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Recurrent home flooding in Detroit, MI 2012-2020: Results of a household survey

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Abstract

Introduction: Household flooding has wide ranging social, economic and public health impacts particularly for people in resource poor communities. The determinants and outcomes of recurrent home flooding in urban contexts, however, are not well understood. A household survey was used to assess neighborhood and household level determinants of recurrent home flooding in Detroit, MI.

Methods: Survey activities covered the years of 2012 and 2020. Researchers collected information on past flooding, housing conditions, flooding outcomes and public health outcomes. Using the locations of homes and flooding occurrences, a "hot spot" analysis was performed to find areas of extreme risk within the City of Detroit. Survey data were linked to environment and neighborhood data and associations were tested using regression methods.

Results: 5,956 households participated in the survey and flooding information was available for 4,677 of them. Among these, 2,546 (42.75%) reported having experienced home flooding as a result of rainfall. Rental occupied units were more likely to report flooding than owner occupied homes (OR 1.71 [95% CI 1.5, 1.94]). Housing conditions such as poor roof quality and cracks in basement walls influenced home flooding risk. Increased percentage of rental units in the vicinity of the home increased flooding risk. When controlling for household and neighborhood factors, primarily African American communities were found to be at high risk for home flooding. Flooding and conditions associated with home flooding were associated with adult and child asthma.

Conclusions: Recurrent home flooding is far more prevalent than previously thought and associated with neighborhood and household factors, in addition to disproportionately impacting African American residents. Programs that support recovery and which focus on home improvement to prevent flooding, particularly by landlords, might benefit the public health. These results draw awareness and urgency to problems of urban flooding and public health in other areas of the country confronting the compounding challenges of aging infrastructure, disinvestment and climate change.

Keywords: flooding; Detroit; environmental justice; climated change
flooding, Detroit, environmental justice, climate change

1 Introduction

Pluvial flooding and sewer overflows are a multifactorial public health problem that raise risks for mortality and morbidity of a host of serious conditions. Health impacts from flooding can be physical or psychological. Physical outcomes include gastrointestinal illnesses, respiratory illnesses, skin rashes and infections and poisoning from exposure to chemical irritants [1, 2, 3, 4, 5, 6, 7]. Psychological distress and trauma are common among people who have experienced sudden flooding as a result of extreme weather events [8, 9, 10].

Flooding impacts different groups of people in distinct ways and impacts can be felt during or after the flooding event [11]. Women, the elderly and small children are more likely to experience physical and psychological outcomes during floods and men are at high risk for mortality during and after flooding events [12, 13, 14, 15, 16]. Intensity of flooding has a graded impact on physical and psychological health. Long term psychological effects such as anxiety, depression and PTSD can occur for several years following a flooding event [17, 18, 8, 19] and flooding can cause serious disruptions to the provisions of mental health treatment [20]. Long term effects include trauma and stress-related problems as a result of displacement, economic insecurity and future housing uncertainty [21]. Mortality has been found to increase in the months following major flood events [22] and flooding impacts can be felt even by persons outside flooded areas through groundwater contamination [23].

Climate and rainfall patterns in the Midwest region of the United States have been altered over the past five decades as a result of climate change [24, 25] and extreme flooding events have become more common in cities such as Detroit, MI during the past decade. Natural hazards and extreme weather events have become more common and increasingly costly in the US over the past two decades [26, 27] . Changes in frequency and intensity of rainfall patterns can overwhelm aging infrastructure in challenged cities like Detroit, and create multiple stormwater issues [28]. Globally, urban land exposed to climate and flooding hazard risks is expected to increase by more than 25 percent compared with current levels [29]. Increasing frequency of extreme weather events and inadequate and aging infrastructure are exacerbating flooding events [30] .

Home flooding is a serious public health problem that has long lasting economic and health impacts for people who experience it [31, 32, 33, 34, 35, 36, 37] . Natural hazards have been shown to exacerbate problems of economic inequality [38]. Serious impacts from flooding are the result of a confluence of factors including extreme weather events, robustness of infrastructure and other factors to mitigate flood risk, housing conditions and individual level vulnerability [39, 40]. Though significant effort has been directed to major flooding events (e.g. dam breaks, flood wave propagation), little work has been done on recurrent, localized pluvial and non-pluvial flooding in urban contexts.

The City of Detroit, MI, like many post-industrial cities, faces a wide range of converging challenges including population loss, demographic change and decades of financial and political neglect [41]. The City covers approximately $230\,\mathrm{km}^2$. As of 2020, Detroit's population is ˜670,000 people, down from a peak population of 1.6 million people in 1960 [42] . It is among the poorest of large cities in the US with a median household income of $31,000, less than half of the state median income of $72,000. Nearly 80 percent of Detroit residents are African-American [42]. The City struggles to provide public services to its residents as a result of declining tax revenues, low levels of investment and decline of population density which forces Detroit to provide services using antiquated systems appropriate for a much larger population [43].

Compounding these problems are broad issues including aging housing and public infrastructure and climate change, all of which combine to create conditions conducive to home flooding. A cross-sectional study of 164 homes in northwest Detroit indicated that 64% of homes experienced at least one flooding event in the past year, with many experiencing three or four events [44]. Researchers of a small qualitative study reported on interviews with residents across the city, confirming that flooding was widespread with many potential risk factors, resources for prevention and recovery were uneven, and social, economic, and mental and physical health implications were extensive [45]. The Detroit Office of Sustainability found that residents report that they experience flooding very often (13%), somewhat often (23%), and occasionally (32%) [46]. Though extreme weather events such as that which caused major flooding in Detroit in 2014 have wide ranging acute impacts, recurrent household flooding may be an under-reported phenomenon in a city like Detroit and may be a problem that worsens with climate change [47].

Detroit's topography is mostly flat, with an overall change of only 33 meters between its highest and lowest points. The City's natural drainage is split between the Detroit and Rouge Rivers, though the natural tributaries were replaced with underground pipes prior to the 1960s. Water runoff and sewage flow through a combined system, discharging more than 58 million liters of treated and untreated sewage [48] which eventually flows into Lake Erie. A result of Detroit's combined system of rain runoff and sewage discharge is that large rain events can overwhelm the City's treatment system, causing sewage backflow into homes during storm weather events [49]. Communities along the Detroit River, most notably the Jefferson-Chalmers area, have historically experienced flooding events of various degrees. Aged housing stock, high prevalence of impervious surfaces and high prevalence of basements put Detroit residents at high risk for home flooding [50].

1.1 Research goals

Recurrent home flooding is an overlooked public health problem that presents a wide range of health risks to populations in economically challenged post-industrial cities like Detroit, Michigan. To inform prevention and recovery efforts, we first describe the extent and frequency of pluvial flooding in Detroit households using data from a house to house survey. As part of this effort, we seek to identify particular locations or areas at high risk for household flooding events. Next, we used location information to link households to other data sets to test for associations of household and neighborhood/tract level determinants of household flooding events. Using the results of the first two aims, we create a predictive model that could be used to predict flooding risk for individual households or households located within specific tracts or areas. Finally, we explore how flooding and factors associated with flooding might determine household asthma prevalence in surveyed households.

We hypothesize that flooding events are concentrated in specific areas and that households that experience flooding events are in proximity to other homes that experience flooding events. We test for associations of flooding with housing conditions, socio-economic factors and neighborhood characteristics. We expect that no one factor in isolation determines household level flooding risk and create a multivariate regression model to predict flood risk using all available variables. Finally, we test the hypothesis that home flooding and factors associated with home flooding also determine household level public health outcomes such as asthma, which may result from exposure to chemicals, bacteria, or mold.

2 Methods

2.0.1 Survey of home flooding in Detroit

Wayne State University's Center for Urban Studies (CUS) seeks to "improve understanding of and provide innovative responses to urban challenges and opportunities." As a part of its commitment to serving Detroit and its metropolitan area, the Center maintains a staff of professionals dedicated to identifying leverage opportunities to meet community need. In 2012, the Center created the Home Safety Assessment (HSA) as a joint effort between AmeriCorps, Wayne State University Center for Urban Studies, FEMA, Detroit Fire Department, Clear Corps, and the Kohl's Injury Prevention Program through the Children's Hospital of Michigan. The HSA is a risk assessment survey to determine if a resident's home has hazardous conditions such as asthma triggers, flood, and moisture/vapor intrusion and the vulnerability of the housing quality. Field staff conduct door-to-door canvasing dividing the zip codes in walkable target areas. Survey workers approached the home to determine if a household member was present. If no one was home at the time, workers returned at a later date, or scheduled visits on nights and weekends if necessary. To elicit residents' participation in the project the project offered a small, non-monetary incentives. Survey staff educated residents on ways to increase home safety, and referred residents to partner services available to them. Survey and community outreach activities are ongoing.

This research was deemed exempt from annual review by Institutional Review Boards at the University of Michigan (study number HUM00177793) and Wayne State University (study number 101619B3X).

2.1 Neighborhood and environmental data

Several other sources of data were leveraged for this study. As a proxy for neighborhood measure, census tract level measures of poverty and neighborhood age were obtained through the American Community Survey, a sample-based yearly survey of American households maintained by the United States Census [42]. Data for administrative boundaries and locations of waterways were obtained from the State of Michigan's GIS Portal [51]. One-meter elevation data was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model from the National Aeronautics and Space Administration (NASA) [52]. Additional residential property information, or parcel data, were obtained from a database of public tax records from real estate analytics company CoreLogic [53]. This database consists of parcel-level property information collected from tax assessor's records as of 2016 and includes data on the year the structure was built, whether the unit is a rental unit or owner occupied, the assessed value of the home and whether the unit was a multifamily unit.

Latitude and longitude for households were obtained with ArcMap ver 10.6.1 geocoder [54] using the home address listed in the CUS survey. Latitude and longitude coordinates that were outside of Detroit city limits were excluded from the analysis. Data from other layers such as elevation and neighborhood information were extracted using the latitude/longitude location of the household obtained from the geocoded address.

2.1.1 Statistical methods

Households were asked if their home had flooded in the past either as a result of rainfall or weather events. Using the data on past flooding, maps of household locations and flooding events were produced using the latitude and longitude coordinates of each home. "Hot" and "Cold" spots for household flooding were determined based on a Getis-Ord statistic at each point. The Getis-Ord Gi* statistic is produced by examining the value of each location in the context of all surrounding locations. Local sums are compared proportionally to the sum of all values surrounding it and z-scores and p-values are produced [55, 56]. Areas of statistically high and low local risk are presented on a map to allow the identification of particular locations of interest. Hot and cold spots are defined as areas where there is statistical evidence that homes that experience/do not experience flooding are in close proximity to other homes that also experience/do not experience flooding.

Next, we tested for associations between households that experience flooding and those which did not using univariate logistic regression models. Significant associations were explored in more depth using locally-estimated scatterplot smoothing (LOESS) curves. Finally, backwards selection from a full model including all relevant and sufficiently represented predictors was used to construct a multivariate model of home flooding.

3 Results

3.0.1 Spatial distribution of flood risk in Detroit

Survey data from the Center for Urban Studies comprised 5,956 households between September 18, 2012 and May 5, 2020. Households were surveyed throughout the Detroit area. Data on the occurrence of flooding (self-reported) were available for 4,677 households. Among the surveyed households that responded to the question, 2546 (42.75%) reported having experienced flooding as a result of rainfall.

Households that reported flooding were located throughout Detroit (see Figure 1) but hot spot analyses indicated that flooding incidence was not homogeneous throughout the city. Specifically, there were significant clusters of flooded homes in and around the Jefferson-Chalmers area. There were also significant clusters of homes that reported never having experienced flooding. See Figure 2.

3.0.2 Household level correlates of home flooding

In univariate analyses, we found that several factors were significantly associated with flooding risk among surveyed households. Rental homes were more likely to have experienced flooding than owner-occupied homes (OR 1.71 [95% CI 1.5, 1.94]). Unfinished basements were associated with a higher odds of flooding than finished basements (OR 0.29 [95% CI 1.06, 1.57]).

Age of the home was initially found to be significant when comparing means of ages between homes that reported flooding vs. those that did not. However, we also explored whether patterns of flood risk might change over time in a non-linear manner. Figure 3 shows a locally estimated scatterplot smoothing (LOESS) based interpolation of flood risk as a function of the year of home construction. Risk for home flooding had a parabolic relationship to home age, with risk being the highest for the oldest homes, decreasing until ˜1960 and then rising again. See Figure 2. We then categorized the age of the home based on historical waves of home construction [57]. Compared with homes built before 1910, risk for flooding decreases for homes built in waves before 1958. Risk for flooding for home built in the late 20th century and early 21st century is similar to that of the oldest homes in Detroit. See Table 1 for full results.

Housing conditions were predictive of home flooding. Homes with roofs that were reported to be in good condition were found to be less likely to experience flooding (OR 0.59 [95% CI 0.5, 0.68]). Homes with mold on the walls (OR 6.3 [95% CI 5.39, 7.37]), moldy smells(OR 5.56 [95% CI 4.8, 6.43]), basement in disrepair (OR 12.73 [95% CI 10.44, 15.51]), uncapped sewer outlets (OR 2.2 [95% CI 1.92, 2.51]) and occurrence of previous sewer backups (OR 17.86 [95% CI 15.11, 21.1]) were found to be more prone to flooding. See Table 2 for full results.

3.0.3 Neighborhood (census tract) and environmental correlates of home flooding

Of interest to this research was how the surrounding environment raised or lowered the risk of home flooding. The following census tract characteristics were considered and found not to be significantly associated with flood risk: poverty, childhood poverty, percent African-American or Hispanic residents, percent of homes built before 1939, elevation and the distance to the nearest waterway. However, percentage of all homes in the census tract that are owner-occupied was inversely associated with flood risk (OR 0.89 [95% CI 0.84, 0.94]). See Table 3 for full results.

3.0.4 Multivariable model of home flooding

We tested associations of all variables with home flooding in a multivariate model. Missing data was a problem for many available variables. Any variable with more than 10% of observations missing was excluded from the analysis. Multiple imputation was used to fill in the missing values for the remaining set of predictors [58] so that we could create a “full model” of household and neighborhood factors on home flooding. Using this model, we used a backward selection procedure to successively delete variables based on significance until a final, optimal model based on Akaike’s Information Criterion (AIC) [59] was obtained. Variables that were sufficiently represented in the data set to allow model inclusion comprised all census tract level variables such as poverty, racial composition, age of homes in the area, elevation and distance to nearest waterway. Rent/own status and variables on various aspects of housing condition such as leaks and cracks in basement and outer walls were also retained.

After model selection, only a handful of variables were dropped including census tract level poverty and childhood poverty, distance to nearest waterway, elevation and chimney leaks. In the multivariate model we found that the percentage of the census tract that is African-American was associated with home flooding (OR 1.14 95% CI [1.04, 1.25].) Rental status (OR 1.43 95% CI [1.19, 1.67]) and neighborhood level home ownership (OR .90 95% CI [.83, .97]) were also found to be associated with water entering the home. Almost all of the variables on home leaks remained in the model even though though roof leaks and chimney leaks were dropped from the final model. Sewer backups were left in the model building process as a proxy for the relative quality of the surrounding sewer and flooding infrastructure. Even when controlling for other factors, the odds of flooding given sewer leaks were very high (OR 11.9 95% CI [9.82, 14.07]). We note that not all homes that experienced flooding experienced sewer backups and not all homes that reported sewer backups reported rain associated flooding. See Table 4 for full results.

3.0.5 Asthma and home flooding

A total of 4,546 residents reported having at least one person in the home who had a diagnosis of asthma from a health care professional. 5,140 residents reported having at least one child in the home with asthma. Having at least one person with asthma in the home was associated with flooding ((OR 1.3 [95% CI 1.14, 1.49])). Adults with asthma were also very likely to live with a child with asthma (OR 1.3 [95% CI 1.1, 1.55]). Nearly all of the household and neighborhood variables were associated with asthma cases with only the exception of the age of the home, roof leaks, chimney leaks and proper sink and bathtub drainage. Other possible predictors of asthma cases such as having a smoker in the home and household breathing problems were also available in the data set and were included in Table 5.

4 Discussion

Using a house-to-house survey of homes and residents throughout the city, we have shown that regular home flooding is a serious problem that impacts Detroit residents. We also found that though people all over Detroit experience home flooding, certain areas are at particular risk for basement and home flooding events. We found that renters and those living in areas where most residents are renters live at particular risk for flooding. We found that poor housing conditions directly impact risk for flooding. When controlling for housing and neighborhood factors, we found that flooding disproportionately impacts communities of color. Finally, we found that flooding is associated with asthma risk in both adults and children.

Our results suggest that home flooding is a far more serious issue than previously thought, disproportionately impacting people who may lack financial means to effectively recover from flooding events and pluvial disasters, and who, due their status as renters, may lack the ability to implement measures to prevent or to mitigate the impacts of floods, such as basement weatherization or roof repairs. This would suggest that a focus on home flooding risk and efforts to improve housing quality should be a priority not only for advocates of urban housing, but also for public health organizations, focusing on programs that educate, work with, and provide resources to renters and incentives to landlords to improve housing quality/maintenance. Research in Germany has also suggested that directly communicating risks of flooding to home owners might encourage them to make improvements to prevent or mitigate flooding risk [60]. Direct communication to landlords, for example, might encourage some to make necessary repairs and improvements to their properties.

The biggest limitation of this study was the measure of the flooding outcome. Reporting of flooding occurred only during the in-home visit by the survey team. Thus, flooding events long before the visit that were not in the recollection of the home occupant, and/or flood events after the survey visit were not recorded. Many homes that did not report flooding were visited prior to the city-wide flood of 2014 with the result that impacts from that event were not recorded for those households. Thus, the outcome measurement should be considered an underestimate. Compliance with survey projects is always a challenge. In the case of this study, certain biases should be assumed. For example, given that the present study was described as pertaining to housing conditions and flooding, we might assume that occupants of homes might be more likely to respond who experienced flooding or whose homes were in poor condition.

The flooding data collected also was not specific enough to make recommendations for specific interventions regarding household level flood mitigation. There are multiple causes of in-home flooding, including: sewer back-up, rising water levels of nearby waterways, ponded water around the home, rising groundwater levels around the home and subsequent leakage through foundation and basement, direct inflow through roof leaks, leaks of interior piping, and others. In many cases the flooding may stem from a variety of causes and problems. Future research efforts might ask residents to report incidence of recurrent home flooding to researchers or community leaders and teams could be dispatched to collect detailed information on sources and outcomes.

Detroit experiences the highest health impacts of asthma in Michigan, with the adult asthma rate 29% higher and the rate of asthma-related hospitalizations three times greater than the state average [61]. In-home triggers account for 40% of all asthma episodes [62]. Detroit has been called the "Epicenter of the Asthma Burden," with at least 11.3% of Detroit children and 15.5% of Detroit adults having diagnosed asthma [63]. Future studies of this kind could focus on the public health impacts of recurrent flooding in households and how home improvement measures can be implemented as a means of reducing risk for serious health problems. Using a crude measurement of asthma prevalence, our research suggested that housing quality and flooding risk were associated with asthma in both adults and children. Future research should work to better characterize the public health impacts of regular flooding by implementing programs that improve housing conditions, such as basic measures to prevent basement leakage, while looking at basic health indicators.

Future survey work should attempt to validate the results of this research and be designed to better understand the causes and outcomes of regular flooding in Detroit. Survey efforts should be conducted on a regular basis, but should also mobilize during or after times of intense precipitation or known flooding events. Any survey work should allow the collection of quantitative data such as high water mark and source location, but should also collect detailed information on individual, home and neighborhood conditions that might contribute to flooding. Qualitative information on residents' experiences and ideas could help inform community and government efforts to mitigate flood and support flood victims. The often overlooked public health implications of regular flooding should, however, be a major focus of future research work to ensure equitable prevention and response.

5 Conclusions

Pluvial household flooding is a serious problem for Detroit residents though risk is clustered in certain areas of the city. People living in rental units experience higher risks for household flooding than those in owner occupied units and poor housing conditions are predictive of water entering the home. When controlling for other factors, African American communities were found to be at higher risk for floods than other communities. Finally, we found that flooding is associated with public health outcomes such as asthma. We conclude that flooding in Detroit is an important environmental justice and public health issue worthy of further attention to researchers and public policy advocates.

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Declarations

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Data and materials are available upon request.

Author's contributions

All authors contributed to the writing of the manuscript. LT, CM, RW, JS, JL participated in the original survey design and data collection. PL performed statistical analyses and wrote the initial draft of the manuscript.

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Consent to publish

All authors consent to have this work published.

Ethical approval

Ethical approval was given by The Ethical Review Committee of the School of Tropical Medicine and Global Health at Nagasaki University (No.24). Additionally, the Public Research Program and Center at KEMRI approved this research under the ongoing project "Health and Demographic Surveillance Systems in Kwale," SSC No. 1088. It has also been approved by The Scientific and Ethical Committees of Kenya Medical Research Institute and the Institutional Review Board of the Institute of Tropical Medicine, Nagasaki University (IRB # 06060604) since 18 Oct 2016.

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Figures

Figure 1 Locations of households which reported that they experienced pluvial flooding. Households that responded that no flooding occurred are not shown.

Figure 2 Hot and cold spots of flooding using the Getis-Ord Gi* statistic. Red dots represent "hot" spots, or locations of statistically significant clusters of homes that experienced flooding. Blue does represent clusters of homes that reported not experiencing flooding.

Figure 3 Estimated flooding risk by year of construction using LOESS interpolation method. Vertical lines represent successive building waves (1870 - 1910, 1911 - 1930, etc.) used to create housing construction categories.

Tables

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Table 1: Comparison of household factors by flooding status. Counts and percentages of categorical predictors are noted. Continuous variables are shown as means with standard deviation in parentheses. Comparisons of flooding with categorical predictors are made using Chi-square tests. Comparisons of flooding for continuous predictors are made using t-tests of means. Odds ratios for continuous predictors are based on standardized values (z-scores). presented for categorical predictors. Both continuous and categorical forms of the year the house was built are presented.

	[ALL] N=4489	No flood N=2065	Flood N=2424	OR	p.ratio
Own or rent home:					
Own	2992 (66.7%)	1507 (73.0%)	1485 (61.3%)	Ref.	Ref.
Rent	1497 (33.3%)	558 (27.0%)	939 (38.7%)	1.71 [1.50;1.94]	0.000
Year house was built (categorical):					
Pre 1910	858 (25.1%)	298 (18.4%)	560 (31.1%)	Ref.	Ref.
1910-1930	1218 (35.6%)	595 (36.7%)	623 (34.6%)	0.56 [0.47;0.67]	¡0.001
1931-1940	387 (11.3%)	237 (14.6%)	150 (8.32%)	0.34 [0.26;0.43]	0.000
1941-1945	97 (2.83%)	51 (3.14%)	46 (2.55%)	0.48 [0.31;0.73]	0.001
1946-1957	641 (18.7%)	351 (21.6%)	290 (16.1%)	0.44 [0.36;0.54]	¡0.001
1958 or later	224 (6.54%)	90 (5.55%)	134 (7.43%)	0.79 [0.59;1.07]	0.133
Building sq ft	1371 (717)	1345 (676)	1394 (752)	1.07 [1.00;1.14]*	0.035
Living space sq ft	1368 (711)	1344 (676)	1390 (740)	1.07 [1.00;1.14]*	0.047
Basement sq ft	817 (278)	803 (259)	831 (294)	1.11 [1.04;1.18]*	0.002
Type of basement:					
Finished	457 (11.8%)	243 (13.2%)	214 (10.5%)	Ref.	Ref.
Unfinished	3427 (88.2%)	1603 (86.8%)	1824 (89.5%)	1.29 [1.06;1.57]	0.010

* Odds ratio from standardized values (z-scores) of continuous measure.

Table 2: Housing conditions and flooding. Housing condition measurements were self reported by residents and confirmed by survey workers where possible.

	[ALL] N=4617	No flood N=2097	Flood N=2520	OR	p
Roof in good condition	861 (23.6%)	477 (28.9%)	384 (19.2%)	0.59 [0.50;0.68]	¡0.001
Mold on walls of basement	3319 (74.4%)	1181 (57.1%)	2138 (89.3%)	6.30 [5.39;7.38]	0.000
Moldy smells	3219 (71.9%)	1128 (54.4%)	2091 (86.9%)	5.55 [4.80;6.44]	0.000
Basement needs repair	3215 (75.5%)	1149 (55.7%)	2066 (94.1%)	12.7 [10.5;15.5]	0.000
Roof leaks	3610 (85.6%)	1565 (81.2%)	2045 (89.4%)	1.95 [1.63;2.32]	¡0.001
Window leaks	3934 (93.3%)	1762 (91.4%)	2172 (94.9%)	1.75 [1.37;2.24]	¡0.001
Chimney leaks	4113 (97.6%)	1864 (96.7%)	2249 (98.3%)	1.95 [1.30;2.94]	0.001
Plumbing leaks	3805 (90.3%)	1638 (85.0%)	2167 (94.7%)	3.16 [2.54;3.95]	0.000
No leaks	1333 (31.6%)	810 (42.0%)	523 (22.9%)	0.41 [0.36;0.47]	0.000
Foundation cracks	3567 (84.6%)	1493 (77.5%)	2074 (90.6%)	2.82 [2.36;3.36]	0.000
Sinks and bathtub drain properly	1286 (27.9%)	684 (32.6%)	602 (23.9%)	0.65 [0.57;0.74]	¡0.001
Uncapped sewer outlets	3101 (71.2%)	1257 (62.6%)	1844 (78.6%)	2.20 [1.92;2.51]	0.000
Ever had sewer backups	3028 (66.8%)	775 (37.4%)	2253 (91.4%)	17.8 [15.1;21.1]	0.000

Table 3: Neighborhood and environmental determinants of recurrent home flooding. Odds ratios for continuous measures produced using standardized values (z-scores).

	[ALL] N=4677	No flood N=2131	Flood N=2546	OR	p.ratio
Census tract poverty (%)	43.8 (11.5)	43.7 (11.4)	43.9 (11.6)	1.02 [0.96;1.08]*	0.586
Census tract under 18 poverty (%)	60.6 (17.4)	60.5 (17.4)	60.6 (17.4)	1.01 [0.95;1.07]*	0.717
African-American population (%)	85.1 (24.9)	84.8 (24.8)	85.4 (25.0)	1.03 [0.96;1.11]	0.376
Hispanic population (%)	8.02 (19.5)	7.87 (19.1)	8.15 (19.9)	1.02 [0.94;1.10]	0.648
Percent of homes owner occupied	50.9 (13.7)	51.8 (12.7)	50.2 (14.4)	0.89 [0.84;0.94]	¡0.001
Percent of homes built before 1939	41.1 (24.6)	40.4 (24.6)	41.6 (24.6)	1.05 [0.99;1.11]	0.115
Distance to nearest waterway (km)	4.64 (2.93)	4.72 (2.98)	4.58 (2.90)	0.95 [0.90;1.01]	0.097
Elevation	188 (7.06)	188 (7.00)	188 (7.11)	0.94 [0.89;1.00]	0.043

Table 4 Full and reduced models of flooding using all sufficiently represented variables. Reduced model found through backwards selection through AIC. All continuous variables have been standardized and thus odds ratios for these variables represent changes in odds given unit changes in z-scores.

	Dependent variable:	
	Flooding	
	Full model	Reduced model
	(1)	(2)
Census tract poverty	1.111 (0.966, 1.255)	
Census tract under 18 poverty	0.927 (0.809, 1.045)	
African-American population	1.156*** (1.040, 1.271)	1.142*** (1.035, 1.249)
Distance to nearest waterway	1.037 (0.922, 1.152)	
Elevation	0.975 (0.857, 1.093)	
Percent of homes owner occupied	0.909** (0.833, 0.984)	0.901*** (0.830, 0.972)
Percent of homes built before 1939	1.165*** (1.059, 1.271)	1.187*** (1.092, 1.281)
Rent home	1.443*** (1.204, 1.683)	1.436*** (1.199, 1.673)
Mold on walls of basement	1.945*** (1.477, 2.413)	1.943*** (1.476, 2.410)
Moldy smells	1.314** (1.006, 1.621)	1.321** (1.012, 1.630)
Basement needs repair	5.432*** (4.220, 6.644)	5.353*** (4.164, 6.541)
Roof leaks	0.846 (0.622, 1.071)	
Window leaks	0.677** (0.420, 0.934)	0.643** (0.418, 0.867)
Chimney leaks	1.177 (0.506, 1.848)	
Plumbing leaks	1.384** (0.955, 1.813)	1.393** (0.973, 1.814)
Foundation cracks	1.374** (1.022, 1.727)	1.347** (1.018, 1.677)
Sinks and bathtub drain properly	0.857* (0.707, 1.007)	0.861* (0.711, 1.012)
Uncapped sewer outlets	1.295*** (1.071, 1.520)	1.282*** (1.061, 1.504)
Ever had sewer backups	12.010*** (9.866, 14.154)	11.947*** (9.821, 14.074)
Gaps large enough for animals and insects	1.061 (0.851, 1.271)	
Constant	0.016*** (0.006, 0.025)	0.018*** (0.010, 0.026)
Observations	4,677	4,677
Log Likelihood	−2,081.237	−2,083.677
Akaike Inf. Crit.	4,204.474	4,195.353
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 5: Prevalence and determinants of asthma in at least one adult member of the household. Odds ratios for continuous measures from standardized values (z-scores).

	No N=1410	Yes N=4154	OR	p.ratio
Experienced flooding	564 (49.2%)	1898 (55.8%)	1.30 [1.14;1.49]	¡0.001
Child in the home with asthma	660 (61.6%)	2743 (87.4%)	4.30 [3.66;5.06]	0.000
Breathing problems	507 (38.8%)	3198 (80.9%)	6.70 [5.84;7.68]	0.000
Smoker in the home	681 (49.4%)	2424 (60.0%)	1.54 [1.36;1.74]	¡0.001
Year house was built (categorical):				
Pre 1910	196 (19.3%)	682 (22.4%)	Ref.	Ref.
1910-1930	420 (41.4%)	1216 (39.9%)	0.83 [0.68;1.01]	0.062
1931-1940	110 (10.8%)	315 (10.3%)	0.82 [0.63;1.08]	0.158
1941-1945	32 (3.16%)	98 (3.22%)	0.88 [0.58;1.37]	0.556
1946-1957	199 (19.6%)	546 (17.9%)	0.79 [0.63;0.99]	0.041
1958 or later	57 (5.62%)	190 (6.24%)	0.96 [0.69;1.35]	0.797
Roof in good condition	259 (25.9%)	696 (23.5%)	0.88 [0.74;1.04]	0.120
Mold on walls of basement	784 (70.4%)	2486 (75.8%)	1.32 [1.13;1.53]	¡0.001
Moldy smells	751 (67.4%)	2416 (73.3%)	1.32 [1.14;1.53]	¡0.001
Basement needs repair	757 (70.6%)	2403 (77.0%)	1.40 [1.19;1.63]	¡0.001
Roof leaks	1073 (83.6%)	3189 (85.1%)	1.12 [0.94;1.33]	0.206
Window leaks	1177 (91.7%)	3503 (93.5%)	1.29 [1.02;1.64]	0.036
Chimney leaks	1243 (96.9%)	3666 (97.8%)	1.46 [0.98;2.13]	0.060
Plumbing leaks	1122 (87.5%)	3361 (89.7%)	1.25 [1.03;1.52]	0.027
No leaks	471 (36.7%)	1221 (32.6%)	0.83 [0.73;0.95]	0.007
Foundation cracks	976 (83.3%)	2940 (84.6%)	1.10 [0.92;1.32]	0.281
Sinks and bathtub drain properly	372 (27.4%)	1062 (26.6%)	0.96 [0.84;1.10]	0.563
Uncapped sewer outlets	803 (67.9%)	2502 (71.0%)	1.16 [1.01;1.34]	0.042
Ever had sewer backups	715 (63.6%)	2249 (67.6%)	1.20 [1.04;1.38]	0.014
Gaps large enough for animals and insects	877 (71.0%)	2745 (76.0%)	1.30 [1.13;1.50]	¡0.001
Census tract poverty (%)	43.2 (11.6)	43.5 (11.5)	0.94 [0.88;1.00]*	0.048
Census tract under 18 poverty (%)	59.2 (17.6)	59.5 (17.4)	1.02 [0.96;1.08]	0.487
African-American population (%)	0.81 (0.30)	0.79 (0.31)	0.94 [0.88;1.00]	0.048
Distance to nearest waterway	4.74 (3.10)	4.55 (2.98)	0.94 [0.89;1.00]	0.041
Elevation	188 (7.13)	188 (7.08)	0.95 [0.89;1.00]*	0.069
Percent of homes owner occupied	0.51 (0.13)	0.50 (0.14)	0.98 [0.92;1.04]	0.486
Percent of home built before 1939	0.42 (0.24)	0.43 (0.24)	1.00 [0.94;1.07]	0.899

Figure 1

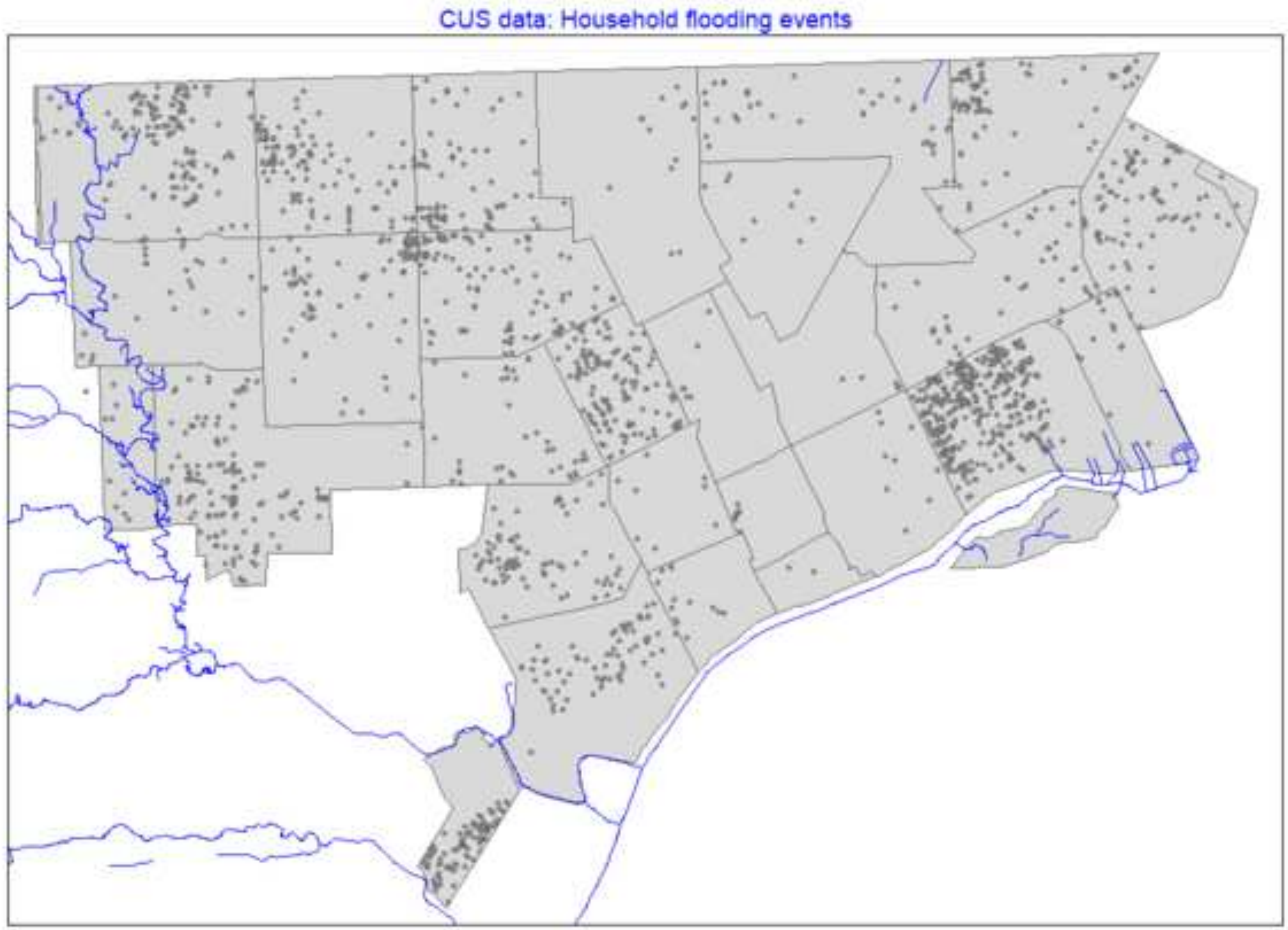


Figure 2

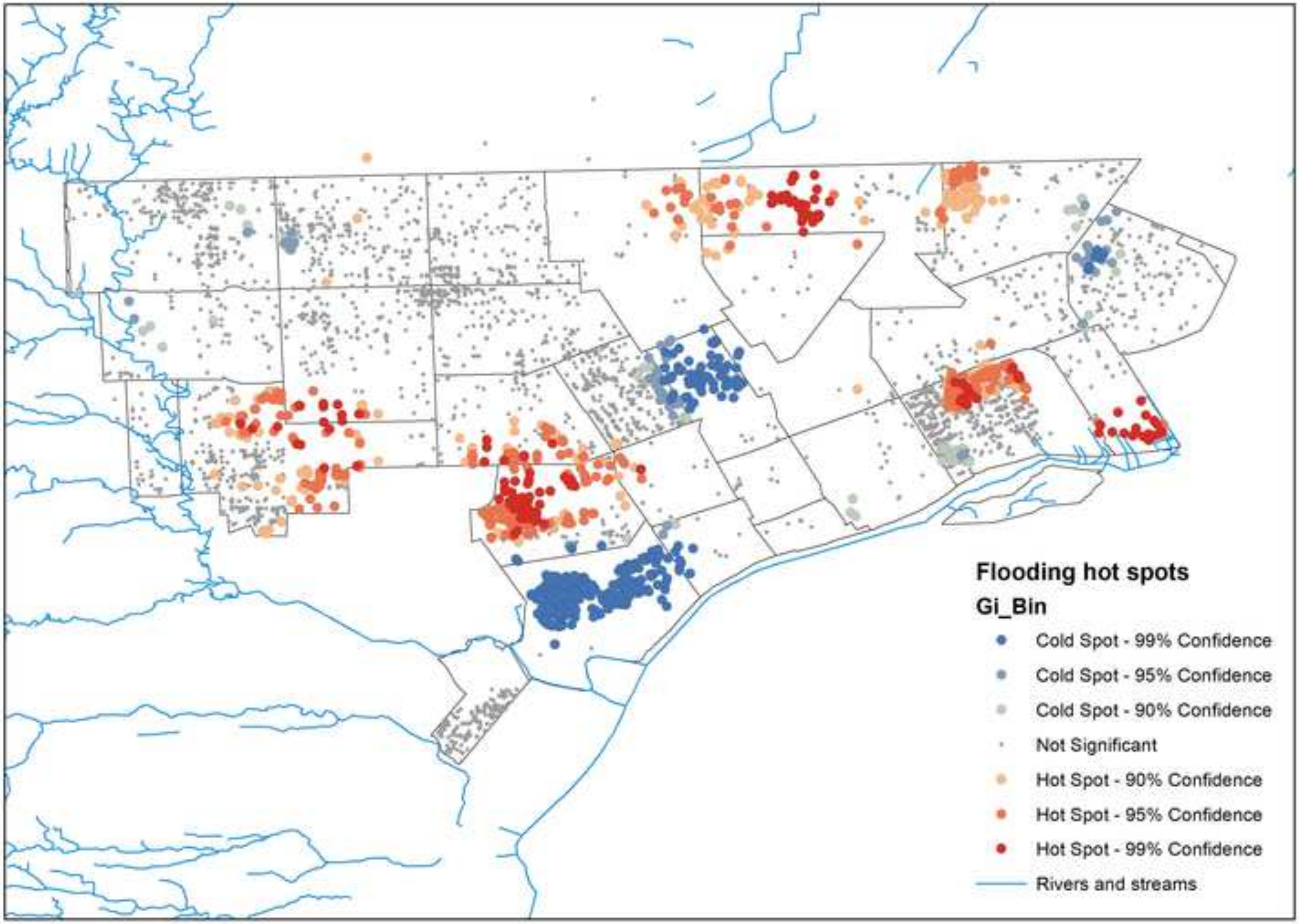
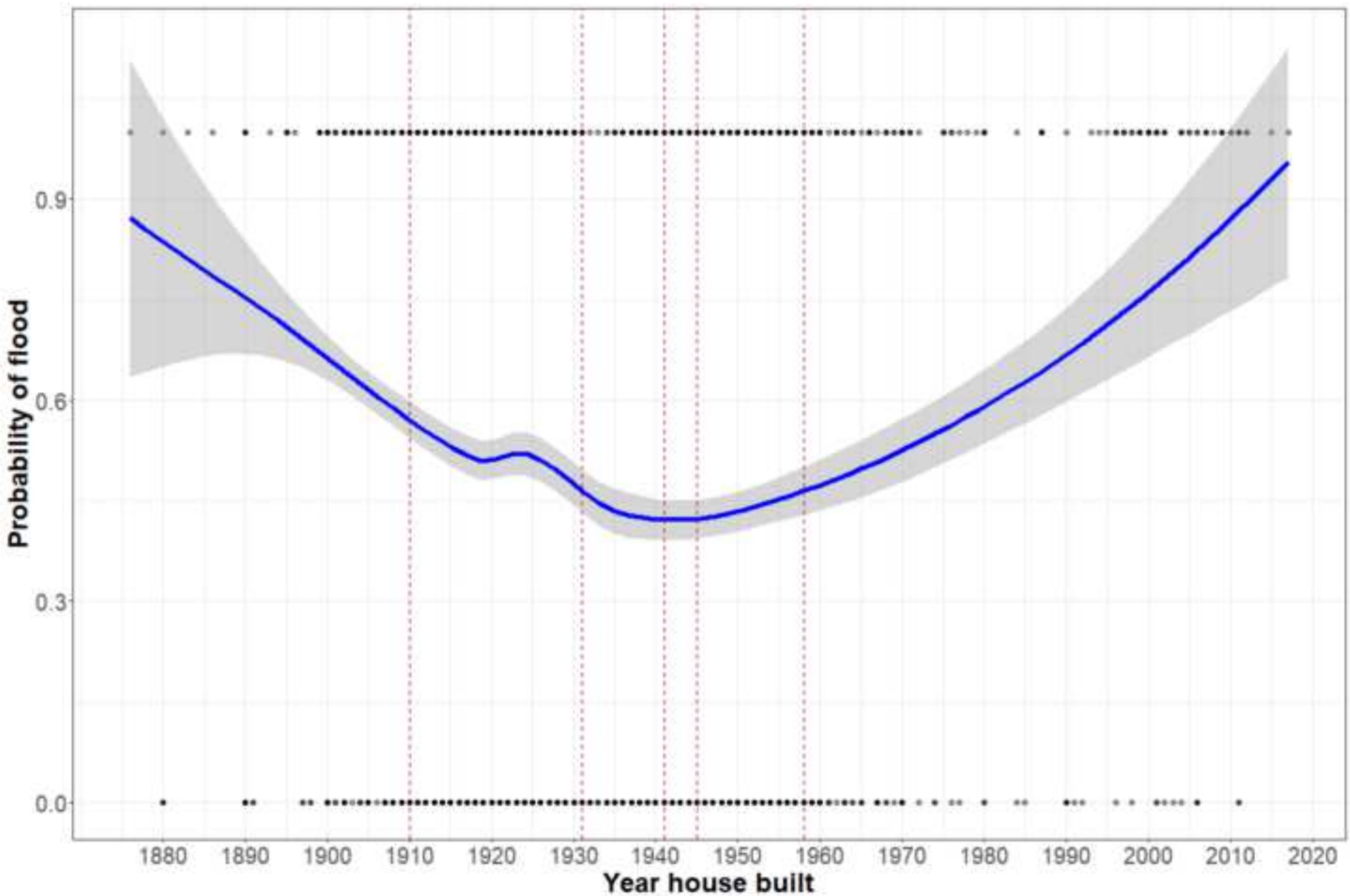

Flooding hot spots
Gi_Bin
Cold Spot - 99% Confidence
Cold Spot - 95% Confidence
Cold Spot - 90% Confidence
Not Significant
Hot Spot - 90% Confidence
Hot Spot - 95% Confidence
Hot Spot - 99% Confidence
Rivers and streams

Figure 3



Probability of flood
0.9
0.6
0.3
0.0
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year house built