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Journal
Proceedings of the National Academy of Sciences, 120(50)

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Publication Date
2023-12-12

DOI
10.1073/pnas.2218789120

Peer reviewed

RESEARCH ARTICLE | ENVIRONMENTAL SCIENCES

Excess risk in infant mortality among populations living in flood-prone areas in Bangladesh: A cluster-matched cohort study over three decades, 1988 to 2017

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Edited by B. Turner, Arizona State University, Tempe, AZ; received November 2, 2022; accepted October 24, 2023

The Ganges–Brahmaputra–Meghna river basin, running through Tibet, Nepal, Bhutan, Bangladesh, and northern India, is home to more than 618 million people. Annual monsoons bring extensive flooding to the basin, with floods predicted to be more frequent and extreme due to climate change. Yet, evidence regarding the long-term impacts of floods on children's health is lacking. In this analysis, we used high-resolution maps of recent large floods in Bangladesh to identify flood-prone areas over the country. We then used propensity score techniques to identify, among 58,945 mothers interviewed in six demographic population-based surveys throughout Bangladesh, matched cohorts of exposed and unexposed mothers and leverage data on 150,081 births to estimate that living in flood-prone areas was associated with an excess risk in infant mortality of 5.3 (95% CI 2.2 to 8.4) additional deaths per 1,000 births compared to living in non-flood-prone areas over the 30-y period between 1988 and 2017, with higher risk for children born during rainy (7.9, 95% CI: 3.3 to 12.5) vs. dry months (3.1, 95% CI: –1.1 to 7.2). Finally, drawing on national-scale, high-resolution estimates of flood risk and population distribution, we estimated an excess of 152,753 (64,120 to 241,386) infant deaths were attributable to living in flood-prone areas in Bangladesh over the past 30 y, with marked heterogeneity in attributable burden by subdistrict. Our approach demonstrates the importance of measuring longer-term health impacts from floods and provides a generalizable example for how to study climate-related exposures and long-term health effects.

climate change and health | flooding | children's health | Bangladesh | infant mortality

Significance

As a result of climate change, populations are predicted to experience more frequent and extreme flooding events in the coming decades. This is particularly true in Bangladesh, a country with low elevation and where annual monsoons bring extensive flooding to the Ganges–Brahmaputra–Meghna river basin. We estimated that infants born to mothers living in flood-prone areas had an 8% higher chance of dying by their first birthday compared to matched infants born to mothers living outside flood-prone areas of Bangladesh over the past 30 y, with important differences across space and over time. The approach illustrated here could be broadly useful for studies of climate-related exposures and their long-term health effects.

Anthropogenic CO_2 emissions and ecosystems degradation have increased the occurrence and magnitude of extreme weather events worldwide (1). Climate-sensitive events such as heat waves, extreme precipitation, cyclones, and floods impose large economic damages to human populations and directly threaten their health and survival (2–4). Among extreme climate events, large floods have increased worldwide with recent severe examples in Bangladesh (5, 6), South Africa, (7) or Pakistan (8) in 2022. The Ganges–Brahmaputra–Meghna river basin, running through Tibet, Nepal, Bhutan, Bangladesh, and northern India, is home to more than 618 million people (2010 data) and regularly floods during the annual monsoon (9). Even in the most optimistic scenarios considered by the Intergovernmental Panel on Climate Change (IPCC) (10), populations living in the region are predicted to experience more frequent and extreme flooding events in the coming decades.

Accurately assessing the human and financial toll in the aftermath of a disaster is essential, but for populations living in flood-prone areas and that are repeatedly exposed to large floods, longer-term health effects are plausible but understudied. In this context, children are a high-risk subgroup and flooding has been associated with adverse birth and child health outcomes (11, 12) through mechanisms that act over both short-term (e.g., exposure to contaminated water) and longer-term (e.g., social displacement) timescales. Most studies of health impacts from floods have focused on single events and to our knowledge no studies have assessed how effects have changed over time among populations that are consistently vulnerable to floods. Measuring excess health risks associated with living in flood-prone areas and how such risks have evolved in recent decades provides essential information for population preparedness and contributes estimates of health burden attributable to extreme climate events.

In low-resource settings, disproportionally affected by climate change (2), such long-term analyses are particularly difficult because of scarce environmental and health data. Large and nationally representative surveys such as Demographic Health Surveys (DHS) provide a unique opportunity to create high-resolution, longitudinal time series for infant mortality by combining birth history information across surveys. Satellites increasingly measure the earth's environment at a fine spatio-temporal resolution, and combining data from remotely sensed climate layers to geo-located DHS survey data creates an opportunity for

Author contributions: F.R., B.F.A., and T.B. designed research; F.R., B.F.A., and T.B. performed research; F.R., B.F.A., and T.B. contributed new reagents/analytic tools; F.R. and B.F.A. analyzed data; and F.R., B.F.A., and T.B. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Although PNAS asks authors to adhere to United Nations naming conventions for maps (https://www.un.org/geospatial/mapsgeo), our policy is to publish maps as provided by the authors.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2218789120/-/DCSupplemental.

Published December 5, 2023.

epidemiologic studies of climate-related exposures on long-term health outcomes in low- and middle-income settings (13).

We conducted a long-term study of infant mortality risk associated with living in flood-prone areas of Bangladesh, a country at the intersection of three major rivers flowing from the Himalayas where two thirds of the territory's elevation lies at or below 5 m. Every monsoon season—May to October—heavy rains lead to floods that often have devastating consequences for millions of people. In May 2022 for instance, 7.2 million people were affected by floods in nine districts and half a million were displaced (6). Infant mortality is an extreme outcome of climate-related exposures, but it is a useful outcome in this context because it likely integrates both acute and longer-term effects from floods. Infant mortality is a relatively rare outcome even in high-mortality populations, so estimating excess mortality risk associated with environmental exposures requires large cohorts monitored over long periods to ensure sufficient deaths and capture sufficient heterogeneity in exposure. We estimated excess risk in infant mortality associated with living in flood-prone areas of Bangladesh using a matched cohort design, reconstructed over a 30-y period from six, nationally representative DHS and high-resolution Global Flood Database (14) derived from earth observation data and public health reports.

Results

Identifying Flood-Prone Areas throughout Bangladesh. The Global Flood Database (14) mapped seven country-wide floods that occurred in Bangladesh between 2000 and 2018. There was a high level of consistency in areas flooded over the events that occurred during the period with earth observation data (*SI Appendix*, Fig. A1). In the main analyses, we therefore used a composite flood layer derived from all spatially characterized floods in Bangladesh under the assumption that the composite would be the best characterization of flood-prone areas over the 30-y study period, including years that preceded earth observation data (sensitivity analyses, presented below, test the validity of this assumption). We derived flood-prone areas throughout Bangladesh using the percentage of days flooded during the seven floods (Fig. 1*A*). Across the 34% of the country classified as flood-prone in the main analysis, defined as areas that flooded during any of the seven recorded floods, there was a range of severity as measured by days flooded over the seven events (Fig. 1*B*). In combination with world population data (15), we estimated that 44 million people lived in Bangladesh's flood-prone areas in 2020.

Reconstructing Infant Mortality Cohorts over 30 y. Of the 60,678 women interviewed in one of the six last DHS surveys conducted in Bangladesh [1999 (16), 2004 (17), 2007 (18), 2011 (19), 2014 (20), and 2017 (21)], 58,945 (97.1%) with complete data were included in the analysis. DHS clusters provided near uniform coverage of both flood-prone and non-flood-prone areas (Fig. 1*C*). With data on 150,081 births, we used children's exact date of birth and age at death to reconstruct infant child mortality time series between September 1988 and September 2017. Over the 30-y period, infant mortality declined substantially in Bangladesh, from over 100 per 1,000 live births in 1988 to below 50 per 1,000 live births in 2017, and populations living in flood-prone areas consistently had higher mortality compared with those living in non-flood-prone areas (Fig. 1*D*).

Socio-demographic characteristics differed between the 43,677 (74.1%) interviewed women living in non-flood-prone areas and the 15,268 (25.9%) women living in flood-prone areas. Women in flood-prone areas tended to have lower levels of education, were poorer as measured by an asset-based wealth index, and lived in more rural areas at lower population density with worse sanitation conditions and more rudimentary floor materials (Table 1). Temperature and rainfall were similar across the study populations (Table 1). There was progressive improvement in overall socio-demographic characteristics over the study period (*SI Appendix*, Table A1).

We matched all mothers living in flood-prone areas to mothers living outside flood-prone areas using a propensity score estimated from characteristics in Table 1 (*Materials and Methods*). After matching, standardized mean differences between groups were <0.1 for all characteristics, indicating adequate covariate balance (*SI Appendix*, Fig. A2).

Excess Infant Mortality Associated with Living in Flood-Prone Areas. We estimated infant mortality over the study period among children born to women living in flood-prone areas and their matched controls living in non-flood-prone areas (30,536 unique mothers, 80,776 births, and 5,376 deaths included in the matched analysis). We estimated the risk difference and risk ratio of infant mortality rates defined as death by age 11 mo (*Materials and Methods*). Over the 30-y period, there was an excess 5.3 deaths (95% CI: 2.2 to 8.4) per 1,000 births among children born in flood-prone areas compared to the matched cohort born outside flood-prone areas (Fig. 2 and *SI Appendix*, Table A2), corresponding to an 8% (2 to 13%) relative increase (*SI Appendix*, Fig. A3 and Table A3).

Heterogeneity in excess risk over time and seasons. We found heterogeneity when testing for subgroup differences across strata defined by decades and seasons (Fig. 2, P = 0.04 test for heterogeneity, *SI Appendix*, Fig. A4). Excess mortality varied over decade: 1988 to 1997 [RD = 5.9 (–1.0 to 12.8) per 1,000 births] 1998 to 2007 [RD = 2.1 (–2.7 to 6.8) per 1,000 births] and 2008 to 2017 [RD = 9.5 (4.1 to 14.8) per 1,000 births] (P = 0.13 test for heterogeneity, *SI Appendix*, Fig. A5). When stratified by rainy and dry seasons, excess risk in infant mortality was higher among births during the rainy season [RD = 7.9 (3.3 to 12.5) per 1,000 births] compared with the dry season [RD = 3.1 (–1.1 to 7.2) per 1,000 births] (P = 0.12 test for heterogeneity, *SI Appendix*, Fig. A6). Stratifying by both decade and season highlights that the causal effect in the earlier 1988 to 1997 decade was concentrated in the rainy season whereas in the most recent 2008 to 2017 decade, the excess risk in infant mortality spanned both the rainy and dry seasons (Fig. 2).

Sensitivity analyses. We conducted a series of sensitivity analyses to test the robustness of the composite definition of flood-prone areas and the estimation approach used in the main analyses. In the first three analyses, we created additional exposure layers for flood-prone areas using alternative definitions and repeated the propensity score matching for mothers identified in flood-prone areas with similar mothers living outside them. In all scenarios, matching led to very good balance in potential confounding characteristics (*SI Appendix*, Fig. A7 provides representative results from the first sensitivity analysis). First, we considered a time-varying definition of flood areas during the period 2003 to 2017 for which the Global Flood Database included events, using only information from the flood preceding each birth (*SI Appendix*, Fig. A7). Second, we considered a graded definition of flood risk severity based on a quantitative measure of flooded days in each 250 m^2 pixel (*SI Appendix*, Fig. A8). Third, we re-classified the flood-prone area using increasing severity of definition by how many times a location was flooded over the seven events (*SI Appendix*, Fig. A9). Fourth, we conducted a leave-one-out cross-validation analysis in which we repeated the analysis defining flood-prone areas with each of the flood events excluded

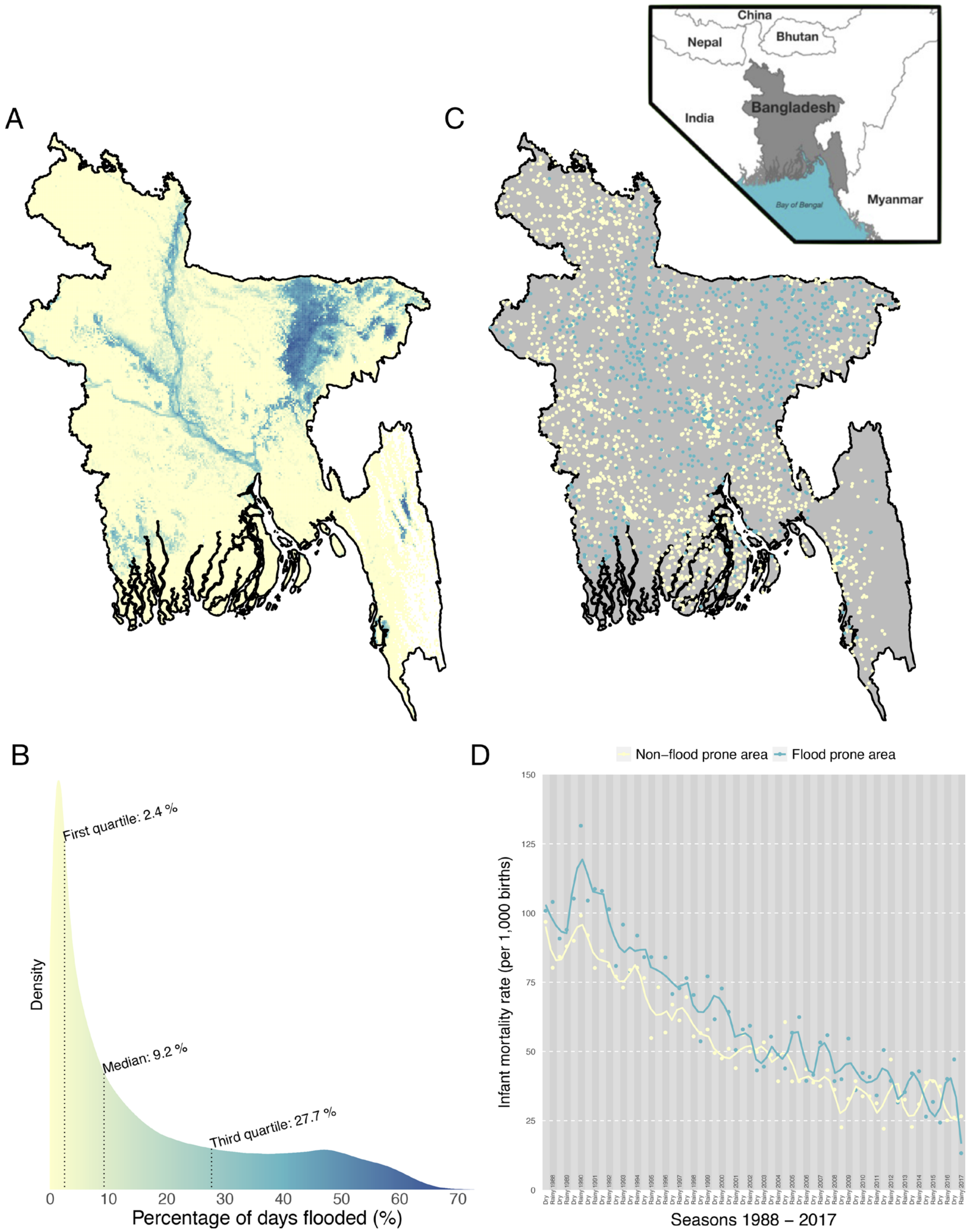

Fig. 1. Map of the percent number of days flooded across seven country-wide flood events available in the Global Flood Database (*A*) and its distribution among areas flooded on at least 1 d (*B*). Locations of clusters included in 1999, 2004, 2007, 2011, 2014, and 2018 DHS waves colored by flood-prone classification (*C*) and infant mortality rate in populations living in flood-prone and non-flood-prone areas of Bangladesh, 1988 to 2017 (*D*). Points represent seasonal averages with locally weighted regression smoothed lines (span = 0.1) superimposed. May to October months defined the rainy seasons.

in turn (*SI Appendix*, Fig. A10). Finally, we repeated the main analysis using the composite flood definition but used a conditional logistic regression estimator that conditioned on each matched pair of mothers rather than analyzing the matched data at the cluster level (*SI Appendix*, Fig. A11). All sensitivity analyses show highly consistent results with the main analyses.

Small Area Estimation of Excess Mortality Burden. We combined estimates of excess risk with the WorldPop (15) population layer to generalize estimates of excess mortality over the country (*Materials and Methods*), highlighting marked fine-scale heterogeneity in populations most affected (Fig. 3*A*). Heterogeneity in excess infant deaths reflects the locations of flood-prone areas (Fig. 1*A*) and actual population settlement patterns. We aggregated 1-km^2 projections of excess infant deaths by subdistrict to generate small area estimates and identify most affected regions throughout Bangladesh (Fig. 3 *B* and *C*). Four subdistricts stand out with excess mortality attributable to living in flood-prone areas above 4 per 1,000 births while the 28 least affected subdistricts had excess infant mortality below 1 per 1,000 births. Aggregating over the entire country, we estimated a total of 152,753 (95% CI: 64,120 to 241,386) excess infant deaths attributable to living in flood-prone areas between 1988 and 2017 in Bangladesh.

Table 1. Population characteristics of mothers in flooded and non-flooded areas (unmatched samples) measured across six DHS surveys, 1999 to 2017

	Non-flood-prone area (N = 43,677)	Flood-prone area (N = 15,268)	Overall (N = 58,945)
Place of residence			
Rural	27,196 (72%)	12,546 (87%)	39,742 (76%)
Urban	16,481 (28%)	2,722 (13%)	19,203 (24%)
Highest level of education			
No education	11,401 (28%)	5,147 (34%)	16,548 (30%)
Primary	13,407 (31%)	5,071 (33%)	18,478 (31%)
Secondary	15,065 (34%)	4,359 (28%)	19,424 (33%)
Higher	3,804 (8%)	691 (4%)	4,495 (7%)
Wealth index quintile			
Poorest	6,144 (14%)	3,274 (22%)	9,418 (17%)
Poorer	7,177 (17%)	3,187 (21%)	10,364 (18%)
Middle	7,825 (18%)	2,950 (20%)	10,775 (19%)
Richer	8,513 (20%)	2,519 (17%)	11,032 (19%)
Richest	9,817 (20%)	1,975 (12%)	11,792 (18%)
Not measured in 1999 survey*	4,201 (10%)	1,363 (9%)	5,564 (10%)
Number of children			
Mean (SD)	2.91 (±1.75)	3.17 (±1.93)	2.98 (±1.81)
Age of mother at first birth (years)			
Mean (SD)	17.8 (±3.23)	17.7 (±3.12)	17.7 (±3.20)
Source of drinking water			
Improved	42,733 (98%)	14,790 (98%)	57,523 (98%)
Unimproved	944 (2%)	478 (2%)	1,422 (2%)
Sanitation			
Improved	26,337 (59%)	7,724 (50%)	34,061 (56%)
Unimproved	17,340 (41%)	7,544 (50%)	24,884 (44%)
Sanitation facilities shared with other HH			
No	23,552 (52%)	7,940 (51%)	31,492 (52%)
Yes	11,210 (27%)	4,242 (28%)	15,452 (27%)
Not measured in 1999 and 2004 surveys*	8,915 (21%)	3,086 (20%)	12,001 (21%)
Main floor material			
Finished	14,173 (30%)	3,058 (19%)	17,231 (27%)
Rudimentary	29,504 (70%)	12,210 (81%)	41,714 (73%)
Main wall material			
Finished	31,279 (69%)	11,091 (75%)	42,370 (71%)
Rudimentary	12,398 (31%)	4,177 (25%)	16,575 (29%)
Main roof material			
Finished	41,753 (95%)	14,528 (96%)	56,281 (95%)
Rudimentary	1,924 (5%)	740 (4%)	2,664 (5%)
Land surface temperature (°C)†			
Mean (SD)	24.6 (±0.589)	24.4 (±0.504)	24.5 (±0.571)
Rainfall (mm)†			
Mean (SD)	2,460 (±720)	2,450 (±766)	2,460 (±733)
Population density (per km^2)†			
Median (IQR)	1,300 (1,000 to 1,900)	1,200 (980 to 1,700)	1,300 (1,000 to 1,800)

All estimates except raw frequencies account for survey sampling weights.
*Wealth index and sanitation sharing were not reported in all DHS questionnaires. As matching was conducted within DHS wave, missingness here is not a problem.
†Land surface temperature, rainfall, and population density are 2015 estimates and were not used in the propensity score matching but are reported for comparison between populations (*Materials and Methods*).

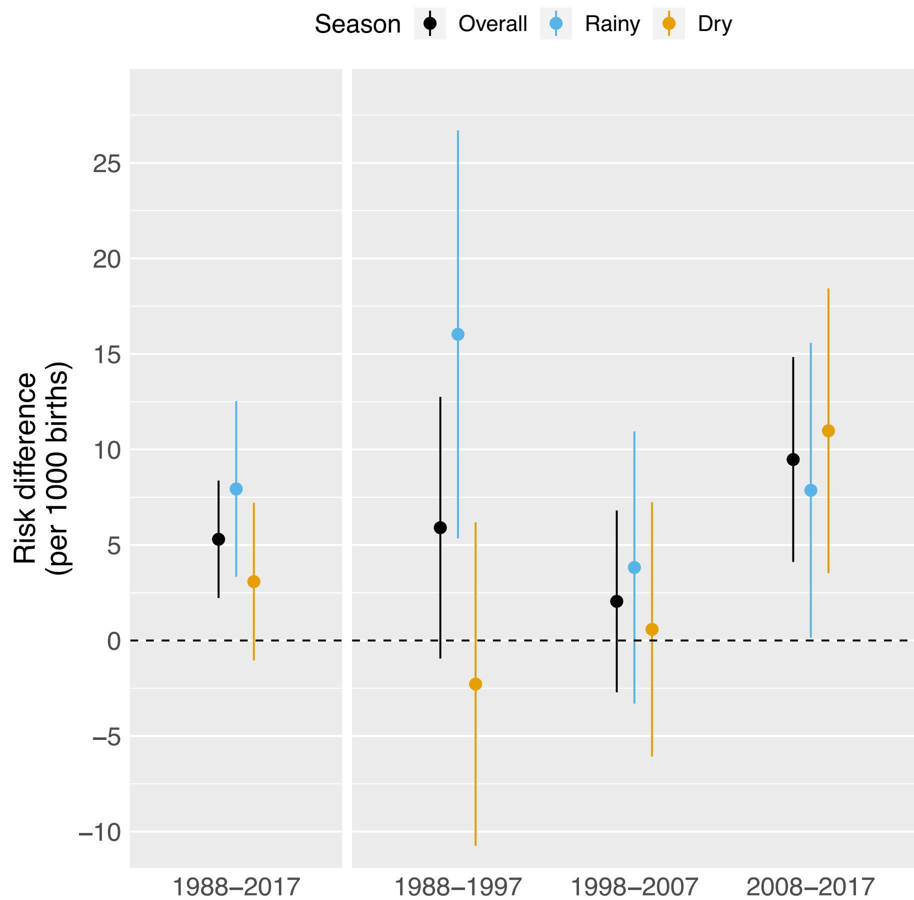

Fig. 2. Risk differences in infant mortality (deaths per 1,000 births) comparing flood-prone areas to non-flood-prone areas of Bangladesh overall and stratified by decade and season. *SI Appendix* includes detailed point estimates and estimates on the risk ratio scale.

Discussion

In this analysis that included 150,081 births from 58,945 mothers in population-based surveys throughout Bangladesh, living in flood-prone areas was associated with an excess risk in infant mortality of 5.3 (2.2 to 8.4) additional deaths per 1,000 births compared to living in non-flood-prone areas over the 30-y period, 1988 to 2017. Drawing on national-scale, high-resolution estimates of flood risk and population distribution, we estimate an excess of 152,753 (64,120 to 241,386) infant deaths over the past 30 y were attributable to living in flood-prone areas in Bangladesh, with marked heterogeneity in attributable burden by subdistrict (Fig. 3) and heterogeneity in excess risk by decade and season (Fig. 2).

Over the study period, excess risk in infant mortality was reduced substantially between the 1988 to 1997 and 1998 to 2007 decades, despite massive flood events in 2004 and 2007, yet excess mortality risk increased during the final 10-y period of the analysis, 2008 to 2017. Although Bangladesh has made remarkable progress to reduce infant mortality rates over the past three decades (Fig. 1*D*), IPCC has forecasted increased flood hazard in the country, and our analysis suggests that heightened mortality associated with living in flood-prone areas could, in part, jeopardize these gains. Furthermore, efforts to include human mortality in cost estimates of carbon emissions have focused primarily on temperature-associated excess mortality (22). The present results suggest that flood-attributable infant mortality and years of healthy life lost could be substantial yet have not been included in economic impact models due to an absence of rigorous estimates in the scientific literature (23).

Our results are consistent with the literature that documents adverse health outcomes among populations exposed to flooding events but goes further by characterizing their evolution over time. Previous studies have reported increased mental health risk (24), infectious diseases (11, 25, 26) or birth outcomes (12, 27) and vulnerability (28, 29) following flooding events but seldom are the studies interested in longer-term effects of such exposure. The matched cohort analysis used here demonstrated a heightened infant mortality risk among Bangladesh's flood-prone areas over the past thirty years that does not appear to have been driven by any single flood event based on fine-scale estimates of temporal heterogeneity in excess risk (*SI Appendix*, Fig. A4). The absence of differences in excess risk between the rainy and dry seasons in the most recent 2008 to 2017 decade, despite flooding during the rainy season because of the monsoon, suggests lasting effects on population health beyond the immediate flood events that may not have been present in the earlier 1988 to 1997 decade when most excess risk was during the rainy season (Fig. 2). As populations adapt to flooding and governments invest in flood risk reduction, further case studies should investigate why Bangladesh's population vulnerability appears to have changed over time. We suggest some plausible mechanisms in our discussion of limitations, below, which could underpin the observed results.

Estimating causal effects of extreme weather events on child health presents methodologic challenges especially because exposure to such events cannot be randomized. Study designs that leverage the apparent randomness of extreme weather events as natural experiments require that health effects are localized close to the event in space and time and that high-resolution data are available

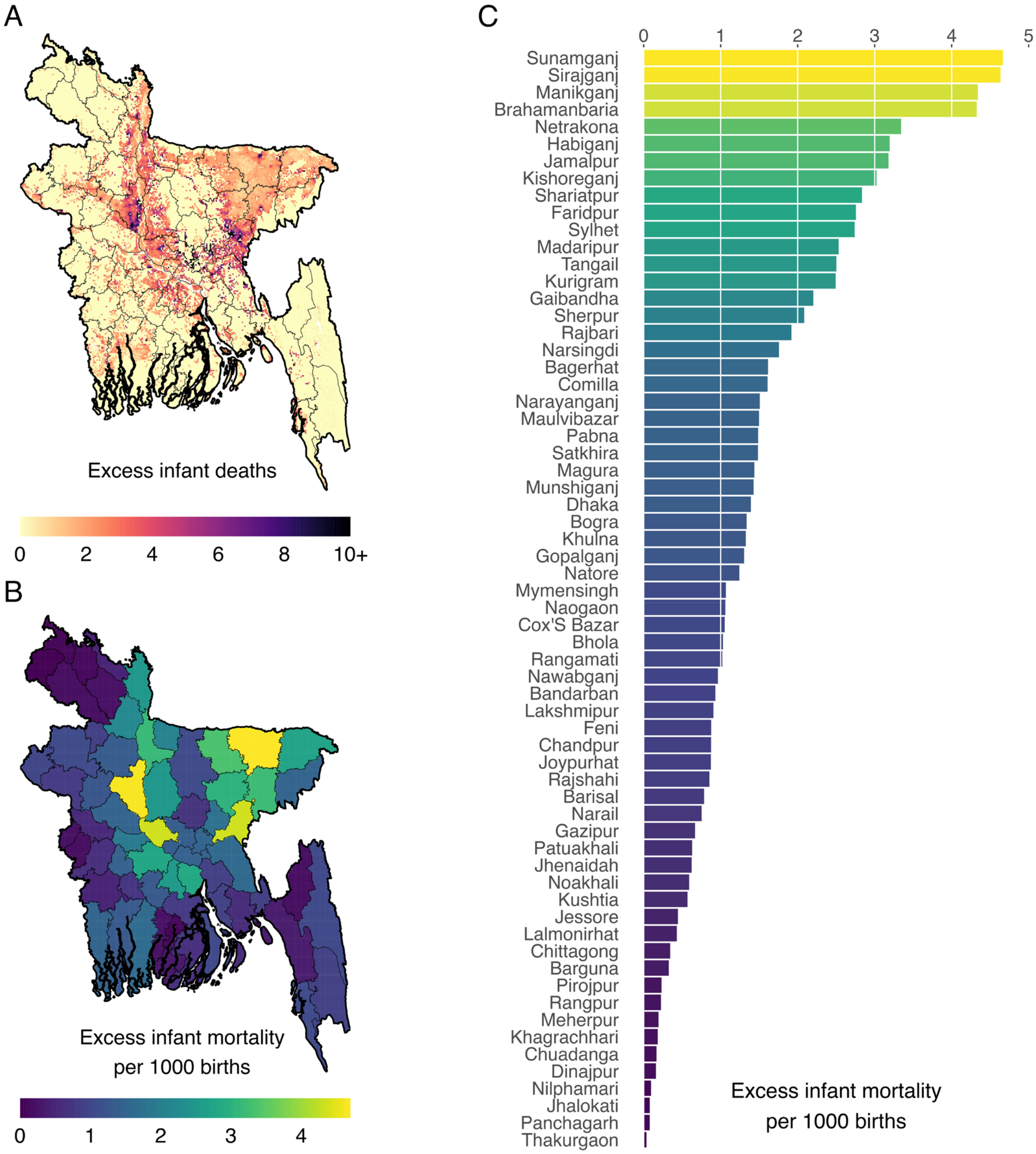

Fig. 3. Excess infant deaths attributable to living in flood-prone areas between 1988 and 2017 at 1-km^2 resolution (*A*) and excess infant mortality per 1,000 births attributable to living in flood-prone areas between 1988 and 2017 aggregated by subdistricts (zilas) (*B* and *C*). *SI Appendix*, Fig. A12 includes 95% CIs on subdistrict-level estimates.

around spatial and temporal event boundaries. Furthermore, such studies typically focus on single events as such designs are not applicable to long-term effects related to floods.

Yet, studying the long-term impacts of such climate-sensitive exposures is important because the population affected by a single, extreme flood is likely to be consistently vulnerable to flooding and is thus more likely to have experienced the effects of previous floods. Many climate-related exposures beyond floods, such as droughts or temperature extremes, face the same challenge of consistently vulnerable populations that face repeated exposures such that health effects may not be limited to periods immediately adjacent to single events. In this study, we proposed a design to overcome such limitations and study long-term impacts. We anticipate that the approach developed here, which combines remotely sensed data with DHS to identify matched, counterfactual groups for populations that are consistently vulnerable to climate-related exposures, will generalize to other countries and other extreme weather events such as heat waves, droughts, heavy precipitation, or wildfires.

Beyond the potential for residual, unmeasured confounding this analysis had some additional limitations. The Global Flood Database uses remote sensing to map water surfaces around flood events notified in the DFO database, itself based on emergency reports and news coverage. Cloud coverage impeding remote sensing and possible biases in the DFO database could limit the representability of the seven country-wide flood events extracted from the Global Flood Database, resulting in measurement bias in the exposure. Recent developments in deep learning may generate even more accurate flood layers from remote sensing data and could be useful in future research on health effects attributable to floods (30). However, even new remote sensing data products are limited to periods with earth observation data. A second limitation of this analysis is that we characterized flood-prone areas of Bangladesh with spatially referenced floods during the period 2003 to 2017, and used the composite definition of flood-prone areas over a 30-y time series of infant mortality that started in 1988. We acknowledge that floods' intensity can vary over time in a given location and that related impacts can be heterogenous for alternative heath or societal outcomes (25). Several sensitivity analyses that varied the severity of the flood definition, excluded individual events using leave-one-out cross-validation, and focused on a time-varying flood exposure limited only to years with spatially explicit flood estimates showed highly consistent results with the main analysis. Although we cannot rule out the possibility that flood extents differed during the 15 y prior to 2003 when the first spatially referenced flood events were recorded, in years for which measurements exist the flood events had similar geographic footprints, a high degree of spatial correlation and repeated flooding in the same locations across flooding events (*SI Appendix*, Fig. A1)—characteristics that lent support to our use of a composite exposure. In countries with more heterogeneous flooding, defining flood-prone areas using the same Global Flood Database may require a different, perhaps more nuanced, approach. In addition, to protect anonymity, latitude and longitude coordinates in the DHS data are provided with a random offset which could result in non-differential misclassification in the exposure, which if anything, would bias results toward the null. Another limitation from the DHS survey is that it records birth histories only from women younger than 49 y old, which means that infant mortality estimates for months closer to interviews may be more representative as earlier estimates miss data from women that were younger than 49 at the time but above 50 at the time of interview. Since DHS surveys were conducted every 3 to 4 y in Bangladesh, this is unlikely to be a major source of error but use of this general approach in other settings may need to restrict their sample of mothers to avoid this potential source of measurement error. Finally, there are several possible mechanisms that could link living in a flood-prone area with infant mortality, including post-disaster mental health effects (24), environmental contamination leading to respiratory infections (26) or diarrheal diseases (31, 32) or longer-term effects affecting nutrition and socio-economics resources (12) within the flooded community. Since these mechanisms could vary geographically and over time, generalizing the effects beyond the present study requires a strong assumption of consistency in the treatment effect, which could be unlikely. This does not harm the validity of the present estimates but suggests that new research to clarify the mechanisms for how living in flood-prone areas increases infant mortality could further guide actionable interventions. Last, we used 2003 WorldPop data to compute excess mortality because population estimates were not available before 2000. The stability of the proportion of Bangladesh's population living in flood-prone areas over time (*SI Appendix*, Fig. A13) suggests that using a population estimate from the midpoint of the study period provides a reasonable estimate of the overall infant mortality burden and relative differences across administrative regions.

In conclusion, this study provided high-resolution estimates of infant mortality attributable to living in flood-prone areas of Bangladesh and evaluated how effects changed over 30 y. The findings suggest that a sole focus on immediate effects from floods may underestimate their impact on population health and that effects on infant mortality manifest over a longer time scale. The study provides a generalizable example for methods to study climate-related exposures and longer-term health effects and demonstrates the importance of measuring longer-term impacts in addition to acute impacts immediately following extreme events.

Materials and Methods

Identifying High-Resolution Flood-Prone Areas. The Global Flood Database (14) provides high-resolution maps of 913 large flood events that have happened around the world since 2000, providing a unique opportunity to measure flood exposure from GPS coordinates alone and identify which communities are living in flood-prone areas or not. In the main analysis, any area that flooded during any of the seven country-wide floods available in the Global Flood Database14 that happened in Bangladesh (2002, 2003, 2004, 2007, 2010, 2010, and 2017) was classified as flood prone. Our exposure is therefore time-invariant and sensitivity analyses are important to assess the stability of our results to our exposure definition. In a robustness check, we performed a leave-one-out cross-validation analysis, each time omitting one of the seven flood events and re-defining flood-prone areas to verify that our primary results were not overly influenced or biased by any single event (*SI Appendix*, Fig. A10). Individual maps of the seven flood events display very similar geographical footprints with a high degree of overlap from one event to another, providing empirical support for assuming a time-invariant exposure (*SI Appendix*, Fig. A1). In addition, we show the high correlation of flood-prone areas over time (*SI Appendix*, Fig. A1*H*) and that areas classified as flood-prone areas in our analyses were predominantly exposed to multiple flood events (*SI Appendix*, Fig. A1*I*).

Infant Mortality. The six last DHS conducted in Bangladesh—1999 (16), 2004 (17), 2007 (18), 2011 (19), 2014 (20), and 2017 (21)—included GPS coordinates and were used to extract infant mortality time series in flood-prone areas and non-flood-prone areas. Each survey wave is a cross-sectional independent random cluster survey of households across the country that collects the birth date of any of the household's children –from interviewed women younger than 49 y old—as well as the age at death for those no longer alive at the time of interview. The proportion of children that died before reaching 12 mo, including stillbirths, along with their date of birth, was used to estimate monthly infant mortality time series in the 30 y leading up to the last DHS survey wave, i.e., between September 1987 and September 2017. Data were restricted to singleton births and births happening before mothers lived where they were interviewed were excluded. A systematic analysis of DHS surveys estimated that birth histories omit less than 2% of births and less than 5% of under-5 deaths and identified no irregularities in the Bangladesh DHS surveys related to neonatal or infant death measures (21).

Matching Analyses. Every mother who gave birth in the flood-prone area was matched to a mother who gave birth in the non-flood-prone area with similar socio-economics and environmental characteristics using a propensity score approach. We estimated propensity scores for living within a flood-prone area for each mother within each DHS survey wave using logistic regression and variables presented in Table 1 as predictors: region, urban/rural place of residence, mother's birth date, age of mother at first birth, total number of children, highest level of education, wealth index, source of drinking water, sanitation, floor, roof, and wall materials, whether the toilets are shared with other households. Although not used in the matching, we additionally report 2015 average land surface temperature (33), precipitation (34), and population density (35). Socio-demographic variables were directly extracted from the questionnaire while environmental covariates, extracted at cluster locations by the DHS program, were downloaded when requesting access to the DHS data. Including sampling weights did not improve covariate balance, and they were therefore discarded for matching but accounted for in statistical analyses below. We used the reciprocal of predicted probabilities from the model as propensity scores for living in a flood-prone area, and matched mothers within each DHS wave 1:1 using nearest neighbor matching without replacement. The matching led to very good balance in measurable characteristics (*SI Appendix*, Figs. A2 and A7).

Estimation of Excess Mortality. Matched infant mortality time series in flood-prone areas and non-flood-prone areas were aggregated by season to compute infant mortality for every dry and rainy season of the 30 y between September 1987 and September 2017. The rainy season consisted of the May to October months, further supported by precipitation data (*SI Appendix*, Fig. A14). The risk difference, risk ratio and odds ratio, and their SEs for these 60 time periods were empirically computed and used in a meta-analysis with random effects, stratified by decade (1988 to 1997 vs. 1998 to 2007 vs. 2008 to 2017) and season (dry vs. rainy). Stratified and overall estimates represent the adjusted causal effect (here our main estimand is the Average Treatment among the Treated: ATT) of living in flood-prone areas on infant mortality.

We combined overall estimates of excess risk with high-resolution population data to compute small-area estimates of excess mortality across Bangladesh. After verifying that the proportion of Bangladesh's population living in flood-prone areas was fairly stable over time (*SI Appendix*, Fig. A13), we used WorldPop (15) 1-km^2 resolution population estimates from 2003, the median of our study period, and considered an average annual birth rate of 25 per 1,000 people (World Bank data) to calculate excess mortality with the following formula:

$$\textit{excess mortality} = \textit{population} \times \textit{birth rate}$$
$$\times\ \textit{study period length} \times \textit{risk difference}.$$

Finally, high-resolution projections were aggregated both over the entire country and by subdistrict to identify most affected regions of Bangladesh.

Sensitivity Analyses. In sensitivity analyses, we explored alternative definitions of flood-prone areas. First, we assessed a graded definition of flood severity based on the proportion of days flooded over the seven major floods used to make the composite layer. The number of flooded days during any of the seven recorded floods was extracted, summed, and divided by the total maximum number of flooded days across all seven flood events. The resulting layer gives, for every 250 m^2 pixel in Bangladesh, the percent number of days it was flooded during these seven flood events and can be leveraged to determine flood-prone areas with increasing levels of severity. We classified as flood-prone area any pixel where the percent number of flooded days was higher than 2.4% and 9.2%, based on the first quartile and median of the distribution of percent number of flooded days among pixels flooded at least once in one of the seven flood events. With a maximum of 206 flooded days across the seven recorded events, the first quartile corresponded to 5 flooded days and the median corresponded to 19 flooded days. Second, we defined flood-prone areas with increasing levels of severity based on the frequency of flooding events. We classified as flood-prone areas any pixel that experienced at least 1, 2, 3, and 4 of the seven recorded floods. Third, we conducted a leave-one-out cross-validation exercise that repeated the entire primary analysis seven times but excluded one of the major flood events in turn when deriving the composite flood-prone area exposure. Finally, in a sensitivity analysis to assess the estimation approach, instead of aggregating births within flooded and non-flooded areas, we used conditional logistic regression to directly estimate the odds ratio of living in a flood-prone area compared to living in a non-flood-prone area on infant mortality conditioning on each matched pair of mothers, with pairs matched using the propensity score approach described above.

Data, Materials, and Software Availability. All the data used are publicly available, but access to DHS data requires a formal request (https://dhsprogram.com) and therefore cannot be deposited in public repositories. All other publicly available data and R code used to run the analyses have been archived through the Open Science Framework: https://osf.io/vrfmz/ (DOI: 10.17605/OSF.IO/VRFMZ) (36).

ACKNOWLEDGMENTS. This work was supported in part by the National Institute of Allergy and Infectious Diseases (R01-AI166671 to B.F.A.).

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