

Geospatial Analysis of Healthcare Accessibility in High Older-Adult Areas under Flood Scenarios: Implications for Disaster Management in an Aging Puerto Rican Population

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Abstract — *Flooding poses a latent challenge to transportation networks in Puerto Rico with critical implications for older-adult populations who depend on localized access to healthcare services. The study analyzes healthcare accessibility under flooded road network scenarios, focusing on census tracts with high concentrations of older adults aged 60 and older. A geospatial network-based analysis was conducted in ArcGIS Pro to study distance-based access to healthcare facilities using a one percent annual flood chance scenario. Accessibility was measured by a one-kilometer network distance threshold to model local access during floods. Census tract origins were based on population-weighted centroids using census tract populations. Older-adult population variables were included as demographic indicators. Analyses were executed for hospitals and Centro 330 facilities separately and combined for accessibility analyses. Results show that spatial patterns of affected access impacting older-adult census tracts feature the sensitivity of healthcare accessibility to disruptions to transportation networks, providing information for evidence-based decision making in disaster planning.*

Keywords — *Disaster Planning, Flooded Transportation Network, Healthcare Accessibility, Older-Adult Populations.*

INTRODUCTION

Like many parts of the world, Puerto Rico is undergoing a pivotal point in its demographic transition. This transition is characterized by a rapidly aging population, with a growing proportion of adults aged 60 years of age and older unevenly distributed across the archipelago. This demographic change represents significant challenges for

equitable access to healthcare, specifically in areas where healthcare facilities are dispersed and transportation infrastructure is limited.

The challenges take center stage under disaster conditions. Flooding is a recurrent event in Puerto Rico due to geographic and topographic characteristics. These events disrupt transportation networks throughout the territory, reducing functional accessibility to essential services such as healthcare facilities. Road interruptions related to floods can isolate communities from hospitals and Centro 330 facilities, aggravating pre-existing access barriers into acute barriers during emergency and post-disaster scenarios. Research has demonstrated that disruptions to road networks can substantially affect spatial accessibility to healthcare services, particularly in hazard-prone areas [1], [2].

Accessibility to healthcare is not only a function of availability of services, but also a compounded outcome including the interaction between population distribution, infrastructure, and environmental risks. Based on this context, accessibility should be evaluated and analyzed as spatial conditions that vary across areas and can deteriorate quickly when transportation networks are affected and become compromised. Geographic Information Systems (GIS) and network-based analyses have been thoroughly employed to measure these spatial dynamics and assess how natural hazards such as floods impact and affect access to healthcare facilities and services [1], [3].

Disasters such as Hurricanes Irma and María in Puerto Rico uncovered significant structural vulnerabilities in transportation and healthcare systems. These vulnerabilities disproportionately impacted and still impact older adults and other vulnerable populations. Studies have reported post-

disaster barriers to healthcare access that are directly related and linked to road closures, infrastructure damage, and geographic isolation. This shows the importance and need of spatially oriented analyses to help make decision-based and informed disaster management and planning strategies [4], [5]. Older adults face higher risks due to chronic health conditions, limited mobility, and heightened dependence on availability of nearby healthcare services and facilities [6].

This study explores and analyzes healthcare accessibility in Puerto Rico under flooded road network conditions, with a particular focus on census tracts representing high concentrations of older adult populations (60+). The analysis focuses on physical accessibility, with specific attention to the transportation network during flood scenarios. Accessibility is interpreted using network-based distance thresholds, identifying census tracts where access to healthcare facilities and services may be limited or eliminated due to flood-related road interruptions.

This analysis highlights the difference between hospitals and Centro 330 primary care facilities, emphasizing their distinct roles within the healthcare system. This study analyses access to each type of the facilities separately and combined. This is purposely designed to avoid overrepresenting healthcare availability. This also allows for the identification of service-specific accessibility gaps.

The findings of this study contribute to disaster management and planning by identifying spatial patterns in which high concentrations of older adults interact with limited healthcare services accessibility under flood scenarios. By combining demographic data, flood exposure, and network-based variables, the study provides evidence-based data to support targeted community- and municipal-level interventions, infrastructure development and planning efforts, and resilience strategies tailored to the needs of aging population in flood-prone areas.

OBJECTIVE

The objective of this study was to analyze healthcare accessibility in Puerto Rico under flooded road network conditions with a particular focus on census tracts where there are high concentrations of adults aged 60 years and older. The study evaluated accessibility to hospitals and Centro 330 primary care facilities using network-based distance thresholds to identify census tracts where access to healthcare services may be limited or eliminated due to flood events in which road access may be interrupted.

METHODOLOGY

The methodology of this study presents a structured and transparent approach to objectively analyzing healthcare accessibility, population distribution, and flooding scenarios. The following sections outline the processes, tools, considerations, and general framework used in the study.

Study Area and Unit of Analysis

The analysis was conducted for the archipelago of Puerto Rico using 2023 Census Tracts as the main unit of analysis. The census tract unit was selected to allow for consistent and spatial analysis of healthcare accessibility while ensuring compatibility with demographic data from the American Community Survey (ACS). All spatial analyses were generated using the *NAD 1983 (2011) StatePlane Puerto Rico & Virgin Islands FIPS 5200 (Meters)* coordinate system to ensure spatial accuracy.

Data Sources and Preparation

Several datasets were integrated to generate the analysis which included demographic, healthcare, transportation, and flood exposure data. Population variables for 60 years and older adults were obtained from the ACS 2019 – 2023 five-year estimates. These were used to calculate the percentage of older adults (60+) at census tract level. This variable was then incorporated as a demographic attribute to categorize gerontological vulnerability.

Healthcare facility locations included hospitals and Centro 330 primary care facilities, which were recovered from federal and local sources available to the public. The facilities were categorized as independent and distinct services because of the differences in functional roles and offered services in the healthcare system.

The transportation network was obtained from road network data sets available to the public. These were then analyzed and standardized to process the network-based analysis in ArcGIS Pro. The obtained data sets were standardized, cleaned, and organized in a designated geodatabase used for this study before proceeding with further analysis.

Flood exposure data were retrieved from Federal Emergency Management Agency (FEMA) flood hazard layers. For this study, the 1% Annual Exceedance Probability (AEP) flood zone layer was used. This set of data was used to identify and target road segments affected by flooding as well as to model disruptions under flood scenarios within a transportation network.

Flooded Road Network Modeling

To represent accessibility conditions under flood scenarios, a network dataset was constructed which simulated a flooded road network. This dataset was generated using ArcGIS Pro and its Network Analysis extension. The road segments that intersected the FEMA 1% AEP flood zone were highlighted and flagged as disrupted. As a result, this reduced the connectivity capacity of the transportation network. This exercise facilitated further analysis to represent a limited transportation network which reflected road interruptions pertaining to flood scenarios instead of assuming full road network connectivity.

Accessibility was considered for evaluation based on network distance, not the travel time variable. This was done to highlight infrastructural connectivity and spatial barriers under flood-scenario, disrupted conditions. This strategy avoided the model to assume variables related to travel speed, traffic congestion, or social responses during disaster events such as those caused by flooding.

Accessibility Analysis

Population-weighted centroids were calculated for each of the 943 census tracts of Puerto Rico using total population counts. These centroids were then used as the origin points for accessibility calculations. It is important to mention that the population aged 60 and over was not employed to generate the centroids. This ensured that spatial origins reflected the overall population distribution of the census tract rather than representing a particular demographic group within the spatial unit selected.

Healthcare accessibility was approached using the network-based distance threshold of 1 kilometer. This threshold represents local and functional access under flood-scenarios. This selection was based on prior spatial accessibility research highlighting the use of short-distance units to avoid overrepresenting or overestimating service availability, specifically for populations with mobility limitations. Luo and Wang [1] demonstrate that smaller network-based distances in healthcare accessibility analyses reduce the risk of inflated coverage estimates while Handy and Niemeier [2] highlight that neighborhood-scale distances are appropriate for evaluating access to essential services. Standard network distance thresholds of 1 km, 3 km, and 5 km were initially considered as commonly employed in GIS-based accessibility analyses. Among these operational thresholds, the 1 km threshold was selected because it is closely aligned with literature pertaining to short-distance measures. In addition, it provides a more adequate representation of neighborhood access conditions for older adult populations, particularly under interrupted network conditions in flood scenarios.

Accessibility analyses were generated separately for hospitals and Centro 330 facilities. As further analysis, a condition was implemented at the census tract level to represent access to either type of healthcare facility without creating a combined service area polygon. This exercise eliminated the possibility of overestimating healthcare availability while still highlighting distinctions between the

services offered by both types of healthcare facilities.

Classification of High Older-Adult Census Tracts

A critical part of the analysis was the consideration of census tracts, its older adult population (60+), and healthcare accessibility under flood-scenarios. For this, census tracts with a high concentration of older adults were identified based on the percentage of residents aged 60 years and older. Tracts on or above the 75th percentile of the 60 years and older distribution were categorized as high older-adults census tracts. This categorization was employed for further analysis and is shown in the analysis of the results.

Output Generation and Visualization of Results

Outputs were generated at census tract level and visualized with maps designed to facilitate analysis and comparative interpretations. The main and primary results consisted of three maps representing healthcare accessibility under flooded road network conditions for:

1. Hospitals only,
2. Centro 330 facilities, and
3. Hospitals and Centro 330 facilities combined

Each map represents the combination census tracts categorized by older-adult population concentration.

Several other maps were also generated at intermediate analysis phases which included but were not limited to service areas and structural accessibility layers. These analysis layers were used for data and result validations as well as methodological robustness. These maps were not considered final outputs or results.

To support spatially orientation prior to presenting the network-based accessibility results and analysis, Figure 1 illustrates the geographic distribution of healthcare facilities across Puerto Rico, including hospitals and Centro 330 primary healthcare facilities.

RESULTS AND ANALYSIS

Results and outputs show that there is considerable and substantial spatial variation in healthcare accessibility across Puerto Rico when considering disruptions to road network in flood-related events. In the flooded network scenarios using a 1-kilometer network distance threshold, several census tracts reflected limited or no access to healthcare facilities conditions. Considering this result, local access to healthcare facilities can change quickly when flood-related road disruptions happen.

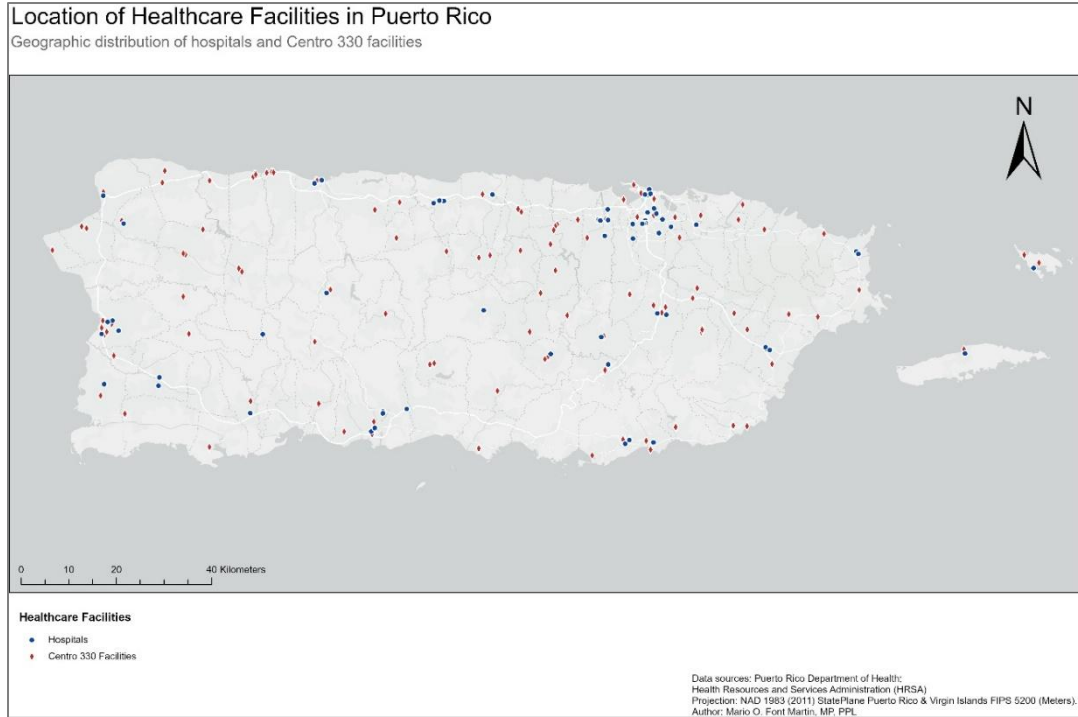
Large variations in accessibility were noted depending on the healthcare facility type. This highlights the importance of evaluating hospitals and Centro 330 facilities separately. This reduces the risk of error by assuming that there is uniformity in availability of services across the area of study.

Hospital Accessibility Patterns

This phase of the analysis considered only hospital facilities. The output and results of this analysis reflected a higher constraint of spatial coverage when considering hospital accessibility in comparison to the combined healthcare facilities accessibility.

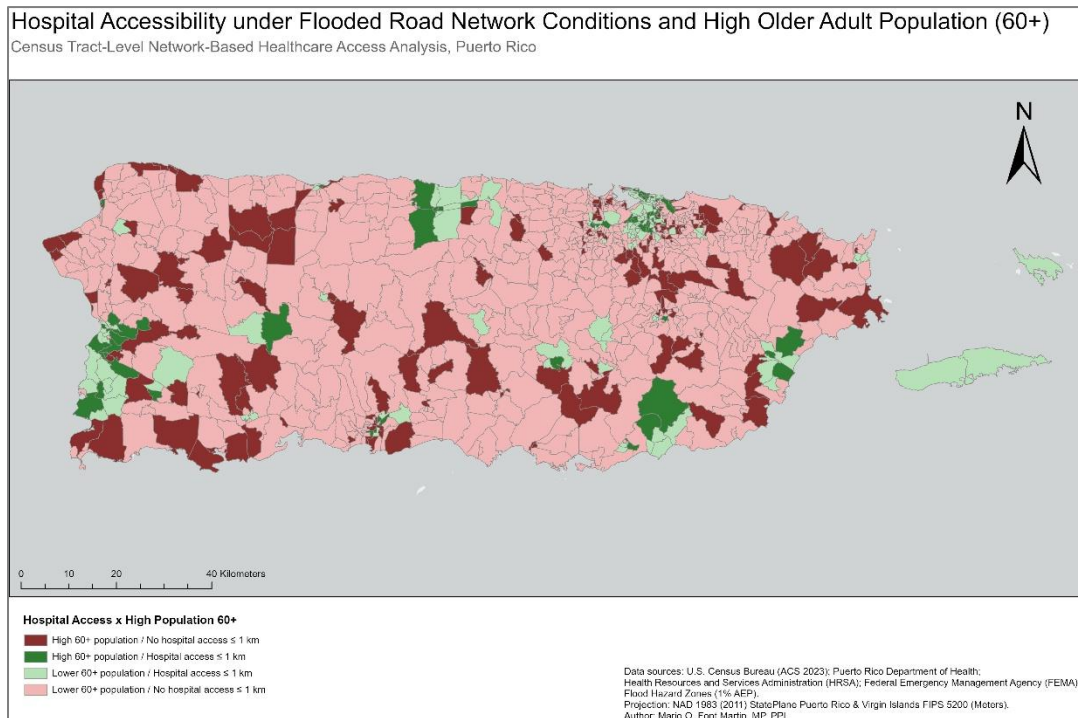
The output and results of this analysis reflected a higher constraint of spatial coverage when considering hospital accessibility in comparison to the combined healthcare facilities accessibility. Under the flooded network scenario, hospital access was concentrated in a smaller number of census tracts. Based on spatial output, it can be inferred that hospital accessibility is concentrated in urban and central-oriented areas. High older-adult census tracts without hospital access within the 1-kilometer distance threshold were focused in rural areas.

Based on these outputs, it can also be inferred that having this segment of the population rely solely on hospital accessibility during flood events may exacerbate vulnerabilities in older-adult populations without nearby access to hospital infrastructure. A detailed spatial distribution of hospital accessibility for high older-adult census tracts is presented in Figure 2.



Contextual overview of the spatial distribution of healthcare facilities across Puerto Rico, including hospitals and Centro 330 primary healthcare facilities. This map does not represent accessibility, service coverage, or network-based analysis results.

Figure 1
Location of Healthcare Facilities in Puerto Rico



Census tract-level hospital accessibility under flooded road network conditions, using a network-based distance threshold (\leq 1 km) and the spatial distribution of older adults (60+). Census tracts are classified based on the combined presence of high older-adult population concentration and hospital access, highlighting spatial patterns of accessibility under flood-impacted conditions.

Figure 2
Hospital Accessibility Under Flooded Road Network Conditions and High Older Adult Population (60+)

Centro 330 Accessibility Patterns

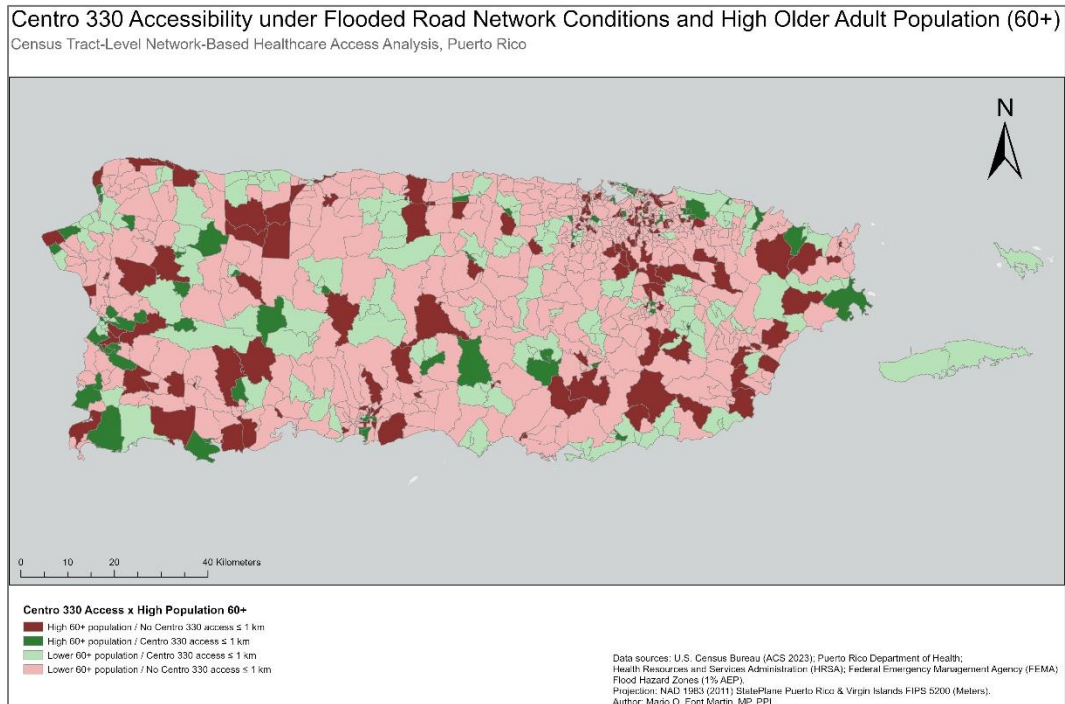
The output from Centro 330 healthcare facilities analysis showed a larger spatial coverage under the flooded network scenario in comparison to hospitals. A substantial number of high older-adult census tracts without hospital access did maintain access to Centro 330 facilities with the 1-kilometer distance threshold. This spatial representation may describe a decentralized infrastructure of this type of primary care facility designed to serve patients at a community level. These patterns are detailed in Figure 3.

From a spatial analysis point of view, Centro 330 facilities provide an extension of healthcare access where there is a lack of or limited hospital coverage access. This phenomenon can be seen particularly in non-metropolitan and urban-adjacent census tracts. These network-based results imply that these types of healthcare facilities have a crucial role in supporting healthcare access at a local level under disrupted transportation scenarios caused by

flooding events. Figure 3 illustrates how Centro 330 facilities can partially diminish spatial limitations related to centralized hospital systems. These outputs underline the significance of primary healthcare infrastructure in sustaining functional access for older-adult populations in disaster situations. This also provides a lookout on the need to evaluate how hospital and Centro 330 facilities access behave when evaluated together.

Combined Healthcare Accessibility and High Older-Adult Population Concentration

The combined healthcare accessibility exercise flagged census tracts with access to either hospitals or Centro 330 facilities under flooded network conditions. On the other hand, this exercise also provided information on all other census tracts where there is no access to either type of healthcare facility. It is important to mention that this analysis was conducted using the 1-kilometer distance threshold.



Census tract-level Centro 330 accessibility under flooded road network conditions, using a network-based distance threshold (≤ 1 km) and the spatial distribution of older adults (60+). Census tracts are classified based on the combined presence of high older-adult population concentration and Centro 330 access, highlighting spatial patterns of accessibility under flood-impacted conditions.

Figure 3

Centro 330 Accessibility Under Flooded Road Network Conditions and High Older Adult Population (60+)

When combined with census tracts categorized as high concentration of older adults (60+), the analysis reflected areas of compounded vulnerabilities. There were 118 census tracts categorized as high older-adult census tracts that had no healthcare access within the 1-kilometer distance threshold under flood conditions. This shows that in these locations where there is a high concentration of older-adult populations there are significant challenges for reaching healthcare services during flooding events.

On the other hand, there are 112 census tracts categorized as high older-adult census tracts which still had access to at least one type of healthcare facility.

Table 1 depicts a summary of the distribution of census tracts by older-adult population concentrations and healthcare accessibility

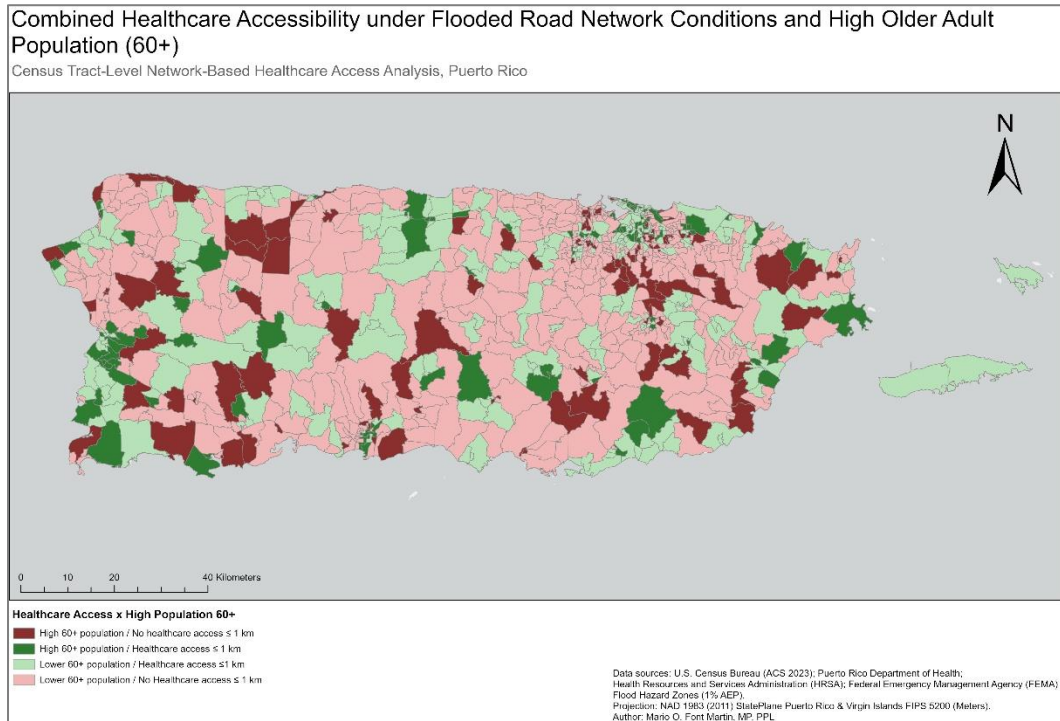
classification, while the spatial patterns described can be visualized in Figure 4.

Table 1
Categorization of Census Tracts by Older-Adult Population Concentration and Healthcare Accessibility Under Flooded Road Network Scenarios

Category	Number of census tracts	Percentage
High 60+ / No Access \leq 1 km	118	12.51%
High 60+ / Access \leq 1 km	112	11.90%
Lower 60+ / Access \leq 1 km	271	28.74%
Lower 60+ / No Access \leq 1 km	442	46.87%
Total	943	100.00%

*Percentages may not sum to 100% due to rounding.

This table summarizes the distribution of census tracts by older-adult population concentration (60+) and healthcare accessibility under flooded road network scenarios with a one-kilometer distance threshold.



Census tract-level healthcare accessibility under flooded road network conditions, using a network-based distance threshold (\leq 1 km) and the spatial distribution of older adults (60+). Census tracts are classified based on the combined presence of high older-adult population concentration and access to healthcare services, highlighting spatial patterns of accessibility under flood-impacted conditions.

Figure 4
Combined Healthcare Accessibility Under Flooded Road Network Conditions and High Older Adult Population (60+)

Comparative Analysis

To further understand the spatial patterns pertaining to healthcare accessibility among the older-adult population, a comparative assessment was conducted between hospitals and Centro 330 facilities. This comparison accentuates the complementary yet spatially distinct roles of healthcare services under the flooded network scenario.

When visualizing the analysis at the archipelago scale, notable differences between hospitals and Centro 330 facilities were identified in terms of spatial distribution and service coverage. Meanwhile, when considering census tracts characterized by high older-adult (60+) concentrations as the unit of analysis, accessibility results under the 1-kilometer distance threshold converged across both facility types.

Under the flooded road network scenario, census tracts characterized by high older-adult populations demonstrated similar behaviors of access or non-access despite whether the closest facility under the distance threshold was a hospital or a Centro 330 facility.

This phenomenon emphasizes the sensitivity of location of healthcare accessibility to transportation network interruptions. This suggests that for the older-adult population, short-distance access systematically fails under flood conditions.

Differentiating between hospitals and Centro 330 facilities becomes less strategic from a planning point of view at the 1-kilometer spatial threshold. This highlights the vulnerability of older-adult communities when infrastructure disruptions occur and reinforces the need to generate and implement targeted and community-based resilience and disaster planning strategies.

CONCLUSION

The presented study provides a view into healthcare accessibility for older-adult populations in Puerto Rico. Healthcare accessibility in this context shows a strong interaction between demographic vulnerability, transportation network

disruptions, and spatial proximity to healthcare services. Under flooded road network scenarios and short-distance accessibility thresholds (1-kilometer), it is shown that census tracts with a high concentration of older adults there is a pattern of localized access limitations and failures. This reveals and flags areas with compounded vulnerability based on the scope of analysis that may remain affected under scenarios that may not necessarily involve flooding.

A key finding suggests that even though the studied healthcare facilities represent particular spatial patterns throughout the archipelago, these differences are not as critical when accessibility is analyzed within a high older-adult census tract condition. Another important observation is that under the flooded network scenario, considering the 1-kilometer distance threshold, accessibility models converge across the analyzed healthcare facilities. This shows that for older-adult populations the presence or absence of healthcare facilities, including both hospitals and Centro 330 facility types, is more critical than the type of service offered. This phenomenon precisely reflects a significant reduction in local healthcare accessibility capacity to tend to the older-adult population needs during flood events.

From a resilience planning and public policy perspective, the findings described in this study emphasize the vulnerabilities that older-adult populations face when considering transportation network disruptions. These findings also highlight the limitations that may be faced when designing mitigation strategies when considering facilities and scenarios that don't consider local connectivity under extreme natural events. It is imperative that when addressing healthcare accessibility for aging communities, an integrated and holistic planning approach is employed which simultaneously considers transportation resilience, local and community-level access, and population vulnerabilities, specifically in areas that may be exposed to increasing climate and environmental hazards.

Although this study focuses on network-based healthcare accessibility under flooded roads and a 1-kilometer distance threshold, further studies and analyses should broaden this approach by including a wider variety of transportation obstacles and limitations as well as other accessibility thresholds. Further research may also examine how disruptions to transportation networks and the availability of healthcare services change and transform in the event of future disasters and extreme events.

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