Characterizing Excess Mortality in Puerto Rico After Hurricane María

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Abstract

Hurricane María caused significant disruptions in Puerto Rico, profoundly impacting mortality rates across demographic groups. This study analyzed excess mortality from 2002 to 2018, focusing on variations by age and sex, using robust statistical modeling (although no formal statistical comparisons within/between groups were conducted). Mortality rates were modeled to estimate expected deaths based on historical trends, accounting for seasonal and demographic variations.

Findings revealed substantial excess mortality following Hurricane María, particularly in older age groups (60–74 and 75+ years), where mortality almost exceeded 100% above expected levels at the peak. Middle-aged groups (40–59 years) showed notable increases, while younger groups (0–4 and 5–19 years) experienced minimal deviations. Across all age groups, males exhibited slightly higher mortality rates and variability than females, suggesting differential vulnerability. Sustained excess mortality into early 2018 highlights the long-term indirect effects of the disaster, including healthcare disruptions and exacerbation of chronic conditions.

This study underscores the importance of disaster preparedness tailored to vulnerable populations, such as the elderly and possibly males in middle-to-older age groups. Future research should incorporate formal statistical comparisons and address unmeasured confounders to enhance understanding of disaster-related mortality patterns and inform public health policies.

Introduction

Hurricanes are among the most destructive natural disasters, inflicting severe and long-lasting social, economic, and health consequences (Waddell et al. (2021)). The Caribbean region, situated in a hurricane-prone zone, is particularly vulnerable due to its geographical location, fragile infrastructure, and existing socioeconomic disparities (Cuervo and Perdomo (2025)). Hurricane María, which devastated Puerto Rico in September 2017, epitomizes the immense

destruction caused by such events. The hurricane led to catastrophic outcomes, including widespread infrastructure collapse, prolonged power outages, and significant disruption to healthcare delivery systems (Coto (2017)). Initially, the Puerto Rican government reported only 64 hurricane-related fatalities—a figure widely criticized for failing to reflect the true scope of mortality (Coto (2017)). Subsequent studies have demonstrated that excess mortality, encompassing both direct and indirect deaths resulting from the hurricane, was far greater than initially acknowledged, underscoring the need for a more rigorous, demographic-specific analysis to reveal the full impact (Santos-Burgoa et al. (2018); Kishore et al. (2018)).

Excess mortality is a crucial public health metric that quantifies deaths above expected baseline levels derived from historical trends (Roser et al. (2020)). This metric accounts for both immediate fatalities caused directly by the storm and indirect deaths arising from secondary effects, such as disrupted healthcare access, infrastructure failure, and deteriorating living conditions over time (Acosta and Irizarry (2022)). While existing studies estimate that Hurricane María led to between 2,975 and 4,645 excess deaths in the months following the disaster, there remains limited understanding of how these deaths were distributed across age groups and sexes (this study reports sex assigned at birth, and not gender, given that it was the measure available in the dataset from which the study is derived) (Santos-Burgoa et al. (2018); Kishore et al. (2018); GWU (2018)). Identifying demographic disparities in excess mortality is essential for pinpointing vulnerable populations, addressing systemic inequities, and developing targeted strategies to improve preparedness and response for future disasters.

This study seeks to address this critical gap by examining and characterizing excess mortality in Puerto Rico after Hurricane María, with an emphasis on age- and sex-based stratifications. Specifically, we aimed to answer the research question: How were excess deaths distributed across different age groups and sexes in the hurricane's aftermath? The study hypothesizes that older adults and males experienced disproportionately higher excess mortality due to their increased vulnerability to healthcare disruptions, physical hazards, and underlying health conditions exacerbated by the disaster. By identifying and analyzing these demographic disparities, the study provides a deeper understanding of the hurricane's human toll and offers evidence-based recommendations for disaster risk reduction and mitigation policies.

This study adopts a novel and robust statistical framework for estimating excess mortality using the `excessmort` R package (Acosta and Irizarry (2022)), to achieve our objective. This methodology is particularly suited for capturing the subtle yet persistent increases in mortality often associated with indirect disaster effects. These effects pose significant statistical challenges due to confounding factors such as demographic shifts, seasonal variations, secular trends, and natural fluctuations in mortality rates. The `excessmort` package addresses these complexities by leveraging smooth time functions to model mortality trends while allowing for sudden shifts to detect the direct effects of catastrophic events. This flexible and rigorous approach enhances statistical power, enabling both retrospective analyses of past disasters and real-time monitoring of any concerning mortality trends.

By providing a detailed demographic analysis of excess mortality following Hurricane María, this study will contribute to a more comprehensive understanding of Hurricane María-related

deaths and will inform future policies aimed at protecting vulnerable populations during and after extreme weather events.

Methods

Purpose and Overview

This study estimates and analyzes excess mortality in Puerto Rico following Hurricane María, focusing on variations across age groups and sexes. The analysis leverages mortality and population data from 2002 to 2018, utilizing statistical modeling to calculate expected mortality rates and quantify deviations during the hurricane's aftermath.

Data Sources, Collection, and Data Preparation and Visualization

The `puerto_rico_counts` dataset from the `excessmort` package was used. This dataset was created by including individual-level mortality records with no personal identifiers from the Department of Health of Puerto Rico's Demographic Registry from January 1985 to August 2020. In addition, population estimates for 1985 to 2000 were interpolated using decennial census data from 1980 to 2000. For 2000 onward, interpolated Population Estimates Program (PEP) data were used. These population counts were critical for calculating mortality rates by providing denominators for standardization; (Acosta and Irizarry (2022); Irizarry et al. (2023)). This dataset contains daily mortality counts for Puerto Rico, stratified by age groups, covering the period from 1985 to 2022. Key variables included are: `date` (the date of each observation); `outcome` (the number of deaths recorded on a given day); `agegroup` (age categories, defined as ranges in four-years increment, up to 85+ years); and `population` (the estimated population for each age group during the given period).

The dataset was restricted to weekly mortality counts (with Wednesday set as the start of the week–Hurricane María's landfall day) and population estimates for Puerto Rico (2002–2018; ensuring more contemporary demographic and reporting practices, which are likely to be more consistent and accurate, as including data from 1985–2001 could introduce biases due to differences in data quality, completeness, and reporting standards over time) to ensure consistency and leverage high-quality data. Mortality data were stratified by age, sex, and date of death, with age categories collapsed into broader intervals (0–4, 5–19, 20–39, 40–59, 60–74, 75+) for simplicity and interpretability given similar mortality rates among several groups.

Please refer to the **Supplemental Methods** document (Data Preparation and Visualization subsection), for more details on data preparation for analysis.

Estimation of Expected Mortality

To establish a baseline, expected mortality rates (2002–2016) were modeled using the `compute_expected` function from the `excessmort` package, stratified by age group and sex. These models estimated the expected mortality counts which were then transformed into rates by leveraging historical data, smoothing temporal trends, and accounting for seasonal effects. Initially, no periods were excluded to ensure a comprehensive understanding of baseline mortality dynamics, and the initial model enabled the identification of populations and periods with significant excess mortality by comparing observed counts against the expected baseline while accounting for variability and trends. Subsequently, several periods of possible excess mortality were excluded. The resulting expected mortality estimates provided a robust baseline for detecting deviations associated with Hurricane María. Important to mention that the `excess_model` function from the `excessmort` package, performs this calculation separately as well. However, this was included as a separate section for illustration purposes. Please refer to the **Supplemental Methods** document (Estimation of Expected Mortality subsection), for more details.

Estimation of Excess Mortality for Hurricane María

Excess mortality for 2017–2018 was calculated as the difference between observed and expected mortality rates, focusing on the event window from September 20, 2017 (Hurricane María's landfall), to one year pre- and post-hurricane. Excess mortality was expressed as absolute counts and percentage increases relative to expected rates. The fitted model was designed to estimate excess mortality in Puerto Rico during the year following Hurricane María, using the `excess_model` function from the `excessmort` package. This model combines observed and expected mortality rates, accounting for seasonal trends, long-term mortality dynamics, and the influence of key events. Models, stratified by age group and sex, applied a `model = "correlated"` argument, introducing a correlated error structure to account for temporal dependencies (extending the standard Poisson model to account for autocorrelation in the data). Please refer to the **Supplemental Methods** document (Estimation of Excess Mortality for Hurricane María subsection) for more details.

Results

Overall, the population size in Puerto Rico has decreased over time for both males and females, with the most pronounced declines occurring among younger age groups. Conversely, the population of elderly individuals (60 years and older) has steadily increased in both females and males, underscoring the importance of using mortality rates rather than total population sizes to account for these demographic shifts when analyzing and comparing mortality trends (**Figure 1**).

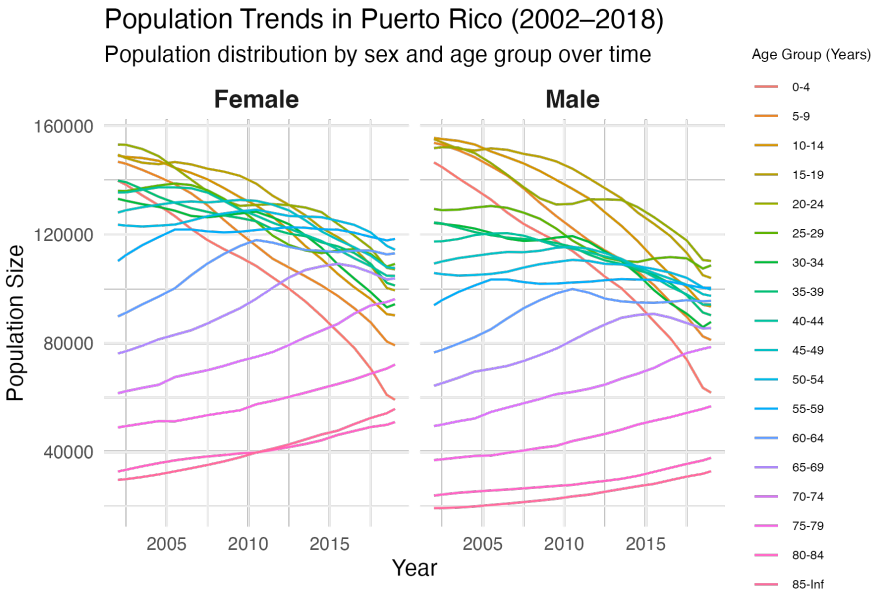

Figure 1. Population Trends in Puerto Rico Over Time

Figure 2 shows the weekly observed and expected death rates per 100,000 people in Puerto Rico, stratified by age group and sex, from 2002 to 2016. The observed death rates are represented as individual data points (gray/black dots), while the expected death rates are shown as smooth lines (magenta), capturing seasonality, long-term trends, and demographic variations.

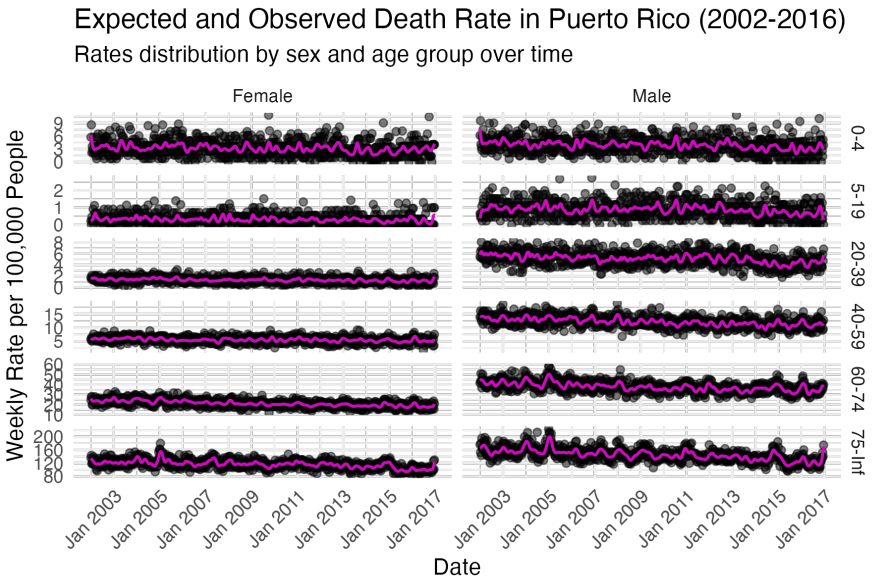

Figure 2. Expected and Observed Death Rate in Puerto Rico Over Time

When evaluating patterns by **age group**, we can evidence that **young age groups (0–4, 5–19)** have death rates that are consistently lower compared to older age groups, and that the variability in observed death rates (gray dots) is more pronounced, likely due to smaller population sizes in these cohorts. The expected rates remain stable with minimal seasonal fluctuations. In the **middle age groups (20–39, 40–59)**, the observed and expected death rates show slight increases with age, particularly in the 40–59 age group, and seasonal fluctuations are evident, though both sexes generally align closely with expected rates. In the **Older Age Groups (60–74, 75+)** death rates appear to increase significantly with age, peaking in the 75+ group, and seasonal trends and deviations from expected rates are more pronounced, particularly during influenza seasons and other health events (as previously specified in the Methods section). When evaluating patterns by **sex**, we evidence that in males, both the expected and observed death rates are higher across all age groups compared to females. This is particularly evident at higher ages (75+), where we see higher variabilities. Generally, across all age groups and sexes, the 2005–2006 and 2014–2015 periods show deviations from expected death rates, likely due to health events or natural disasters (i.e., Dengue, Chikungunya). The consistency of the predicted expected death rate (magenta line) underscores the model's robustness in capturing baseline trends across demographics.

Figure 3 shows expected death rates per 100,000 in Puerto Rico (2002–2016), stratified by age group and sex (side by side for easier comparability). Across all groups, especially 75+, males consistently have higher predicted rates and greater variability than females.

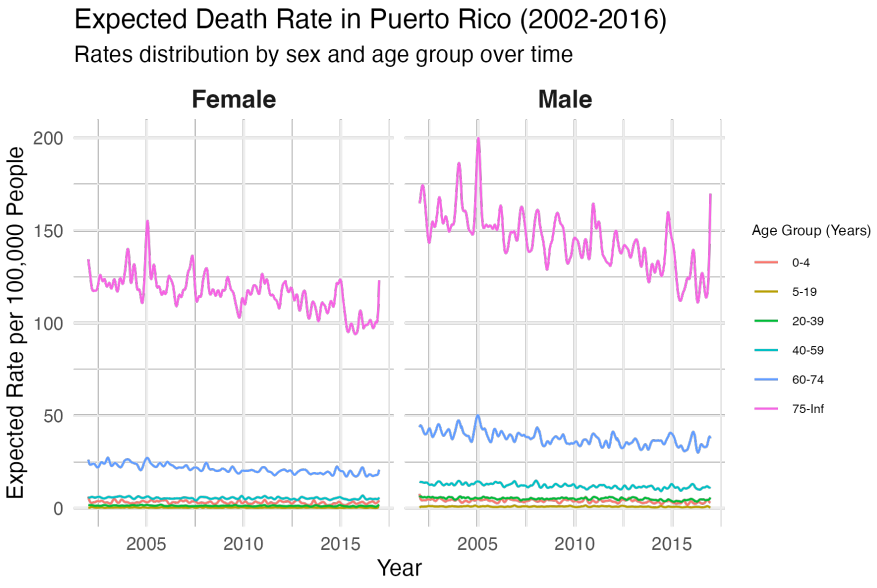

Figure 3. Expected Death Rate in Puerto Rico Over Time

Figure 4 illustrates the percentage increase in observed mortality rates compared to expected death rates in Puerto Rico, stratified by age group and sex, from September 2016 to September 2018. Observed data points are represented as gray dots, while the blue lines indicate the modeled percentage increase in mortality. The shaded regions around the blue lines represent 95% confidence intervals.

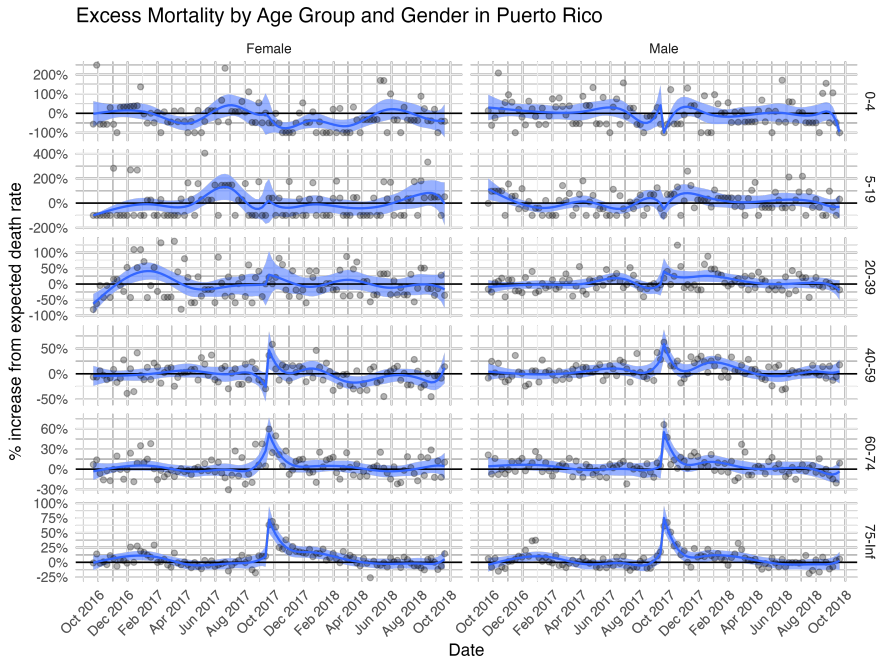

Figure 4. Excess Mortality in Puerto Rico Within 1 Year From Hurricane María

When evaluating patterns by **age group**, we can evidence that in the **young age groups (0–4, 5–19)** the excess mortality is minimal, with observed rates aligning closely with expected rates, there are slight fluctuations in the confidence intervals that are clearly visible, but no significant spikes occur during the period studied. In the **middle age groups (20–39, 40–59)**, there is a more noticeable increases in excess mortality, particularly around late 2017, these spikes in the observed mortality align temporally with Hurricane María's impact, particularly in the 40–59 group (where the spike is more pronounced). In the **older age groups (60–74, 75+)**, there is the highest level of excess mortality, with pronounced spikes observed immediately following Hurricane María in September 2017.Mortality rates in the 75+ group increase sharply, almost exceeding 100% above expected rates at the peak of the event, followed by a gradual return to baseline by mid-2018. When evaluating patterns by **sex**, for most age groups, males and females experience similar patterns of excess mortality; however, the magnitude of increase tends to be slightly higher among males in the 40–59 years and 60–74 years groups.

Overall, significant increases in excess mortality are observed in late 2017, coinciding with Hurricane María's landfall in September 2017. The impact of the hurricane is particularly evident in older age groups, with sustained increases in mortality extending into early 2018. By mid-2018, excess mortality across most age groups and sexes appear to return to expected levels, reflecting a normalization of mortality trends.

Discussion

This study aimed to characterize and analyze mortality trends in Puerto Rico following Hurricane María, focusing on demographic variations by age and sex and identifying periods of excess mortality. By leveraging robust statistical modeling and comprehensive mortality data, the findings provide valuable insights into the hurricane's impact on public health and highlight specific populations most affected by the disaster. However, it is important to note that no formal statistical tests were conducted to compare differences among age groups or between sexes. As such, the observations presented in this study should be interpreted descriptively and not as definitive evidence of statistically significant differences.

Interpretation of Key Findings

The results reveal significant demographic trends in mortality before, during, and after Hurricane María. Puerto Rico's population has shifted notably, with declining younger populations and increasing elderly cohorts (Abel and Deitz (2014)). This underscores the importance of adjusting for age structure to avoid misestimating mortality burdens. The steady increase in those aged 60 and older aligns with global aging trends (World Health Organization (2024)) and partly explains higher baseline mortality rates in this group. From 2002 to 2016, mortality rates showed predictable seasonal and long-term trends, with occasional deviations tied to health events such as influenza and vector-borne disease outbreaks (i.e., Dengue fever and Chikungunya; Sharp et al. (2016), CDC (2006)). Excluding such periods when establishing baselines is critical. Consistency between observed and expected mortality during this time validates the robustness of the modeling approach.

Hurricane María caused a sharp mortality increase, particularly among older age groups (60–74 and 75+ years), where excess mortality nearly doubled at the peak, reflecting the profound vulnerability of elderly populations to these type of disasters. Middle-aged cohorts (40–59 years) saw moderate spikes, while younger groups (0–19 years) experienced minimal deviations, reflecting lower baseline risks and greater resilience or reliance on caregivers. Sex differences were observable, with males exhibiting what appears to be a slightly higher mortality rates and variability across all age groups. These differences, potentially linked to behaviors, health conditions, and access disparities, require cautious interpretation without formal statistical tests (as in this case).

Implications and Observational Findings

The temporal patterns of excess mortality after Hurricane María highlight both immediate and prolonged disaster impacts. The late-2017 spike likely reflects acute effects, such as injuries and disrupted infrastructure, while sustained excess mortality into 2018 may suggest delays in healthcare, exacerbated chronic conditions, and mental stress. These findings stress the need for disaster plans addressing short- and long-term health impacts, especially for vulnerable populations such as the elderly.

The relatively modest excess modest excess mortality in middle-aged groups (20–39 and 40–59 years) may reflect greater resilience/physiologic reserve and resource access compared to older populations but still indicates risks for those with possibly preexisting conditions. Higher variability and mortality among males suggest the need for targeted interventions addressing health behaviors and access barriers. The relative resilience of females may highlight protective factors worth exploring further with other validation studies. Again, these observations are descriptive and should not be overstated without formal statistical confirmation.

Limitations

Despite the robustness of the methods, this study has limitations. First, no formal statistical tests were conducted to compare differences among age groups or between sexes; therefore, the observed patterns are descriptive rather than inferential. Second, while the statistical model accounted for seasonal and demographic variations, unmeasured confounders such as economic disruptions, changes in healthcare infrastructure, baseline health differences across individuals, and other stressors were not included. These factors may have contributed to the observed mortality trends and should be addressed in future research. Another limitation is that we assumed consistent reporting practices for mortality data, and there is the potential for underreporting of mortality immediately following the hurricane due to disruptions in vital statistics systems.

Future Directions and Policy Implications

Research should explore Hurricane María's long-term health effects, particularly among the elderly and those with chronic conditions (and/or depleted physiologic reserve), and how disasters exacerbate health disparities. Examining the roles of sex, socioeconomic status, and healthcare access is crucial for addressing disaster-related inequalities. Policymakers must prioritize tailored disaster response systems, enhance rural healthcare infrastructure, and integrate sex- and age-specific considerations. Targeted interventions, such as improving medical access and community programs for the elderly, are essential to mitigate health impacts and reduce disaster-related mortality.

Conclusion

Hurricane María had a profound and disproportionate impact on mortality in Puerto Rico, with older age groups and males experiencing the greatest burden. While this study offers valuable descriptive insights, the lack of formal statistical testing underscores the need for caution in interpreting observed patterns. These findings underscore the importance of robust disaster preparedness and response systems that address demographic-specific vulnerabilities. By understanding the factors contributing to excess mortality, policymakers and researchers can develop targeted interventions to reduce the health impacts of future disasters and improve population resilience.

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