ASSESSING RESOURCE ACCESSIBILITY OF VULNERABLE POPULATIONS DURING EVACUATION

by

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I. INTRODUCTION

Urban areas present a myriad of challenges to emergency management (EM) professionals, because of their potential for disasters exacerbated by population density (Alexander 1991; Saadatseresht 2009). In times of severe natural disasters, large scale evacuation has often created chaos and led to casualties worldwide (Unal 2016). While EMs meticulously strategize to orchestrate organized and timely evacuations, the chaotic and unpredictable nature of large-scale disasters, such as hurricanes, often undermines such plans (Cova 1997). Recent advances in Geographic Information Systems (GIS) have provided pivotal tools for scrutinizing the multi-faceted variables that influence evacuation efficacy (Kumar 2013).

Understanding the needs of an urban population during an evacuation away from a hazard (e.g., hurricane) is crucial to the full range of experience, skillsets, and knowledge of disaster prevention planning for emergency management professionals (Unal 2016). The Federal Emergency Management Agency (FEMA) supplies required training for local EMs on hurricane preparedness and evacuation planning to cover basics of evacuation behaviors and methods. However, the most effective evacuation plans stem from local expertise, honed through years of experience and supplemented by advanced planning technologies (FEMA 2021).

Crucially, these plans should be accessible for EM professionals who may not have in-depth GIS expertise but are proficient in evacuation logistics (Liu 2016). Recent developments in disaster response simulation technology, active incident warning systems, and understanding of evacuation behaviors have prevented reoccurring profound loss of life, yet there remains a considerable scope for the refinement of evacuation strategies (White 1988). The principal objective of this study was to rigorously assess a phased evacuation plan which, in its current state, lacks a focus on the equitable distribution of evacuation resources. By incorporating GIS analyses of various additional parameters, this study aimed to provide a more holistic framework for the use of GIS in disaster preparedness by EMs.

Hurricane Impacts in the Houston-Galveston Area

The Houston-Galveston Area (H-GA) has been directly affected by hurricanes 31 times since 1851, the year the Hurricane Research Division of the United States (US) National Oceanic and Atmospheric Administration's (NOAA) Atlantic Oceanographic & Meteorological Laboratory (AOML) begins to track historical hurricane data (AOML 2020). The first documented Category 4 storm that hit the H-GA coastline was in 1900, directly striking the City of Galveston to the southeast of the City of Houston. This storm is still known as the deadliest storm in the US, taking somewhere between 8,000 and 12,000 lives. Approximately $200 million (adjusted) in damages decimated the entire coastal region of the H-GA (City of Houston 2018; FEMA 2017). Many existing hurricane evacuation strategies within the emergency management discipline are rooted in mitigation strategies derived from the impacts of the 1900 storm. It laid the foundation for many of the hurricane preparedness initiatives in contemporary emergency management, such as investments in hurricane planning and infrastructure like a nearly 5-meter-high seawall (Ramos 1998).

A little over one hundred years later, Hurricane Katrina would strike the Gulf of Mexico hitting the neighboring State of Louisiana in August 2005 as a Category 5 major hurricane, causing catastrophic devastation with wide-spread flooding that left hundreds of thousands stranded and killing almost 2,000 people (Levin 2015). The impacts on the New Orleans area gave Katrina the title of costliest tropical cyclone on record at the time (NHC 2018). Only a few weeks later in September 2005, Hurricane Rita moved into the Gulf of Mexico as the strongest Gulf storm on record, a title Rita keeps today. With the recent memories still fresh from the impacts of Hurricane Katrina and the promise of record-breaking destruction, approximately 3.5 million people tried to evacuate ahead of Hurricane Rita (Levin 2015).

The chaos that ensued was marked by a bus fire, traffic jams, and heat stroke, killing dozens (Domonoske 2017).

Due to the general confusion and traffic congestion during the evacuation of the H-GA during Hurricane Rita, the H-GA Council of local governments, in conjunction with local, state, and federal EMs, revised the regional evacuation plan. The resulting plan finalized in 2008 set up four well-defined evacuation zones based on groups of zip codes for the entire coastal region, consisting of: Zip-Zone Coastal, Zip-Zone A, Zip-Zone B, and Zip-Zone C (Figure 1). This systematic zoned evacuation planning method is referred to as a phased evacuation, which was established along the densely populated H-GA of the Texas coastline due to a task force assembled to study and prevent a repeat of the failures of the Hurricane Rita evacuation (Henk 2008).

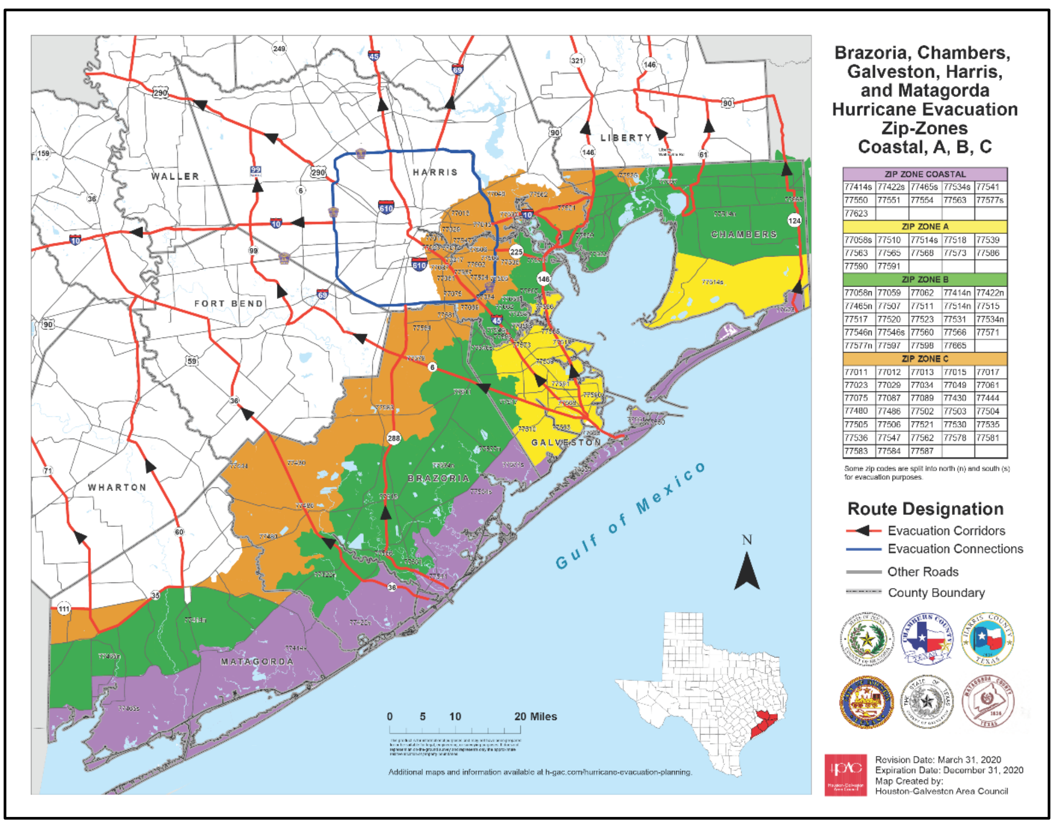

Figure 1: Houston-Galveston Area Council Hurricane Evacuation Zip-Zone Map (Gage 2021)

In late August 2017, Hurricane Harvey developed in the Southern Gulf of Mexico along the Yucatan Peninsula and spurred devastation across the entire Texan coastline. At the time this research was conducted, Hurricane Harvey was not only the most expensive tropical weather event on record, but also ranked as the second-most financially devastating natural disaster globally. Over 780,000 Texas residents were subjected to mandatory or voluntary evacuations, and FEMA received an unprecedented 87,000 flood insurance claims. At least 2,400 families found themselves transplanted into hotels spread across the region as temporary shelters, adding a layer of complexity to an already strained mass care effort. Despite immediate disaster response and relief operations having ended, the long-term ramifications of this devastating event will define social, economic, and infrastructural landscapes for decades to come. (FEMA 2017).

The financial toll of Hurricane Harvey exceeded $200 billion, with most of the economic impact caused directly by floodwater inundation across the H-GA. The Harris County Flood Control District (HCFCD) reported that floodwaters totaled over one trillion gallons, rising to historic highs across all 140 zip codes included within the H-GA. The area saw widespread damage to critical infrastructure, including roads, bridges, and water treatment facilities, complicating immediate recovery and future preparedness measures alike (HCFCD 2018). As of late September 2017, the Harris County Institute of Forensic Sciences had attributed thirty-six deaths to Hurricane Harvey’s direct and indirect effects, but the storm's unquantifiable psychological and emotional costs beyond the immediate human loss of life are no less significant (Sanchez 2017).

Medically Fragile Population Evacuation Planning in Texas

During an emergency, data and information are evaluated in real-time by emergency management professionals to facilitate a dynamic and effective response to each unique incident (Unal 2016). Development of a comprehensive evacuation plan prior to a hazardous event was one of the first steps to provide a solid foundation for disaster response by local officials and decision makers (Yuan 2017). Ideally, EMs consider the composition of the population they plan to protect. Scholars and emergency management practitioners have studied how socioeconomic characteristics affect disaster planning (Baker 1991), but, despite these efforts, the state of emergency preparedness remains inadequate for vulnerable subsets of the population, specifically the Medically Fragile Population (MFP) (Ng 2015).

The MFP, as defined by multiple scholarly and institutional sources, encompasses individuals with a range of physical and cognitive limitations restricting vision, hearing, physical, cognitive, or mobility (Van Willigen 2002; Frieden 2006; Fraser 2016; WHO 2011). The MFP are by large self-identified individuals who will need more time and resources beyond the general population during an evacuation (Ng 2015). For this study, data on the geographic location of those citizens included in the MFP was determined by those persons who have registered through the State of Texas Emergency Assistance Registry (STEAR) to request additional aid during an evacuation (See Appendix A). Preliminary data from STEAR, overseen by the Texas Division of Emergency Management (TDEM), exposed the insufficiencies of the current systems in catering to the MFP during events such as Hurricane Harvey in 2017 (Riker 2017).

Prior to Hurricane Harvey, the MFP of the H-GA zip codes that had registered through STEAR had totaled 8,716 citizens (OpsTech 2017). However, there were many instances of MFP who had not received the assistance requested through the STEAR program days after the storm had passed (Riker 2017). If utilized as intended, local EMs would have begun contacting those MFP registered through the STEAR program up to 120 hours (about 5 days) prior to an incoming storm (OpsTech 2017). Hurricane Harvey had intensified from a Tropical Storm to a Category 4 storm so quickly that the ability to create specialized transportation arrangements for the MFP had become unmanageable across such a large spatial area, exposed severe limitations in the logistical capabilities for assisting the MFP during rapid-onset disasters (Riker 2017). The Texas Division of Emergency Management (TDEM) registration form states that registration with the STEAR program does not explicitly guarantee any preferential access to evacuation assistance during an incident, however, the MFP location information from STEAR is provided directly to local jurisdictions and state search and rescue teams alike (OpsTech 2017).

Purpose Statement and Research Questions

This study advanced emergency management evacuation planning by investigating and developing a method to find areas within any urban setting that required prioritized resources in the event of a phased evacuation. This directed research focused on the following two questions:

1. Are there any significant differences in MFP%, resource accessibility and travel time across the designated Zip-Zones and hypothetical equal distribution of MFP within the H-GA?
2. Which zip codes within each Zip-Zone should be prioritized for phased evacuation in terms of resource allocation to support the needs of MFP?

The broader research hypothesis stated that a significant difference existed in spatial accessibility to defined evacuation resources for the MFP between zip codes within each of the Zip-Zones across the H-GA study area. The process of evaluating the initial central research question led to the development of a replicable method to further refine current phased evacuation plans by identifying areas that could be prioritized within existing zones, thereby providing insights into the second question of this study.

Having employed a Spatial Accessibility Analysis (SAA) of available emergency resources, this study questioned the impact of the distribution of vital emergency resources in relation to the dispersion of the defined subset of MFP within a community and its impact on the efficacy of established phased evacuation zones (Correia 1998; Ng 2015). The parameters of this research defined emergency resources as open shelters beyond the boundaries of the existing evacuation Zip-Zones and local emergency service resources; including law enforcement, emergency medical services, and fire stations combined. The SAA process outlined in this study used datasets provided to local jurisdiction by TDEM, enabling EMs with access to geospatial analytics tools to combine MFP location information with spatial emergency resource data to fill a notable gap in current evacuation planning methods (Radke 2000, Liu 2006).

II. LITERATURE REVIEW

This investigation drew from and contributed to three major bodies of literature: 1) phased evacuation planning in an urban context, 2) evacuation behavior of Medically Fragile Populations (MFP), and 3) spatial accessibility analysis of phased disaster evacuation.

Phased Evacuation Planning in an Urban Context

Hurricanes have created immense destruction across the coastal areas of the US recently so it is important to develop "effective evacuation policies and plans" (Ng 2015) to mitigate disaster impacts (Baker 1991; Sorenson 1991; Yin 2014). Evacuation phasing is a planned disaster response to ensure the efficacy and efficiency of orchestrating the movement of thousands, or even millions, of people across a city to a safe shelter. Phased evacuation, using zones defined by well-known boundaries (e.g., zip codes), is a risk-based technique designed to reduce traffic congestion along existing road networks and allow for the dispersal of limited resources across a region (Wilmot 2005; Hsu 2014; Zhang 2014). Phasing is important in highly populated areas and is widely employed in evacuation planning, permitting those in the "most critically threatened areas" to travel to safety first despite foreseeable traffic congestion (Zhang 2014).

Phased evacuation plans are designed to be logical and simple conceptually, but they often have some practical challenges. Past instances of urban evacuation have shown that people in the same disaster are likely to respond to phased evacuation orders differently based on their perceived risk and experiences with similar disasters in the past (Ng 2015; Zhang 2014). This type of hazard can also limit the effectiveness of a phased evacuation plan. Hazards with longer warning times (e.g., hurricanes) are better suited to these types of plans (Zhang 2014). Conveying phasing instructions and ensuring comprehension of orders during an emergency is extremely problematic with a large urban area being socially and culturally diverse (Morrow 1999; Zhang 2014). The unnecessary evacuation by those in less dangerous areas and the inability to reach those who have the most pressing need to evacuate are leading causes for the traffic congestion that phased evacuations try to alleviate (Liu 2016).

Mass evacuations are extremely infrequent but are often ordered with little warning while the natural disaster threat is still forming or evolving. When implemented correctly, evacuees are staggered across the area both spatially and temporally to incrementally clear people from those zones of increased hazard risk, with the areas of most potential hurricane impact are issued orders with greater urgency (Zhang 2014). Literature on criteria important for the design of evacuation zones is sparse but increasing in number (Wilmot 2005). In line with the current H-GA Evacuation Zip-Zones Map, Wilmot and Meduri's (2005) recommendations include the following in defining evacuation zones:

- Easily distinguished not only by authorities but also by the public
- The boundaries of the zones should be either major roads or landmarks such as bridges, rivers, lakes, etc.
- Island formation (one zone inside the other) should be avoided.

Other studies have built upon the work of Wilmot and Meduri (2005) through the inclusion of more advanced clustering analysis, mathematical models, and added variables (e.g., wind speed of the impact areas) (Zangeneh 2010; Liu 2016). The contiguous zip codes in the current Zip-Zones in the H-GA may be easier for evacuees to decide whether it is their turn to evacuate during a phased evacuation, compared to the potentially scattered zip codes that could result from a multi-factor approach (Wilmot 2005). On the other hand, the latter approach often creates scattered zip codes across a densely populated area that could increase the efficiency of an evacuation plan by reducing concentrated traffic congestion. This analysis of hurricane evacuations builds upon a robust body of urban disaster evacuation planning and traffic modelling literature and seeks to explore other influencing factors beyond contiguous Zip-zones based simply on proximity to the coast (Kirschenbaum 1992; Lewis 1995; Liu 2006; Mitchell 2006; Chen 2008; Chiu 2008; Montz 2013; Liu 2016).

Evacuation Characteristics of the Medically Fragile Population

Existing literature has extensive research focusing on the needs of general population throughout the evacuation process (Baker 1991; Whitehead 2001; Gladwin 2001; Dow 2002; Fu 2004; Lindell 2005; Elliot 2006; Dash 2007; Czaikowski 2011). Research investigating hurricane evacuation as experienced by the MFP is rare and much work is needed to bolster the intuitive importance placed on the issue by emergency management personnel (Zhao 2010; Ng 2015). Federal regulations, such as the Americans with Disabilities Act and the Post-Katrina Emergency Management Reform Act, mandate inclusive emergency plans, yet the execution is impeded by substantial knowledge deficits (Risoe 2013).

Many factors have contributed to the unbalanced experiences between the MFP and the general population throughout the evacuation decision making process (Van Willigen 2002). Ng (2015) reaffirmed the presence of “critical differences” between the MFP and the general population that require added evacuation time and emergency resources (Zhao 2010). During an imminent storm event, if a household with a MFP member perceives the threat of a potential flood in their neighborhood based on previous experience, the MFP household will begin evacuation measures earlier than other households (Ng 2015). Therefore, the travel time of the MFP household to their nearest shelter with proper resources (e.g. medical supplies, mobility support) is an indicator of evacuation resources needed.

Earlier studies of evacuation during hurricanes strengthen the need to involve the MFP in disaster planning. Litman (2006) found that the MFP was the most vulnerable population during the evacuation of Hurricane Katrina as the City of New Orleans left most of the “responsibility, safety, and evacuation on the individual”. In fact, the National Council on Disability said in 2006 that most of the fatalities during Katrina were among the elderly and disabled (Frieden 2006). By examining when the MFP chose to leave their homes during an evacuation in coastal Virginia and North Carolina in preparation for Hurricane Irene in 2011, Ng (2015) determined the presence of "critical differences" between the needs of the MFP and the non-disabled through telephone surveys covering topics such as past hurricane experiences, existing medical conditions, and evacuation departure time.

The evacuation of dialysis patients from the US Virgin Islands to Puerto Rico post-Hurricane Irma of 2017 originating in the Gulf of Mexico highlights the unique needs of certain subgroups within the MFP, particularly the need for consideration of specialized medical care and facilities in evacuation plans. These patients required not only safe relocation but also access to essential treatment units and temporary infirmaries. The logistics of transporting these daily dialysis patients during incident response underscores the complexity and importance of detailed evacuation planning for the MFP. Essential medical supplies, such as refrigeration for insulin and waste disposal solutions, were critical, highlighting the importance of resource pre-planning and allocation. The management of acute medical conditions during evacuation necessitated immediate medical intervention, reinforcing the need for medical personnel in the evacuation process (Guillermo 2021). This case study aligns with previous research, like Ng (2015), indicating that households with MFP members often require evacuation earlier due to specific medical requirements, underscoring the need for tailored evacuation strategies in emergency management.

FEMA's Planning Considerations: Evacuation and Shelter-in-Place 2019 guide provides critical insights into the complex needs of the MFP during disasters. This comprehensive framework underscores the importance of individual and family preparedness, particularly for MFPs, who require well-equipped shelter locations with adequate medical supplies, durable medical equipment, and resources to arrange ongoing medical care. FEMA emphasizes the need for MFPs to have robust evacuation plans, which include identifying primary evacuation routes and ensuring access to essential services like dialysis during displacement. The document also highlights the pivotal role of state, local, tribal, and territorial governments in facilitating these processes through community engagement in preparedness training, clear messaging, and efficient warning systems. The Planning Considerations guide also encourages local jurisdictions to adopt a zone-based approach to evacuation, as previously discussed in this study, to minimize the number of people moved and the distances they travel, reducing overall resource (FEMA 2019).

The MFP are also unique in that they are often concentrated within a larger institution such as a nursing home or long-term care facility. These groupings of MFP carry their own burden on resources and requirements for transport along existing evacuation routes and represent a uniquely challenging environment. The evacuation of nursing homes is burdened by complex logistical demands given the needs of residents who may be bed-ridden, comatose, cognitively impaired, or reliant on life-sustaining medical equipment. Evacuation efforts of these MFP are often exacerbated by the need to transport not only residents but also medical records, medications, medical equipment, and other essentials. Even within the same geographic area, different concentrations of MFP may require vastly different evacuation resources, but it is certain that they will require intentional planning and additional resources beyond the non-MFP citizens (FHCA 2008).

The issue of MFP evacuation is exacerbated in the context of individuals who are normally self-sufficient but require specialized equipment and medical supplies during disasters (Risoe 2013). Van Willigen (2002) and Ng (2015) were the only two studies at the time of this research that investigated the MFP living among non-MFP persons in residential urban areas rather than focusing only on the MFP that live in group-living institution settings amongst the evacuation literature. The study of MFP living within a standard residential setting is relevant to understand and plan for the impact on the entire community to accommodate the aid required by the MFP during phased evacuations (Wilson 2015). This "potentially vulnerable population" continues to be understudied despite a demonstrated need for further research (Ng 2015, Zhao 2010). While the exact number of MFP is not known, the disabled population constitutes a substantial part (12.1%) of the US population (USCB 2010), supplying a lower bound estimate to justify the need for this study.

Spatial Accessibility Analysis of Disaster Evacuation

The use of a GIS in spatial analysis is the key "to possible risk reduction by furnishing disaster managers with access to information and methodologies that may help them in analyzing, evaluating, and mapping hazard models" (Abdalla 2016). There has been a technical barrier often experienced by EMs with GIS analysis in evacuation planning, limitations ranging from insufficient GIS experience to inability to access data needed for advanced analysis (Zergera 2003). This challenge is compounded by the evolving nature of geospatial technologies, which require ongoing training and adaptation, potentially hindering their full utilization in emergency management contexts. Moreover, the integration of GIS with other technological tools, such as real-time data collection systems and predictive modeling software, remains an underexplored area that could greatly enhance evacuation planning. Addressing these barriers is essential, as the effective use of GIS in evacuation planning can significantly improve the accuracy and efficiency of emergency responses, particularly in densely populated urban environments.

Among the literature of evacuation planning there is also a gap in the consideration of MFP and their needs in mobility aid from residential areas during an urban evacuation (Han 2001; Urbina 2003; Yuan 2009). Yuan and Han (2009) conducted a study that began to address this gap by exploring a range of "measures of effectiveness" (MOE) for evacuation planning (e.g., average evacuee travel time, reducing delays, and temporal-spatial-based exposure to risks). Studies focused on optimizing evacuations based on a single measurement, especially solely on an evacuation travel time-based MOE, or a few poorly chosen MOE, do not always create the best evacuation plans (Yuan 2009). The literature suggests that efficient spatial accessibility of evacuation plans is best guided by combining MOE that include space-based risk evaluation, optimal destination (e.g., shelters) assignment, population density, and evacuee travel time along existing routes (e.g., Cova 1997; Mitchell 2006; Yuan 2009; Ng 2015; Liu 2016; Unal 2016).

The geographic disparity of vulnerability across an impact area may exacerbate accessibility to effective evacuation in areas of inadequate resources (Hsu 2014; Liu 2016). As hurricanes can bring an unpredictable variation of damage across a wide space, the physical proximity of a resident to the disaster impact location (e.g., coastline) cannot be the sole factor in analysis of vulnerability (Hsu 2014). The spatial analysis of various impact factors as an indicator of physical risk is well documented in the literature (Cova 1997; Thywissen 2006; Chen 2008; Moreri 2008; Liu 2016; and Abdalla 2016). Often wide-spread impactful events, such as Hurricane Harvey, define a clear need for EMs to reassess potential demand for evacuation across the entire area based on factors beyond simple physical proximity to coastline (Vogt 1992; Liu 2016).

Accessibility to emergency services facilities (e.g., police stations, fire stations, and emergency medical services) and allocation of evacuation resources are critical spatial elements of accessibility analysis (Wolshon 2005; Parr 2012; Abdalla 2016). Two areas with the same residential density and proximity to coastal flooding from the same disaster could potentially have differing population densities or transportation network connectivity that affect evacuation effectiveness (Yuan 2009; Hsu 2014). Hsu (2014) outlined a Risk-based Spatial Zone Determination Problem as a real-time alternative to a potential physical threat criteria-based method for phased evacuations. This study will build upon the dialogue set up by Hsu (2014) to enhance evacuation planning by considering "the population currently with the highest evacuation risk" while working within a reproducible spatial accessibility framework using common datasets available to most EMs (Liu 2016; Abdalla 2016).

Reflections on Literature Review

Existing studies address systematic phased evacuations, medically fragile populations access to resources during evacuations, and the use of spatial accessibility analysis to build a broad picture of resource accessibility across the area. The analysis works to fill gaps in these bodies of literature, such as extending phased evacuations beyond just proximity to coastline in the Zone-based scheme (Wilmont and Meduri, 2005), and through the inclusion of MFP considerations in evacuation analysis. Investigating the differences in the spatial accessibility of evacuation resources justifies the need for a method to further prioritize areas within larger evacuation zones and outlines a methodological framework that local EMs can approach for use in other areas with similar criteria.

The nature of the emergency event, the availability of response resources, and the geographical scope of an incident's impact are all crucial considerations in evacuation planning. An MFP's location within a pre-determined evacuation zone, the concentration of other MFP within that zone, and their accessibility to adequate evacuation support resources all significantly influence their vulnerability to the outlined evacuation risk factors in this study. The existing literature reviewed in highlighted the extensive planning and consideration required to ensure the safety and well-being of MFP during complex emergencies, emphasizing the need for highly refined spatial analysis to execute an orderly and comprehensive phased evacuation.

III. METHODOLOGY

Study Area

The study area of this research starts with the Houston-Galveston Area Council that acts as a regional support organization for all county and municipal jurisdictions across its 13-county area. The H-GA Council is one of 24 regional councils of governments (COG) across the State of Texas. In Texas, a region's COG facilitates collaboration and representation across their area on several issues, including economic development, emergency communications, disaster recovery, transportation planning, and health and human services. The H-GA Council was founded in 1966 and has been fostering a coordinated effort across its over 12,500 square mile service area since (H-GAC 2021).

The H-GA is situated along the central Gulf Coast, encompassing two significant counties within the state. The first, Harris County, is the most populus county in Texas with over four million people and the fourth most populated city in the United States, the City of Houston (City of Houston 2021). The second, Galveston County, contains the coastal city of Galveston and a significant portion of the populated gulf coastline of Texas, adding over 350,000 residents alone to the H-GA (USCB 2022). The geography of the H-GA is defined prominently by twenty-two bayou systems and waterways running through Houston into Galveston County and eventually the Gulf of Mexico (Simon 2018). The study area is also defined by the Galveston Bay, the estuary fed body of water separating the mainland of Texas from the long narrow coastal barrier island of Galveston Island that is often subject to significant storm surge flood inundation during tropical weather incidents (Ricklis 2009).

Within the two highlighted counties of the H-GA for this study, Harris County contains 133 zip codes, joined by another 17 zip codes in Galveston County, totaling 150 zip codes across the study area (USCB 2010). Between the two counties, there are four pre-determined evacuation Zip-Zones of adjacent zip codes. During a qualifying incident, these Zip-Zones are issued evacuation orders as a larger group of zip codes in a phased manner. The Coastal Zip-Zone is nearest the Gulf of Mexico, followed by Zip-Zones A, B, and C, increasing in distance from the coast (Figure 2). Some zip codes are subdivided by the established H-GA Council in the H-GA Zip-Zones map by either County or Zip-Zone boundaries and remained as separate zip code areas in this study to support continuity within public messaging.

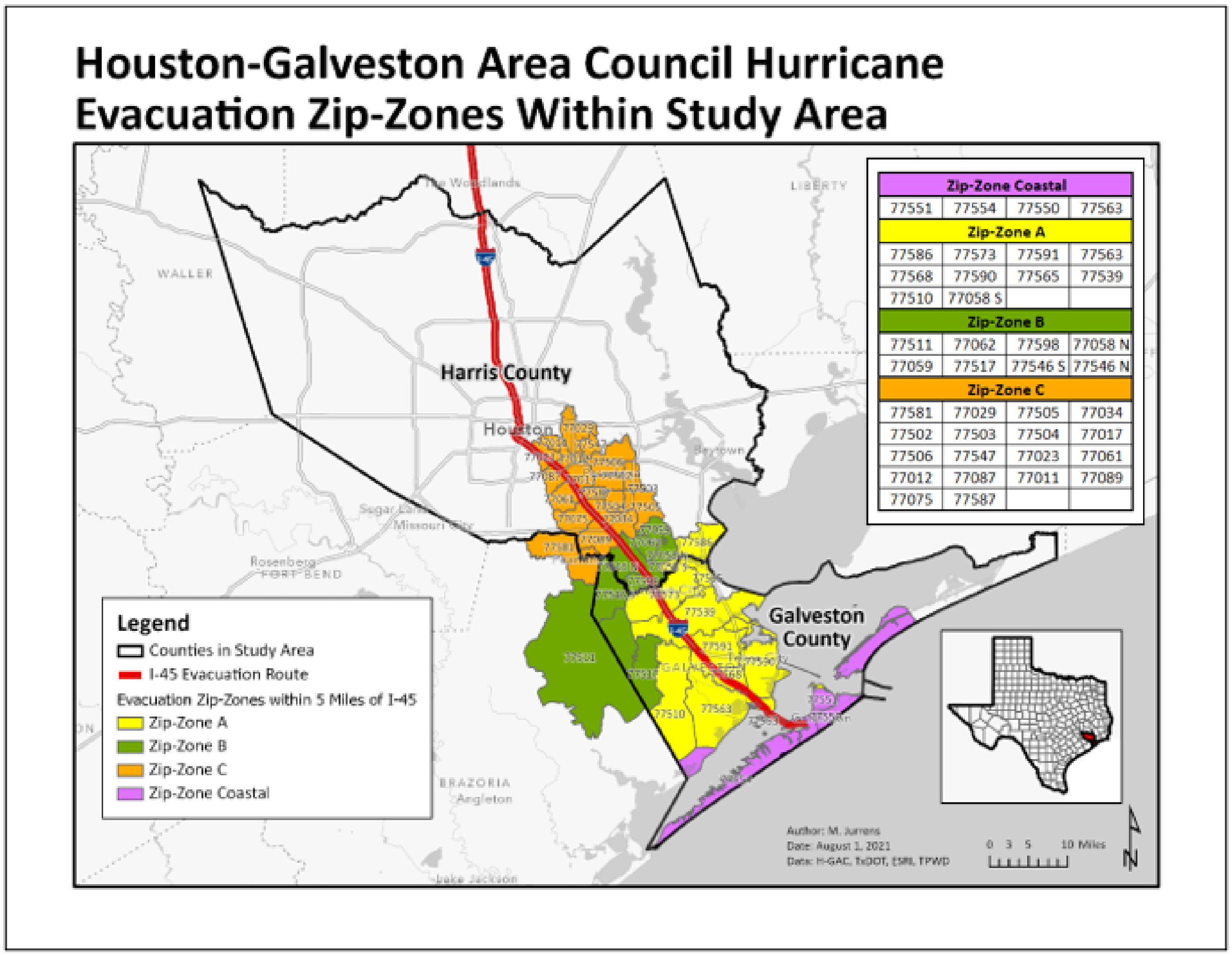

Figure 2: Hurricane evacuation Zip-Zones within study area (Ruiz 2021)

Of the 53 zip codes within the 4 Zip-Zones across the H-GA, 39 zip code areas are within 5 miles of the I-45 evacuation route running from Galveston Island through the heart of Houston, defining the extent of this study area. While there are alternate evacuation routes that serviced areas alongside the city centers, this stretch of I-45 remains the main evacuation route for residents living in both Houston and Galveston (Gage 2021). Due to the introduction of phased evacuation Zip-Zones in early 2008, voluntary evacuation times along the 50-mile stretch between Galveston and Houston during Hurricane Harvey were somewhere between 5 and 7 hours (Mason 2017). The same stretch of I-45 during Hurricane Rita in 2005 saw simultaneous and widespread evacuation orders across the study area, with travel times as slow as 5 miles per hour in some sections, taking nearly 14 hours to travel the entire distance (Hardy 2017).

Spatial Accessibility Analysis

SAA consists of a logical method that can be applied to test the degree of access to defined resources by a study subject across a given area (Mokgalaka 2015) and to assess travel time to a type of destination within the study area (Antwi 2020). In this study, SAA was used as an established methodological framework to analyze variations in evacuation times required for zip codes within each Zip-Zone along the I-45 evacuation route in the H-GA (Unal 2016). An index of defined evacuation resource accessibility factors was outlined to effectively compare the zip codes across each of the four Zip-Zones within the study area.

An Evacuation Vulnerability Index (EVI) was devised for this study to create a standard on which to evaluate the spatial accessibility to the established impactful factors of each zip code systematically with considerations to MFP. All zip codes within each of the Zip-Zones of the study area were individually assessed on 1) the ratio of the total evacuation resources (fire, police, and EMS stations) located within the zip code (Figure 3) to total number of MFP, 2) the percentage of total population within the zip code (Figure 4) that are registered MFP to STEAR, and 3) the travel time from the mean geographic center of MFP population (Figure 5) to the nearest shelter located beyond the Zip-Zone boundaries, along the existing road network during evacuation conditions.

Along with inputs from academic and government stakeholders, the H-GA Council conducted a social vulnerability and natural hazards study to establish the current Zip-Zones. The 4 Zip-Zone designations prioritize minimizing the number of zones in the interest of streamlining evacuation messaging to the public during an active incident and focus mainly on the order of impact from storm surge due to direct proximity to the coastline (Fink 2023). All zip codes within a single Zip-Zone were then given a designation of equal risk from coastal storm surge flooding (Gage 2021). The SAA methods, as utilized in this study and outlined in the following sections, looked beyond an area's proximity to the coastal storm surge hazard, considering the accessibility of evacuation resources for the area's citizens most known to be highly vulnerable during an evacuation, the MFP. A multi-factor spatial accessibility analysis approach offered a nuanced and comprehensive perspective on emergency evacuation planning in an urban setting.

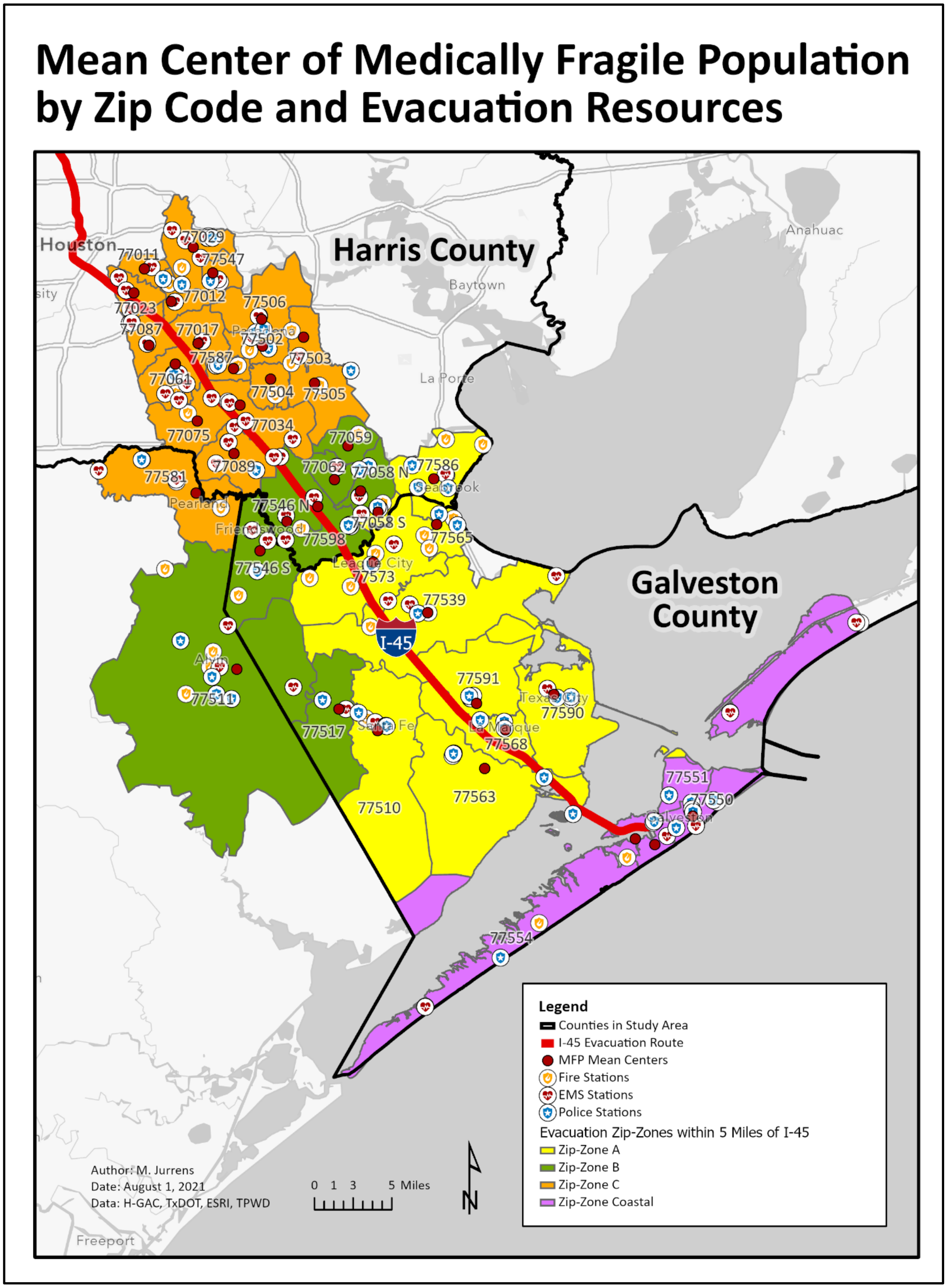

Figure 3: Mean Center of Medically Fragile Population by Zip Code and Evacuation Resources

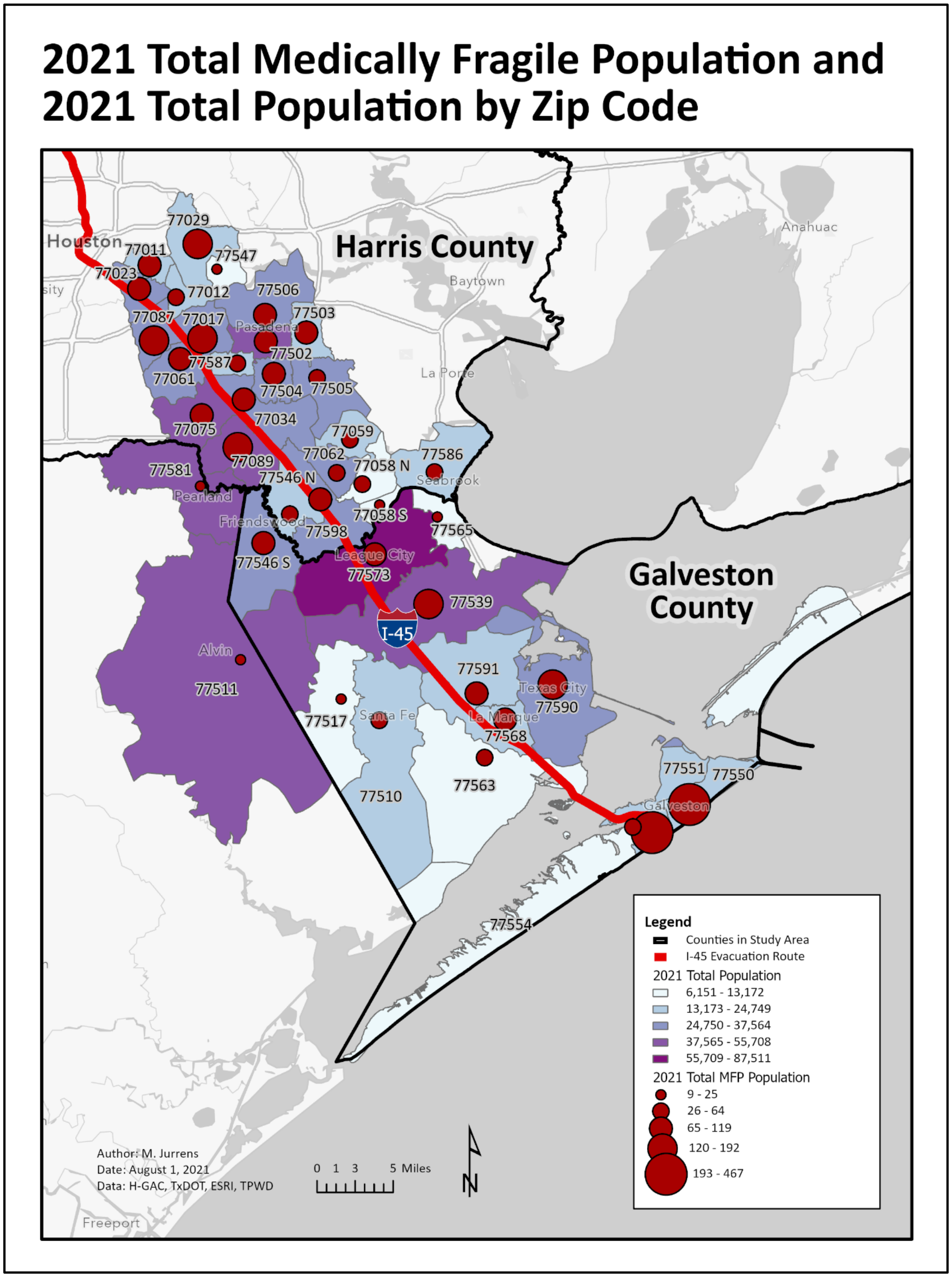

Figure 4: 2021 Total Medically Fragile Population and 2021 Total Population by Zip Cod

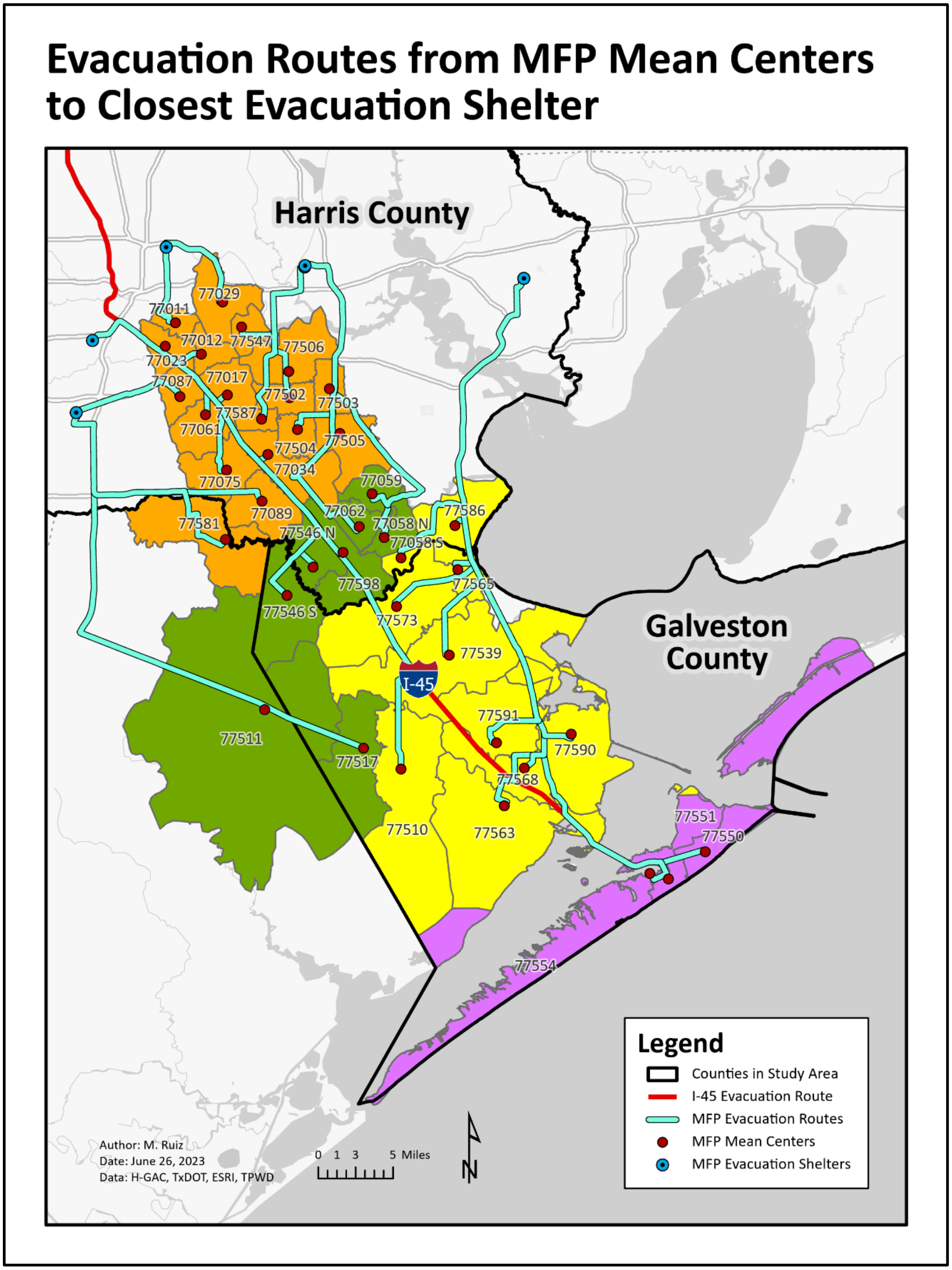

Figure 5: Evacuation Routes from MFP Mean Centers to Closest Evacuation Shelter

The MFP residents hold a prominent role in the EVI criteria due to their intrinsic strain to access needed resources during an evacuation (Littman 2006). Evacuation resources are used to help transport MFP from their home to the nearest shelter, which creates added traffic and travel time along a road network within that evacuation area (Ng 2015). This study defines MFP as those persons that have registered in STEAR, the State of Texas Evacuation Assistance Request assistance program run by TDEM developed specifically to capture information on Texas residents that have medical needs and require more resources to access effective evacuation. The STEAR form is a qualitative approach to define MFP based on phone interviews after the Hurricane Irene evacuation (Ng 2015).

Data Preparation

Data collection and processing is the beginning of GIS analysis. One of the goals in this research was to streamline a method using datasets easily accessible to all governmental EMs across Texas at any level of jurisdiction. This approach ensures that other departments of emergency management can reproduce this GIS technique to create a potentially lifesaving evacuation plan without the need for advanced technical staff. Many national and state level organizations publish GIS datasets for basic political borders and emergency facilities (e.g., shelters, police stations, fire stations, and EMS stations) online and TDEM coordinates the release of other confidential datasets to local emergency management officials (e.g., STEAR registrant locations). The following data was collected and analyzed for this study (Table 1):

Table 1: Datasets for GIS-Based Spatial Accessibility Analysis

Dataset	SAA Utilization	Source
Harris and Galveston County Boundaries	• Study Area	Texas National Resources Information System
Zip Codes	• Sub-regions within Study Area	US Census Bureau
Harris and Galveston County Road Networks	• Existing Road Network for Network Analysis	Texas Department of Transportation
Houston-Galveston Area Hurricane Evacuation Zip-Zones	• Study Area	Houston-Galveston Area Council
Houston-Galveston Area Evacuation Routes	• Evacuation Routes for Network Analysis	Houston-Galveston Area Council
Fire Stations	• Ratio to MFP	US Department of Homeland Security
Police Stations	• Ratio to MFP	US Department of Homeland Security
EMS Stations	• Ratio to MFP	US Department of Homeland Security
Shelters Utilized During Hurricane Harvey	• Destinations for MFP in Hurricane Evacuation Scenarios	Texas Division of Emergency Management
2021 Population Estimates	• Total Population	ESRI
STEAR Registrants	• Total Percentage of Population that is MFP • Origins for MFP mean center in Network Analysis	Texas Division of Emergency Management
Drive Time	• Drive Time from MFP Mean Center to Nearest Evacuation Shelter	ESRI Traffic Network Analyst

Analysis Approach in GIS

The methodology of the SAA framework utilized in this study is as follows:

1. Establish the study area
    a. Find the zip codes that are either partially or fully within the H-GA Zip-Zones of both Harris and Galveston Counties
    b. Eliminate the zip codes not found within 5 miles of I-45
2. Evaluate EVI factors for each zip code in the study area
    a. Calculate percentage of MFP (*MFP %*) as MFP residents / total population
    b. Calculate the ratio of total evacuation resources (considered to be police, fire, and EMS stations) per MFP (*Resource/MFP*)
    c. Determine the travel time between MFP to its nearest shelter beyond the boundaries of the Zip-Zone evacuation areas ($Travel\ Time_{MFP}$)
        i. Derive the geographical mean center of all MFP locations within each zip code
        ii. Locate the nearest local hurricane evacuation shelter to each MFP Mean Center under the following constraints:
            - Configure the destination points as the Shelters outside of the evacuation zones
            - Configure the origin points as the MFP Mean Centers of each zip code being evaluated
            - Set the road network to estimate the driving conditions during an evacuation scenario by setting max speeds of 30 mph (Ballard 2008)

2. Calculate EVI for each zip code

    d. The inverse of the three variables created in the previous step will be normalized by a min-max stretch to a 0-1 scale and equally weighted to sum up to an EVI ranging from 0-3 where:

$$\text{MFP EVI} = ((1\text{-Score}_{\text{MFP\%}}) + (1\text{-Score}_{\text{Resources/MFP}}) + (1\text{-Score}_{\text{Travel Time MFP}})) \quad (1)$$

    e. The Min-Max scale for both Score $_{\text{MFP\%}}$ and Score $_{\text{Travel Time MFP}}$ are reverse scale. The more MFP per total people and the longer the distance to the nearest shelter, the greater impact on resource accessibility:

$$\text{Score}_{\text{MFP\% or Travel Time MFP}} = (X_{max} - X) / (X_{max} - X_{min}) \quad (2)$$

    f. The Min-Max scale for Score $_{\text{Resources/MFP}}$ is calculated in a way that the greater the evacuation resource facilities per MFP available, the less they will be affected:

$$\text{Score}_{\text{Resources/MFP}} = (X - X_{min}) / (X_{max} - X_{min}) \quad (3)$$

3. Classify the zip codes within each Zip-Zone by MFP EVI

    a. Utilize Natural Breaks to classify the zip codes within each Zip-Zone of the study area into 3 priority levels

4. Examine the null hypothesis of the EVI factors *MFP %, Resource/MFP,* and *Travel Time* $_{MFP}$ using a Chi-Square test of Independence determining if the factors are no different from what would be expected for the MFP population of each zip code within the Zip-Zones:

    a. The null hypothesis (H_0) states that there is no significant association between the SAA factors (MFP %, Resource/MFP, and Travel Time $_{\text{MFP}}$) and existing classification (all zip codes within each Zip-Zone)

b. Reject the null hypothesis in favor of the alternative hypothesis if the test statistic is greater than the critical value, suggesting that there is a significant association or relationship between the factors and the categories

c. Accept the null hypothesis if the test statistic is not greater than the critical value.

IV. RESULTS

Establish Study Area

Zip Code Identification

A total of 58 zip code areas were found to be either partially or fully within the 4 H-GA Zip-Zones throughout Harris and Galveston Counties. After filtering for those zip codes situated within 5 miles of I-45, 40 individual zip codes areas were selected for further analysis (Figure 2). They were distributed between the Zip-Zones as follows:

- Zip-Zone Coastal (4): 77550, 77551, 77554, 77563
- Zip-Zone A (10): 77510, 77539, 77563, 77565, 77568, 77573, 77586, 77590, 77591, 77058 S
- Zip-Zone B (8): 77059, 77062, 77511, 77517, 77598, 77058 N, 77546 N, 77546 S
- Zip-Zone C (18): 77011, 77012, 77017, 77023, 77029, 77034, 77061, 77075, 77087, 77089, 77502, 77503, 77504, 77505, 77506, 77547, 77581, 77587

Evaluation of EVI Factors

MFP Distribution

The average MFP% across the evaluated zip codes was 0.40%, with a range from 0.02% in zip code 77511 of Zip-Zone B up to 1.89% in zip code 77550 of Zip-Zone Coastal (Table 2 and Figure 4). The percentage of MFP between the Zip-Zones was as follows:

- Zip-Zone Coastal: 4.49%
- Zip-Zone A: 3.72%
- Zip-Zone B: 2.00%
- Zip-Zone C: 5.76%

Table 2: Zip Code Evacuation Vulnerability Index Results

Zip-Zone	Zip Code	Total Pop	Total MFP	MFP/Pop	Score (MFP%)	1-Score (MFP%)	Evacuation Resources	Evacuation Resources/MFP	Score (Resources/MFP)	1-Score (Resources/MFP)	Travel Time (in minutes)	Score (Travel Time MFP)	1-Score (Travel Time MFP)	EVI
Zip-Zone Coastal	77550	24749	467	1.89%	0.0000	1.0000	8	0.0171	0.0044	0.9956	91	0.0000	1.0000	2.9956
Zip-Zone Coastal	77551	20961	327	1.56%	0.2147	0.7853	5	0.0153	0.0000	1.0000	87	0.2750	0.7250	2.5103
Zip-Zone Coastal	77554	9890	36	0.36%	1.0000	0.0000	11	0.3056	0.7024	0.2976	90	0.0977	0.9023	1.1999
Zip-Zone Coastal	77563	1025	7	0.68%	0.7906	0.2094	3	0.4286	1.0000	0.0000	77	1.0000	0.0000	0.2094
Zip-Zone A	77510	17442	46	0.26%	0.7347	0.2653	5	0.1087	0.4588	0.5412	72	0.1263	0.8737	1.6802
Zip-Zone A	77539	46695	159	0.34%	0.5714	0.4286	8	0.0503	0.1126	0.8874	53	0.5882	0.4118	1.7278
Zip-Zone A	77563	11479	53	0.46%	0.3265	0.6735	8	0.1509	0.7090	0.2910	77	0.0000	1.0000	1.9645
Zip-Zone A	77565	13172	17	0.13%	1.0000	0.0000	3	0.1765	0.8607	0.1393	42	0.8458	0.1542	0.2935
Zip-Zone A	77568	16529	89	0.54%	0.1633	0.8367	5	0.0562	0.1476	0.8524	67	0.2354	0.7646	2.4537
Zip-Zone A	77573	87511	112	0.13%	1.0000	0.0000	9	0.0804	0.2910	0.7090	52	0.6091	0.3909	1.0999
Zip-Zone A	77586	24162	64	0.26%	0.7347	0.2653	10	0.1563	0.7410	0.2590	36	1.0000	0.0000	0.5243
Zip-Zone A	77590	31850	192	0.60%	0.0408	0.9592	6	0.0313	0.0000	1.0000	65	0.2915	0.7085	2.6677
Zip-Zone A	77591	15752	97	0.62%	0.0000	1.0000	4	0.0412	0.0587	0.9413	69	0.1919	0.8081	2.7495
Zip-Zone A	77058 S	6564	25	0.38%	0.4898	0.5102	5	0.2000	1.0000	0.0000	45	0.7838	0.2162	0.7264
Zip-Zone B	77059	17829	39	0.22%	0.5918	0.4082	2	0.0513	0.0115	0.9885	45	0.9167	0.0833	1.4800
Zip-Zone B	77062	26484	61	0.23%	0.5714	0.4286	3	0.0492	0.0099	0.9901	44	1.0000	0.0000	1.4187
Zip-Zone B	77511	54300	9	0.02%	1.0000	0.0000	12	1.3333	1.0000	0.0000	54	0.5248	0.4752	0.4752
Zip-Zone B	77517	6151	12	0.20%	0.6327	0.3673	3	0.2500	0.1647	0.8353	66	0.0000	1.0000	2.2026
Zip-Zone B	77598	31151	88	0.28%	0.4694	0.5306	9	0.1023	0.0508	0.9492	44	0.9823	0.0177	1.4975
Zip-Zone B	77058 N	10777	55	0.51%	0.0000	1.0000	2	0.0364	0.0000	1.0000	46	0.8988	0.1012	2.1012
Zip-Zone B	77546 N	18687	51	0.27%	0.4898	0.5102	4	0.0784	0.0324	0.9676	47	0.8410	0.1590	1.6368
Zip-Zone B	77546 S	29999	82	0.27%	0.4898	0.5102	5	0.0610	0.0190	0.9810	50	0.7245	0.2755	1.7667
Zip-Zone C	77011	20983	83	0.40%	0.4706	0.5294	2	0.0241	0.0499	0.9501	13	0.9798	0.0202	1.4997
Zip-Zone C	77012	21101	50	0.24%	0.7059	0.2941	4	0.0800	0.2424	0.7576	17	0.8069	0.1931	1.2448
Zip-Zone C	77017	33407	131	0.39%	0.4853	0.5147	2	0.0153	0.0196	0.9804	22	0.5924	0.4076	1.9027
Zip-Zone C	77023	29560	100	0.34%	0.5588	0.4412	6	0.0600	0.1736	0.8264	13	0.9698	0.0302	1.2979
Zip-Zone C	77029	17810	128	0.72%	0.0000	1.0000	11	0.0859	0.2627	0.7373	12	1.0000	0.0000	1.7373
Zip-Zone C	77034	34366	106	0.31%	0.6029	0.3971	4	0.0377	0.0968	0.9032	29	0.2596	0.7404	2.0407
Zip-Zone C	77061	25608	86	0.34%	0.5588	0.4412	8	0.0930	0.2872	0.7128	22	0.5884	0.4116	1.5655
Zip-Zone C	77075	45296	112	0.25%	0.6912	0.3088	2	0.0179	0.0286	0.9714	30	0.2396	0.7604	2.0406
Zip-Zone C	77087	36924	139	0.38%	0.5000	0.5000	4	0.0288	0.0661	0.9339	16	0.8127	0.1873	1.6212
Zip-Zone C	77089	55708	142	0.25%	0.6912	0.3088	6	0.0423	0.1126	0.8874	35	0.0387	0.9613	2.1575
Zip-Zone C	77502	39907	119	0.30%	0.6176	0.3824	4	0.0336	0.0826	0.9174	23	0.5507	0.4493	1.7490
Zip-Zone C	77503	23788	95	0.40%	0.4706	0.5294	2	0.0211	0.0396	0.9604	21	0.6063	0.3937	1.8835
Zip-Zone C	77504	25612	104	0.41%	0.4559	0.5441	1	0.0096	0.0000	1.0000	30	0.2161	0.7839	2.3281
Zip-Zone C	77505	26071	60	0.23%	0.7206	0.2794	3	0.0500	0.1391	0.8609	25	0.4447	0.5553	1.6956
Zip-Zone C	77506	37564	118	0.31%	0.6029	0.3971	3	0.0254	0.0544	0.9456	19	0.7195	0.2805	1.6232
Zip-Zone C	77547	9762	22	0.23%	0.7206	0.2794	4	0.1818	0.5930	0.4070	18	0.7427	0.2573	0.9438
Zip-Zone C	77581	51205	20	0.04%	1.0000	0.0000	6	0.3000	1.0000	0.0000	35	0.0000	1.0000	1.0000
Zip-Zone C	77587	17417	38	0.22%	0.7353	0.2647	4	0.1053	0.3295	0.6705	26	0.4129	0.5871	1.5223

Resource Accessibility

There were a total of 206 fire, police, and EMS stations considered to be evacuation resources distributed across the determined study area that are positioned to support the 3,741 Total MFP citizens. The average number of evacuation resources per zip code was 5.15 stations while the average Resource to Total MFP ratio per zip code was 0.1248. The highest accessibility was in zip code 77511 of Zip-Zone B at 1.3333 stations per MFP, whereas zip code 77504 of Zip-Zone C demonstrated the most limited access to resources per MFP at 0.0096 stations (See Table 2 and Figure 3).

Travel Time to Shelters

After the network analysis, a total of 5 different large scale congregate shelters utilized during Hurricane Harvey were determined to represent the nearest destination shelters to the MFP Mean Centers across the study's 40 zip codes (Table 3 and Figure 5):

- Wayne Gray Sports Complex, 5115 E Rd, Baytown, TX 77521
- First Presbyterian Church of Houston, 5300 Main St, Houston, TX 77004
- North Shore Ninth Grade Campus, 13501 Hollypark Dr, Houston, TX 77015
- Bayou City Events Center, 9401 Knight Rd, Houston, TX 77045
- McCrane-Kashmere Garden Neighborhood Library, 5411 Pardee St, Houston, TX 77026

In this study's examination of travel times for MFPs from their mean center points within each zip code to the nearest qualifying shelters, some intriguing variations were found. On average, it took about 43 minutes for the trips from MFP Mean Centers to the shelters. However, this average masks quite a bit of diversity in the travel times across the region. The MFPs in the 77550 zip code of the Coastal Zip-Zone faced the longest travel times, requiring nearly an hour and a half to travel the 44 miles to Wayne Gray Sports Complex. In sharp contrast, MFPs in the 77029 zip code of Zip-Zone C had a much quicker trip of just over 10 minutes to travel the 6 miles to reach the McCrane-Kashmere Garden Neighborhood Library.

These findings highlight significant disparities in the current evacuation accommodations. The longest travel time we observed was 91 minutes, and the shortest was just 12 minutes. This range indicates that some MFPs, especially those in more remote, less accessible, or more vulnerable areas, might be at a disadvantage in a time-sensitive evacuation scenario. Such insights emphasize the importance of revisiting evacuation strategies. It's crucial that geographic and infrastructural differences are considered to ensure that all MFPs, regardless of their zip code, have equitable access to swift evacuation. This approach is not only about balancing averages; it's about ensuring that each individual, despite vulnerability status, has a fair chance to reach safety promptly with the resources they might require to do so.

Table 3: Travel Time from MFP Mean Centers to Closest Evacuation Shelter

Zip-Zone	Zip Code	Closest Evacuation Shelter	Travel Time (min)	Total Miles
Zip-Zone Coastal	77550	Wayne Gray Sports Complex	91	43.9523
Zip-Zone Coastal	77551	Wayne Gray Sports Complex	87	42.2629
Zip-Zone Coastal	77554	Wayne Gray Sports Complex	90	43.0634
Zip-Zone Coastal	77563	Wayne Gray Sports Complex	77	36.6674
Zip-Zone A	77510	First Presbyterian Church of Houston	72	35.3059
Zip-Zone A	77539	Wayne Gray Sports Complex	53	25.3110
Zip-Zone A	77563	Wayne Gray Sports Complex	77	36.6674
Zip-Zone A	77565	Wayne Gray Sports Complex	42	20.0039
Zip-Zone A	77568	Wayne Gray Sports Complex	67	32.2907
Zip-Zone A	77573	Wayne Gray Sports Complex	52	24.4056
Zip-Zone A	77586	Wayne Gray Sports Complex	36	16.9965
Zip-Zone A	77590	Wayne Gray Sports Complex	65	31.3486
Zip-Zone A	77591	Wayne Gray Sports Complex	69	32.6781
Zip-Zone A	77058 S	Wayne Gray Sports Complex	45	21.3541
Zip-Zone B	77059	North Shore Ninth Grade Campus	45	20.7248
Zip-Zone B	77062	North Shore Ninth Grade Campus	44	20.8985
Zip-Zone B	77511	Bayou City Events Center	54	26.2572
Zip-Zone B	77517	Bayou City Events Center	66	32.2300
Zip-Zone B	77598	First Presbyterian Church of Houston	44	21.1664
Zip-Zone B	77058 N	North Shore Ninth Grade Campus	46	21.4000
Zip-Zone B	77546 N	First Presbyterian Church of Houston	47	22.2299
Zip-Zone B	77546 S	First Presbyterian Church of Houston	50	24.3911
Zip-Zone C	77011	McCrane-Kashmere Garden Neighborhood Library	13	5.3494
Zip-Zone C	77012	First Presbyterian Church of Houston	17	7.8502
Zip-Zone C	77017	First Presbyterian Church of Houston	22	10.3464
Zip-Zone C	77023	First Presbyterian Church of Houston	13	5.6701
Zip-Zone C	77029	McCrane-Kashmere Garden Neighborhood Library	12	5.9617
Zip-Zone C	77034	First Presbyterian Church of Houston	29	14.3439
Zip-Zone C	77061	First Presbyterian Church of Houston	22	10.1710
Zip-Zone C	77075	First Presbyterian Church of Houston	30	14.1776
Zip-Zone C	77087	Bayou City Events Center	16	6.9502
Zip-Zone C	77089	Bayou City Events Center	35	16.3582
Zip-Zone C	77502	North Shore Ninth Grade Campus	23	9.8357
Zip-Zone C	77503	North Shore Ninth Grade Campus	21	9.5099
Zip-Zone C	77504	North Shore Ninth Grade Campus	30	13.2612
Zip-Zone C	77505	North Shore Ninth Grade Campus	25	11.9068
Zip-Zone C	77506	North Shore Ninth Grade Campus	19	8.3721
Zip-Zone C	77547	North Shore Ninth Grade Campus	18	7.9968
Zip-Zone C	77581	Bayou City Events Center	35	16.6130
Zip-Zone C	77587	North Shore Ninth Grade Campus	26	11.3122

Research Question 1:

Are there any significant differences in MFP%, resource accessibility and travel time across the designated Zip-Zones and hypothetical equal distribution of MFP within the H-GA?

Focusing on the needs of the MFPs, the citizen's readiness for evacuation across the Houston-Galveston region varied significantly across Zip-Zones based on the vulnerability factors established in the literature review: MFP concentration, availability of essential support resources, and duration required to reach safe shelters. The statistical analysis utilized in this study revealed statistically significant differences in MFP% of population, evacuation resource accessibility, and travel time between MFP mean centers and the nearest adequate shelter across zip codes within each Zip-Zone at the 0.05 level (See Tables 4, 5, and 6). The Chi-Square test of Independence applied to assess the significance of these variations confirmed statistically significant differences at the 0.05 level in all three metrics (See Tables 4, 5, and 6). This implies that the distribution of MFP, resources, and travel time to shelters is uneven across the studied Zip-Zones, highlighting a significant inequity in emergency preparedness and response capabilities.

Particularly, the finding of a significant difference ($P < 0.001$) in MFP%, resource accessibility, and evacuation travel time across all Zip-Zones (Table 7) is a critical revelation. It underscores a systemic issue in the current emergency management framework within the H-GA, whereby certain Zip-Zones are at a disadvantage due to either a higher concentration of MFP, fewer resources, or longer travel times to safety. The acceptance of all research hypotheses and the rejection of the null hypotheses paint a compelling picture. These findings suggest that the existing evacuation plans may not be adequately serving all segments of the population, particularly the MFP.

Table 4: Chi-Square Test for Equality of Proportions for MFP Population %

Observed

Zip Code	Non-MFP	Total MFP	Sums
77550	24282	467	24749
77551	20634	327	20961
77554	9854	36	9890
77563	1018	7	1025
Sums	55788	837	56625

Expected

Zip Code	Non-MFP	Total MFP	Sums
77550	24383.1737	365.8263	24749
77551	20651.1659	309.8341	20961
77554	9743.8114	146.1886	9890
77563	1009.8490	15.1510	1025
Sums	55788	837	56625

Chi-Square Test Statistic

Zip Code	Non-MFP	Total MFP	Sums
77550	0.4198	27.9808	
77551	0.0143	0.9510	
77554	1.2461	83.0539	
77563	0.0658	4.3851	
Sums			118.1168

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	118.1168
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Observed

Zip Code	Non-MFP	Total MFP	Sums
77510	17396	46	17442
77539	46536	159	46695
77563	11426	53	11479
77565	13155	17	13172
77568	16440	89	16529
77573	87399	112	87511
77586	24098	64	24162
77590	31658	192	31850
77591	15655	97	15752
77058 S	6539	25	6564
Sums	270302	854	271156

Expected

Zip Code	Non-MFP	Total MFP	Sums
77510	17387.0668	54.9332	17442
77539	46547.9351	147.0649	46695
77563	11442.8471	36.1529	11479
77565	13130.5151	41.4849	13172
77568	16476.9423	52.0577	16529
77573	87235.3860	275.6140	87511
77586	24085.9023	76.0977	24162
77590	31749.6891	100.3109	31850
77591	15702.3894	49.6106	15752
77058 S	6543.3268	20.6732	6564
Sums	270302	854	271156

Chi-Square Test Statistic

Zip Code	Non-MFP	Total MFP	Sums
77510	0.0046	1.4527	
77539	0.0031	0.9686	
77563	0.0248	7.8507	
77565	0.0457	14.4513	
77568	0.0828	26.2157	
77573	0.3069	97.1269	
77586	0.0061	1.9232	
77590	0.2648	83.8084	
77591	0.1430	45.2677	
77058 S	0.0029	0.9056	
Sums			280.8555

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	280.8555
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Observed

Zip Code	Non-MFP	Total MFP	Sums
77059	17790	39	17829
77062	26423	61	26484
77511	54291	9	54300
77517	6139	12	6151
77598	31063	88	31151
77058 N	10722	55	10777
77546 N	18636	51	18687
77546 S	29917	82	29999
Sums	194981	397	195378

Expected

Zip Code	Non-MFP	Total MFP	Sums
77059	17792.7722	36.2278	17829
77062	26430.1856	53.8144	26484
77511	54189.6647	110.3353	54300
77517	6138.5014	12.4986	6151
77598	31087.7025	63.2975	31151
77058 N	10755.1016	21.8984	10777
77546 N	18649.0288	37.9712	18687
77546 S	29938.0433	60.9567	29999
Sums	194981	397	195378

Chi-Square Test Statistic

Zip Code	Non-MFP	Total MFP	Sums
77059	0.0004	0.2121	
77062	0.0020	0.9595	
77511	0.1895	93.0695	
77517	0.0000	0.0199	
77598	0.0196	9.6404	
77058 N	0.1019	50.0363	
77546 N	0.0091	4.4705	
77546 S	0.0148	7.2645	
Sums			166.0099

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	166.0099
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Observed

Zip Code	Non-MFP	Total MFP	Sums
77011	20900	83	20983
77012	21051	50	21101
77017	33276	131	33407
77023	29460	100	29560
77029	17682	128	17810
77034	34260	106	34366
77061	25522	86	25608
77075	45184	112	45296
77087	36785	139	36924
77089	55566	142	55708
77502	39788	119	39907
77503	23693	95	23788
77504	25508	104	25612
77505	26011	60	26071
77506	37446	118	37564
77547	9740	22	9762
77581	51185	20	51205
77587	17379	38	17417
Sums	550436	1653	552089

Expected

Zip Code	Non-MFP	Total MFP	Sums
77011	20920.1752	62.8248	20983
77012	21037.8219	63.1781	21101
77017	33306.9767	100.0233	33407
77023	29471.4949	88.5051	29560
77029	17756.6754	53.3246	17810
77034	34263.1054	102.8946	34366
77061	25531.3275	76.6725	25608
77075	45160.3800	135.6200	45296
77087	36813.4465	110.5535	36924
77089	55541.2057	166.7943	55708
77502	39787.5152	119.4848	39907
77503	23716.7768	71.2232	23788
77504	25535.3156	76.6844	25612
77505	25992.9413	78.0587	26071
77506	37451.5303	112.4697	37564
77547	9732.7718	29.2282	9762
77581	51051.6880	153.3120	51205
77587	17364.8521	52.1479	17417
Sums	550436	1653	552089

Chi-Square Test Statistic

Zip Code	Non-MFP	Total MFP	Sums
77011	0.0195	6.4789	
77012	0.0083	2.7488	
77017	0.0288	9.5933	
77023	0.0045	1.4929	
77029	0.3140	104.5749	
77034	0.0003	0.0937	
77061	0.0034	1.1347	
77075	0.0124	4.1137	
77087	0.0220	7.3196	
77089	0.0111	3.6857	
77502	0.0000	0.0020	
77503	0.0238	7.9375	
77504	0.0292	9.7300	
77505	0.0125	4.1778	
77506	0.0008	0.2719	
77547	0.0054	1.7876	
77581	0.3481	115.9211	
77587	0.0115	3.8384	
Sums			285.7582

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	285.7582
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

2

Table 5: Chi-Square Test for Independence for Evacuation Resources per MFP

Observed

Zip Code	Stations	Total MFP	Sums
77550	8	467	475
77551	5	327	332
77554	11	36	47
77563	3	7	10
Sums	27	837	864

Expected

Zip Code	Stations	Total MFP	Sums
77550	14.8438	460.1563	475
77551	10.3750	321.6250	332
77554	1.4688	45.5313	47
77563	0.3125	9.6875	10
Sums	27	837	864

Chi-Square Test Statistic

Zip Code	Stations	Total MFP	Sums
77550	3.1553	0.1018	
77551	2.7846	0.0898	
77554	61.8517	1.9952	
77563	23.1125	0.7456	
Sums			93.8366

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	93.8366
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Observed

Zip Code	Stations	Total MFP	Sums
77510	5	46	51
77539	8	159	167
77563	8	53	61
77565	3	17	20
77568	5	89	94
77573	9	112	121
77586	10	64	74
77590	6	192	198
77591	4	97	101
77058 S	5	25	30
Sums	63	854	917

Expected

Zip Code	Stations	Total MFP	Sums
77510	3.5038	47.4962	51
77539	11.4733	155.5267	167
77563	4.1908	56.8092	61
77565	1.3740	18.6260	20
77568	6.4580	87.5420	94
77573	8.3130	112.6870	121
77586	5.0840	68.9160	74
77590	13.6031	184.3969	198
77591	6.9389	94.0611	101
77058 S	2.0611	27.9389	30
Sums	63	854	917

Chi-Square Test Statistic

Zip Code	Stations	Total MFP	Sums
77510	0.6389	0.0471	
77539	1.0515	0.0776	
77563	3.4622	0.2554	
77565	1.9240	0.1419	
77568	0.3292	0.0243	
77573	0.0568	0.0042	
77586	4.7536	0.3507	
77590	4.2495	0.3135	
77591	1.2448	0.0918	
77058 S	4.1907	0.3091	
Sums			23.5169

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	23.5169
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Observed

Zip Code	Stations	Total MFP	Sums
77059	2	39	41
77062	3	61	64
77511	12	9	21
77517	3	12	15
77598	9	88	97
77058 N	2	55	57
77546 N	4	51	55
77546 S	5	82	87
Sums	40	397	437

Expected

Zip Code	Stations	Total MFP	Sums
77059	3.7529	37.2471	41
77062	5.8581	58.1419	64
77511	1.9222	19.0778	21
77517	1.3730	13.6270	15
77598	8.8787	88.1213	97
77058 N	5.2174	51.7826	57
77546 N	5.0343	49.9657	55
77546 S	7.9634	79.0366	87
Sums	40	397	437

Chi-Square Test Statistic

Zip Code	Stations	Total MFP	Sums
77059	0.8187	0.0825	
77062	1.3945	0.1405	
77511	52.8365	5.3236	
77517	1.9280	0.1943	
77598	0.0017	0.0002	
77058 N	1.9841	0.1999	
77546 N	0.2125	0.0214	
77546 S	1.1028	0.1111	
Sums			66.3520

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	66.3520
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Observed

Zip Code	Stations	Total MFP	Sums
77011	2	83	85
77012	4	50	54
77017	2	131	133
77023	6	100	106
77029	11	128	139
77034	4	106	110
77061	8	86	94
77075	2	112	114
77087	4	139	143
77089	6	142	148
77502	4	119	123
77503	2	95	97
77504	1	104	105
77505	3	60	63
77506	3	118	121
77547	4	22	26
77581	6	20	26
77587	4	38	42
Sums	76	1653	1729

Expected

Zip Code	Stations	Total MFP	Sums
77011	3.7363	81.2637	85
77012	2.3736	51.6264	54
77017	5.8462	127.1538	133
77023	4.6593	101.3407	106
77029	6.1099	132.8901	139
77034	4.8352	105.1648	110
77061	4.1319	89.8681	94
77075	5.0110	108.9890	114
77087	6.2857	136.7143	143
77089	6.5055	141.4945	148
77502	5.4066	117.5934	123
77503	4.2637	92.7363	97
77504	4.6154	100.3846	105
77505	2.7692	60.2308	63
77506	5.3187	115.6813	121
77547	1.1429	24.8571	26
77581	1.1429	24.8571	26
77587	1.8462	40.1538	42
Sums	76	1653	1729

Chi-Square Test Statistic

Zip Code	Stations	Total MFP	Sums
77011	0.8069	0.0371	
77012	1.1144	0.0512	
77017	2.5304	0.1163	
77023	0.3858	0.0177	
77029	3.9138	0.1799	
77034	0.1443	0.0066	
77061	3.6212	0.1665	
77075	1.8092	0.0832	
77087	0.8312	0.0382	
77089	0.0393	0.0018	
77502	0.3659	0.0168	
77503	1.2019	0.0553	
77504	2.8321	0.1302	
77505	0.0192	0.0009	
77506	1.0108	0.0465	
77547	7.1429	0.3284	
77581	20.6429	0.9491	
77587	2.5128	0.1155	
Sums			53.2662

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	53.2662
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Table 6: Chi-Square Test for Independence for Travel Time from MFP Mean Center to Nearest Shelter

Observed

Zip Code	Travel Time	Total MFP	Sums
77550	91	467	558
77551	87	327	414
77554	90	36	126
77563	77	7	84
Sums	345	837	1182

Expected

Zip Code	Travel Time	Total MFP	Sums
77550	263.4213	395.1320	558
77551	195.4416	293.1624	414
77554	59.4822	89.2234	126
77563	39.6548	59.4822	84
Sums	345	837	1182

Chi-Square Test Statistic

Zip Code	Travel Time	Total MFP	Sums
77550	112.8577	13.0716	
77551	60.1693	3.9056	
77554	15.6573	31.7487	
77563	35.1701	46.3060	
Sums			318.8863

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	318.8863
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Zip Code	Travel Time	Total MFP	Sums
77510	72	46	118
77539	53	159	212
77563	78	53	131
77565	43	17	60
77568	68	89	157
77573	53	112	165
77586	36	64	100
77590	66	192	258
77591	70	97	167
77058 S	45	25	70
Sums	584	854	1438

Zip Code	Travel Time	Total MFP	Sums
77510	47.9221	70.0779	118
77539	86.0974	125.9026	212
77563	53.2017	77.7983	131
77565	24.3672	35.6328	60
77568	63.7608	93.2392	157
77573	67.0097	97.9903	165
77586	40.6120	59.3880	100
77590	104.7789	153.2211	258
77591	67.8220	99.1780	167
77058 S	28.4284	41.5716	70
Sums	584	854	1438

Zip Code	Travel Time	Total MFP	Sums
77510	12.0976	8.2729	
77539	12.7232	8.7007	
77563	11.5590	7.9045	
77565	14.2479	9.7433	
77568	0.2819	0.1927	
77573	2.9290	2.0030	
77586	0.5237	0.3582	
77590	14.3521	9.8146	
77591	0.0699	0.0478	
77058 S	9.6600	6.6059	
Sums			132.0880

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	132.0880
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Zip Code	Travel Time	Total MFP	Sums
77059	46	39	85
77062	44	61	105
77511	55	9	64
77517	67	12	79
77598	44	88	132
77058 N	46	55	101
77546 N	48	51	99
77546 S	50	82	132
Sums	400	397	797

Zip Code	Travel Time	Total MFP	Sums
77059	42.6600	42.3400	85
77062	52.6976	52.3024	105
77511	32.1205	31.8795	64
77517	39.6487	39.3513	79
77598	66.2484	65.7516	132
77058 N	50.6901	50.3099	101
77546 N	49.6863	49.3137	99
77546 S	66.2484	65.7516	132
Sums	400	397	797

Zip Code	Travel Time	Total MFP	Sums
77059	0.2615	0.2635	
77062	1.4355	1.4464	
77511	16.2972	16.4204	
77517	18.8681	19.0107	
77598	7.4718	7.5282	
77058 N	0.4339	0.4372	
77546 N	0.0572	0.0577	
77546 S	3.9852	4.0153	
Sums			97.9897

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	97.9897
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Zip Code	Travel Time	Total MFP	Sums
77011	13	83	96
77012	17	50	67
77017	22	131	153
77023	13	100	113
77029	13	128	141
77034	30	106	136
77061	22	86	108
77075	30	112	142
77087	17	139	156
77089	35	142	177
77502	23	119	142
77503	22	95	117
77504	31	104	135
77505	26	60	86
77506	19	118	137
77547	19	22	41
77581	36	20	56
77587	26	38	64
Sums	414	1653	2067

Zip Code	Travel Time	Total MFP	Sums
77011	19.2279	76.7721	96
77012	13.4194	53.5806	67
77017	30.6444	122.3556	153
77023	22.6328	90.3672	113
77029	28.2409	112.7591	141
77034	27.2395	108.7605	136
77061	21.6313	86.3687	108
77075	28.4412	113.5588	142
77087	31.2453	124.7547	156
77089	35.4514	141.5486	177
77502	28.4412	113.5588	142
77503	23.4340	93.5660	117
77504	27.0392	107.9608	135
77505	17.2250	68.7750	86
77506	27.4398	109.5602	137
77547	8.2119	32.7881	41
77581	11.2163	44.7837	56
77587	12.8186	51.1814	64
Sums	414	1653	2067

Zip Code	Travel Time	Total MFP	Sums
77011	2.0172	0.5052	
77012	0.9554	0.2393	
77017	2.4385	0.6107	
77023	4.0998	1.0268	
77029	8.2252	2.0600	
77034	0.2798	0.0701	
77061	0.0063	0.0016	
77075	0.0854	0.0214	
77087	6.4947	1.6266	
77089	0.0057	0.0014	
77502	1.0410	0.2607	
77503	0.0877	0.0220	
77504	0.5802	0.1453	
77505	4.4703	1.1196	
77506	2.5959	0.6501	
77547	14.1725	3.5496	
77581	54.7628	13.7156	
77587	13.5545	3.3948	
Sums			144.8937

Degrees of Freedom (df)	1
Significance Level (α)	0.05
Test Statistic (χ^2)	144.8937
CHI SQ p-value	0.0000
Null Hypothesis (H_0)	**Reject**

Table 7: Summary of Chi-square Test of Independence Results

Zip-Zones	**MFP %**	**Resource Accessibility**	**Travel Time to Shelters**
Coastal	118.1168 *	93.8366 *	318.8863 *
A	280.8555 *	23.5169 *	132.0880 *
B	166.0099 *	66.3520 *	97.9897 *
C	285.7582 *	53.2662 *	144.8937 *

** indicates P < 0.001*

<u>Research Question 2:</u>

<u>Which zip codes within each Zip-Zone should be prioritized for MFP in terms of resource allocation for evacuation?</u>

The Evacuation Vulnerability Indices calculated through the methodology outlined in this study ranged from 2.9956 to 0.2094, with both the highest and lowest EVI scores observed in Zip-Zone Coastal (Table 2 and Figure 6). Based on the MFP EVI factors calculated through this study, the zip codes within each Zip-Zone were categorized into three priority levels:

- Zip-Zone Coastal
  - Priority 1 (1): 77550
  - Priority 2 (1): 77551
  - Priority 3 (2): 77554, 77563
- Zip-Zone A
  - Priority 1 (3): 77568, 77590, 77591
  - Priority 2 (3): 77510, 77539, 77563
  - Priority 3 (3): 77565, 77573, 77586, 77058 S
- Zip-Zone B
  - Priority 1 (2): 77517, 77058 N
  - Priority 2 (5): 77059, 77062, 77598, 77546 N, 77546 S
  - Priority 3 (1): 77511
- Zip-Zone C
  - Priority 1 (6): 77017, 77034, 77075, 77089, 77503, 77504
  - Priority 2 (8): 77011, 77029, 77061, 77087, 77502, 77505, 77506, 77587
  - Priority 3 (4): 77012, 77023, 77547, 77581

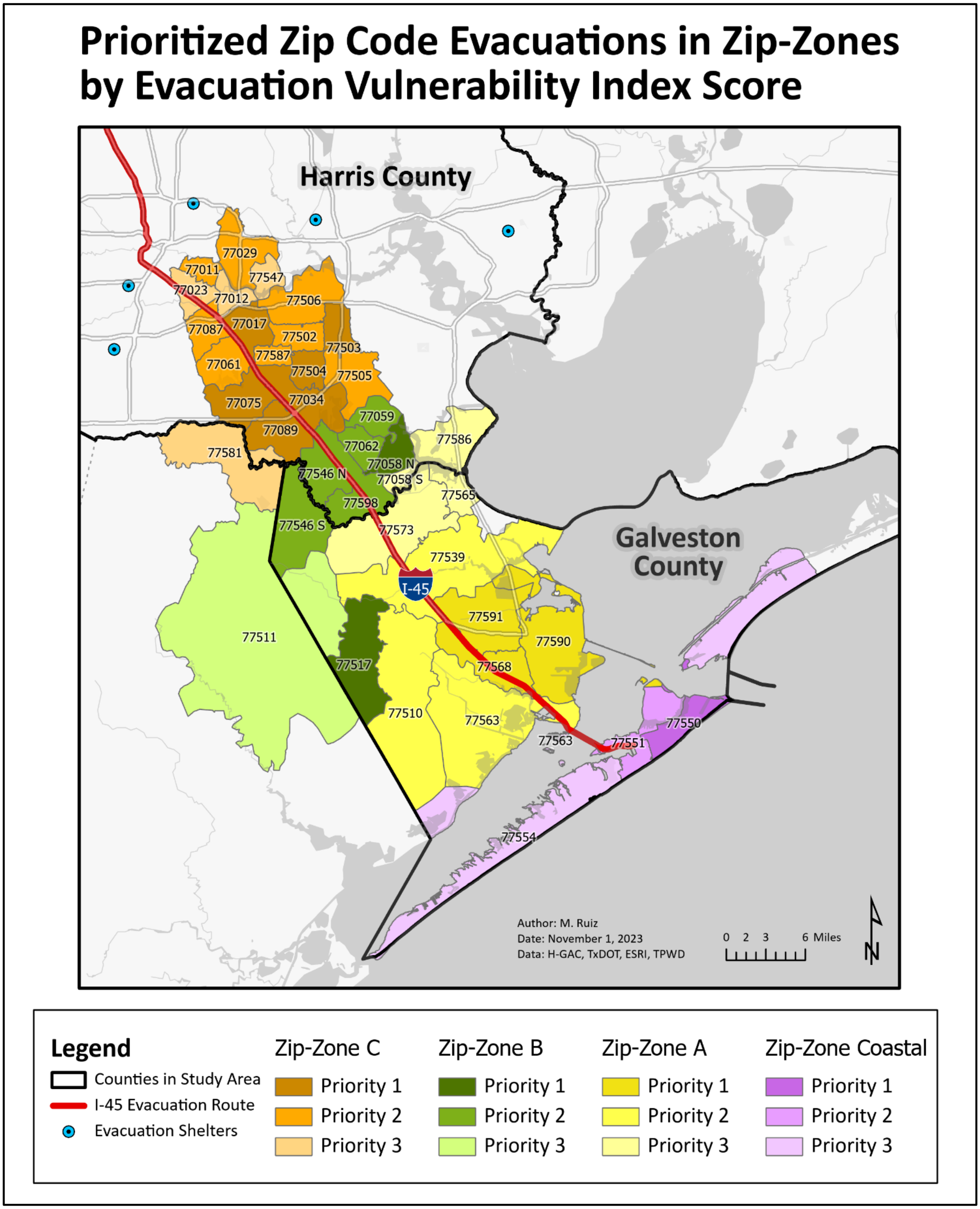

Figure 6: Prioritized Zip Code Evacuations in Zip-Zones by Evacuation Vulnerability Index Score

IV. DISCUSSION

Significant disparities in accessibility of evacuation resources for the Medically Fragile Population have been defined through this research across the Houston-Galveston Area (H-GA) Zip-Zones. The comprehensive Spatial Accessibility Analysis accounted for MFP distribution, availability of evacuation resources, and proximity to available shelters along evacuation routes for MFP within a zip code. The EVI scoring system and Chi-Square Test of Independence highlighted the different vulnerability to risk factors across each Zip-Zone and offered an objective way for emergency management officials to prioritize evacuation efforts based on conditions faced by their MFP. This approach not only provided expanded support for MFP during a phased evacuation but also built upon existing evacuation messaging. A notable gap in relevant literature was addressed by providing a framework that considered the unique challenges faced by MFP during phased evacuations, looking beyond geographic proximity to hazards.

The results of this study not only answered the primary research question of statistical significance, but also highlighted the need for a more nuanced evacuation strategy. While the distribution of the highest priority zip codes within each Zip-Zone did not follow a uniform spatial distribution pattern overall, there were a few characteristics of note. In Zip-Zone C, the majority of Priority 1 zip codes were located near or along I-45 (Figure 6), but that trend was less pronounced for Zip-Zones A, B, and Coastal. Once the density of MFP was also factored in to the EVI, the results highlighted the trend that concentrations of MFP were found near the major roadway arteries. While additional research would be necessary for definitive observations, it was hypothesized that the concentration of MFPs along the primary evacuation routes stems from their need for easy access to outpatient medical services and the strategic location of institutional congregate living facilities in these heavy traffic areas. This observation suggests a nuanced relationship between the location of MFPs and major evacuation routes. However, this pattern's inconsistency across different Zip-Zones suggests the complexity of evacuation dynamics and the need for area-specific evacuation strategies. The variation in actual travel times and the outcomes of the road network simulation highlighted a key insight: emergency evacuation planning cannot rely solely on major thoroughfares like I-45 but should encompass a broader network of routes tailored to the unique evacuation dynamics of each area.

The methodological approach of using the mean center of MFP/total population as a significant factor in the EVI calculation could potentially introduce certain biases. For instance, this method might not accurately represent the complex and uneven spatial distribution of MFPs within larger zip codes. Additionally, the subjective nature of assigning weights to different EVI components necessitates careful calibration to ensure that they genuinely reflect the urgency of needs and resource distribution for MFPs. These methodological nuances underscore the importance of refining and validating the EVI calculation to ensure its robustness and accuracy. Examining the application of the methodology outlined in this study across various jurisdictional settings with differing population densities and geographical characteristics would further provide valuable insight into the approachability, adaptability, and effectiveness of an Evacuation Vulnerability Index.

Additionally, the EVI scores for the zip codes within all four Zip-Zones were classified by a natural breaks distribution, placing between a 1/4 and a 1/3 of all zip codes at a Priority 1. This result did provide a sense of continuity across the H-GA, but also brought up questions for further research, such as a possible need for spatial normalization. Each of the four Zip-Zone areas considered in this study contained a different areal footprint, a differing number of zip codes, and an inconsistent variance in surface area among the zip codes within. Moreover, the disparity in area size and number of zip codes across the four Zip-Zones raises crucial questions for future research. These include the determination of the smallest geographic area that can be effectively communicated to the public during emergency evacuations, and the practicality of first responders distinguishing between priorities in real-time scenarios.

A major constraint to any SAA methodology is the availability and quality of the necessary GIS data for the analysis. Texas is one of only a small handful of states that has a multi-jurisdictional, coordinated registry for evacuation assistance for those MFP with function, access, or medical needs. The STEAR program operated by TDEM captures information about the nature of the registrants' assistance needs. Taking a deeper dive into this unique dataset would allow for further investigation into categorizing the vast range of those considered MFP and their varying resource needs and travel recommendations during a phased evacuation. An MFP citizen with mobility complications may be a good candidate for early transportation by local first responders to a standard large-scale general population shelter since they do not require ongoing medical attention, while another STEAR registrant that requires highly specialized medical equipment may be best supported through a shelter in place plan with post-incident evaluation by local emergency resources.

The potential for local municipalities to adopt this framework is promising, yet several challenges need to be navigated. Each region, be it within Texas or other parts of the US, exhibits unique characteristics in terms of population density, geographical layout, and existing emergency management infrastructure. This diversity necessitates localized adaptations of the framework to effectively meet regional requirements and constraints. This study contributes significantly to the existing body of literature by integrating spatial analysis within the realm of emergency management. It offers a structured and data-driven approach to prioritizing evacuation efforts for MFPs, a perspective that is notably underrepresented in current research. This methodological contribution is particularly valuable as it presents a practical tool that can be tailored and applied in a variety of emergency management contexts.

The methodology and findings of this study hold promising implications for diverse geographical and environmental contexts. The adaptability of the SAA and the EVI framework could be invaluable for tailored emergency management response in regions with distinct topographies, climate conditions, and population distributions. Areas with varied terrain, differing climate threats, and diverse populations would benefit from this data-driven approach, allowing for a customized assessment of evacuation needs. The adaptability of this methodology lies in its ability to factor in local geographical peculiarities through a well-defined SAA, thus offering a versatile tool for emergency managers in varied settings. The potential for adaptation underscores the importance of considering local environmental and demographic factors in disaster planning, ensuring that evacuation strategies are not only effective but also equitable across diverse landscapes and communities.

A possible alternate research question could investigate ranking the EVI of zip codes across all of the existing Zip-Zones in a single Spatial Accessibility Analysis, allowing emergency managers to focus on MFP needs more holistically. Future research in this area should continue to dissect these patterns, enhancing our collective capacity to manage and execute large-scale evacuations effectively. Further work could also explore the potential benefits and limitations of Zip-Zones consisting only of contiguous zip codes, as well as the implications of different types of natural disasters on evacuation strategies, further suggesting a need for additional research and potential evacuation planning protocol adjustments. Adopting a more data-informed, equitable approach that prioritizes the needs of all, particularly vulnerable groups, will result in more responsive and effective emergency management.

V. CONCLUSIONS

This study has strived to answer the following research questions:

1. Is there any significant difference in the spatial accessibility of evacuation resources for the MFP across the zip codes within each Zip-Zone in the H-GA of TX?
2. If there is a significant difference, which areas would be prioritized for evacuation and distribution of evacuation resources within each Zip-Zone of the existing H-GA Evacuation Zip-Zones map?

To answer these questions, this study highlighted areas of increased demand across an urban environment during a phased evacuation. This method introduced SAA to a process largely driven by physical vulnerability alone to spatially assess accessible evacuation resources and, in turn, provide local EMs with a methodological framework to potentially save more lives in any impact area. The MFP has a unique set of additional needs and challenges that require more time and access to resources during an urban evacuation (Ng 2015). Using datasets that are openly available to EMs, the SAA model outlined in this paper supplied an accessible method for local EMs to prioritize those areas of an urban environment that will need the most time and attention to properly execute large scale phased evacuation orders. This analysis not only challenged traditional evacuation planning methods but also underscored the significance of considering both spatial and social vulnerabilities in the MFP as well as the larger community.

It was hypothesized that there are significant differences in spatial accessibility on demand of evacuation resources across zip codes within each existing Zip-Zone. Having rejected the null hypotheses, as outlined in the SAA results; the SAA MFP EVI methodological framework utilized in this study demonstrates statistically significant differences among the zip codes within each Zip-Zone for each of the EVI factors. The process of considering the MFP in further evaluation of refining phased evacuations continues to aid in the classification of zip codes within each Zip-Zone into three priority levels based on evacuation vulnerability. This classification method allows for more spatially accessible phased evacuations and distribution of evacuation resources across an impact area, supplementing an existing large-scale evacuation plan. This effort builds upon phased evacuations through the inclusion of spatial and social vulnerability of the zip codes within each Zip-Zone designation rather than simply the physical proximity to the coastline and perceived hurricane hazard. The classification of zip codes into priority levels, as determined by the EVI, suggests a pathway to more efficient and equitable evacuations, ensuring that resources are distributed where they are needed most.

The implications of this study extend beyond mere academic interest. These findings underscore the importance of incorporating detailed and area-specific data analyses into the planning and execution of emergency management strategies. By doing so, the possibility of tailoring evacuation plans to better meet the diverse needs withing existing Zip-Zones was explored. Key steps toward obtaining this goal include improving evacuation routes, upgrading transportation infrastructure, and ensuring a fair distribution of emergency resources. By providing a data-driven framework, this study advocates for a balanced approach in resource allocation and evacuation planning. Additionally, community-awareness initiatives and training programs for emergency responders in resource-limited areas could markedly enhance the effectiveness of evacuation operations regarding MFP. This study leads the local EM toward an adaptive approach in emergency management, one that is perpetually refined based on demographic shifts, infrastructure developments, and changes in neighborhood support services.

Future research could explore real-time dynamic modeling of various evacuation scenarios to develop intel for informed decisions during active critical situations. There is still significant room to continue studies and the inclusion of Agent-based Modeling (ABM) simulations of the MFP would lead to refined assessment of the efficiency and effectiveness of prioritization within evacuation zones.

While ABM would be beneficial for estimating time required for specific individuals, the population density of the H-GA creates significant barriers to the feasibility of ABM within the scope of this study (Masuya 2015). It's noteworthy that while ABM may present challenges in terms of computational resources, these can be mitigated with advancements in cloud computing. The potential of ABM in enhancing our comprehension of evacuation dynamics is immense and offers a window into the complex interplay of human behavior, resource allocation, and infrastructure utilization during emergencies.

This study's implications extend to the need for a systematic assessment of strategies to better understand and prepare for the resource requirements of the MFP population during evacuations. This insight is crucial for developing evacuation strategies that are not just efficient but also equitable, ensuring resources are allocated where they are needed most. The lack of detailed guidance regarding the MFP during phased evacuations from subject matter authorities like FEMA left a substantial gap in literature regarding comprehensive resource planning. This study highlighted that refining stakeholder definitions, prioritizing knowledge of the MFP, and establishing a link between personal preparedness and jurisdictional resource requirements are crucial steps towards developing policies and best practices for local emergency planners (Risoe 2013).

Policy implications of this study included taking the added demands of the MFP within the H-GA into account, as well as including the City of Houston and surrounding areas into the area's evacuation planning measures. Another potential benefit of this research is to bring more awareness of the TDEM managed STEAR program prior to another urban hazard event. A more balanced approach to resource allocation and evacuation planning would also ensure that MFP in all areas, regardless of their Zip-Zone classification, have equitable access to evacuation support resources and could be transported to shelters efficiently. Moreover, these results could inform the development of targeted strategies to bolster evacuation plans in areas identified as particularly deficient in resources or with disproportionately long travel times.

In conclusion, this study has initiated an important conversation about evacuation planning in the H-GA. It advocates for a more data-driven and fair approach, particularly in addressing the needs of vulnerable groups. The outcomes of this research signaled a necessary shift in how evacuation planning is approached particularly within the Houston-Galveston Area, but more so highlighted the benefits of community centered awareness and refinement. A strategy that is more data-informed, equitable, and sensitive to the needs of vulnerable groups will lead to more efficient and effective emergency management, ensuring better protection for all against natural disasters.

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Appendix A

State of Texas Emergency Assistance Registry (STEAR)

Local Jurisdiction:

Organization Collecting Information:

Organization Contact Telephone: Ext:_______________

Organization Contact E-mail: ____

STEAR Individual Registration Form

Not for use by assisted living facilities or nursing homes. That form can be found https://tdem.texas.gov/wp-content/uploads/2019/08/NursingAsstdLvngRegForm.pdfhttps://tdem.texas.gov/wp-content/uploads/2019/08/NursingAsstdLvngRegForm.pdf

One (1) form should be completed for each registrant.

****By registering in STEAR you are consenting to sharing your information with first responders and other state agencies during a disaster. ****

Please understand that the Emergency Assistance Registry assists emergency officials in planning for emergency events. Having your information helps to determine what kinds of services might be required during a disaster and helps responders plan and train more effectively. Communities use the information in different ways, so realize that having your information in the registry **DOES NOT** guarantee that you will receive a specific service during an emergency. Registration is not a substitute for developing and maintaining your own family disaster plan.

We would like to gather some basic information from you. To be registered, some basic information is required. *If filling out a paper form, please write the registrant's name in the designated space at the bottom of every page of the form.*

Basic Registrant Information - *Required information marked with red* *

1. * **Primary Language**. If you speak more than one language, choose the best language that you would use for emergency communications. For persons who cannot communicate vocally, please enter non-verbal.

☐ *English* ☐ *Spanish* ☐ *Vietnamese* ☐ *Hindi* ☐ *Korean*

☐ *Chinese*_______________*(dialect)* ☐ *Other:* ______________________________

2. * Do you need a sign language interpreter? ☐ *Yes* ☐ *No*

Basic Registrant Information	
3a. * **First** Name:	
3b. * **Last** Name:	
____4. * **Physical Street Address**	
4a. * Street Number and Name:	
4b. Apt/Suite Number:	
4c. * ZIP code (5-digit):	4e. +4 Zip code, if known:
4d. * City:	
5. County, if known:	
☐6. * **Mailing Street Address** Check this box if the mailing address is the same.	
6a. Street Number and Name: _	
6b. Apt/Suite Number:	
6c. ZIP code (5-digit):	6e. +4 Zip code, if known:
6d. City:	
7. E-mail Address (if you have one):	
8. * Best phone number to reach you:	Ext:
9. Do you have a second telephone number in case we cannot reach you at the previous number?	Ext:
10. If you are a minor (younger than 18) or if the person you are registering is a minor, please enter their age in years. Enter 0 for children less than 1 year old. Leave blank for adults.	

(cont.) - *Required information marked with red* *

Emergency Contact Information
In these questions, emergencies are defined as hazards to public health and safety, such as hurricanes, tornadoes, terrorist attacks, chemical accidents, and other disasters that may cause death, injury, or damage, which could require evacuation and sheltering of the public.
11. We need to gather some information about the best person for emergency planners to contact in case of an emergency.
11a. Emergency contact person's **First** Name:
11b. Emergency contact person's **Last** Name:

Emergency Contact Information
11c. What is this person's relationship to you? ☐ *Spouse* ☐ *Parent* ☐ *Sister/Brother* ☐ *Daughter/Son* ☐ *Aunt/Uncle* ☐ *Guardian* ☐ *Friend* *Other:* ______________________
11d. Emergency contact's telephone number. Remember, this needs to be the best way to contact this person in case of an emergency:____________________________Ext: _________

Caregivers and Animals
12. * If you had to evacuate your home, would you be accompanied by a service animal? ☐ *Yes* ☐ *No*
13a.* Do you have a caregiver, advocate or legal guardian? This person may or may not be the same person who is your emergency contact. ☐ *Yes* ☐ *No*
13b. **[If answered Yes to Q13a]** During an emergency would your caregiver, advocate or legal guardian evacuate with you? ☐ *Yes* ☐ *No*
14.* How many people do you expect to accompany you when you evacuate? Include your caregiver or legal guardian if evacuating with you: ____
15a.* If you had to evacuate your home, would you take a pet with you? ☐ *Yes* ☐ No
15b. **[If answered Yes to Q15a]** How many total pets would need to evacuate with you? _____
15c. **[If answered Yes to Q15a]** Do you have carriers for all of your pets? ☐ *Yes* ☐ *No*

Emergency Warnings and Instructions
16a.* Do you have a disability or medical condition that would prevent you from receiving or understanding emergency warnings or instructions whether in your home or away from home? ☐ *Yes* ☐ *No*
16b. **[If answered Yes to Q16a]** Would you need help reading information because you are blind or have low vision? ☐ *Yes* ☐ *No*
16c. **[If answered Yes to Q16a]** Do you have any other communication needs? ☐ *Yes* ☐ *No* If "*Yes*", please describe here: ____________________________________

Transportation Assistance
17.* Do you have transportation to evacuate? Answer **"Yes"** if you have a vehicle or someone you know to drive you to an out-of-town location. Answer "*No*" if you **DO NOT** have a way to evacuate. Planners use this question to estimate how many people need transportation during an evacuation. ☐ *Yes* ☐ *No*
18.* Do you need transportation assistance to get to a **local** evacuation assembly point or shelter? A **"Yes"** means you **DO NOT** have a way to get from your home to a local assembly point. ☐ *Yes* ☐ *No*
19.* Do you need physical assistance because of a disability to evacuate your home? ☐ *Yes* ☐ *No*

Medically Fragile
20.* Do you identify as a medically fragile individual? If "*Yes*", proceed to answer questions 21- 25b. If "*No*", proceed to question 26. ☐ *Yes* ☐ *No*
21. Have you been diagnosed with Alzheimer's or other related disorders? ☐ *Yes* ☐ *No*
22. Have you been diagnosed with a debilitating chronic illness? ☐ *Yes* ☐ *No*
23. Do you receive dialysis services? ☐ *Yes* ☐ *No*
24. Do you have a medical condition that requires 24-hour supervision from a skilled nurse? ☐ *Yes* ☐ *No*
25a. Do you use life sustaining medical devices that requires power? (Examples would include a breathing machine, suction unit, oxygen concentrator, ventilator, or feeding pump) ☐ *Yes* ☐ *No*
25b. **[If answered Yes to Q25a]** How many hours of power are provided by your back-up power source?_______hours

Functional Needs
26.* Do you have a disability or access and functional need that will require additional assistance during an emergency? If "*Yes*", proceed to answer questions 27-31. If "*No*", proceed to question 32. ☐ *Yes* ☐ *No*
27. Do you receive critical medical treatment from a nurse or doctor at your home or in a doctor's office more than 2 times a week? ☐ *Yes* ☐ *No*
28a. If you were away from home, would you need help carrying out activities of daily living, such as bathing, eating, walking, or toileting? Your answer helps to improve plans made for shelters. ☐ *Yes* ☐ *No*
28b. **[If answered Yes to Q28a]** Are these services currently provided by someone other than family or friends? If "*Yes*", please record the service provider and their contact information in the comments section [Question 33]. ☐ *Yes* ☐ *No*
29. Do you have a disability or medical need that will require you to lie down while traveling? ☐ *Yes* ☐ *No*
30. Do you weigh more than 350 lbs.? Emergency transport requires special equipment in certain cases if this weight is exceeded. ☐ *Yes* ☐ *No*
Functional Needs (cont.)
31a. What durable or bulky medical equipment, such as a wheelchair, cane, or walker, do you need to have evacuated with you in an emergency? Please check all that apply. Your answer helps evacuation transportation planners. ☐ *Wheelchair* ☐ *Cane* ☐ *Walker* ☐ *Nebulizer* ☐ *Crutches* ☐ *Other:*_______________________________ ☐ *None*
31b. **[If Yes to Wheelchair to Q27a]** Do you have a motorized or custom wheelchair? Please answer "*Yes*" if you have a scooter or power wheelchair. ☐ *Yes* ☐ *No*
32.* Do you have a storm cellar or safe room in your residence? ☐ *Yes* ☐ *No*

33. Are there any additional comments or notes that we should enter into your record?

☐ *Yes* ☐ *No*

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