Differential and persistent risk of excess mortality from Hurricane Maria in Puerto Rico: a time-series analysis

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Summary

Background Hurricane Maria struck Puerto Rico on Sept 20, 2017, devastating the island. Controversy surrounded the official death toll, fuelled by estimates of excess mortality from academics and investigative journalists. We analysed all-cause excess mortality following the storm.

Methods We did a time-series analysis in Puerto Rico from September, 2017, to February, 2018. Mortality data were from the Puerto Rico Vital Statistics System. We developed two counterfactual scenarios to establish the population at risk. In the first scenario, the island’s population was assumed to track the most recent census estimates. In the second scenario, we accounted for the large-scale population displacement. Expected mortality was projected for each scenario through over-dispersed log-linear regression from July, 2010, to August, 2017, taking into account changing distributions of age, sex, and municipal socioeconomic development, as well as both long-term and seasonal trends in mortality. Excess mortality was calculated as the difference between observed and expected deaths.

Findings Between September, 2017, and February, 2018, we estimated that 1191 excess deaths (95% CI 836–1544) occurred under the census scenario. Under the preferred displacement scenario, we estimated that 2975 excess deaths (95% CI 2658–3290) occurred during the same observation period. The ratio of observed to expected mortality was highest for individuals living in municipalities with the lowest socioeconomic development (1·43, 95% CI 1·39–1·46), and for men aged 65 years or older (1·33, 95% CI 1·30–1·37). Excess risk persisted in these groups throughout the observation period.

Interpretation Analysis of all-cause mortality with vital registration data allows for unbiased estimation of the impact of disasters associated with natural hazards and is useful for public health surveillance. It does not depend on certified cause of death, the basis for the official death toll in Puerto Rico. Although all sectors of Puerto Rican society were affected, recovery varied by municipal socioeconomic development and age groups. This finding calls for equitable disaster preparedness and response to protect vulnerable populations in disasters.

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Introduction On Sept 20, 2017, category 4 Hurricane Maria affected every region of Puerto Rico, devastating its infrastructure and disrupting its organisations. The intensity of hurricanes has continually increased globally with an even larger destructive potential per storm.1 In the aftermath of Maria, a controversy erupted over hurricane-related mortality. By December, 2017, the Puerto Rico Government certified 64 deaths related to Hurricane Maria. Public perception was that mortality was higher than that in the government’s report.2 In ensuing months, research by academics and investigative journalists estimated mortality to be much higher than the official count, between 800 and 100 excess deaths.3,4 Survey-based research provided the highest estimate of 4645 deaths, fuelling public debate and uncertainty.⁵

As a result, the Puerto Rico Government commissioned the Milken Institute School of Public Health at The George Washington University (Washington, DC, USA) for an independent assessment of post-hurricane excess mortality and evaluations of death certification, as well as public risk communication processes.⁶ The research was done with the Graduate School of Public Health of the University of Puerto Rico (San Juan, Puerto Rico).

We aimed to investigate all-cause mortality associated with Hurricane Maria.

Methods Data sources All data used in this time-series analysis are from officially published or collected federal or commonwealth sources. We obtained vital registration mortality data, including deaths by age, sex, and residential municipality, for July 1, 2010, to Feb 28, 2018, from the Puerto Rico Vital Statistics System. We derived baseline population size estimates in each month from US Census Bureau annual estimates.
Research in context

Evidence before this study
Accounting for deaths is a priority to assess the magnitude of a disaster and to orient interventions. After Hurricane Maria in Puerto Rico, government-certified death counts were questioned. We did not do a systematic review, but we reviewed journals and the grey literature for methods on mortality surveillance, death certification, reporting of direct and indirect deaths, and registration quality in disasters caused by natural hazards such as hurricanes, as well as man-made disasters such as wars. No language restrictions were applied. Several analyses attempted to estimate all-cause mortality attributable to the hurricane using vital registration data. These analyses used different strategies for estimating counterfactual mortality—or what mortality would have been if the storm had not occurred—and different methods for producing estimates. Experts from the US Centers of Disease Control and Prevention recognised a lack of a standardised methodology for analysis of disaster-related mortality data.

Added value of this study
This study considered longer timeframes and more diverse information sources than did previous studies and reports.

Unlike previous studies, this study also modelled the time-series and the effect of a large population displacement. This study provides the methodology for a reproducible, unbiased quantification of post-disaster all-cause excess mortality, through the application of time-series analysis methods to government mortality data. The approach accounts for seasonality of mortality, age, demographic changes, population displacement (before and after the disaster), socioeconomic, and geographical differences. The study emphasises the importance of carefully establishing and defining the counterfactual estimate of what mortality would have been if a disaster such as Hurricane Maria had not occurred. We attempted identification of municipalities at greater risk and addressed issues with the choice of time-series from which this counterfactual is drawn and, most importantly, accounted for population displacement after a disaster. The study identified differential mortality by municipal socioeconomic development, as well as by age and sex. We estimated that 2975 excess deaths (95% CI 2658–3290) occurred between September, 2017, and February, 2018, under the displacement scenario. The ratio of observed to expected mortality was highest for individuals living in municipalities with the lowest socioeconomic development (1·43, 95% CI 1·39–1·46), and for men aged 65 years or older (1·33, 95% CI 1·30–1·37).

Implications of all the available evidence
The study shows that all-cause excess mortality based on registry surveillance is a practical public health approach to identify the overall impact of a disaster, and to monitor conditions after a disaster associated with natural hazards. This approach could become a standard methodology for post-disaster mortality data analysis and public health performance assessment. Since excess mortality for all affected groups in Puerto Rico did not return to baseline by February, 2018, in future practice the mortality surveillance system should incorporate the model into its routine monitoring of mortality and extend the analysis incorporating the data on all covariates as they become available. All systems should consider stratification by socioeconomic development and the ageing population for equity in the future implementation of interventions. It is crucial that governments and global institutions concerned about disasters agree on total excess mortality as a practical, timely, and sensitive indicator for impact assessment and monitoring. Quantification of the magnitude of a disaster’s mortality impact, with reduced uncertainty, greatly enhances policy makers’ capacity to develop and implement interventions to protect against the loss of life, morbidity, and disability, and to identify socioeconomically vulnerable locations in greater need of resource allocation.

by age, sex, and residential municipality.19 We estimated cumulative monthly population displacement after the hurricane using US Bureau of Transportation Statistics data on monthly net domestic migration provided by the Puerto Rico Institute of Statistics and a Puerto Rico Planning Board survey of airline travellers.18

The George Washington University Institutional Review Board exempted the project because it posed minimal risk.

Determination of the counterfactual
Estimation of excess mortality from disasters associated with natural hazards requires establishing a counterfactual estimate of mortality had the disaster not occurred.15 In a time-series analysis, determination of the counterfactual crucially requires establishing the previous period for counterfactual estimation and an appropriate analytical strategy for that series.12 If the previous period chosen is too short, the counterfactual estimate might be biased because of short-term systematic (such as seasonal) or random fluctuations in the outcome under consideration. If the estimate is too long, and both long-term and systematic short-term variation are not accounted for analytically, the counterfactual estimates might also be biased.

An appropriate counterfactual must also account for the size of, and changes to, the at-risk population distribution over the series. We identified three stratifying dimensions for consideration: age, sex, and socioeconomic development of residential municipality. In all analyses, age was categorised as 0–39 years, 40–64 years, and 65 years or older, reflecting substantial differences in the profile of the risk of mortality under normal circumstances. Sex was defined as male and female. The Municipal Socioeconomic Development Index (SEI),14 which captures the underlying strength of municipal-level structural and institutional capacities, was grouped by tertiles (appendix).
We defined two population counterfactual scenarios for analysis. The first, census counterfactual scenario, assumes that the change rate in the resident population composition and distribution was the same before the hurricane as after the hurricane. The second, displacement counterfactual scenario, estimates cumulative excess net migration from Puerto Rico from September, 2017, to February, 2018, and decrements excess migration from the census population estimates in these months.

Census counterfactual estimates of population size by strata of age, sex, and municipality of residence, aggregated to SEI tertiles from July 1, 2010, to July 1, 2017, were derived from annual census estimates. Projections for July 1, 2018, were made through stratum-specific regressions of population size from 2010 to 2017 on a quadratic specification of year. Monthly estimates over the entire series were interpolated with a cubic spline between July 1 of each year and adjusted to represent stratum-specific population size on day 15 of each month.

For the displacement counterfactual, we used net domestic air travel data from August, 2009, to February, 2018, from the Bureau of Transportation Statistics and proportions of travellers in each stratum estimated from the Puerto Rico Planning Board survey of air travellers to develop model-based estimates of excess migration by stratum at mid-month from September, 2017, to February, 2018.

Descriptive analyses
We described Puerto Rico’s crude mortality by age, sex, and month, before and after the hurricane. We compared estimated age-standardised mortality from July, 2017, to February, 2018, to mortality in the same period on a yearly basis from 2010 to 2017, using mid-2015 as the standard population, which allowed us to assess the degree of variation over time and departures from these trends after the hurricane. To describe differences by residential municipality, we compared crude mortality from September, 2017, to February, 2018, to mean mortality in the same period over 2015–16. We looked only at these years to reduce the influence of demographic changes.

Statistical analysis
We estimated the counterfactual estimation of all-cause mortality with a series of generalised linear models (GLMs)—specifically, over-dispersed log-linear regressions fit to monthly data for the pre-hurricane period of July, 2010, to August, 2017, of the general form:

$$\log(E(Y)) = \log(n_i) + x_i \beta$$

where i indexes the strata defined by the intersection of age, sex, and municipal SEI; t indexes month and year; $E(Y)$ is the expected number of deaths for each stratum or month combination; $n$ is the population at risk of dying [$\log(n)$ is called an offset] corresponding to Y; and $x$ is the vector of covariates that includes a smooth longer-term trend over the 86-month period, seasonal variation, and different specifications of dependence on the covariates age (three categories, 0–39 years, 40–64 years, and ≥65 years), sex (male or female), and SEI (tertiles of the SEI). $\beta$ is the vector of coefficients associated with these covariates. Under the null assumption that Hurricane Maria caused no excess deaths, we used the fitted model predictions as the counterfactual estimates for each month between September, 2017, and February, 2018. Our estimates of excess all-cause mortality from Hurricane Maria are the differences between

| Month             | Observed deaths | Predicted deaths | Excess deaths (95% CI) | Ratio of observed to expected mortality |
|-------------------|-----------------|------------------|------------------------|----------------------------------------|
| September, 2017   | 2506            | 2332             | 174 (515–630)         | 1.25                                   |
| October, 2017     | 2915            | 2332             | 583 (635–757)         | 1.30                                   |
| November, 2017    | 2657            | 2332             | 325 (285–409)         | 1.25                                   |
| December, 2017    | 2797            | 2332             | 465 (416–543)         | 1.21                                   |
| January, 2018     | 2799            | 2332             | 467 (497–620)         | 1.25                                   |
| February, 2018    | 2434            | 2332             | 320 (260–379)         | 1.15                                   |
| September-October, 2017 | 5921            | 4650             | 1271 (1154–1383)      | 1.27                                   |
| September-December, 2017 | 11375           | 9277             | 2098 (1872–2315)      | 1.23                                   |
| September, 2017, to February, 2018 | 16608          | 13633            | 2975 (2658–3290)      | 1.22                                   |

| Month             | Observed deaths | Population Deaths | Estimated excess deaths (95% CI) | Ratio of observed to expected mortality |
|-------------------|-----------------|-------------------|----------------------------------|----------------------------------------|
| September, 2017   | 787031          | 102              | 90                               | 12 (5–19)                              |
| October, 2017     | 779080          | 134              | 94                               | 40 (32–47)                             |
| November, 2017    | 768840          | 102              | 100                              | 2 (–6 to 9)                            |
| December, 2017    | 761373          | 124              | 101                              | 23 (15 to 30)                          |
| January, 2018     | 755020          | 129              | 94                               | 35 (28 to 42)                          |
| February, 2018    | 750671          | 91               | 84                               | 7 (0 to 13)                            |
| September-October, 2017 | 783056          | 236              | 184                              | 52 (38 to 64)                          |
| September-December, 2017 | 774081         | 462              | 386                              | 76 (53 to 98)                          |
| September, 2017, to February, 2018 | 767002         | 682              | 564                              | 118 (90 to 146)                        |
Table 2: Excess mortality after Hurricane Maria by sex and age under the displacement scenario

| Age            | Population | Deaths | Estimated excess deaths (95% CI) | Ratio of observed to expected mortality (95% CI) |
|----------------|------------|--------|---------------------------------|-----------------------------------------------|
|                | Observed   | Expected|                                 |                                               |
| 40–64 years of age (Continued from previous page) |           |        |                                 |                                               |
| **Men**        |            |        |                                 |                                               |
| September, 2017 | 495 551    | 358    | 274                             | 84 (72 to 95)                                 |
| October, 2017  | 485 463    | 316    | 274                             | 42 (29 to 54)                                 |
| November, 2017 | 471 518    | 331    | 280                             | 51 (38 to 63)                                 |
| December, 2017 | 465 218    | 368    | 291                             | 77 (64 to 90)                                 |
| January, 2018  | 456 549    | 311    | 291                             | 70 (57 to 83)                                 |
| February, 2018 | 453 774    | 308    | 279                             | 57 (44 to 70)                                 |
| September-October, 2017 | 490 527   | 674    | 548                             | 126 (102 to 149)                              |
| September-December, 2017 | 478 948   | 1373   | 1119                            | 254 (213 to 294)                              |
| November, 2017  | 557 358    | 176    | 160                             | 16 (9 to 24)                                  |
| December, 2017  | 551 856    | 159    | 167                             | 8 (4 to 11)                                   |
| January, 2018   | 547 446    | 185    | 168                             | 17 (9 to 24)                                  |
| February, 2018  | 545 421    | 129    | 161                             | 72 (51 to 92)                                 |
| September-October, 2017 | 569 600   | 346    | 307                             | 39 (26 to 53)                                 |
| September-December, 2017 | 562 104   | 681    | 633                             | 48 (33 to 72)                                 |
| February, 2018  | 556 880    | 995    | 963                             | 32 (26 to 65)                                 |
| **Women**      |            |        |                                 |                                               |
| September, 2017 | 527 870    | 168    | 153                             | 15 (8 to 22)                                  |
| October, 2017   | 566 330    | 178    | 154                             | 24 (17 to 31)                                 |
| November, 2017  | 557 358    | 176    | 160                             | 16 (9 to 24)                                  |
| December, 2017  | 551 856    | 159    | 167                             | 8 (4 to 11)                                   |
| January, 2018   | 547 446    | 185    | 168                             | 17 (9 to 24)                                  |
| February, 2018  | 545 421    | 129    | 161                             | 72 (51 to 92)                                 |
| September-October, 2017 | 569 600   | 346    | 307                             | 39 (26 to 53)                                 |
| September-December, 2017 | 562 104   | 681    | 633                             | 48 (33 to 72)                                 |
| February, 2018  | 556 880    | 995    | 963                             | 32 (26 to 65)                                 |

a≥65 years of age

| Age            | Population | Deaths | Estimated excess deaths (95% CI) | Ratio of observed to expected mortality (95% CI) |
|----------------|------------|--------|---------------------------------|-----------------------------------------------|
|                | Observed   | Expected|                                 |                                               |
| **Men**        |            |        |                                 |                                               |
| September, 2017 | 275 520    | 1131   | 873                             | 258 (234 to 281)                               |
| October, 2017  | 259 943    | 1132   | 849                             | 283 (258 to 307)                               |
| November, 2017 | 237 043    | 992    | 814                             | 178 (155 to 201)                               |
| December, 2017 | 222 038    | 1076   | 794                             | 282 (253 to 306)                               |
| January, 2018  | 209 674    | 1078   | 749                             | 329 (307 to 352)                               |
| February, 2018 | 205 774    | 971    | 701                             | 270 (248 to 291)                               |
| September-October, 2017 | 267 732   | 2263   | 1722                            | 541 (493 to 586)                               |
| September-December, 2017 | 248 636   | 4331   | 3330                            | 1001 (916 to 1084)                             |
| February, 2018  | 234 999    | 6380   | 4780                            | 1600 (1483 to 1715)                            |
| **Women**      |            |        |                                 |                                               |
| September, 2017 | 368 646    | 1117   | 912                             | 205 (180 to 230)                               |
| October, 2017  | 358 746    | 1219   | 915                             | 304 (277 to 329)                               |
| November, 2017 | 343 763    | 1030   | 922                             | 108 (81 to 135)                                |
| December, 2017 | 333 745    | 1039   | 932                             | 107 (80 to 134)                                |
| January, 2018  | 325 565    | 1074   | 908                             | 166 (139 to 192)                               |
| February, 2018  | 322 251    | 909    | 861                             | 48 (21 to 74)                                  |
| September-October, 2017 | 361 696   | 2336   | 1827                            | 509 (459 to 559)                               |
| September-December, 2017 | 351 225   | 4405   | 3680                            | 725 (629 to 816)                               |
| February, 2018  | 342 286    | 6388   | 5449                            | 939 (801 to 1067)                              |

We used over-dispersed log-linear regression instead of Poisson regression because the variation in the number of monthly deaths is greater than its mean, violating a basic condition of the Poisson model.14 Over-dispersed log-linear models produce the same estimates but different assessments of uncertainty compared with Poisson regression.

In all GLMs, the longer-term trend was approximated by a natural spline of time with 2 degrees of freedom (df). Seasonality is modelled in two ways: with a series of monthly indicator variables (11 df), or with a more parsimonious periodic function of the form:

$$\frac{\cos \left( \frac{2\pi t}{12} \right) + \sin \left( \frac{2\pi t}{12} \right)}{\cos \left( \frac{2\pi t}{6} \right) + \sin \left( \frac{2\pi t}{6} \right)}$$

where $t$ is the calendar month. We denominated seasonality as the trigonometric form of the variable in the tables and figures.

For each specification of seasonality, we estimated four models. Model 1 serves as the baseline, estimating mortality as an additive function of the covariate stratum defined by interaction between age, sex, and socioeconomic development specified as indicator variables, the smooth trend, and the seasonal variation. Model 2 extends model 1, allowing the seasonal effect to interact both with age and a halfway indicator separating the observation period before and after July, 2014, to account for the apparent increase in seasonal variability observed in this period’s crude death rate. Model 3 is identical to model 2, except that the three-way interaction between age, sex, and socioeconomic development, as well as the two-way interaction between socioeconomic development and sex are constrained to be zero. Model 4 is the fully saturated version of model 3, specifying interactions between the stratum specification in that model, the annual trend, and seasonality.

In addition, we fitted a generalised additive model (GAM), assuming Poisson distribution, analogous to model 3. We used GAM to add a smoother function of year with stratum interactions, keeping month as a factors predictor, and to choose the degrees of smoothness to optimise estimates of prediction error.7 As such, GAMs are a more flexible alternative to, and specification check on, the GLMs (appendix).

Estimates of expected mortality and CIs in all models were obtained through parametric bootstrapping to estimate the joint mean and covariance matrix of the counterfactual predictors. We approximated the joint distribution of the regression coefficients by a Gaussian distribution, with mean equal to the maximum likelihood estimate and variance equal to its asymptotic covariance matrix that includes adjustment for the over-dispersion. The CIs presented only reflect uncertainty in the estimates of these counterfactual estimates and the observed mortality in these months.
of the expected numbers of deaths for a particular parametric model. Another relevant measure of uncertainty is the prediction interval, which estimates the uncertainty between the observed deaths and their counterfactual value for that single year. A prediction interval includes the uncertainty in the mean value like the CI, but adds the uncertainty due to the variation from year to year in the period before the hurricane. Our methods and estimates of prediction intervals involve more technical details and will be reported elsewhere.

Role of the funding source
The funder of the study facilitated access to the data but had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results
2119–2862 deaths occurred monthly in Puerto Rico between July, 2010, and July, 2017, the period of observation before the hurricane (data available online). 16860 people died between September, 2017, and February, 2018, (table 1); 9054 were men and 7554 were women (table 2). Age and sex noted previously appear to have reversed in the placement scenario (figure 1). Of particular note, after 2014, this mortality showed a pronounced seasonality, peaking in mid-level Municipal Socioeconomic Development Index, under the displacement scenario and January under the census scenario, but remaining higher than returning to the general seasonal pattern in November under the census scenario and January under the displacement scenario (figure 1). Mortality showed a pronounced seasonality, peaking in winter and early spring. Of particular note, after 2014, this seasonal variation increased (figure 1).

No substantive difference in mortality was observed from the general pattern for the younger age group in any month (figure 1). For the 40–64 years age group, we saw an increase in mortality relative to previous years in September, October, and November, returning to within the general range seen in other years in December under the census scenario and January under the displacement scenario (figure 1). Among the population aged 65 years or older, mortality was higher in September and October, returning to the general seasonal pattern in November under the census scenario, but remaining higher than previous years throughout the period under the displacement scenario (figure 1).

The disaster’s impact on mortality was greater for men than for women (figure 2). The declining trends by age and sex noted previously appear to have reversed in the period between September, 2017, and February, 2018, most substantially under the displacement scenario.

When comparing the age-standardised monthly mortality from September, 2017, to February, 2018, with specific earlier years, we saw significant differences. Under
the census scenario, the mortality ratio in October, 2017, increased by 27% (95% CI 20–34) compared with October, 2016 (table 5). A similar pattern was observed with the 2015 comparison, but not with the 2014 comparison (table 5).

Under the displacement scenario, a significant increment of 7% (95% CI 2–13) was shown when mortality in October, 2017, was compared with that in October, 2014 (table 5). Under the census scenario, mortality in February, 2018, did not show significant differences with other years; however, under the displacement scenario, all the comparisons showed significant differences (table 5).

The largest post-hurricane mortality differentials were concentrated in the island’s northeast, and to a lesser extent, southwest portions (figure 3). Overall, mortality significantly increased in approximately 40% of municipalities (based on two sample tests of proportions; figure 3).

Mortality was disproportionately higher among populations in municipalities in the lowest SEI tertile than in those in other municipalities (figure 4).

Fit statistics for each model estimated—including the ratio between deviance and residual degrees of freedom and sensitivity, defined as the percentage of interval estimates containing the observed monthly mortality over the entire series and in the 1 and 2 years before September, 2017—are shown in table 2. In both the monthly and trigonometric specifications, models 2 and 3 had the lowest ratio of deviance to degrees of freedom, indicating better model fit. Comparing the first three models, relative to the specification of seasonality with monthly indicators over the 6 months under observation, the trigonometric specification consistently predicts slightly greater numbers of deaths in September, November, and February, and slightly lower numbers of deaths in October, December, and January (appendix). Model 1, controlling only for stratum, seasonal, and annual trends, consistently predicts fewer deaths than models 2 and 3, which also allow for the seasonal pattern to vary by age and between the two periods defined before and after July, 2014. Model 3’s more parsimonious specification, allowing only main effects of the covariates and interactions between age and sex, and age and municipal SEI, predicts virtually identical numbers of deaths in each month as model 2, which saturates interactions in the covariates (tables 2, 3, 5). Model 4’s specification, compared with models 1–3, exhibits irregular deviations in predicted deaths by month and is an unrealistic model for generalisation and prediction, conforming closely to patterns of random variation over time (appendix).

Figure 1: Age-standardised and age-specific monthly mortality by year in Puerto Rico
2017–18 estimates are presented under both the census and displacement scenarios. (A) Age-standardised mortality by month from July to February for each year from 2010–11 to 2017–18. (B) Age-specific mortality from July to February for each year from 2010–11 to 2017–18.
Table 5: Age-standardised mortality rate ratios in Puerto Rico by month

| Month            | September | October | November | December | January | February |
|------------------|-----------|---------|----------|----------|---------|----------|
| 2017 vs 2016 SRR | 1.22 (1.16–1.29) | 1.27 (1.20–1.34) | 1.07 (1.01–1.13) | 0.98 (0.93–1.04) | 1.01 (0.96–1.06) | 0.93 (0.88–0.98) |
| 2017 vs 2015 SRR | 1.27 (1.20–1.34) | 1.24 (1.17–1.31) | 1.16 (1.09–1.22) | 1.10 (1.04–1.16) | 1.00 (0.94–1.05) | 0.99 (0.93–1.04) |
| 2017 vs 2014 SRR | 1.13 (1.07–1.19) | 1.01 (0.96–1.07) | 0.98 (0.93–1.03) | 0.95 (0.90–1.00) | 1.08 (1.02–1.14) | 1.06 (1.00–1.12) |
| 2017 vs 2013 SRR | 1.12 (1.07–1.19) | 1.21 (1.14–1.27) | 1.12 (1.06–1.19) | 1.07 (1.01–1.13) | 0.91 (0.86–0.97) | 1.03 (0.97–1.08) |
| 2017 vs 2012 SRR | 1.11 (1.05–1.17) | 1.16 (1.10–1.22) | 1.01 (0.96–1.07) | 1.02 (0.97–1.08) | 0.99 (0.94–1.04) | 0.91 (0.86–0.97) |
| 2017 vs 2011 SRR | 1.13 (1.07–1.19) | 1.11 (1.06–1.18) | 1.04 (0.98–1.10) | 0.98 (0.93–1.03) | 0.93 (0.88–0.98) | 0.94 (0.88–0.99) |
| 2017 vs 2010 SRR | 1.14 (1.08–1.21) | 1.10 (1.04–1.16) | 0.95 (0.90–1.01) | 0.91 (0.86–0.96) | NA         | NA       |
| Range            | 1.11–1.27 | 1.01–1.27 | 0.95–1.16 | 0.91–1.11 | 0.91–1.08 | 0.91–1.06 |
| Median (IQR)     | 1.13 (1.12–1.22) | 1.16 (1.10–1.24) | 1.04 (0.98–1.12) | 0.98 (0.95–1.07) | 0.99 (0.93–1.01) | 0.99 (0.93–1.05) |

Data are SRR (95% CI), unless otherwise stated. Puerto Rico age distribution in 2015 is the standard population. SRR=standardised rate ratio. NA=not applicable.

Figure 2: Age-standardised monthly mortality by sex in Puerto Rico

Age-standardised monthly mortality by sex from July, 2010, to February, 2018. 2015 is used as the standard population under the census and displacement scenarios.

Median (IQR) for Male census from July, 2010, to February, 2018, 2015 is used as the standard population under the census and displacement scenarios.
Although both the monthly and seasonal specifications adequately capture fluctuations due to seasonal variation, the trigonometric form of seasonality smooths the exaggerated variability from month to month seen in the other specification (figure 5), which is more sensitive to spikes probably associated with periodic winter increases in viral mortality, which we believe was not likely a factor in the post-hurricane period.18 As such, we believe the trigonometric specification model 3 is the preferable mortality measure over this series with which to project expected mortality in the period after the hurricane, although it should be noted that marginal predicted excess deaths under each model are almost identical (appendix).

By use of our preferred model (model 3), we estimated 1271 excess deaths (95% CI 1154–1383) in September–October, 2017; 2098 excess deaths (1872–2315) from September–December, 2017; and 2975 excess deaths (2658–3290) across the entire 6-month period (table 1). Under the census scenario, we estimated 1077 excess deaths (95% CI 952–1193) for September–October, 2017; 1237 excess deaths (993–1471) for September–December, 2017; and 1191 excess deaths (836–1544) for September, 2017, to February, 2018 (appendix).

Although municipalities at all SEI tertiles were affected by the hurricane, the greatest impact in terms of relative mortality increase was in the lowest SEI tertile (table 3). The middle and upper SEI tertile municipalities saw immediate decreases in excess mortality ratios after September, 2017, with small variation from month to month. Municipalities in the lowest category saw continual increases through December, 2017. The lowest SEI tertile had 43% higher than expected mortality (ratio of observed to expected deaths 1·43, 95% CI 1·39–1·46) from September, 2017, to February, 2018, and highest SEI tertile had 17% (table 3).

The largest impact of the hurricane was on the older population in all months, particularly individuals aged 65 years or older. From September, 2017, to February, 2018, the ratio of observed to expected mortality was highest for men aged 65 years or older (1·33, 95% CI 1·30–1·37). A disproportionately higher number of male individuals of all ages died in all months than female individuals (table 2). Increased mortality due to the hurricane was observed for males over a longer period than for females at all ages. The impact on women, especially younger women, declined rapidly after October, 2017, whereas it persisted through February, 2018, for males (table 2).

**Discussion**

Our study presents a methodology for an unbiased estimation of post-disaster excess mortality through a time-series analysis using vital registry and other official government data. This method can be applicable for Puerto Rico, the USA, and globally. Although measurement error is an issue with all data, we believe that these sources are the most complete and accurate available for this analysis. This Article addresses the lack of standardised methodology for analysis of disaster-related mortality,19 and it provides a point estimate with a relatively narrow CI for excess mortality. This greater degree of certainty helps to move to the next stage of interventions.

The official government estimate of 64 deaths from the hurricane was low because they based their mortality count on attribution of deaths to the hurricane in death certificates. During our broader study, we found that many physicians were not familiar with the appropriate certification protocol, which translated into an inadequate indicator for monitoring mortality in the hurricane’s aftermath.

Several previous registration-based analyses have produced estimates of all-cause mortality related to Hurricane Maria between 822 and 1052 excess deaths.6–7 Key differences between these estimates and those presented here include the definition of the counterfactual period, the adjustment for long-term trends (where applicable), seasonal trends, and the population at risk of mortality. Such estimates are consistent with those reported here for the same time period under the census counterfactual
(1077, 95% CI 952–1193; appendix), which is the appropriate comparison because none attempted to account for post-hurricane population displacement. Another study, based on self-reported deaths from a household survey, estimated excess mortality from Sept 20, 2017, to Dec 31, 2017, to be 4645 (95% CI 793–8498). However, this estimate was biased because it was not conditional on household size.

We produce what we conclude are appropriate estimates of all-cause excess mortality due to Hurricane Maria by month and by various aggregate periods to allow comparison of our results to previous ones. This study’s strengths include estimation of predicted mortality based on a long counterfactual period that allows for adjustment for long-term and seasonal trends in mortality; appropriate adjustment for changes in population size and distribution by age, sex, and SEI over the period; and, in the displacement scenario, adjustment for the massive population displacement occurring in the hurricane’s immediate aftermath. Massive population displacement unequivocally has to be considered in the analysis.

A limitation of using mortality as an indicator of the overall impact of disasters on health is that it does not quantify the elevated burden of disease from morbidity and disability or large impacts on the health-care system. Our research does not attempt to address these factors, but there is a pressing need to do so.

Our operational definitions of covariates to adjust for age and municipal level effects were limited. Given the relatively small numbers of deaths in Puerto Rico in the period under observation before the storm (monthly range 2119–2862), strata along the dimensions of age, sex, and municipality were defined broadly to preserve monthly stratum-specific cell sizes that could yield accurate and efficient estimates. More finely defined strata—e.g., which allow estimates of the hurricane’s effects on infants and children or on the individual municipal level—were not possible.

All information on covariates was from official government sources. Our estimates of the number of deaths and population size are as accurate as possible, with currently available data and concordant with most other preliminary estimates. The distribution along these dimensions in 2018 based on the census data we used is an estimate—one that is subject to change with any future revisions published by the Census Bureau. Although official census estimates of population size and distribution after September, 2017, had the hurricane not occurred will never be produced, we believe those that we have presented here would have proved to be highly accurate if they existed. The population at risk under the displacement counterfactual, based on decrements of excess migration to the census estimates, is also potentially subject to revision. Since the review of this paper for publication, for example, the Puerto Rico Institute of Statistics published a blog comment modifying the net migration data for January and February, 2018. Our initial review of these revisions suggests that they would result in only minor differences to the results published here (appendix).

Because the Puerto Rico Institute of Statistics has not yet provided enough statistical information to evaluate these new estimates, we have not included these revisions in this paper. Accounting for revisions in officially published data is a limitation of any secondary data analysis; however, it is also a strength, allowing for a continuous use of such data in surveillance to update the trends in the statistics produced by these analyses.

Differences in the functional forms and estimation methods used in our multivariate models might yield slightly different estimates from those presented here. We
believe our models’ sensitivity with regard to monthly mortality and the general convergence of the GLM monthly and trigonometric functions of seasonality and the GAM results suggest that our estimates are relatively insensitive to changes in functional form given the covariate set we use.

Hurricane Maria affected Puerto Ricans of all ages, sex, and socioeconomic groups, and the heterogeneous mortality distribution calls for action.25 6 months after the disaster, the poorest and oldest males remained at risk for excess mortality, underscoring the need for equitable disaster preparedness policies and response policies that protect the most vulnerable populations.

All-cause excess mortality is a useful indicator to monitor progress, and the method presented in this Article can be added to the standards for disaster-related mortality analysis for use throughout the USA and globally. This method can help to identify the most vulnerable groups and target them for intervention and care until indicators return to baseline conditions. Use of deaths certified as hurricane-related as the indicator for monitoring mortality underestimated the existing problem. Recovery is a multiyear process, and public health-relevant research is crucial to understand the causal pathways of the conditions that lead to extended duration of morbidity and time to death and to establish protective measures for future disasters. The strengthening of public health surveillance, including the Puerto Rico Vital Statistics System and the death certification process, depend on this understanding. Next, public health actions require building resilient public health systems, identifying the context surrounding excess deaths, with disproportionately more resources targeted to those in disadvantaged groups, both immediately after the hurricane and in the months that follow.

Contributors
CS-B is the principal investigator of this study, and along with LG, first conceived the study, prepared the proposal, and secured funding for it. CS-B and JS contributed equally to the study design, development of methods, data analysis, data interpretation, and writing of this manuscript. SZ and ES equally participated in the development of methods and analysis of excess mortality with contributions by NE-M. AG-H served as project coordinator and, along with AG-M, had a key role in the acquisition and organisation of data and in writing of the manuscript. CMP, UC-R, and CMN contributed to the discussion of the methodology and results. AR contributed to the discussion of methods and results, and review of the manuscript. EA reviewed the manuscript and approved the final version of the paper.

Declaration of interests
We declare no competing interests.

Data sharing
We have made all code and data sources for generating our results, tables, and figures available at https://prstudy.publichealth.gwu.edu/datasets.

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