the possibility of this occurring, it would be better to have shelters with multiple access points or in areas with a well-constructed grid-like road network. Also, shelters should not be placed in or near areas that are at risk for flooding.

These solutions do not help communities that may become trapped by nearby road closures. In areas that are susceptible to this type of occurrence, the dissemination of this hazard would be the best course of action. By providing citizens with the risks associated with not evacuating, the citizens can make a more informed decision. The residents of barrier islands understand that they have limited access points to the mainland which are often closed during a striking hurricane. Residents of coastal communities on the mainland may not be aware that they too are at risk of losing access to the rest of the region and access to shelters. In addition, knowledge of where these vulnerable communities exist would help law enforcement better allocate their efforts in enforcing evacuation orders.

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