Spatial disparities in flood vulnerability in New York City

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Background: Flooding in New York City is an increasing challenge. Recent storm events, such as Hurricane Ida, brought flash floods to the city for the first time, with property damage and deaths. The identification of vulnerable populations and how to increase flood resilience to coastal and pluvial events are climate change adaptation goals for city officials, bureaucrats, scholars, and stakeholders.
Methods: This analysis examines coastal and pluvial flood vulnerability by census tract in New York City. A variety of data sources are combined to create flood vulnerability maps using the exposure-sensitivity-adaptive capacity framework. A principal components analysis (PCA) with orthogonal rotation of social variables identifies four distinct hazard-sensitive populations clustered in different parts of the city. Publicly provided adaptive capacity resource (transportation and evacuation, health, communications and information, and hazard mitigation) accessibility is defined by distance. Moderate and extreme flooding levels from coastal and pluvial storm events define exposure.
Results: We identify specific areas in the city where flood exposure and hazard sensitivity are high and access to adaptive capacity resources is low. These locations are defined as high flood-vulnerable areas. Within the high flood-vulnerable areas, there are differences in the size of hazard-sensitive group populations (Hispanic poor, Asian immigrant, elderly living in high-rise buildings, and African American low-income).
Conclusions: The spatial combination of these variables identifies locations where targeted policies can promote hazard resilience. Our results illustrate a potential model to address and enhance flood vulnerability policy in the city.

Keywords: Coastal and pluvial flooding; New York City; vulnerability; sensitivity; adaptive capacity

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Introduction

Flooding is a significant global natural hazard (1), as it accounts for approximately 44% of all natural disasters. From 2000 to 2019, the world experienced over 3,200 floods that affected over 1.5 billion people, killed over 100,000, and caused over $650 billion in damages (2). Most deaths from flooding in Europe and the United States occur from drowning, electrocution, and physical trauma (3). Floods also affect mental health, including childhood development (4,5), interrupt health services that are essential for those who depend on electronic medical devices (6), and have knock-on effects for damaging water supply, increasing air pollution, and generating mold (7).

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There are several different types of flooding events (pluvial, fluvial, coastal, and groundwater) and each is associated with a range of impacts. For example, coastal flood hazards can include powerful storm surges and coastal 'sunny day' floods, which occur during high tides, with low levels of damage (8). No matter what type, however, flood events are increasing in number, strength, and frequency (9,10). Scholars project that continued climate change will lead to more frequent, powerful, and longer rainfall and storm events resulting in unprecedented levels of flooding (11).

Flooding is particularly critical for cities and urban residents. Urban areas have undergone physical changes (loss of vegetation, large areas of impermeable surfaces, etc.), which increase the potential for flooding. Cities are also locations of high population sizes and densities. Urban residents also have differential abilities to address hazards, including flooding. Studies suggest that a disproportionate share of the urban population affected by floods are from disadvantaged communities (12,13).

This study contributes to the growing literature on flood vulnerability using New York City as a case study. New York City is a coastal city and is exposed to multiple types of flooding including sea level rise, coastal storms and hurricanes (14), and pluvial flooding (15). Research suggests that flooding threats have increased for the city (16). For example, in 2012, Tropical Storm Sandy, the worst storm in the city's history, generated both pluvial and coastal flooding, killed 44 New Yorkers, destroyed over 300 houses, knocked out power for hundreds of thousands of residents, cost the city billions of dollars in losses, and generated an extended recovery process which continued for months, if not years (17,18). Studies also project that the city will experience an increasing number and intensity of coastal storms, and storm surges (19-23).

Residents in New York City are differentially vulnerable to climate change impacts, including heat waves (24) and flooding. For example, the most severely affected by Superstorm Sandy and Hurricane Ida were working-class, low-income, immigrant families and those in disadvantaged communities (25-28). This study attempts to address questions of flood vulnerability in the city. We ask the following questions:

- ❖ Where are the most hazard-sensitive communities in New York City?
- ❖ Where are the adaptive capacity facilities that can reduce hazard sensitivity located in relation to the most hazard-sensitive communities in the city?
- ❖ Given flood exposures, where are the opportunities to provide adaptive capacity facilities to the most highly hazard-sensitive communities?

Highlight box

Key findings

- We identify the location and potential size of populations living in highly vulnerable coastal and pluvial flood areas in New York City. Our method is a new technique that can help to provide targeted spatial policies for greater climate resilience.

What is known and what is new?

- New York City is exposed to coastal and pluvial flooding of increasing strength and frequency. We present an analysis that identifies the population exposure in sensitive communities of different types and the level of access to publicly provided adaptive capacity resources. This analysis facilitates the identification and location of specific vulnerable communities allowing for prioritization of resilience actions.

What is the implication, and what should change now?

- Our results can be used immediately to enhance health provision, transport policy, communications, and hazard mitigation actions for highly flood-vulnerable communities.

Background

Recent storms and flooding in New York City

The city, as part of the North American eastern seaboard area, typically experiences 4–6 Hurricanes annually from August to November. New York City, as a coastal city in the region, is exposed to these events as well as numerous mid-latitude cyclones and nor-easters all of which can result in coastal and pluvial flooding (14,15). The New York City Panel for Climate Change notes that these storms are getting more frequent and intense (8). A recent history, since 2020, demonstrates flooding risk in the city.

During the summer of 2020, Tropical Storm Fay passed west of New York City followed by Tropical Storm Isaias. While Fay's impact was due entirely to flooding (29), Isaias had a greater impact, although not through flooding. During Isaias little rain fell across the metro area, with 0.48 inches (12 mm) recorded in Central Park. High winds, however, created damage across the city. Wind gusts reached 78 mph (126 km/h) at the Battery (30). The storm knocked down over 3,100 trees in Queens, and one person was killed in the borough when a tree fell on their car (31). In Brooklyn, a building partially collapsed because of combined storm damage, resulting in evacuations, and a woman was taken to the hospital in critical condition after being struck in the head by a falling tree branch. Five overturned trucks on the Verrazzano-Narrows Bridge forced the bridge to shut down (32). The New York City Subway service at outdoor stations was suspended in the afternoon, due to sustained winds over 39 mph (63 km/h) (33). Service along the Metro-North Railroad and Long Island Rail Road was also suspended and the high winds caused widespread power outages during the event; Con Edison reported that some 93,000 customers lost electricity at the height of the storm (34).

On 21 August 2021, New York City experienced the first of two historic storms that hit within weeks of each other. Tropical Storm Henri stayed off the Long Island coast, but with New York City being on the western side of the storm, the city recorded record rainfall (35). Central Park reported 7.01 inches (178 mm). The hourly rainfall record was the wettest in 150 years. Brooklyn drivers abandoned their cars after waist-deep flooding inundated their vehicles (36). Approximately 4.45 inches (113 mm) in total fell on August 21 alone, the highest total in a day for the city since 2014, while the 7.01-inch (178 mm) total for the storm was the highest since Irene in 2011 (37).

On 1 September 2021, Hurricane Ida arrived. Ida was a Category 3 hurricane in Louisiana before weakening into a post-tropical system when it hit New York City and produced rainfall of biblical proportions. Approximately, 3.15 inches (80 mm) of rain fell in Central Park in 1 hour, which eclipsed the record-breaking 1-hour rainfall of 1.94 inches (42 mm) from Tropical Storm Henri, a few weeks earlier (38). The National Weather Service, struggling to depict the level of danger, declared a flash flood emergency in New York City for the first time. The storm was the deadliest New York had seen since Superstorm Sandy in 2012. Thirteen New Yorkers died, most of them residents living in basement apartments that flooded so quickly that they had no time to escape. Damage to the subway system reached $75 million (39). Approximately 33,500 buildings sustained damage, and the inland nature of the storm, the scale of the damage across the outer boroughs, and the swiftness of the rainfall represented a dramatic shift from severe weather events previously experienced (40).

During September 2023, Tropical Storm Ophelia brought a slow, yet soaking rain to New York. For 4 days between September 23 and 27, the city experienced alternating dark skies and periods of rainfall, with about 3 inches (76 mm) of rain falling across the city. The remnants of Tropical Storm Ophelia over the Atlantic Ocean combined with a mid-latitude cyclone system arriving from the west. This storm combination created a system that lingered over New York for 12 hours. Midtown Manhattan received 6.09 inches (155 mm) of rain, while more than 7.25 inches (184.2 mm) fell in parts of Brooklyn by nightfall. The 8.65 inches (217 mm) of rain at John F. Kennedy Airport surpassed its record for any September day since Hurricane Donna in 1960 (41). Floodwater spilled into subways and onto railways, which caused "major disruptions", including suspensions of service on 10 train lines in Brooklyn and all three Metro-North train lines.

The concept of vulnerability

The study of the vulnerability of human and natural systems to climate change brings together a variety of perspectives from a wide range of fields including, *inter alia*, climate science, development studies, disaster management, health, social science, policy development, and economics. Given the diversity of disciplines involved in vulnerability studies, there are differing conceptual models that define the subject (42-44).

Notwithstanding differences, two general approaches to vulnerability studies exist. Neither is considered better than the other but choosing one over the other implicates the focus of research and how vulnerability ultimately can be addressed (42). The first is the categorical or physical science approach, which often focuses on the quantification of damages (42,45). This approach centers on the predisposition of exposed elements to suffering damage and the potential of natural hazards to cause damage (46) and typically results in cost or physical loss estimates (47). That is, vulnerability is defined as the degree of loss, in terms of the percentage of structural damage, to a given element or set of elements subjected to a shock event of a given type and intensity (48). Vulnerability in this approach is an outcome and therefore reducing vulnerability involves reducing exposure through climate change mitigation, or developing adaptations to limit negative outcomes (42). Vulnerability curves, vulnerability matrices, and indicator-based methodologies are the main methods for assessing physical vulnerability (49-52).

The second model is the contextual or social science approach. Vulnerability in these studies examines the likelihood that an individual household or a community will suffer harm or experience losses related to environmental hazards and includes an examination of the social context that influences vulnerability (53). The social science approach focuses on political, institutional, economic, and social structures, their interactions, and how they condition the context for exposure, sensitivity, and capacity to address climate events (42,54). Vulnerability, in this case, is a ‘preexisting condition’, and reducing vulnerability involves altering the context in which climate change is experienced so that individuals and groups can better respond to changing conditions (42,55). Underpinning the focus is the belief that social vulnerability to hazards is driven by social inequality and is deeply embedded in social structures (56).

Due to the need for pragmatic indicators that identify levels and determinants of variability to inform planners on the interventions that would reduce vulnerability in an equitable manner, many researchers use the indicator-based approach (57-59). A number of different variants of the inductive approach to mapping vulnerability fields exist (60,61). Reviews of vulnerability assessment and indicator construction identify the use of a wide variety of approaches including multivariate statistical techniques, expert judgment, multi-criteria decision analysis, and many others (62-65), suggesting no consensus on best practices. Challenges remain in these approaches as there are complications related to weighting, aggregation, and standardization methods (66).

Components of vulnerability in our model

In our analysis, we use a social science approach and define vulnerability based on exposure, sensitivity, and adaptive capacity indicators (67). That is, our framework is based on the context under which populations interact with climate change events. Vulnerability is a function of the intensity of the shock, the exposure to the event for the population or infrastructure, the sensitivity of the population (estimated from socioeconomic and political status) exposed to that shock, and the adaptive capacity accessible to communities to avoid or ameliorate the shock (68). In our case, exposure is defined as the number of persons and buildings that are potentially confronted by flooding. We view intensity as the level of flooding, either moderate or extreme based on modeled forecasts. Sensitive populations are identified using socioeconomic variables as proxies for those populations that have reduced capacity to cope with hazards. We refer to this specific form of sensitivity as hazard sensitivity. We base our understanding of this form of sensitivity on research from previous studies. We view adaptive capacities as the collective resources and services that help individuals or communities adjust to actual or expected hazards and their effects, including material or social resources that moderate harm or provide benefits (59). While we provide general categories of adaptive capacity, we do not combine different themes to generate a single value. Rather, we examine the potential effect of each general theme for adaptive capacity on exposed, hazard-sensitive communities separately.

While we use the well-known model of vulnerability, we understand that the concept is not easily reduced to a solitary metric and is not easily calculable (12). We attempt to avoid direct weighting, aggregation, and standardization methods typically found in other models. Therefore, our solution is a social vulnerability framework for flooding based on geospatial co-location mapping. The framework provides the location and level of hazard sensitivity in different communities, their level of access to community adaptive capacity services and resources, and their exposure to either coastal or pluvial flooding. We argue that understanding the social context, the location, and the specific adaptive capacity necessary to reduce vulnerability can be used to prioritize and create targeted policies to reduce vulnerability. Our presentation of this framework is illustrative and demonstrates the usefulness of this method in performing vulnerability analyses.

Methods

For this study, we developed a set of maps of social vulnerability for flooding by census tract in New York City (*Figure 1*) that includes two different types of flood exposure (coastal and pluvial) of two different intensities (moderate and extreme), hazard-sensitive populations, and common resource adaptive capacity facilities or services. We used census tracts for the 2020 U.S. Census extracted from the National Historical Geographic Information System (NHGIS) (see https://www.nhgis.org/). The NHGIS provides easy access to summary tables and time series of population, housing, agriculture, and economic data, along with Geographic Information System (GIS)-compatible boundary files, for years from 1790 through the present and for all levels of U.S. Census Bureau geography, including states, counties, tracts, and blocks.

To identify hazard-sensitive populations, we employed a principal components analysis (PCA) that aggregates correlated variables believed to be related to hazard sensitivity. For adaptive capacity, we identified public and common resource facilities and infrastructure or services geographically across the city. The sets of resources were aggregated into four different themes or categories (health, flood mitigation, transport, and information). We identified the distance from each census tract to the location of each service as representing access to the resource. We choose the lowest (or nearest) resource to each census tract in each

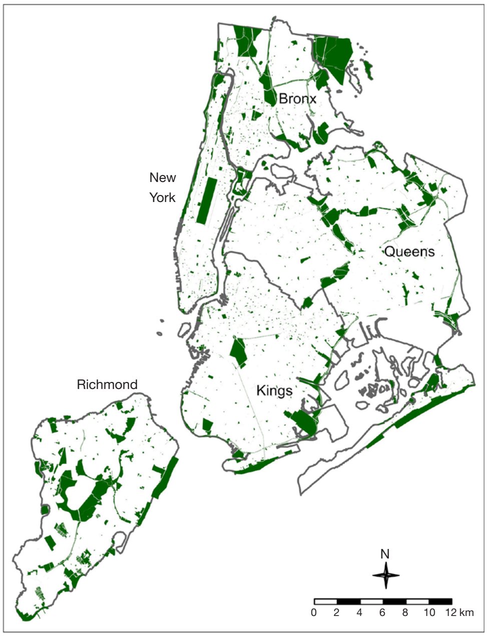

Figure 1 New York City counties (also known as boroughs) and park system. Note that Bronx County is also known as The Bronx, Kings County is also known as Brooklyn, New York County is also known as Manhattan and Richmond County is also known as Staten Island.

category to represent a proxy for access to these adaptive capacity resources. For exposure, we used two different sets of spatial datasets that defined the extent of coastal and pluvial flooding in the city. We defined a range of exposures based on the percentage of the building lot that was potentially flooded. This section describes the data used and details the analyses of those data in creating the vulnerability maps.

Data sources

Hazard sensitivity

Hazard sensitivity refers to the potential negative effects on individuals and communities caused by external stresses from natural, or other forms of hazards (see https://toolkit.climate.gov/). The level of sensitivity comes from a variety of socio-economic conditions and reduces individual coping mechanisms. The Center for Disease Control/Agency for Toxic Substance and Disease Registry's Social Vulnerability Index (CDC/ATSDR SVI) is a well-known index for use in climate and hazard adaptive and vulnerability studies (69). The social variables used in the index help local officials identify communities that may need support before, during, or after disasters (see https://www.atsdr.cdc.gov/placeandhealth/svi/data_documentation_download.html). We use these variables to identify hazard sensitivities of communities. We started with 18 U.S. Census variables identified by the CDC SVI including persons below poverty, persons unemployed, persons without a high school diploma, those aged 65 years and older, those aged 17 years and younger, persons with disabilities, single-parent households, individuals without English language proficiency, racial and ethnic minority status (non-Hispanic African American, non-Hispanic Asian, Hispanic), housing cost burden, the number of multi-unit structures and the number of mobile homes in the census tract, the number of crowded (more than one person per room) households, the number of households with no vehicles and the number of people living in group quarters (70,71). Rather than a vulnerability index, however, we viewed these data as providing proxies for hazard sensitivity. That is, census tracts with high numbers of young and older individuals, high numbers of persons with disabilities, and high numbers of residents without high school diplomas, for example, are more sensitive to hazards than census tracts with lower levels of these indicators. We collected the data for all these variables from the Census Bureau except for the housing cost burden. We use the housing cost burden collected by the CDC data for 2020. The census data we used came from the NHGIS database (72). (We performed the analysis on the data collected from the NHGIS database and the CDC data. The only variable shared is housing burden, which is calculated by the CDC, but not available in the NHGIS. The different datasets return similar results. We use the NHGIS data due to the easy ability to link to census tract maps and the availability of 2020 Decennial census data in the NHGIS data, but not the CDC data). Data were from the 2020 Decennial Census or the American Community Survey, 5-year average estimates [2016–2020] (see *Table 1* for variable basic statistics by census tracts). We discuss how each variable relates to flooding sensitivity below.

Age group (under 18 and over 64 years)

Children, specifically toddlers, and infants, are sensitive to flooding as they cannot properly evacuate or seek help for themselves. They cannot by themselves handle flood-related conditions, such as disease outbreaks, lack of safe drinking water, lack of food, and lack of ability to escape even low levels of water inundation, and therefore must be cared for by others (73). Elderly people have physical, sensory, or cognitive challenges that also make them sensitive to

Table 1 Basic statistics for variables related to hazard sensitivity in New York City by census tract

Variables	Total	Mean	Median	SD	Range	
					Max	Min
Total population	8,802,998	3,955	3,684	1,933	17,222	109
Occupied housing units	3,370,105	1,514	1,333	928	8,332	0
Population under 18 years	1,737,348	780	681	497	4,532	0
Population over 64 years	1,252,376	563	462	405	3,562	0
Number of crowded households	286,652	129	91	124	1,270	0
Persons with disabilities	908,839	408	315	318	2,736	0
Persons without high school diplomas	1,022,011	459	342	425	4,425	0
Persons in group quarters	182,657	82	8	273	6,600	0
Persons without English language proficiency	1,734,665	779	531	762	5,978	0
Households in multi-unit buildings	1,929,039	867	428	1,093	8,199	0
Number of mobile homes	5,132	2	0	10	189	0
Number of persons in poverty	1,422,827	639	419	641	4,350	0
Number of Black, non-Hispanic persons	1,776,692	798	298	1,010	7,431	0
Number of Asian, non-Hispanic persons	1,373,388	617	302	816	8,708	0
Number of Hispanic persons	2,489,981	1,119	671	1,189	9,641	8
Housing cost burdened housing units	1,194,569	537	450	362	3,020	0
Single parent households	236,289	106	67	120	869	0
Number of unemployed persons	287,426	129	96	118	1,459	0
Number of households without vehicles	1,748,510	785	561	762	6,076	0
Median household income	–	74,606	69,375	36,555	250,001	11,343

SD, standard deviation.

the impact of flooding disasters (71). The elderly are more likely to require financial support, medical care, and/or assistance from others due to issues such as fixed incomes, comorbidities, frailty, chronic illnesses, and complex medical conditions (6).

Minority residents

Minority communities in the U.S., specifically Black, and Hispanic, are socially and economically marginalized. Some of the disadvantages are due to historical legacies of institutional racism that have encouraged real estate discrimination and financial disempowerment (74-76). As a result, these communities are often rendered sensitive to hazards (77). Recent studies suggest that Black and Hispanic people are more likely to live in areas at high risk of flooding than other communities (78).

Crowding and group homes

Crowding includes households with more than one person per room. Lack of space can intensify problems during evacuation in flooding events. Many of those who died during Hurricane Ida were living in small basement apartments, which were difficult to evacuate (79). Crowding within housing units also exacerbates other aspects of hazard sensitivity (80). Populations residing in group quarters have special evacuation concerns (81). In the U.S., group quarters, such as prisons, are located in areas exposing them to climate disasters including flooding events (82).

Disability

People with physical and mental challenges are also likely to be more sensitive to hazards than others (83). Mobility, sensory, and cognitive disabilities prevent individuals from moving quickly. Those with mental disabilities may not address stress well and often require others for help. There is also the possibility that during the evacuation process, a lack of accessibility infrastructure slows or even prevents those with disabilities from evacuating. For example, some residents have medical equipment that is difficult to transport and therefore require specialized evacuation procedures similar to hospital evacuations (84).

Education

The level of education has been identified as useful indicator of vulnerability to flooding (85). For example, in the US, recent research has found that educational attainment is much lower in hotspots of flood exposure and vulnerability (86). This suggests that higher education enhances an understanding of flood hazards (87). Recent research supports this notion. For example, research into coping strategies for flooding suggests that developing one or another type of coping strategy in response to the risk of flooding is associated with knowledge of the characteristics of the hazard and the nature of the phenomenon. Hence, education and awareness of event is imperative to improving responses (88). Individuals aged 25 years or older without a high school diploma are not as likely to have the resources, knowledge, and experience to address hazards, including flooding, compared to their peers who have a high school or higher degree. In particular, during a flooding event, individuals and communities are often isolated from the support and intervention of emergency service providers making education and awareness of both preparation and how to respond, important to reducing harm and loss of property (89).

Limited English-speaking

Lack of proficiency in English is associated with social isolation (90) and research has demonstrated that social isolation is associated with increased mortality risk (91). This makes sense, as those who speak English "less than well" may not be as knowledgeable of early warning events or understand how to address hazards as those who can listen and easily understand instructions given by email, television, and radio. The result is social vulnerability (92). For example, immigrants without English language skills are more likely to rely on relatives and local social networks (i.e., friends and neighbors) for information than on official information sources, which may lead to uninformed decisions (93). It is not surprising then that many studies have identified English proficiency as a component of flood vulnerability (94-97).

Median household income and poverty status

Census tracts that have a lower median household income are more sensitive to flooding than those that have a higher median household income, due to economic disadvantages. In 2021, almost 2.7 million New York State residents lived in poverty and poverty rates are higher than 13% in New York City (98). Income and poverty are key drivers of hazard sensitivity to hazards because income is closely coupled with other forms of capital helpful in addressing hazards, such as flooding (99). For example, lower incomes suggest limited abilities to access automobiles, television, radio, phones, and other transportation and communications devices. This prevents preparation and coping capacities before, during, and after a hazard event. People in poverty are less likely to have the means or funds needed to prepare and/or recover from flooding damage. For them, having to replace lost or damaged property is an inordinately expensive task compared to those who are financially capable of recovering after a flooding disaster. This is true even if their property and/or household assets are not as costly as those who are financially well off, especially if they don't have any property insurance.

Multi-unit structures and mobile homes

Multi-unit housing in densely populated urban areas poses high sensitivity to hazards for tenants (60). Those who live in buildings with five or more units are vulnerable to overcrowding during evacuation processes. In high-rise towers, if there is a power outage, elevators may not work, and therefore individuals who live on higher floors may not be able to leave quickly, or at all. Alternatively, mobile homes are less sturdy structurally and are more damaged during strong storms than wood, brick, and mortar homes (100,101).

Single-parent households

Single-parent households with children under 18 years are especially vulnerable during a flooding disaster, as the parent must take care of their own needs and their already vulnerable child, with little to no assistance in a high-stress situation. The burden of financially recovering after flooding damage is also left with just one person, which can be stressful in addition to daily caretaker responsibilities (95).

Unemployment

Unemployed individuals may not have the financial networks necessary to recover and rebuild after damaging flood events compared to those who are employed. Because they don't have a steady stream of income, they have a harder time replacing lost or damaged property. Without employment, individuals often lack important benefits, such as health insurance in case of a severe injury or death.

Table 2 Variables used to construct the four themes of flood-related hazard adaptive capacity for New York City

Adaptive capacity themes	Variables used
Information	New York City Wi-Fi hotspot locations
	Ready New York events
Flood mitigation	DEP green infrastructure
	Hazard mitigation investments
Transportation	Bus stop shelters
	Subway stations
	Hurricane evacuation centers
Health	Hospitals

Data sources: New York State Department of Health and New York City Open Data. DEP, Department of Environmental Protection.

Housing cost burden

Housing costs include expenses like rent and utilities for renter-occupied households, and mortgage payments, taxes, insurance, and utilities for owner-occupied households. In 2022, New York State had 2.9 million households paying 30% or more of their income for housing and approximately 20% of New York State households were severely cost-burdened paying more than 50% of their income for housing (102). In the U.S. and New York, housing cost burdens have declined since 2010 among homeowners, but remain high for renters (103-105). Homeowner cost burdens are driven by changes in interest rates and home price increases which translate into a larger share of mortgages. Renters, however, experience a broader range of housing problems than do owners, and disasters worsen these problems (106). People whose rent payments take up a great portion of their income are more severely handicapped than those with lower relative payments. For example, they have reduced opportunities for transportation and communications devices. Sometimes high rent-burdened households must give up eating so that they can maintain thermal comfort in their apartments (107). High rent-burdened individuals also do not have access to resources and aid that homeowners would if their property or assets were damaged by flooding. Recent research suggests that disasters are associated with significant increases in evictions in the year of a disaster and the 2 years following a disaster and that eviction rates increase within a higher housing cost burden (108).

Automobile ownership

Rates of automobile ownership are generally lower in urban areas than in suburban and rural areas, especially among inner-city poor populations (109). Automobile ownership has been increasing in New York City over the past decade (110). For those who do not have vehicles, mobility is limited to public transit and less efficient modes (walking and bicycles) making transportation out of a flood evacuation zone problematic. Moreover, while transportation energy is typically not included in energy burden studies in the U.S. (111), data suggest that the poorest households in the country spend up to 40% of their net income on transportation, compared with the 19% the average American spends (112). In terms of flooding vulnerability, a study of the impacts of Hurricane Katrina found that those households lacking automobiles were most likely to be left behind during emergency evacuation efforts in advance of the storm (113). That is, the city had plans to use all lanes on major highways to accommodate outbound vehicle traffic, but there was no effective plan to evaluate transit-dependent residents (114).

Adaptive capacity variables and themes

Flood adaptive capacity includes economic and social capital, awareness and training, technology, infrastructure, and institutions (115). Several of these characteristics are included in the sensitivity element of the vulnerability equation (i.e., economic and social capital at the individual or household level), but others are not. Examples of variables that are not included are timely and relevant information, and provision of emergency services, which are important specific flood adaptive capacities (116,117), and are outside of individual and household socio-economic characteristics. We focus our adaptive capacity themes on community-level common and public resources and infrastructure for four types of services: transportation, health, information, and flood mitigation. Eight variables from several different datasets were used to construct these four themes (*Table 2*), as per a version of adaptive capacity published by the New York City Emergency Management Office (118). The Health Facility General Information from the New York State Department of Health identified hospitals throughout the state (see https://health.data.ny.gov/Health/Health-Facility-General-Information/vn5v-hh5r/data). All other adaptive capacity data were extracted from the New York City Open Data system. Each data point was geolocated on a map of New York City. The following subsections explain each category and which datasets were grouped into the different categories.

Information and communication

Emergency management information includes teaching disaster preparedness and the ability to provide and update information on potential hazard events. In this category, we included data on New York City Wi-Fi hotspot counts (see https://data.cityofnewyork.us/City-Government/NYC-Wi-Fi-Hotspot-Locations/yjub-udmw/data) and Ready New York event counts (see https://data.cityofnewyork.us/w/hyur-qpyf/25te-f2tw?cur=S-NfXY6yett&from=0UsI4dKbTtJ). Ready New York events are provided by the New York City Emergency Management Office, which sends knowledgeable staff members and New York City Community Emergency Response Team volunteers to educate communities about preparing for emergencies (see https://www.nyc.gov/site/em/ready/request-event.page). New York City Wi-Fi includes free Wi-Fi by the New York City and CityBridge (a consortium of companies that owns, operates, and oversees the LinkNYC program). The LinkNYC structure provides fast, free public Wi-Fi, phone calls, device charging, and tablet access for city services and maps (see https://www.link.nyc/). For those who do not have Wi-Fi or have poor connections at home, Wi-Fi hotspot locations are essential for keeping up with emergency preparedness protocols and other essential news. For these data, we included all Wi-Fi locations.

Hazard mitigation

Hazard mitigation includes cost-effective and sustained actions to reduce the long-term risk to human life, property, and infrastructure from hazards provided by New York City. Two variables in this category were used to construct hazard mitigation investments (see https://www.nyc.gov/site/planning/data-maps/open-data/dwn-capital-planning-database.page) and green structure infrastructure (see https://data.cityofnewyork.us/Environment/DEP-Green-Infrastructure/spjh-pz7h). The city's green infrastructure presents an alternative approach to improving water quality that integrates "green infrastructure", such as swales and green roofs, with investments to optimize the existing system. In addition to providing stormwater runoff mitigation, green infrastructure can provide ecological and social benefits, as well as physical and psychological benefits that contribute to community health and resilience. This helps build community rapport in times of crisis when city officials are unable to attend to a given community's needs (119,120). Hazard mitigation investments are the financial investments in infrastructure, planning, response, and resource protection that the city has already made to reduce hazard impacts.

Public health

Public health capacity is defined as access to nearby medical services, specifically hospitals. Access to nearby medical services during a flooding disaster is essential in case of life-threatening injuries that cannot be treated at home (60). In this category, we included one variable: hospital location.

Public transportation and evacuation

Public transportation includes bus (see https://data.cityofnewyork.us/Transportation/Bus-Stop-Shelters/qafz-7myz), subway (see https://new.mta.info/open-data), and hurricane evacuation centers (see https://data.cityofnewyork.us/Public-Safety/Hurricane-Evacuation-Centers-Map-/ayer-cga7). The three variables for this theme include bus and subway stops and evacuation centers. The city runs a massive public transit program that can move large numbers of people (121). Access to public transportation is important before ongoing flood events when evacuation by private vehicles is not possible. Evacuation centers are shelters outside hurricane evacuation areas (see https://maps.nyc.gov/hurricane/). Access to nearby evacuation centers is essential in the case of severe damage to a person or family's household and renders the place uninhabitable (122).

Flood exposure

Two types of maps inform flooding exposure in New York City. The first was coastal flooding. We used the Federal Emergency Management Agency (FEMA) 2015 Current 100-year Floodplain Preliminary Flood Rate Insurance Map (PFIRM) to represent moderate coastal flooding (see https://www.fema.gov/flood-maps). This map identifies locations within New York City that have up to a 1% chance of being flooded annually. This preliminary flood hazard data provides projected exposure and is not considered a final product but rather the most up-to-date information publicly available. The 2015 Current 100-year Floodplain PFIRM dataset includes special flood hazard areas (SFHAs) and the risk premium zones, all of which reside on New York City's coastline (123). Flood zones that are either denoted with A, AE, AO, or VE, known as SFHAs, are high-risk areas (124). A, AE, and AO zones all have a 1% chance of flooding each year. V zones also have a 1% change in flooding each year but have additional hazards associated with storm-induced waves. Homeowners located in A or V zones are required to purchase flood insurance if they have a mortgage from a federally backed or federally regulated lender. For the extreme coastal flooding case, we use the Sea Level Rise Maps (2050s 500-year Floodplain) map, which is based on FEMA's Preliminary Work Map data, and the New York Panel on Climate Change's 90th Percentile Projects for Sea-Level Rise (31 inches).

The second set of flood exposure maps is the New York City Stormwater Flood Maps (see https://experience.arcgis.com/experience/6f4cc60710dc433585790cd2b4b5dd0e). We identified moderate pluvial flooding with the Moderate Stormwater Flood Map without sea level rise that approximates pluvial flooding of approximately 2 inches in 1 hour. This event has a 10% annual chance of occurrence each year. For extreme pluvial flooding, we used the Moderate Stormwater Flood Map with 2050 sea level rise as the extreme pluvial case. This map also uses 2 inches in 1 hour of rainfall but also includes 2.5 feet of sea level rise. It also includes impacts of potentially blocked storm drains and outfalls from sea level rise. The base models that were used to develop this dataset were the city's calibrated long-term control plan (LTCP) models which added a two-dimensional overland component and improved the resolution of the sewer network. The maps were further enhanced with an innovative composite rain-on-mesh approach to model extreme rainfall events (125).

Analysis

Several analyses were performed for the study. First, we used a PCA analysis to identify various hazard-sensitive areas in the city. These composite or latent variables were then used in further analysis with adaptive capacity and exposure variables. Second, the adaptive capacity data was mapped and the distance to all facilities and infrastructures was calculated. We used the shortest distance from a community to the adaptive capacity site as representing the ability of a community to access the service. For example, from a variety of different locations of hospitals in the city, we identified the distance from the center of each census tract to the center of the nearest census tract that has a hospital. This distance represented a proxy for the access that those in the census tract had to health care. Third, we identified exposure after we performed a dasymetric geospatial analysis of the census tract data (126,127). We allocated variables based on shares of residential units within lots for each census tract. We also identified differences in plot inundation by the percentage of the lot that was exposed to flooding (10%, 50%, and 90% inundation levels). Finally, we used a modified vulnerability equation that includes exposure, sensitivity, and adaptive capacity by census tract (128). Rather than generating an index that standardizes and aggregates different variables, we provide a spatial analysis that avoids aggregation and weighting to generate the final set of flood vulnerability maps for the city.

The following steps outlined the processes undertaken: (I) factor scores of the rotated PCA analysis were used for each census tract to identify the level of hazard sensitivity and was then mapped by quintile; (II) the hazard sensitivity map was clipped by the lowest adaptive capacity value for each theme (i.e., the farthest distance from each of the four types of adaptive capacity resources) to identify neighborhoods for each hazard-sensitive group with the lowest capacity; (III) these data were clipped again with the flood exposure results to define areas of high hazard sensitivity by group, low adaptive capacity and exposure to different types of flooding. From this analysis, we identified areas where the local government can focus on specific services for different communities. In this section, we describe each of the sets of analyses in more detail.

Hazard sensitivity data preparation and analysis

PCA is a multivariate statistical dimensionality reduction method, which attempts to identify a limited number of "latent" variables that retain as much information of the original data as possible. There are several steps in applying this technique. The first task is to scale and center the data. We did this by calculating z-scores for each variable. This allowed for the comparison of the impact of variables with distinctly different values.

Second, we then created a correlation matrix from the scaled data. We performed a PCA on the correlation matrix to identify how much variance each component explained and generated a scree plot using the results of the PCA to determine which components to extract. Thereafter, we performed an orthogonal rotation on the extracted components to improve interpretability. The loading values represent the strength of the variable on the specific rotated component. We then calculated factor scores for each rotated component for each census tract. In our case, high factor scores represent high hazard sensitivity for a census tract for the specific rotated component. We divided each of the factor score distributions into quintiles to identify those areas of highest hazard sensitivity (80% highest and above).

Adaptive capacity data preparation and analysis

Adaptive capacity was calculated as a distance measure from each census tract. We first performed a spatial join on each

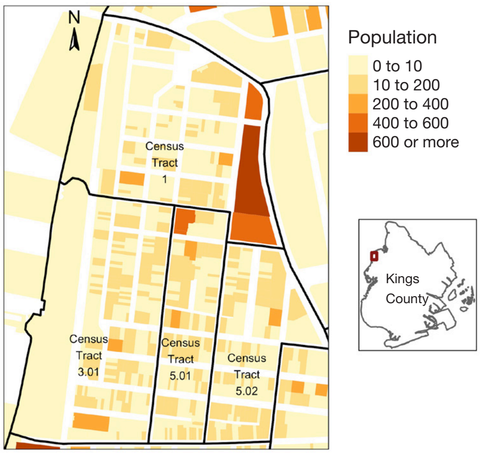

Figure 2 Location of population within selected census tracts using building residential units to distribute population; an example from northwestern Brooklyn, New York City.

adaptive capacity dataset to the New York City census tract geometry to get a count of adaptive capacity variables in each tract. The number of hospitals, evacuation centers, subway stations, bus stop shelters, mitigation investments, green infrastructure projects, Wi-Fi hotspots, and Ready New York events were identified for each census tract. We then calculated the Euclidean distance from each census tract centroid to each tract that had adaptive capacity services or facilities and found the shortest distance from each census tract centroid to a census tract centroid with an adaptive capacity variable. We aggregated the adaptive capacity distances for variables into four themes and identified the quintile distributions for each theme. In this case, the highest quintile represented the lowest adaptive capacity (i.e., had the longest distance).

Exposure data preparation and analysis

We performed a dasymetic analysis which uses building lots within a census tract to locate population. As demonstrated in *Figure 2*, the census tract population is not uniformly distributed. In the figure, if half of Census Track 1 was flooded along the north-south axis, it would not affect half the population of this area. We used building lot information for all of New York City to identify population and building levels of exposure. The number of residential units for each lot is available from the Primary Land Use Tax Lot Output (PLUTO) database, which identifies over one million lots of which 950,000 are residential buildings in New York City. We used the residential units to allocate the population proportionately. That is, we added up all residential units within a census tract and then allocated the population and appropriate socio-economic data based on the residential unit share of each plot within the tract. This technique is believed to provide a more rigorous allocation than assuming an even distribution of population and infrastructure across census tracts (129).

Then, for coastal and pluvial flooding, we overlayed the flood maps and calculated exposure by census tracts through the aggregation of lot information. A question arises of how much inundation can be considered flooded. Are those who live in a plot that has been 25% or 100% flooded considered exposed? Rather than choosing an arbitrary percentage, we identified lots that were 10%, 50%, and 90% flooded to get a range of exposed populations.

Vulnerability mapping

For location and estimates of flood-vulnerable populations, we combine multiple analyses. We identify census tract populations with high factor scores (highest quintile) as highly hazard-sensitive and remove those census tracts with all but the lowest adaptive capacity scores (all but the longest distances to the adaptive capacity resource). We then overlay the exposure map and extract the census tract that is exposed to either coastal or pluvial flooding. The result is the high flood vulnerability areas. Finally, we then calculate the populations living in these areas. This helps to identify the location and potential population size of different highly vulnerable flood locations.

Ethical statement

All data were openly sourced. No human or animal experiments were conducted, and no case reports were used.

Results

This section describes the outcomes of the various analyses (sensitive populations, adaptive capacity, and exposure), and presents the results of vulnerability to coastal and pluvial flooding in New York City. Each subsection below describes different analyses and includes numerical and spatial results. Given space constraints, we present examples of each. The supplemental material includes further information.

Hazard-sensitive populations

To identify the hazard-sensitive populations a PCA was conducted on 14 items with orthogonal rotation (varimax). PCA assumes that that if variables measure different aspects of the same things there should be high correlations between the variables relating to these sub-traits, sometimes called latent variables. If the correlations are low across the correlation matrix, then the variables do not relate to any of the dimensions and are therefore not useful. Since this was the case for two variables (persons in group quarters, and number of mobile homes) with low correlations we removed them from the original 18 variables examined. Both variables had correlations below 0.3 with 10 or more other variables. There is an objective statistical test of whether correlations (overall) are too small. If the variables in our correlation matrix did not correlate at all, then our correlation matrix would be an identity matrix (i.e., the off-diagonal values are zero). Bartlett's test of sphericity examines whether the correlation matrix resembles an identity matrix. If the correlation matrix resembles an identity matrix, it means that every variable correlates very badly with all other variables (i.e., all correlation coefficients are close to zero). Given that we're looking for clusters of variables that measure the same things, this scenario is problematic; if no variables correlate, then there are no clusters to find (130). Our Barlett's test resulted in a chi-square statistic =25,180.22, P<0.001, degree of freedom (df) =78, which indicated that correlations between the 16 items were sufficiently large for PCA.

Alternatively, variables can correlate too highly, although mild multicollinearity is not a problem for PCA. In the analysis, however, it is important to avoid extreme multicollinearity. As with regression analysis, multicollinearity causes problems in PCA because it becomes impossible to determine the unique contribution of highly correlated variables to the component. Our analysis of the correlation matrix suggested that "households with no vehicles" and "housing cost burden" had high correlations with other variables and were therefore removed, leaving 14 variables. Multicollinearity can be detected by looking at the determinant of the correlation matrix. One simple heuristic is that the determinant of the correlation matrix should be greater than 0.00001 (130). Our determinant, with the 14 variables, is larger than this value, so the set of variables identified is not too highly correlated.

The reliability of the results depends upon the sample size. The Kaiser-Meyer-OIkin (KMO) measure of sampling adequacy (131) can indicate whether the PCA is inappropriate given our sample size. The KMO statistic varies between 0 and 1. A value of 0 indicates that the sum of partial correlations is large relative to the sum of correlations, indicating diffusion in the pattern of correlations. This suggests that the analysis is likely to be inappropriate. A value close to 1 indicates that the patterns of correlations are relatively compact so PCA should yield distinct and reliable factors. Values greater than 0.5 are barely acceptable. Values between 0.7 and 0.8 are good, values between 0.8 and 0.9 are great and values above 0.9 are superb (132). The KMO test for our data provided an overall value of 0.86 with values for the 14 variables ranging between 0.71 and 0.97. These are adequate results for the PCA analysis.

An initial analysis was run to obtain eigenvalues for each component in the data. Four components had eigenvalues over Jolliffe's criterion (133,134) of 0.7 and in combination explained 78% of the variance. The scree plot also suggested four, at most, components at the inflection point. Given the large sample size (over 2,200) (the sample size in our case was the number of census tracts with data; there are over 2,300 census tracts in New York City for the 2020 census and we had data for over 2,200) and the convergence of the scree plot and Jolliffe's criterion, four components were retained for the final analysis. *Table 3* presents the variable loadings after rotation. We only show variables with 0.4 or higher loading values. As mentioned previously, the loadings describe how much each variable contributes to the rotated principal component. Large values (either positive or negative) indicate a strong relationship between the variable and the rotated principal component. The items that load highly on the first rotated component, by strength, include the Hispanic population, crowded quarters, poverty, and high numbers of children. We called this group "Hispanic poor". For the second rotated component, the Asian population and poor fluency in the English language load highly. We call this component, "Asian immigrant". For rotated component 3, the elderly population, multiunit residents, and disabled population load highly. We call this component "Elderly in high-rise apartments". Finally, variables that load strongly onto rotated component 4 include the African American population, low-income, single-parent households, and disabilities. We call this component "African American low-income".

The map of factor scores for each component identifies different locations for each hazard-sensitive group and corresponds to our general understanding of the social geography of New York City neighborhoods. We use two examples to demonstrate. *Figure 3* demonstrates mapped factor scores for the Asian immigrant and African American

Table 3 The variable loadings on the four principal components used in the study

Variables	Rotated components			
	Hispanic poor	Elderly in high-rise apartments	African American low income	Asian immigrant
Hispanic persons	0.88			
Crowded units	0.79			
Poverty	0.78			
Persons under 18 years of age	0.75			
Persons without a high school diploma	0.75			
Lack of English proficiency	0.69			0.66
Single parent households	0.63		0.53	
Unemployed persons	0.63			
Disabled persons	0.56	0.56	0.4	
Persons over 64 years		0.85		
Households in multi-unit buildings		0.8		
African American persons			0.77	
Median household income			−0.72	
Asian persons				0.87
Sum of square loadings	4.98	2.2	1.96	1.79
Proportion of variance	0.36	0.16	0.14	0.13
Cumulative variance	0.36	0.51	0.65	0.78

Values less than four were excluded. Summary statistics show the percent variance accounted for in each principal component, cumulative variance and the sum of the squared loadings.

low-income components. We divided the factor scores into quintiles to allow for easy identification of the location of the most hazard-sensitive sub-groups might be located. The darker the red color of the census tract, the higher the level of hazard sensitivity for the specific community. The areas of dark red are the locations of the top 20% highest factor scores. For example, in *Figure 3*, the map on the left identifies areas of dark red where there is a high Asian population and a high population with a lack of English proficiency. This represents a relative value of a hazard-sensitive population, in this case, Asians with low English proficiency. We did this for each community but, given space needs only show examples. The mapped factor scores for all components can be seen in Figure S1. *Table 4* presents the size of each population within different factor score quintiles. For example, the census tracts with the top 20% highest factor scores for African American low-income contain over 50% of the city's total African American population (over 900,000 population). The census tracts with the top 20% highest factor scores for the Asian immigrant component also hold over 50% of the city's total Asian population (over 689,000 population).

Adaptive capacity

The shortest distances to each of the four different sets of adaptive capacity resources were computed for each census tract. That is, if there was a hospital within the census tract, the value for the "health" adaptive capacity given would be zero. If the closest hospital was in a census tract further away, we used the Euclidean distance from the centroid of the origin census track to the centroid of the census tract that housed the hospital to demonstrate differences in the distribution of public capacities. When dividing these data into quintiles, the high levels represent the largest values and therefore the lowest adaptive capacities. The further

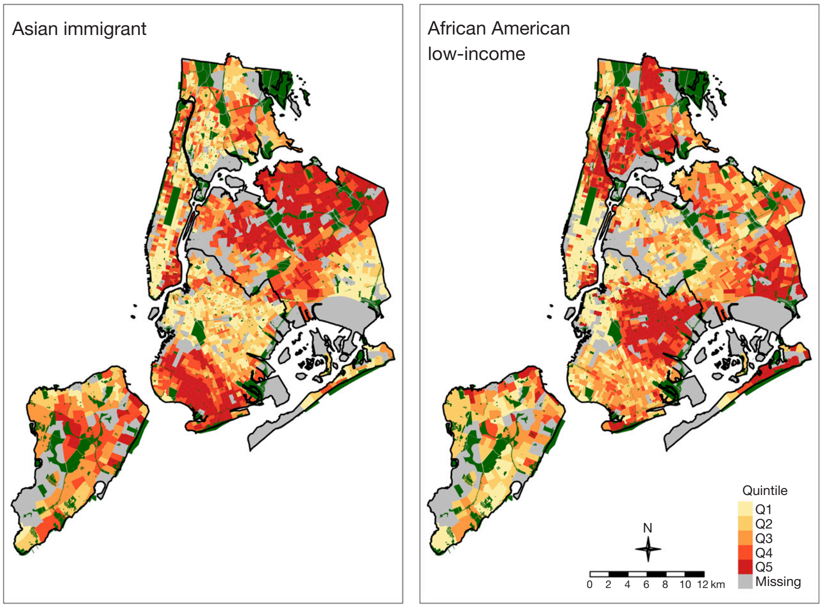

Figure 3 Examples of the spatial distribution of quintiles of factor scores for rotated principal components. On the left is the Asian immigrant results. On the right represent African American low-income areas. Yellow colors represent low factor scores, which translates into low levels of these variables in those census tracts. The darker red areas translate into high levels of these variables within census tracts.

Table 4 Vulnerable populations of different hazard-sensitive areas by quintile

Quintile	Hispanic poor	Asian immigrant	Elderly in high-rise apartments	African American low income
Q1 (lowest sensitivity)	132,116	90,388	107,475	79,688
Q2	190,146	71,481	143,778	83,393
Q3	293,315	119,252	184,878	143,307
Q4	475,011	238,300	255,386	379,696
Q5 (highest sensitivity)	1,162,037	689,341	436,799	905,265

away from a census tract, the lower the access and therefore the adaptive capacity of that resource. *Figure 4* shows two examples, health and transportation. In these cases, the darkest red colors designate census tracts that are further from the adaptive capacity resource. The left side of *Figure 4* demonstrates that health capacities are high in Manhattan, as most of the island is yellow. However, in Brooklyn, Queens, and Staten Island the hospitals are dispersed. Within the city, parts of Staten Island and Eastern Queens are the furthest from hospitals.

Coverage of the various adaptive capacity services varies across the city. As opposed to health the coverage of public transportation is more evenly distributed all around the city. For the other adaptive capacities see Figure S2. The mean, standard deviation, and ranges for each of the adaptive capacity group quintiles are presented in *Table 5*.

Hazard-sensitive communities with low adaptive capacity

To demonstrate the potential effectiveness of our analysis we combined the adaptive capacity theme values with the hazard-sensitive data which helps to focus on areas of the city where the adaptive capacity infrastructure or service was farthest from all census tracts and hazard sensitivity is high. In this case, we only mapped areas where the adaptive capacity for each set of capacities was at its lowest (80–100% quintile). Therefore, areas on the maps that are red indicate both low adaptive capacity and high sensitivity.

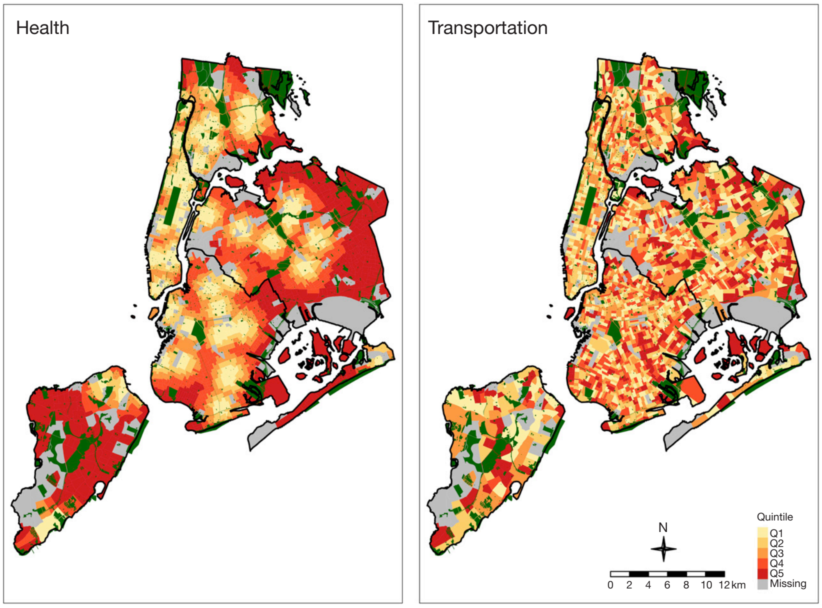

Figure 4 Examples of spatial distribution of quintiles for public resource adaptive capacity. On the left is the quintiles for health and on the right for transportation. The yellow areas are locations of high adaptive capacity scores (low quintiles) and the red areas are low adaptive capacity scores (high quintiles).

Figures 5,6 presents samples of the analysis. *Figure 5* shows all areas of the city that have the highest distance from hospitals and in those areas are mapped the levels of sensitivity for the Asian Immigrant component (left) and the African American low-income component (right). Areas where the adaptive capacity is above the below the quintile are removed and therefore appear as white. The results highlight where the sensitivity is highest, and the adaptive capacity is lowest. For health this is evident in Southeastern Queens and Southeastern Brooklyn for African American low-income component, Northeast Queens, and central Staten Island for the Asian immigrant component. *Figure 6* does the same for transportation adaptive capacity and these same two sensitivity components. In this case, areas of high sensitivity are scattered, although there are clustered locations in Southeastern Queens and Southern Brooklyn for the African American low-income component and Northeastern Queens for the Asian immigrant component. For the full set of hazard-sensitive components and adaptive capacities see Figure S3.

Exposure

Coastal

For moderate coastal flooding, we chose the 100-year coastal flood map to represent exposure. For extreme coastal flooding, we chose the 2050 100-year flood map with sea level rise (*Figure 7*). The coastal storm exposure analysis presents ranges of populations projected to experience flooding given levels of inundation within city lots. According to these calculations, the range of the total population exposed to a 100-year coastal flood is between 316,000 and 688,000 or between 3.6% and 7.9% of the total population that would be directly affected by such an event (*Table 6*). In terms of the extreme coastal flooding event, the total population affected ranges from 923,000 to 1.9 million or between 10.5% and 22.1% of the total current city population. Populations presented in the table are totals and are not limited to hazard-sensitive communities.

We then map the location of hazard-sensitive populations on the coastal exposure maps. We again present only the Asian immigrant and African American low-income components of sensitivity as examples for both moderate and extreme coastal flooding. All locations that are not exposed to flooded are white. The areas that are exposed to flooding have mapped onto them the quintiles of sensitivity of the two components. The dark red areas demonstrate areas where highly sensitive populations are exposed to flooding (*Figure 8*). For the full set of sensitive components and coastal flooding see Figure S4.

Table 5 Basic statistics for adaptive capacity for each theme by quintile

Adaptive capacity themes	Quintile	Mean	SD	Max	Min
Health	Q1 (highest adaptive capacity)	0.52	0.24	0.83	0.00
	Q2	1.08	0.14	1.32	0.83
	Q3	1.58	0.15	1.87	1.33
	Q4	2.29	0.29	2.88	1.87
	Q5 (lowest adaptive capacity)	4.40	1.41	8.46	2.88
Information	Q1 (highest adaptive capacity)	0.00	0.00	0.00	0.00
	Q2	0.00	0.00	0.00	0.00
	Q3	0.00	0.00	0.00	0.00
	Q4	0.30	0.10	0.42	0.00
	Q5 (lowest adaptive capacity)	0.70	0.39	3.48	0.42
Mitigation	Q1 (highest adaptive capacity)	0.00	0.00	0.00	0.00
	Q2	0.00	0.00	0.00	0.00
	Q3	0.24	0.16	0.44	0.00
	Q4	0.57	0.08	0.73	0.44
	Q5 (lowest adaptive capacity)	1.13	0.44	3.76	0.73
Transport	Q1 (highest adaptive capacity)	0.00	0.00	0.00	0.00
	Q2	0.00	0.00	0.00	0.00
	Q3	0.00	0.00	0.00	0.00
	Q4	0.21	0.15	0.38	0.00
	Q5 (lowest adaptive capacity)	0.65	0.38	3.48	0.38

Adaptive capacity quintiles represent the distance from the nearest facility in kilometers. SD, standard deviation.

Given that the initial dasymetric analysis was based upon building lots, we were able to identify the number of different types of buildings flooded in each case (*Table 7*). Flooded buildings were identified as being exposed to having, at least, 10% of the lot inundated. We present the New York City Department of City Planning building typology as defining building types. According to our results approximately 64,000 one-family, 44,000 two-family, and 16,000 multi-family residential buildings would be exposed to at least a 10% inundation level of flooding during a moderate coastal storm. During an extreme coastal event, approximately 147,000 one-family, 132,000 two-family, and 51,000 multi-family residential buildings would be exposed to similar levels of flooding.

Pluvial

We use New York City Stormwater Flood Maps for what we called moderate and extreme pluvial flooding (*Figure 9*). The results suggest that the range of population exposed to moderate pluvial flooding is between 300 and 157,000 persons or between less than 0.01% to 1.8% of the total city population (*Table 8*, Figure S5). The range of those exposed to extreme pluvial flooding is from 6,000 to 192,000 or between 0.1% and 2.2% of the total population. According to our results approximately 9,400 one-family, 6,800 two-family, and 2,700 multi-family residential buildings would be exposed to at least a 10% inundation level of flooding during moderate pluvial flooding. During an extreme pluvial event, approximately 13,000 one-family, 9,000 two-family, and 3,400 multi-family residential buildings would be exposed to similar levels of flooding (*Table 9*).

Most vulnerable populations

Finally, we present estimates of the high hazard-sensitive populations within each different component, who are

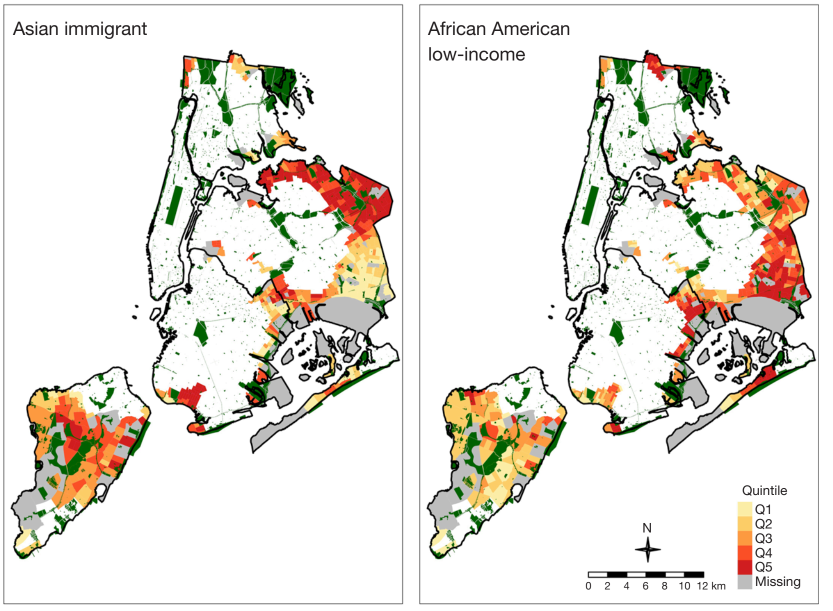

Figure 5 Examples of combining hazard sensitivity and adaptive capacity. These maps only show locations where adaptive capacity is low for health. The values are quintiles for hazard sensitivity. On the left is the rotated principal component factor scores for Asian immigrant component. Areas in dark red designate high hazard sensitivity for this component and low adaptive capacity. The map on the right is the same for the African American low-income component. Areas in dark red show high levels of the variables for this hazard-sensitive component and low adaptive capacity.

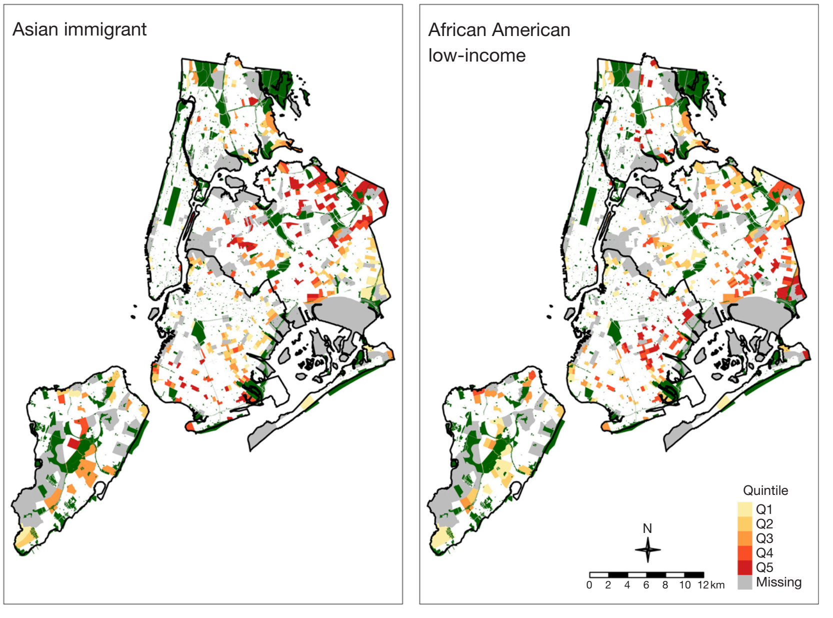

Figure 6 Examples of combining hazard sensitivity and adaptive capacity. These maps only show locations where adaptive capacity is low for transportation. The values are quintiles for hazard sensitivity. On the left is the rotated principal component factor scores for Asian immigrant component. Areas in dark red designate high hazard sensitivity for this component and low adaptive capacity. The map on the right is the same for the African American low-income component. Areas in dark red show high levels of the variables for this hazard-sensitive component and low adaptive capacity.

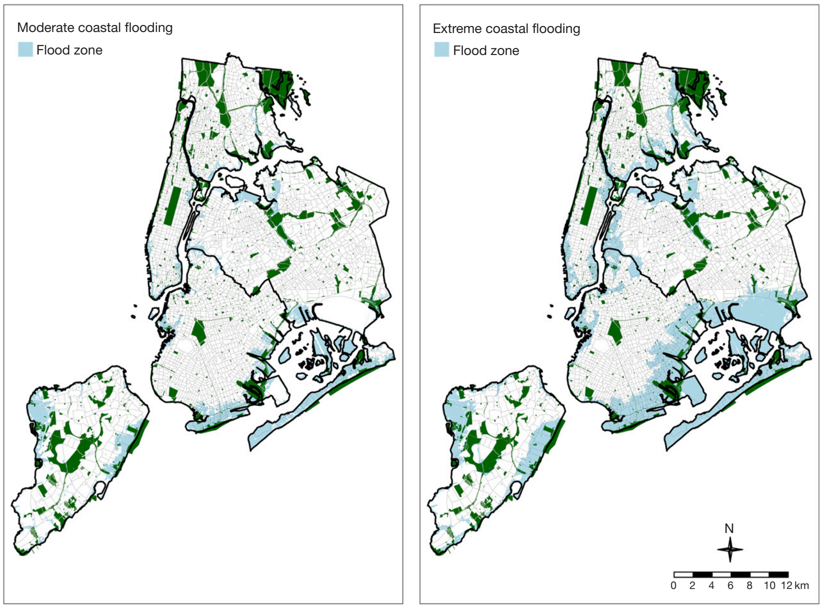

Figure 7 Moderate and extreme coastal flooding exposure in New York City.

Table 6 Total populations exposed to coastal flooding by intensity (moderate and extreme), and the percentage of lot inundated

Variables	Exposed to moderate coastal storm			Exposed to extreme coastal storm		
	10% inundation	50% inundation	90% inundation	10% inundation	50% inundation	90% inundation
Total population	687,535	459,167	316,448	1,934,039	1,354,033	923,389
Persons under 18 years	136,930	90,107	63,485	385,922	268,095	184,042
Persons over 64 years	115,942	77,883	53,666	303,625	209,971	138,315
Crowded housing units	19,031	12,795	8,805	55,286	38,647	26,169
Persons with disabilities	86,439	57,834	38,579	228,408	154,546	100,607
Persons without a high school diploma	75,196	48,962	30,852	213,127	142,759	92,848
Persons without English language proficiency	15,672	10,086	6,668	37,804	26,786	17,315
Households in multi-unit buildings	140,274	99,051	67,922	357,177	249,140	165,234
Persons in poverty	125,387	79,876	49,596	346,803	228,096	143,426
Single parent households	21,863	13,936	9,081	62,012	41,110	26,221
Persons unemployed	20,574	13,332	9,047	58,699	40,092	27,035
Persons non-Hispanic Black	139,554	92,212	63,026	450,415	328,545	228,765
Persons non-Hispanic Asian	89,923	58,198	38,238	249,491	168,788	110,490
Persons Hispanic	148,089	94,177	59,856	446,424	297,237	191,508

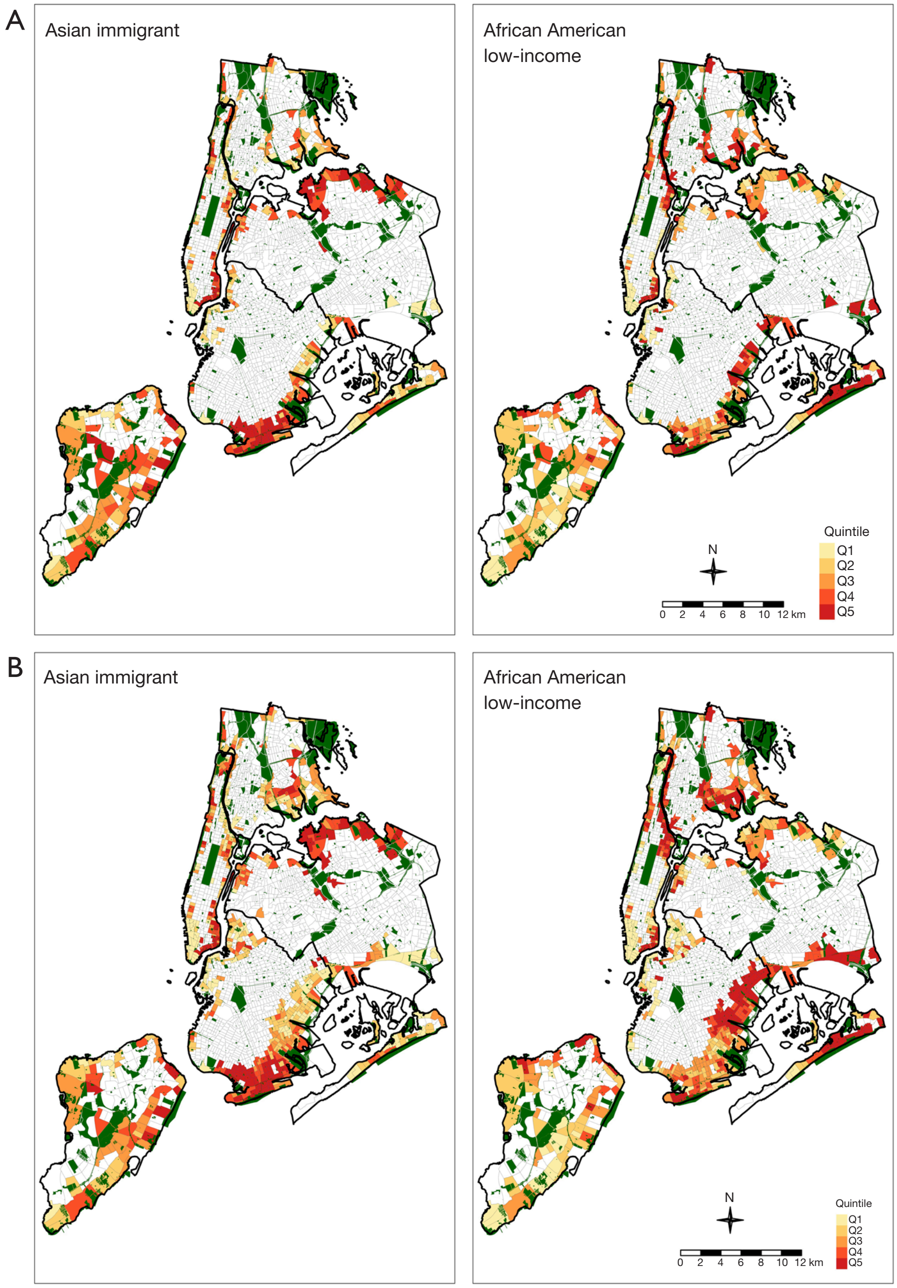

Figure 8 Examples of combining hazard sensitivity and coastal flood exposure. These maps only show locations where there is some flood exposure. The values are quintiles for hazard sensitivity. Maps on the left are the rotated principal component factor scores for Asian immigrant component. Areas in dark red designate high hazard sensitivity for this component and exposure to coastal flooding. The maps on the right are the same for the African American low-income component. Areas in dark red show high levels of the variables for this hazard-sensitive component and low adaptive capacity. The top maps (A) are for moderate coastal flooding exposure and the bottom maps (B) are extreme coastal flooding exposure.

Table 7 Buildings exposed to moderate and extreme coastal flooding

Building type	Moderate flooding, number flooded	Extreme flooding, number flooded
One family residence	63,811	147,197
Two family residence	44,362	131,729
Multi-family walkup	13,969	45,617
Multi-family elevator	1,615	4,990
Mixed residential/commercial	5,767	19,531
Commercial & office	3,868	10,854
Industrial & manufacturing	2,859	9,915
Public & institutions	1,669	4,682
Transport & utility	2,664	5,257
Open space & outdoor recreation	2,502	3,701

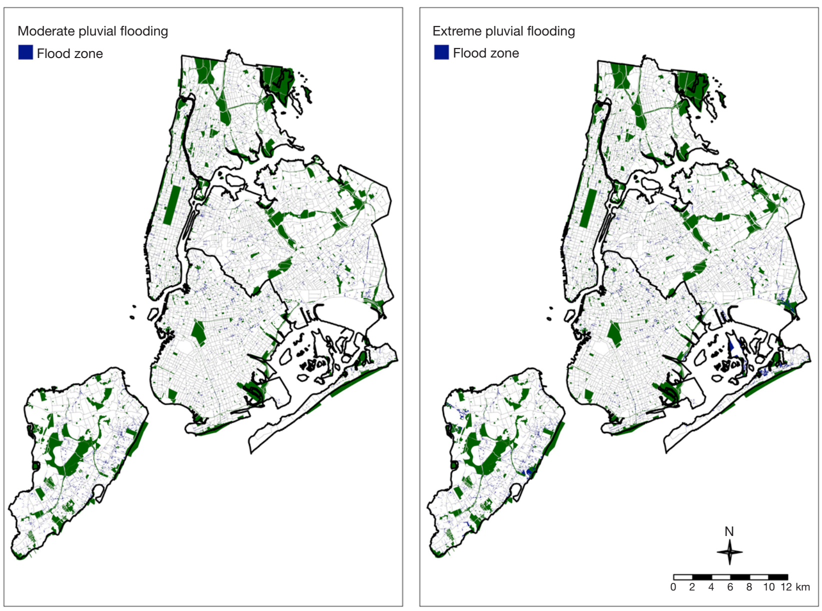

Figure 9 Moderate and extreme pluvial flooding exposure in New York City.

exposed to coastal and pluvial flooding and have the lowest adaptive capacities to the resources identified. We consider these locations as the highest flood-vulnerable areas.

An example of the different hazard-sensitive communities identified by quintile for each health and transportation adaptive capacities is presented in *Figure 10*. The areas identified by the map indicate locations where the analysis identifies high hazard-sensitive communities with low adaptive capacity and flooding exposure. In the specific case, these are census tracts identified with highly sensitive African American low-income components with low adaptive capacity for health and transportation resources that are exposed to moderate and extreme coastal flooding. A set of maps for this community for all adaptive capacities is presented in Figure S6.

Finally, we sum the different populations for all sensitive components (i.e., Hispanic, African American, Asian, and elderly) for each adaptive capacity characteristic (*Table 10*). We present an example figure with estimates for only moderate coastal flooding (*Figure 11*). This analysis suggests

Table 8 Total populations exposed to pluvial flooding by intensity (moderate and extreme), and the percentage of lot inundated

Variables	Exposed to moderate pluvial flooding			Exposed to extreme pluvial flooding		
	10% inundation	50% inundation	90% inundation	10% inundation	50% inundation	90% inundation
Total population	156,564	9,731	293	191,927	22,713	5,988
Persons under 18 years	34,049	2,019	154	41,926	5,150	1,387
Persons over 64 years	19,816	1,292	15	25,410	2,974	796
Crowded housing units	5,160	284	22	6,048	574	125
Persons with disabilities	15,209	913	16	19,699	2,296	564
Persons without a high school diploma	16,734	1,031	32	20,864	2,251	571
Persons without English proficiency	2,143	143	1	3,055	426	115
Households in multi-unit buildings	27,079	1,512	72	32,746	2,907	595
Persons in poverty	25,271	1,416	133	31,289	3,363	867
Single parent households	4,290	263	4	5,365	657	171
Persons unemployed	4,586	293	3	5,622	679	170
Persons non-Hispanic Black	37,850	3,005	29	47,586	6,561	1,557
Persons non-Hispanic Asian	19,392	1,178	10	23,138	1,873	359
Persons Hispanic	42,790	2,266	40	50,047	4,760	1,261

Table 9 Buildings exposed to moderate and extreme pluvial flooding

Building type	Moderate flooding, number flooded	Extreme flooding, number flooded
One family	9,424	13,249
Two family	6,818	8,957
Multi-family elevator	147	183
Multi-family walkup	2,586	3,289
Mixed residential/commercial	712	915
Commercial & office	430	544
Industrial & manufacturing	124	248
Public & institutions	201	281
Transport & utility	207	465
Open space & outdoor recreation	164	661

two things. First, that among public resources for adaptive capacity, the highest vulnerable population estimates are for high hazard-sensitive areas with low access to health resources. Second, among hazard-sensitive groups, African American populations have the highest number of persons living in the high vulnerability flood areas: those areas with flooding exposure, high hazard-sensitive, and low adaptive capacity. For example, under moderate coastal flooding with 10% inundation of lots, approximately 27,000 African Americans live in areas identified as highly hazard-sensitive with low adaptive capacity in the health resource's theme. Approximately 12,000 elderly, 8,000 Hispanics, and 5,000 Asians live under similar conditions. The higher number of African Americans can be seen across all adaptive capacity themes. It must be noted that we do not suggest these entire populations are highly sensitive. We cannot identify

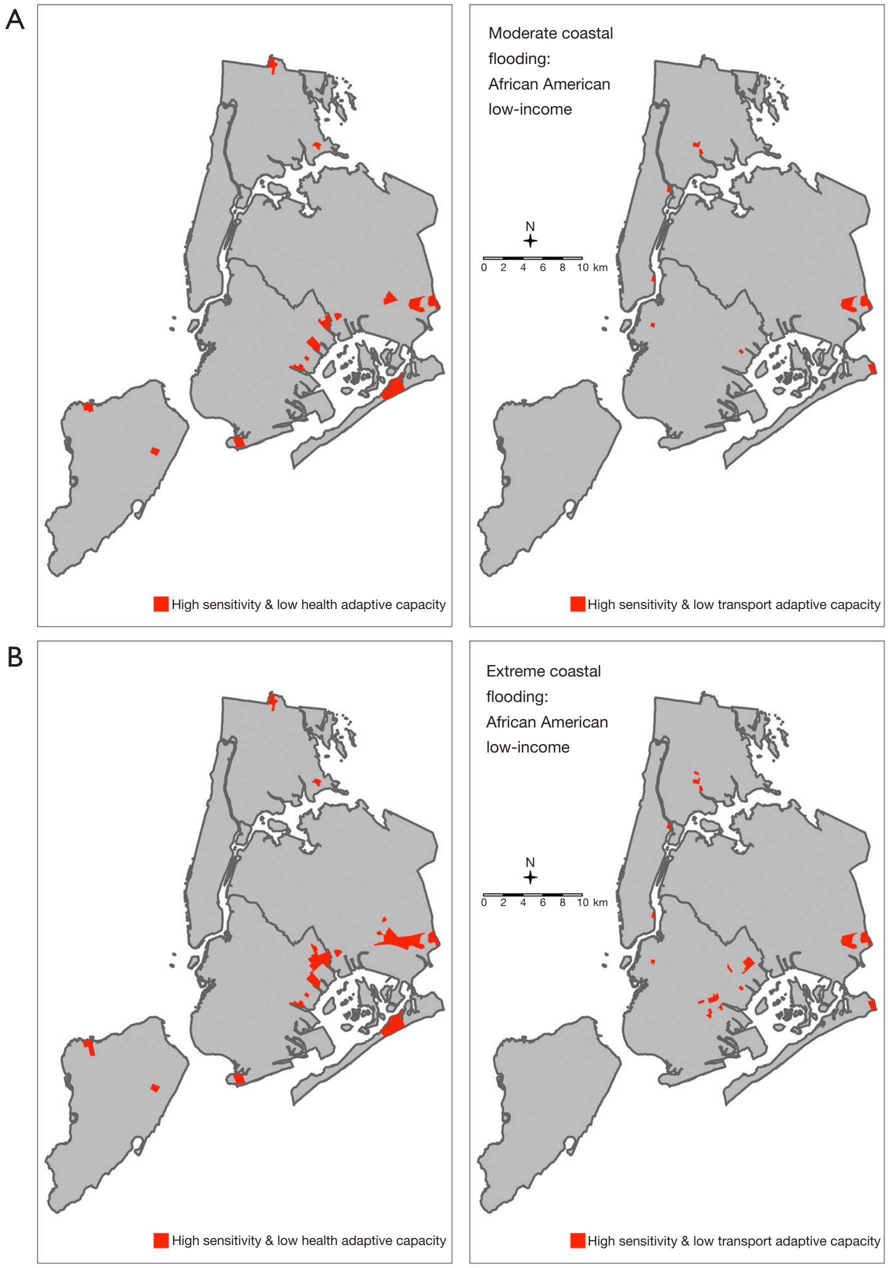

Figure 10 Examples of combining hazard sensitivity, adaptive capacity, and coastal flood exposure. These maps only show locations where there is some flood exposure. The red locations are where the hazard sensitivity for the African American low-income component is high, and the adaptive capacity for is low. The maps on left are where adaptive capacity for health is low and the maps on the right are where the adaptive capacity for transportation is low. The top maps are for moderate exposure and the maps on the bottom are for extreme coastal exposure.

Table 10 Total populations that are residents in highly vulnerable census tracts exposed to moderate and extreme coastal and pluvial flooding by the percentage of the lot inundated and adaptive capacity themes

Category	Coastal flooding		Pluvial flooding	
	Residents in areas of moderate conditions	Residents in areas of extreme conditions	Residents in areas of moderate conditions	Residents in areas of extreme conditions
10% inundation				
Health	52,139	152,871	12,515	18,782
Information	7,193	52,863	7,616	8,205
Mitigation	24,650	96,448	7,314	10,759
Transportation	23,236	72,307	7,959	10,036
50% inundation				
Health	39,384	122,568	1,281	3,967
Information	3,248	44,277	701	856
Mitigation	20,066	79,355	922	3,306
Transportation	11,729	51,296	681	1,622
90% inundation				
Health	29,319	81,323	1	1,330
Information	2,669	33,781	0	0
Mitigation	17,317	55,733	0	1,267
Transportation	6,391	38,372	0	221

which individuals are highly sensitive, only that the census tract are areas are highly vulnerable to coastal flooding. The figures for all hazard-sensitive area with low adaptive capacity for coastal and pluvial flooding are presented in Figure S7.

Discussion

We present a discussion of the results in five sub-sections. First, we compare our exposure numbers to those of previous studies to allow for data validation. Second, we highlight the methodological and theoretical contributions of the research. Third, we discuss policy implications of the findings. Fourth, we discuss uncertainties. Finally, we present areas for potential future studies.

Comparison of our results to previous studies

Our range of exposure of the total New York City population to moderate coastal storms is between 316,000 and 688,000. This range captures the findings of other studies that have estimated the total population flooded in New York City. For example, the city suggests that more than 400,000 New Yorkers live in areas with a 1% annual chance of flooding, although these estimates are based on a total city population of 8.2 million from the 2010 Census and there is no mention of the level of inundation in the study (135). However, in terms of buildings, others find that 33,000 and 66,000 buildings are located in the 100- and 500-year flood zones, respectively (136). We find much larger numbers of buildings including over 143,000 exposed to moderate flooding and 383,000 exposed to extreme flooding. The difference might be due to changes in the FEMA maps. The previous study used the 100- and 500-year flood zones before Super Storm Sandy were smaller than those created afterward. According to the City Council, higher flood elevations and a larger 100-year (1% annual chance) flood zone, contain roughly twice as many buildings as before (137). It may also be due to differences in levels of inundation used in previous studies compared to our study.

Our estimate for extreme coastal flooding exposure is larger (between 923,000 and 1.9 million) than that of New York City. The city has suggested that 800,000 residents will

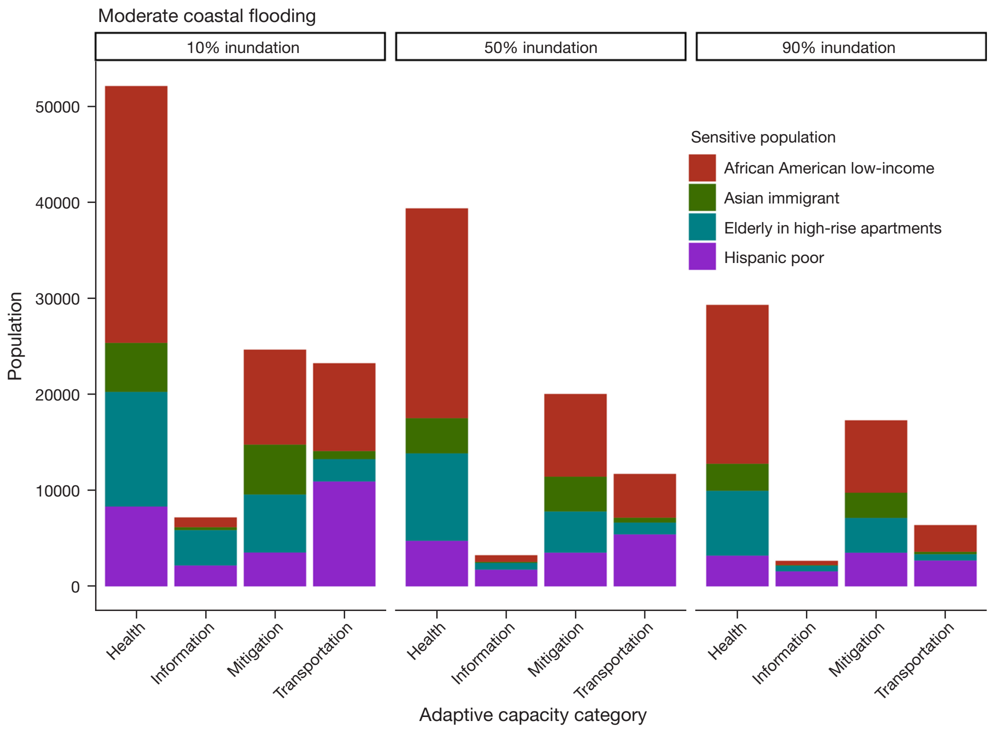

Figure 11 An example of the populations that live in areas of high vulnerability to flooding. In this case, the focus is on various populations that reside in areas of high sensitivity, low adaptive capacity, and moderate coastal flooding exposure.

be exposed to similar flooding by 2050 (135). The use of the 2050 scenario may be comparable to our extreme case, but that is not known. Alternatively, other estimates based on population figures from the 2010 census, suggest about 2.5 million New York City residents are exposed to category 4 Hurricane storm surge, and 3 million live in a Storm Surge Evacuation Zone (which is larger than the potential area flooded) (see https://nychazardmitigation.com/documentation/nyc-hazard-mitigation-plan/). These figures are much larger than ours. Differences between our values and others may be due to different definitions of extreme cases. Recent changes in flood mapping exposure after Superstorm Sandy have increased total population exposure and increased the exposure of populations living in vulnerable communities (138).

Our range of exposure of the total New York City population to moderate pluvial flooding is between 300 and 157,000 and extreme pluvial flooding is 6,000 and 192,000. This estimate does not include coastal flooding exposure. It should be noted that pluvial and coastal flooding often occur together making the distinction in impact between the two difficult. We are not aware of other estimates for pluvial flooding exposure in the city.

For coastal flooding, the difference between the moderate and extreme cases increases the numbers of vulnerable populations three-fold, at least. For pluvial flooding, our estimate suggests no vulnerable population is exposed to moderate flooding. Despite this finding, however, we know of the dangers of pluvial flooding for vulnerable communities. Several Asian low-income households experienced pluvial flooding during Hurricane Ida (38). This suggests that our estimates may be conservative.

Contributions of the research

New York City's natural habitat has been radically modified (139) and in combination with current climate change suffers from frequent and increasingly severe flooding. With increasing density, over the past 100 years, the value at risk in flood zones in New York City has increased by a factor of four to seven (136,140). Among states, New York has one of the highest levels of affordable units exposed to extreme water levels both in absolute terms and as a share of their affordable housing stock (141). New York City is a flood risk hotspot in the U.S. (21).

Scientists argue that climate change will increase exposure and risk. Climate studies suggest that the current 100-year flood events will become approximately 30-year flood events by 2080 under central estimates of sea level rise (19,22,23). Mean flood height and tropical cyclone characteristics will lead to increases in the extremes of the types of storms that create increases in coastal inundation (20).

Research into resilience and vulnerability highlights that flooding has significant impacts on New Yorkers. While there is variability across the city, studies suggest that those most vulnerable include middle- and low-income homeowners, disabled and/or chronically ill residents, and non-White households (26). Therefore, research into flooding vulnerability and how and where to address lack of resilience is imperative.

As a contribution to knowledge in this area, this study provides advances in both theory and methods. First, most studies aggregate vulnerable populations and communities. Current research tends to focus on identifying the social and biophysical factors responsible for hazard sensitivity and vulnerability, leaving out the divergent needs and responses of different communities. When it comes to responding to flood vulnerability, knowledge of different communities is not leveraged for policy. However, recent research in rural areas suggests that climate vulnerability is socially differentiated across social groups (142). In the urban flood context, communicating with and policies for groups may require different venues, different mediums, different actors, and different priorities (143,144). In our case, the priorities for flood risk reduction strategies for elderly living in high-rise apartment buildings may be different than those of immigrant Asian households. This study finds variable-sized flood-sensitive populations of New Yorkers within the total exposed population. Moreover, these different hazard-sensitive variables are clumped spatially in different locations across the city. This suggests that not only does sensitivity vary across the city, but that it varies by social and cultural group.

Second, by disaggregating adaptive capacity into different types, the study suggests that it may be effective to examine the impacts of different capacities individually. This also overcomes previous problems of weighting and aggregation. Using a simple distance feature can help to identify areas in need of specific community-level, public resources. The effects of different adaptive capacities on vulnerabilities open opportunities for developing policies to address vulnerability hot spots (areas where two or more adaptive capacity services are lacking). For example, eastern and southeastern Queens is an area lacking several adaptive capacity resources provided by the city (see below).

Third, we have included pluvial flooding vulnerable for each of these hazard-sensitive groups. As mentioned, pluvial flooding may not be new to New York City, but flash flooding is. The first-ever flash flood emergency warning was generated during Hurricane Ida in 2021. The data provided could help in identifying both the location and types of capacities necessary for affected populations.

Policy implications

The policy implications of this research center on the ability to spatially identify areas of potentially significant populations that are highly sensitive to hazards and have low access to public adaptive capacity resources. Resilience to environmental harms as a concept for urban planning must be associated with improving the lives of disadvantaged groups and in many cases these groups are spatially concentrated in cities (145). Currently, there is growing interest in spatially explicit policies, for example in the "smart city" movement (146). This study points to two opportunities for spatially focused flood resilience policies. First, the importance of focusing specific policies based upon community characteristics (sensitivities). Second, the importance of focusing specific policies based upon community needs (lack of adaptive capacities).

In the first case, there are different characteristics among communities that require different approaches to flood resilience policies. For example, spatially specific policies could help in communicating hazard risk reduction. Research suggests that institutions that citizens obtain information on local weather and climate varies across communities that are community specific (143). Research also finds that community-based policy approaches can contribute to risk communication and risk perception (147).

In the second case, the study also suggests the potential to identify the types of resources needed by specific communities. For example, spatial distribution plays a significant role in the accessibility to hospital services (148). In the case of disasters, in areas where there are long distances to hospitals or where hospitals have been evacuated, mobile clinics have been useful in providing for health services to underserved communities (149-151). This study identifies potential areas for this policy intervention.

Finally, the model presented is flexible. The method can be expanded to include other adaptive capacity resources. For example, New York City is currently engaged in several adaptation strategies (135). As these projects finish, they could be included in the analysis.

Uncertainties

There are significant uncertainties in his work. Our hazard sensitivity estimates are based on census tract resolution. Therefore, the analysis misses finer, but important potential areas of vulnerability, such as public housing. Over 400,000 New Yorkers are residents of New York City Housing Authority (NYCHA) buildings. Many of these residents are exposed to flooding (152,153). While the general population could be included in the analysis, we do not highlight these and other potentially important locations. Our measures of adaptive capacity rely on distance, which may not be the best measure of access or use of services. Distance is used in infrastructure studies as a measure of access. For example, a quarter-mile distance (10-minute walk) from the city residence to the nearest park is used to judge access (154,155). The indicator, however, misses other factors related to access that may be more reliable. Finally, we use flood hazard maps for exposure that provide areas exceeding a specific depth of inundation associated with an event. Given advancing climate change the moderate and extreme cases can change sooner than expected. Also, areas within flooded zones experience a spectrum of exposure—with different locations exposed to different water depths and/or different combinations of flood hazards. These differences are not recorded in the analyses.

Future work

The literature suggests one of the important challenges for further vulnerability research is to foster the development of dynamic vulnerability assessments that consider the adaptive capacity of communities and take the uncertainty involved in all steps of the index-building process into account, including the selection of indicators, normalization, weighting, and aggregation (64). Our method attempts to avoid the problems of weighting and aggregation, but at the same time, keeps the multidimensional approach, and site-specific indicators required for this work (65). However, as mentioned above, there remain significant uncertainties that can define future work.

Future work can focus on specific communities, such as NYCHA residents. The vulnerability of these residents is exacerbated by a legacy of multidecadal deferred maintenance in many NYCHA properties (156). We also would like to develop, update, and refine the community adaptive capacity themes. Other more detailed adaptive capacity services, can also be added, such as hospital beds, numbers of doctors, etc. Other work includes exposure estimates that include both those directly and indirectly affected by flooding. For example, those who live in multi-unit buildings on higher floors are not affected in a similar way as those who live in single-family homes. Identifying these differences will further improve the analysis.

Conclusions

This research attempts to point to areas that are among the most vulnerable to coastal and pluvial flooding in New York City. Our methods present plausible numbers and verifiable locations of these vulnerable areas and populations. Furthermore, the method can be further refined in the future with the addition of new data.

This research is based upon the work of others but also includes new types of analysis. We disaggregate hazard-sensitive populations and adaptive capacities allowing for the location of communities that may have specific hazard risk reduction needs and the analysis of different sets of capacities provided by the New York City. We also include an analysis of pluvial flooding vulnerability.

The results identify the location of communities of different groups that are highly vulnerable to flooding. We believe that this work can help to identify targeted spatial and community-based efforts to increase hazard resilience and reduce flood-related tragedies in New York City.

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Footnote

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Peer Review File: Available at https://jhmhp.amegroups.com/

article/view/10.21037/jhmhp-23-92/prf

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All data were openly sourced. No human or animal experiments were conducted, and no case reports were used.

References

1. Paprotny D, Sebastian A, Morales-Nápoles O, et al. Trends in flood losses in Europe over the past 150 years. Nat Commun 2018;9:1985.
2. UNDRR. The human cost of disasters: an overview of the last 20 years (2000-2019). 2020. Available online: https://www.undrr.org/publication/human-cost-disasters-overview-last-20-years-2000-2019
3. Jonkman SN, Kelman I. An analysis of the causes and circumstances of flood disaster deaths. Disasters 2005;29:75-97.
4. Koslov L, Merdjanoff A, Sulakshana E, et al. When rebuilding no longer means recovery: the stress of staying put after Hurricane Sandy. Clim Change 2021;165:59.
5. Mort M, Walker M, Williams AL, et al. Displacement: Critical insights from flood-affected children. Health Place 2018;52:148-54.
6. Merdjanoff AA, Piltch-Loeb R, Friedman S, et al. Housing Transitions and Recovery of Older Adults Following Hurricane Sandy. J Gerontol B Psychol Sci Soc Sci 2019;74:1041-52.
7. Manuel J. The long road to recovery: environmental health impacts of Hurricane Sandy. Environ Health Perspect 2013;121:a152-9.
8. Rosenzweig B, Montalto FA, Orton P, et al. Climate Change and New York City's Flood Risk. Ann N Y Acad Sci 2024. In press.
9. IPCC. Global Warming of 1.5 ℃. 2022. Available online: https://www.ipcc.ch/sr15/
10. Moustakis Y, Papalexiou SM, Onof CJ, et al. Seasonality, intensity, and duration of rainfall extremes change in a warmer climate. Earth's Future 2021;9:e2020EF001824.
11. Rosenzweig C, Solecki W. New York City Panel on Climate Change 2019 Report Chapter 1: Introduction. Ann N Y Acad Sci 2019;1439:22-9.
12. Adger WN. Vulnerability. Global Environmental Change 2006;16:268-81.
13. Zhang W, Villarini G, Vecchi GA, et al. Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. Nature 2018;563:384-8.
14. Insurance Business. Top 10 cities at risk for hurricane damage. 2015. Available online: https://www.insurancebusinessmag.com/us/news/catastrophe/top-10-cities-at-risk-for-hurricane-damage-18950.aspx
15. Patrick L, Solecki W, Gornitz V, et al. New York City Panel on Climate Change 2019 Report Chapter 5: Mapping Climate Risk. Ann N Y Acad Sci 2019;1439:115-25.
16. Reed AJ, Mann ME, Emanuel KA, et al. Increased threat of tropical cyclones and coastal flooding to New York City during the anthropogenic era. Proc Natl Acad Sci U S A 2015;112:12610-5.
17. Faber JW. Superstorm Sandy and the demographics of flood risk in New York City. Human Ecology 2015;43:363-78.
18. Lane K, Charles-Guzman K, Wheeler K, et al. Health effects of coastal storms and flooding in urban areas: a review and vulnerability assessment. J Environ Public Health 2013;2013:913064.
19. Lin N, Emanuel K, Oppenheimer M, et al. Physically based assessment of hurricane surge threat under climate change. Nature Climate Change 2012;2:462-7.
20. Marsooli R, Lin N. Impacts of climate change on hurricane flood hazards in Jamaica Bay, New York. Climatic Change 2020;163:2153-71.
21. Sajjad M, Lin N, Chan JCL. Spatial heterogeneities

of current and future hurricane flood risk along the U.S. Atlantic and Gulf coasts. Sci Total Environ 2020;713:136704.
22. Horton R, Little C, Gornitz V, et al. New York City Panel on Climate Change 2015 Report. Chapter 2: Sea level rise and coastal storms. Ann N Y Acad Sci 2015;1336:36-44.
23. Orton P, Lin N, Gornitz V, et al. New York City Panel on Climate Change 2019 Report Chapter 4: Coastal Flooding. Ann N Y Acad Sci 2019;1439:95-114.
24. NYC. 2023 NYC Heat-Related Mortality Report. 2023. Available online: https://a816-dohbesp.nyc.gov/IndicatorPublic/key-topics/climatehealth/heat-report/
25. Lieberman-Cribbin W, Gillezeau C, Schwartz RM, et al. Unequal social vulnerability to Hurricane Sandy flood exposure. J Expo Sci Environ Epidemiol 2021;31:804-9.
26. Madajewicz M. Who is vulnerable and who is resilient to coastal flooding? Lessons from Hurricane Sandy in New York City. Climatic Change 2020;163:2029-53.
27. NOAA National Centers for Environmental Information. In Harm's Way: Hurricane Ida's Impact On Socially Vulnerable Communities. 2023. Available online: https://storymaps.arcgis.com/stories/780e11bd19cc4dfca54ac8fb1d5e926f
28. De Vries D. New York's Ida disaster: A social crime in the center of world capitalism. 2021. Available online: https://www.wsws.org/en/articles/2021/09/04/pers-s04.html
29. NOAA National Centers for Environmental Information. Storm Events Database. 2020. Available online: https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=904747
30. Spectrum News. Tropical Storm Isaias Causes Widespread Power Outages, Downed Trees in NYC. 2020. Available online: https://ny1.com/nyc/all-boroughs/weather/2020/08/04/isaias-new-york-city-august-4
31. Spectrum News. Tree Falls Onto Car in Queens, Crushing It and Killing Man Inside. 2020. Available online: https://ny1.com/nyc/all-boroughs/news/2020/08/04/damage-from-tropical-storm-isaias-tree-falls-nyc#:~:text=The%20NYPD%20identified%20the%20victim,pronounced%20dead%20at%20the%20scene
32. Staten Island Advance. Isaias' Verrazzano wrath comes into focus: 5 trucks flipped during storm. 2020. Available online: https://www.silive.com/weather/2020/08/isaias-verrazzano-wrath-comes-into-focus-5-trucks-flipped-during-storm.html
33. Patch. MTA Suspends Outdoor Train Service Over Isaias High Winds. 2020. Available online: https://patch.com/new-york/new-york-city/mta-suspends-outdoor-subway-service-over-isaias-high-winds
34. AMNY Environment. NYC FLOODING | Recent history of major rainstorms that wrought damage across the Five Boroughs. 2023. Available online: https://www.amny.com/new-york/nyc-flooding-major-rainstorms-history-2020-2023/
35. The New York Times. Tropical Storm Henri Brings Power Outages and Record Rain to Northeast. 2021. Available online: https://www.nytimes.com/2021/08/22/nyregion/tropical-storm-henri.html
36. NBC New York. Drivers Rescued From Flooded Cars as Henri Gives NYC Rainiest Hour in History. 2021. Available online: https://www.nbcnewyork.com/weather/henri-gives-nyc-rainiest-hour-in-recorded-history-before-making-landfall/3234590/
37. Fox5 New York. How much rain did we get from Henri? 2021. Available online: How much rain did we get from Henri? Available online: https://www.fox5ny.com/news/tropical-storm-henri-leaving-impressive-rainfall-totals-in-its-wake
38. The New York Times. New York Flooding: Flooding From Ida Kills Dozens of People in Four States. 2021. Available online: https://www.nytimes.com/live/2021/09/02/nyregion/nyc-storm
39. Newsweek. Ida Sent 75 Million Gallons of Water Into NY Subway System, Caused $75M in Damages. 2021. Available online: https://www.newsweek.com/ida-sent-75-million-gallons-water-ny-subway-system-caused-75m-damages-1629826
40. NYC. Hurricane Ida. 2021. Available online: https://www.nyc.gov/site/cdbgdr/hurricane-ida/hurricane-ida.page#:~:text=Although%20the%20storm%20had%20been,%2C%202021%2C%20President%20Joseph%20R
41. NOAA National Environmental Satellite, Data and Information Service. Heavy Rains Cause Flooding in New York City. 2023. Available online: https://www.nesdis.noaa.gov/news/heavy-rains-cause-flooding-new-york-city
42. O'Brien K, Eriksen S, Nygaard LP, et al. Why different interpretations of vulnerability matter in climate change discourses. Climate Policy 2007;7:73-88.
43. Adger WN. Social vulnerability to climate change and extremes in coastal Vietnam. World Development 1999;27:249-69.
44. Brooks N. Vulnerability, risk and adaptation: A conceptual framework. 2003. Available online: https://www.ipcc.ch/apps/njlite/srex/njlite_download.php?id=5463
45. Kienberger S, Lang S, Zeil P. Spatial vulnerability units-expert-based spatial modelling of socio-economic

vulnerability in the Salzach catchment, Austria. Natural Hazards and Earth System Sciences 2009;9:767-78.
46. Papathoma-Köhle M, Gems B, Sturm M, et al. Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows. Earth-Science Reviews 2017;171:272-88.
47. Papathoma-Köhle M, Kappes M, Keiler M, et al. Physical vulnerability assessment for alpine hazards: state of the art and future needs. Natural Hazards 2011;58:645-80.
48. Glade T. Vulnerability assessment in landslide risk analysis. Erde 2003;134:123-46.
49. Papathoma-Köhle M. Vulnerability curves vs. vulnerability indicators: application of an indicator-based methodology for debris-flow hazards. Natural Hazards and Earth System Sciences 2016;16:1771-90.
50. Papathoma-Köhle M, Schlögl M, Dosser L, et al. Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices. Journal of Hydrology 2022;607:127501.
51. Garrote J, Díez-Herrero A, Escudero C, et al. A framework proposal for regional-scale flood-risk assessment of cultural heritage sites and application to the Castile and León Region (Central Spain). Water 2020;12:329.
52. Leal M, Reis E, Pereira S, et al. Physical vulnerability assessment to flash floods using an indicator-based methodology based on building properties and flow parameters. J Flood Risk Manag 2021;14:e12712.
53. Blaikie P, Cannon T, Davis I, et al. At Risk, Natural Hazards, People's Vulnerability and Disasters. London: Routledge; 2014.
54. Kelly PM, Adger WN. Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Climatic Change 2000;47:325-52.
55. Jurgilevich A, Räsänen A, Groundstroem F, et al. A systematic review of dynamics in climate risk and vulnerability assessments. Environmental Research Letters 2017;12:013002.
56. Phillips BD, Fordham M. Introduction. In: Phillips BD, Thomas DSK, Fothergill A, et al. editors. Social Vulnerability to Disasters. Boca Raton: CRC Press; 2009.
57. Brooks N, Adger WN, Kelly PM. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change 2005;15:151-63.
58. Cinner JE, Adger WN, Allison EH, et al. Building adaptive capacity to climate change in tropical coastal communities. Nature Climate Change 2018;8:117-23.
59. Yu J, Castellani K, Forysinski K, et al. Geospatial indicators of exposure, sensitivity, and adaptive capacity to assess neighbourhood variation in vulnerability to climate change-related health hazards. Environmental Health 2021;20:31.
60. Cutter SL, Boruff BJ, Shirley WL. Social Vulnerability to Environmental Hazards*. Soc Sci Q 2003;84:242-61.
61. Cutter SL. The landscape of disaster resilience indicators in the USA. Natural Hazards 2016;80:741-58.
62. Nasiri H, Mohd Yusof MJ, Mohammad Ali TA. An overview to flood vulnerability assessment methods. Sustainable Water Resources Management 2016;2:331-6.
63. Berry P, Enright PM, Shumake-Guillemot J, et al. Assessing Health Vulnerabilities and Adaptation to Climate Change: A Review of International Progress. Int J Environ Res Public Health 2018;15:2626.
64. Moreira LL, de Brito MM, Kobiyama M. A systematic review and future prospects of flood vulnerability indices. Natural Hazards and Earth System Sciences 2021;21:1513-30.
65. Rehman S, Sahana M, Hong H, et al. A systematic review on approaches and methods used for flood vulnerability assessment: Framework for future research. Natural Hazards 2019;96:975-98.
66. Birkmann J, Cardona OD, Carreño ML, et al. Framing vulnerability, risk and societal responses: the MOVE framework. Natural Hazards 2013;67:193-211.
67. Jamshed A, Birkmann J, Rana IA, et al. The effect of spatial proximity to cities on rural vulnerability against flooding: An indicator based approach. Ecological Indicators 2020;118:106704.
68. IPCC. Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, et al. editors. Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2014.
69. Ramesh B, Jagger MA, Zaitchik B, et al. Flooding and emergency department visits: Effect modification by the CDC/ATSDR Social Vulnerability Index. Int J Disaster Risk Reduct 2022;76:102986.
70. CDC/ATSDR. SVI 2020 Documentation. 2022. Available online: https://www.atsdr.cdc.gov/placeandhealth/svi/documentation/pdf/SVI2020Documentation_08.05.22.pdf
71. Flanagan BE, Gregory EW, Hallisey EJ, et al. A social vulnerability index for disaster management. J Homel Secur Emerg Manag 2011;8:0000102202154773551792.
72. Manson S, Schroeder J, Van Riper D, et al. IPUMS

National Historical Geographic Information System: Version 16.0]. Minneapolis: IPUMS; 2021.
73. Anderson WA. Bringing children into focus on the social science disaster research agenda. International Journal of Mass Emergencies & Disasters 2005;23:159-75.
74. Banzhaf S, Ma L, Timmins C. Environmental Justice: the Economics of Race, Place, and Pollution. J Econ Perspect 2019;33:185-208.
75. Bullard RD. The legacy of American apartheid and environmental racism. John's J Legal Comment 1993;9:445.
76. Mohai P, Pellow D, Roberts JT. Environmental justice. Annu Rev Environ Resour 2009;34:405-30.
77. Christensen P, Sarmiento-Barbieri I, Timmins C. Racial discrimination and housing outcomes in the United States rental market. National Bureau of Economic Research; 2021.
78. Bakkensen LA, Ma L. Sorting over flood risk and implications for policy reform. J Environ Econ Manage 2020;104:102362.
79. The New York Times. New York storm updates: As Ida Deaths Rise, N.Y. Leaders Look Toward Future Storms. 2021. Available online: https://www.nytimes.com/live/2021/09/03/nyregion/nyc-flooding-ida
80. Tierney K. Social Inequality: Humans and Disasters. In: Daniels RJ, Keitl DF, Kunreuther H. editors. On Risk and Disaster: Lessons From Hurricane Katrina. Philadelphia: University of Pennsylvania Press; 2006.
81. Vogt BM. Evacuation of institutionalized and specialized populations. Oak Ridge: Oak Ridge National Lab. (ORNL); 1990.
82. Cowan KN, Peterson M, LeMasters K, et al. Overlapping Crises: Climate Disaster Susceptibility and Incarceration. Int J Environ Res Public Health 2022;19:7431.
83. McGuire LC, Ford ES, Okoro CA. Natural disasters and older US adults with disabilities: implications for evacuation. Disasters 2007;31:49-56.
84. Bagaria J, Heggie C, Abrahams J, et al. Evacuation and sheltering of hospitals in emergencies: a review of international experience. Prehosp Disaster Med 2009;24:461-7.
85. Fekete A. Validation of a social vulnerability index in context to river-floods in Germany. Natural Hazards and Earth System Sciences 2009;9:393-403.
86. Tate E, Rahman MA, Emrich CT, et al. Flood exposure and social vulnerability in the United States. Natural Hazards 2021;106:435-57.
87. Pathak S, Panta HK, Bhandari T, et al. Flood vulnerability and its influencing factors. Natural Hazards 2020;104:2175-96.
88. Navarro O, Restrepo-Ochoa D, Muñoz-Duque L A, et al. Determinants of coping strategies in two types of natural hazards: Flash floods and costal flooding. Int J Disaster Risk Reduct 2020;46:101514.
89. King D. You're on your own: Community vulnerability and the need for awareness and education for predicatable natural disasters. Journal of Contingencies and Crisis Management 2000;8:223-8.
90. Jang Y, Park J, Choi EY, et al. Social isolation in Asian Americans: risks associated with socio-demographic, health, and immigration factors. Ethn Health 2022;27:1428-41.
91. Smith SG, Jackson SE, Kobayashi LC, et al. Social isolation, health literacy, and mortality risk: Findings from the English Longitudinal Study of Ageing. Health Psychol 2018;37:160-9.
92. Martin SA. A framework to understand the relationship between social factors that reduce resilience in cities: Application to the City of Boston. Int J Disaster Risk Reduct 2015;12:53-80.
93. Hilfinger Messias DK, Barrington C, Lacy E. Latino social network dynamics and the Hurricane Katrina disaster. Disasters 2012;36:101-21.
94. Rasch RJ. Assessing urban vulnerability to flood hazard in Brazilian municipalities. Environment and Urbanization 2016;28:145-68.
95. Tapsell SM, Penning-Rowsell EC, Tunstall SM, et al. Vulnerability to flooding: health and social dimensions. Philos Trans A Math Phys Eng Sci 2002;360:1511-25.
96. Mason K, Lindberg K, Haenfling C, et al. Social Vulnerability Indicators for Flooding in Aotearoa New Zealand. Int J Environ Res Public Health 2021;18:3952.
97. Rhubart D, Sun Y. The social correlates of flood risk: variation along the US rural-urban continuum. Population and Environment 2021;43:232-56.
98. Office of the New York State Comptroller. A Look at Poverty Trends in New York State for the Last Decade. 2022. Available online: https://www.osc.ny.gov/reports/new-yorkers-need-look-poverty-trends-new-york-state-last-decade
99. Rufat S, Tate E, Burton CG, et al. Social vulnerability to floods: Review of case studies and implications for measurement. Int J Disaster Risk Reduct 2015;14:470-86.
100. Rumbach A, Sullivan E, Makarewicz C. Mobile home parks and disasters: Understanding risk to the third housing type in the United States. Natural Hazards

Review 2020;21:05020001.
101. Headwaters Economics. Mobile home residents face higher flood risk. 2022. Available online: https://headwaterseconomics.org/natural-hazards/mobile-home-flood-risk/
102. Office of the New York State Comptroller. New Yorkers in Need: The Housing Insecurity Crisis. 2024. Available online: https://www.osc.ny.gov/reports/new-yorkers-need-housing-insecurity-crisis
103. Population Reference Bureau. U.S. Housing Cost Burden Declines Among Homeowners but Remains High for Renters. 2022. Available online: https://www.prb.org/articles/u-s-housing-cost-burden-declines-among-homeowners-but-remains-high-for-renters/
104. NYU. State of Homeowners and Their Homes. 2022. Available online: https://furmancenter.org/stateofthecity/view/state-of-homeowners-and-their-homes#:~:text=The%20share%20of%20severely%20cost,to%2025.3%20percent%20in%202021
105. National Equity Atlas. Housing burden: All residents should have access to quality, affordable homes. 2022. Available online: https://nationalequityatlas.org/indicators/Housing_burden
106. Lee JY, Van Zandt S. Housing tenure and social vulnerability to disasters: A review of the evidence. J Plan Lit 2019;34:156-70.
107. Bhattacharya J, DeLeire T, Haider S, et al. Heat or eat? Cold-weather shocks and nutrition in poor American families. Am J Public Health 2003;93:1149-54.
108. Brennan M, Srini T, Steil J, et al. A perfect storm? Disasters and evictions. Housing Policy Debate 2022;32:52-83.
109. Pucher J, Renne JL. Urban-Rural differences in mobility and mode choice: Evidence from the 2001 NHTS. New Brunswick: Bloustein School of Planning and Public Policy, Rutgers University; 2004.
110. StreetsBlog NYC. Komanoff Dissects New York City's Car Baby Boom. 2023. Available online: https://nyc.streetsblog.org/2023/04/19/komanoff-dissects-new-york-citys-car-baby-boom
111. Brown MA, Soni A, Lapsa MV, et al. High energy burden and low-income energy affordability: Conclusions from a literature review. Progress in Energy 2020;2:042003.
112. Wellman GC. Transportation apartheid: the role of transportation policy in societal inequality. Public Works Management & Policy 2014;19:334-9.
113. Raphael S, Berube A, Deakin E. Socioeconomic Differences in Household Automobile Ownership Rates: Implications for Evacuation Policy. Berkeley: University of California Transportation Center; 2006. Available online: https://escholarship.org/uc/item/7bp4n2f6
114. Litman T. Lessons from Katrina and Rita: What major disasters can teach transportation planners. Journal of Transportation Engineering 2006;132:11-8.
115. Thanvisitthpon N, Shrestha S, Pal I, et al. Assessment of flood adaptive capacity of urban areas in Thailand. Environmental Impact Assessment Review 2020;81:106363.
116. Birkholz S, Muro M, Jeffrey P, et al. Rethinking the relationship between flood risk perception and flood management. Sci Total Environ 2014;478:12-20.
117. Koerth J, Jones N, Vafeidis AT, et al. Household adaptation and intention to adapt to coastal flooding in the Axios-Loudias-Aliakmonas National Park, Greece. Ocean & Coastal Management 2013;82:43-50.
118. NYC Emergency Management. Tune in to NYC Emergency Management's Podcasts. 2021. Available online: https://nyc.gov/site/em/index.page
119. Li D, Newman G, Zhang T, et al. Coping with post-hurricane mental distress: The role of neighborhood green space. Soc Sci Med 2021;281:114084.
120. Schmeltz MT, González SK, Fuentes L, et al. Lessons from Hurricane Sandy: a community response in Brooklyn, New York. J Urban Health 2013;90:799-809.
121. NYC Department of Transportation. New York City Mobility Report. 2019. Available online: https://www.nyc.gov/html/dot/downloads/pdf/mobility-report-singlepage-2019.pdf
122. National Research Council. Facing hazards and disasters: Understanding human dimensions. Washington, DC: National Academies Press; 2006.
123. Federal Emergency Management Agency. How to Read a Flood Map. 2022. Available online: https://www.fema.gov/sites/default/files/documents/how-to-read-flood-insurance-rate-map-tutorial.pdf
124. Federal Emergency Management Agency. FEMA NFIP Metadata Profile for Draft, Preliminary and Final FIRM Datasets. 2022. Available online: https://www.fema.gov/sites/default/files/documents/fema_NFIP-profile-FIRM_112021.pdf
125. New York City Mayor's Office of Resiliency. New York City Stormwater Resiliency Plan. 2021. Available online: https://www1.nyc.gov/assets/orr/pdf/publications/stormwater-resiliency-plan.pdf
126. Maantay JA, Maroko AR, Herrmann C. Mapping population distribution in the urban environment: The

cadastral-based expert dasymetric system (CEDS). Cartogr Geogr Inf Sci 2007;34:77-102.
127. Maantay J, Maroko A. Mapping urban risk: Flood hazards, race, & environmental justice in New York. Applied Geography 2009;29:111-24.
128. Carley S, Evans TP, Graff M, et al. A framework for evaluating geographic disparities in energy transition vulnerability. Nature Energy 2018;3:621-7.
129. Maantay J, Maroko A, Culp G. Using Geographic Information Science to Estimate Vulnerable Urban Populations for Flood Hazard and Risk Assessment in New York City. In: Showalter PS, Lu Y. editors. Geospatial Techniques in Urban Hazard and Disaster Analysis. Dordrecht: Springer; 2010:71-98.
130. Field A, Field Z, Miles J. Discovering statistics using R. London: Sage; 2012.
131. Kaiser HF. A second generation little jiffy. Psychometrika 1970;35:401-15.
132. Hutcheson GD, Sofroniou N. The multivariate social scientist: Introductory statistics using generalized linear models. London: Sage; 1999.
133. Jolliffe IT. Discarding variables in a principal component analysis. I: Artificial data. J R Stat Soc Ser C Appl Stat 1972;21:160-73.
134. Jolliffe IT. Principal Component Analysis. New York: Springer; 1986.
135. NYC Mayor’s Office of Climate and Environmental Justice. Neighborhood Coastal Flood Protection Project Planning Guidance. 2021. Available online: https://www.nyc.gov/assets/orr/pdf/publications/Coastal-Protection-Guidance.pdf
136. Aerts JCJH, Botzen WJW. Managing exposure to flooding in New York City. Nature Climate Change 2012;2:377.
137. NYC Council. Flood Resilience Zoning Text Amendment - Approved! 2013. Available online: https://www.nyc.gov/assets/planning/download/pdf/plans/flood-resiliency/flood_resiliency.pdf
138. Herreros-Cantis P, Olivotto V, Grabowski ZJ, et al. Shifting landscapes of coastal flood risk: environmental (in) justice of urban change, sea level rise, and differential vulnerability in New York City. Urban Transform 2020;2:9.
139. Sanderson EW, Brown M. Mannahatta: An ecological first look at the Manhattan landscape prior to Henry Hudson. Northeastern Naturalist 2007;14:545-70.
140. Aerts JC, Botzen WJ. Flood-resilient waterfront development in New York City: bridging flood insurance, building codes, and flood zoning. Ann N Y Acad Sci 2011;1227:1-82.
141. Buchanan MK, Kulp S, Cushing L, et al. Sea level rise and coastal flooding threaten affordable housing. Environmental Research Letters 2020;15:124020.
142. Kuchimanchi BR, Nazareth D, Bendapudi R, et al. Assessing differential vulnerability of communities in the agrarian context in two districts of Maharashtra, India. Climate and Development 2019;11:918-29.
143. Mabon L. Making climate information services accessible to communities: What can we learn from environmental risk communication research? Urban Clim 2020;31:100537.
144. Pearson AR, Ballew MT, Naiman S, et al. Race, class, gender and climate change communication. Oxford: Oxford Research Encyclopedia of Climate Science; 2017.
145. Vale LJ. The politics of resilient cities: whose resilience and whose city? Building Research & Information 2014;42:191-201.
146. Angelidou M. Smart city policies: A spatial approach. Cities 2014;41:S3-S11.
147. Wolff E. The promise of a “people-centred” approach to floods: Types of participation in the global literature of citizen science and community-based flood risk reduction in the context of the Sendai Framework. Progress in Disaster Science 2021;10:100171.
148. Cheng L, Yang M, De Vos J, et al. Examining geographical accessibility to multi-tier hospital care services for the elderly: A focus on spatial equity. Journal of Transport & Health 2020;19:100926.
149. Maghfiroh M, Hanaoka S. Mobile clinics: Medical service strategy for disaster healthcare response operation. Journal of Industrial Engineering and Management 2022;15:470-83.
150. Ahmad R, Mohamad Z, Noh AYM, et al. Health major incident: The experiences of mobile medical team during major flood. Malays J Med Sci 2008;15:47.
151. Attipoe-Dorcoo S, Delgado R. Mobile clinics in the United States and the COVID-19 Pandemic: A response strategy model. In: Kumar V. editor. SARS-CoV-2 Origin and COVID-19 Pandemic Across the Globe. London: InTechOpen; 2021:185-93.
152. New York City Housing Authority. Climate Change at NYCHA. 2021. Available online: https://www.nyc.gov/assets/nycha/downloads/pdf/Climate-Change-at-NYCHA_lores_single-pages.pdf
153. NYC Major's Office of Management and Budget. CDBG-DR Action Plan for The Remnants of Hurricane Ida: Substantial Amendment 1. 2023. Available online: https://

www.nyc.gov/assets/cdbgdr/documents/NYC_Hurricane_Ida_Action_Plan_SA1Submission.pdf
154. Citizens Committee for Children of New York. Walking Distance to a Park. 2017. Available online: https://data.cccnewyork.org/data/map/1377/walking-distance-to-a-park#1377/a/4/1623/25/a/a
155. Trust for Public Land. 2023 ParkScore Index®. 2023. Available online: https://parkserve.tpl.org/downloads/pdfs/New%20York%20City_NY.pdf
156. La Mort J R. Public Housing and Public Health: The Separate and Unequal Protection of Private and Public Housing Tenants' Health in New York City. Journal of Affordable Housing & Community Development Law 2018;27:385-400.

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Supplementary

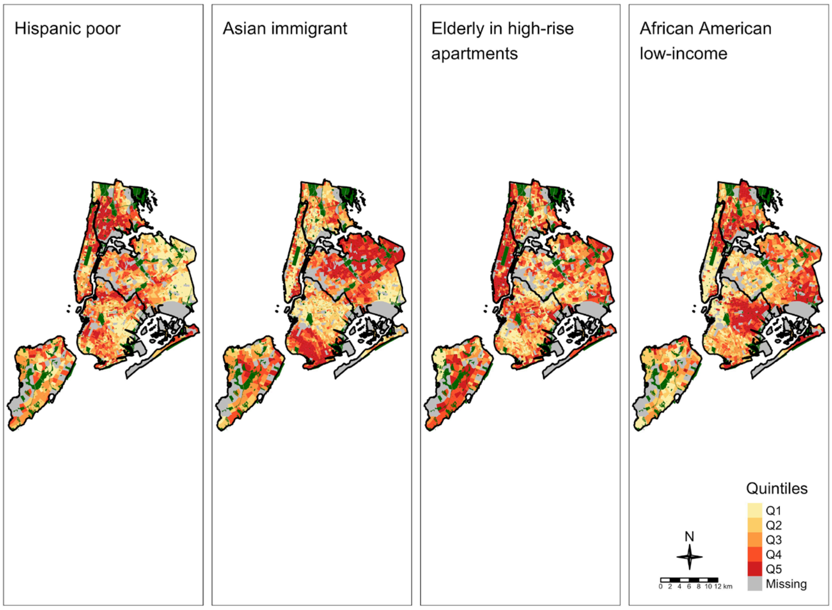

Figure S1 Hazard-sensitive communities by quintiles in New York City.

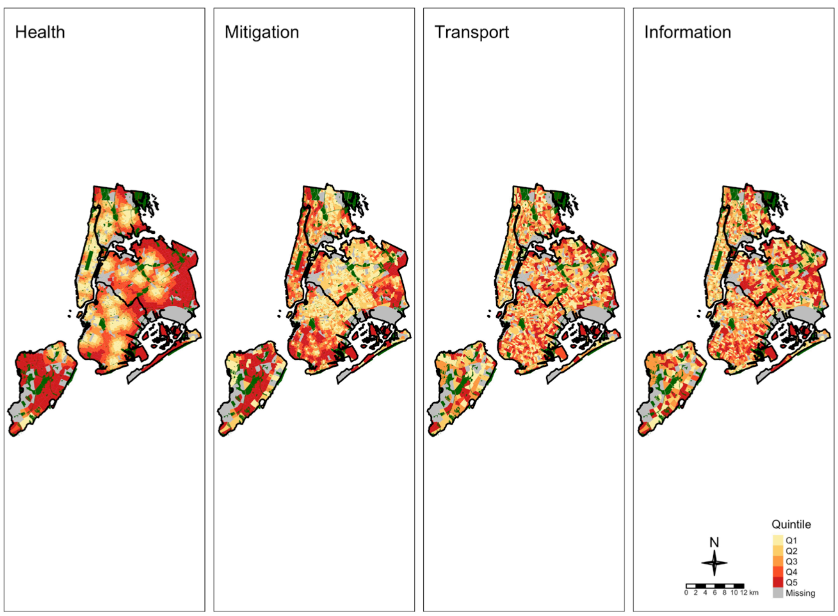

Figure S2 Adaptive capacity quintiles for different types of community resources in New York City.

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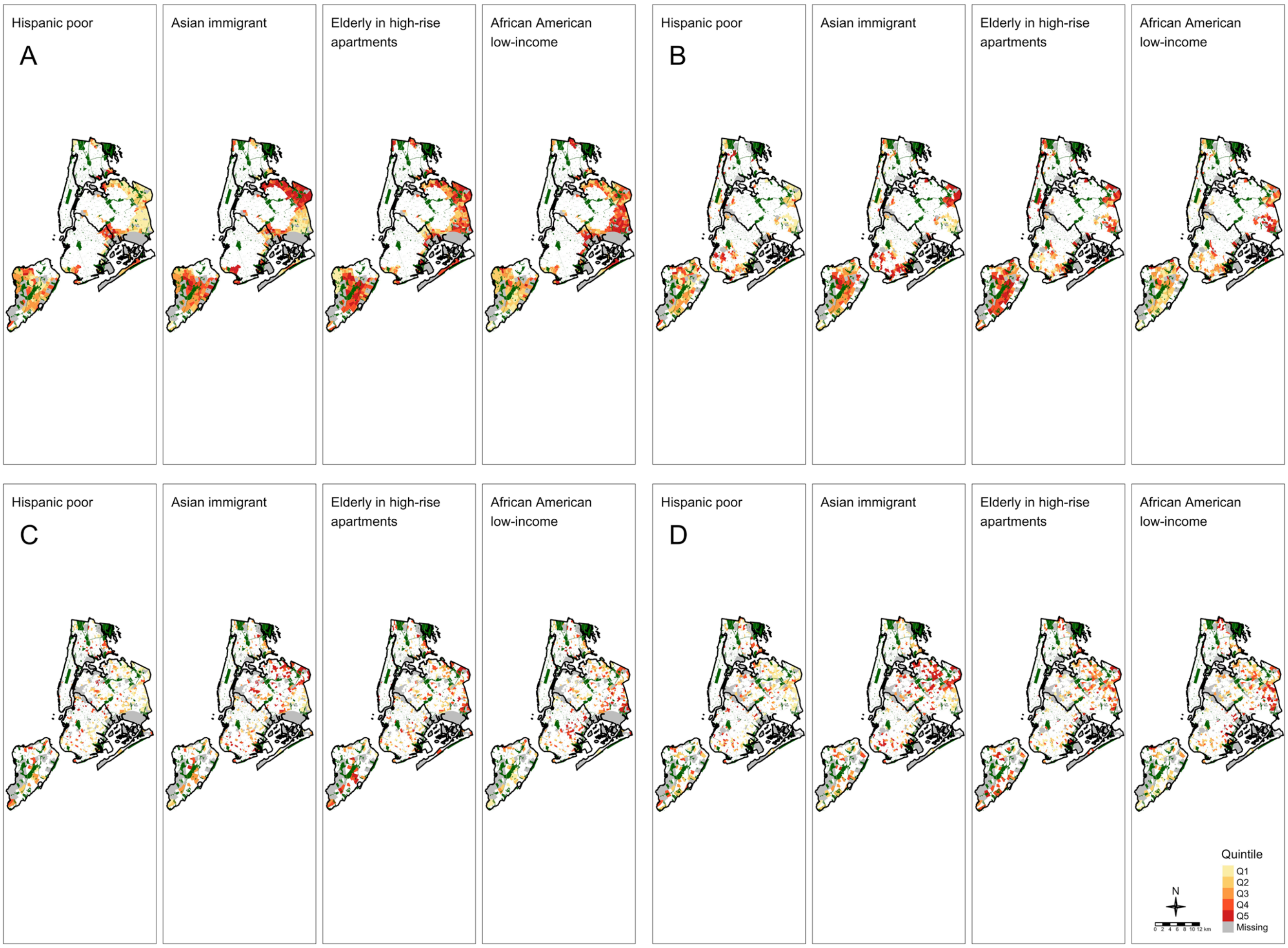

Figure S3 Hazard-sensitive populations by quintiles of sensitivity and only for the lowest adaptive capacity for community resources in New York City. (A) Lowest adaptive capacity in health. (B) Lowest adaptive capacity for mitigation actions. (C) Lowest adaptive capacity for transportation. (D) Lowest adaptive capacity for information.

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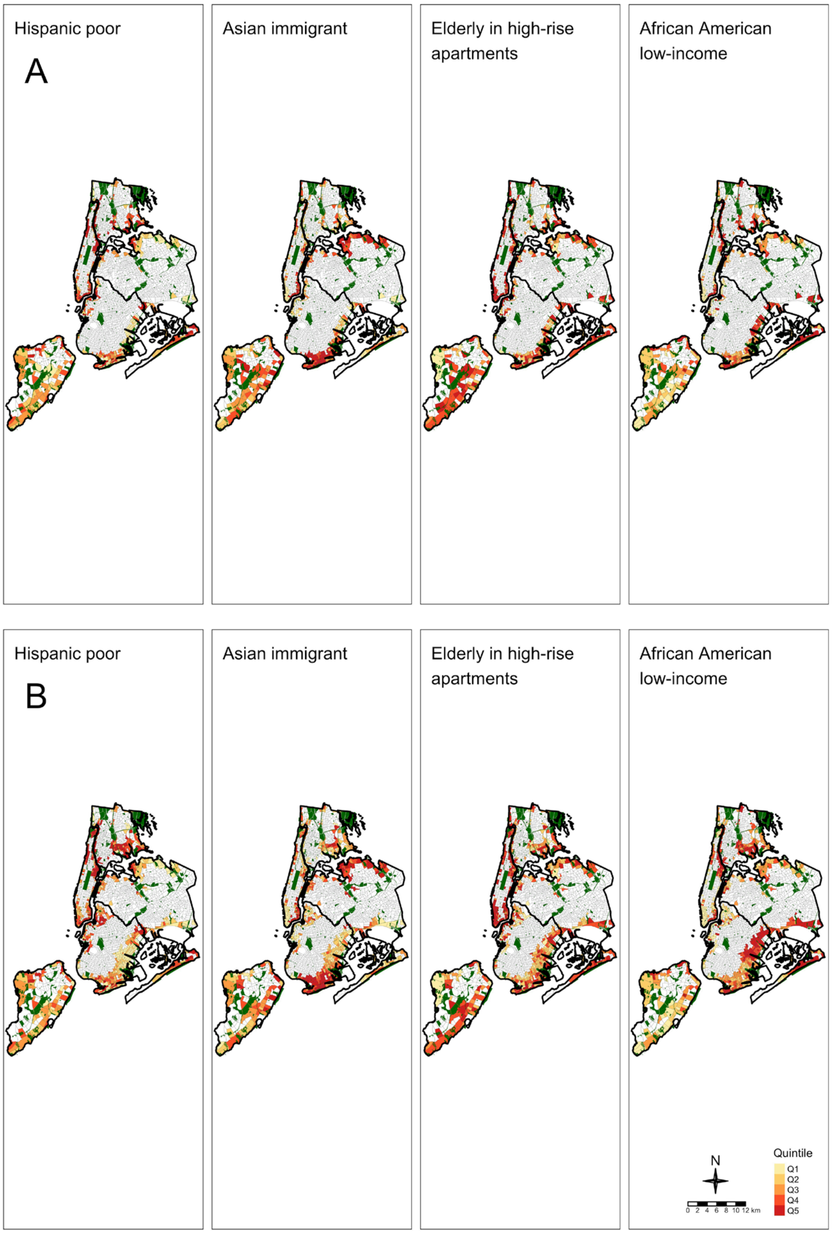

Figure S4 Hazard-sensitive populations by quintiles that are exposed to moderate (A) and extreme (B) coastal flooding in New York City.

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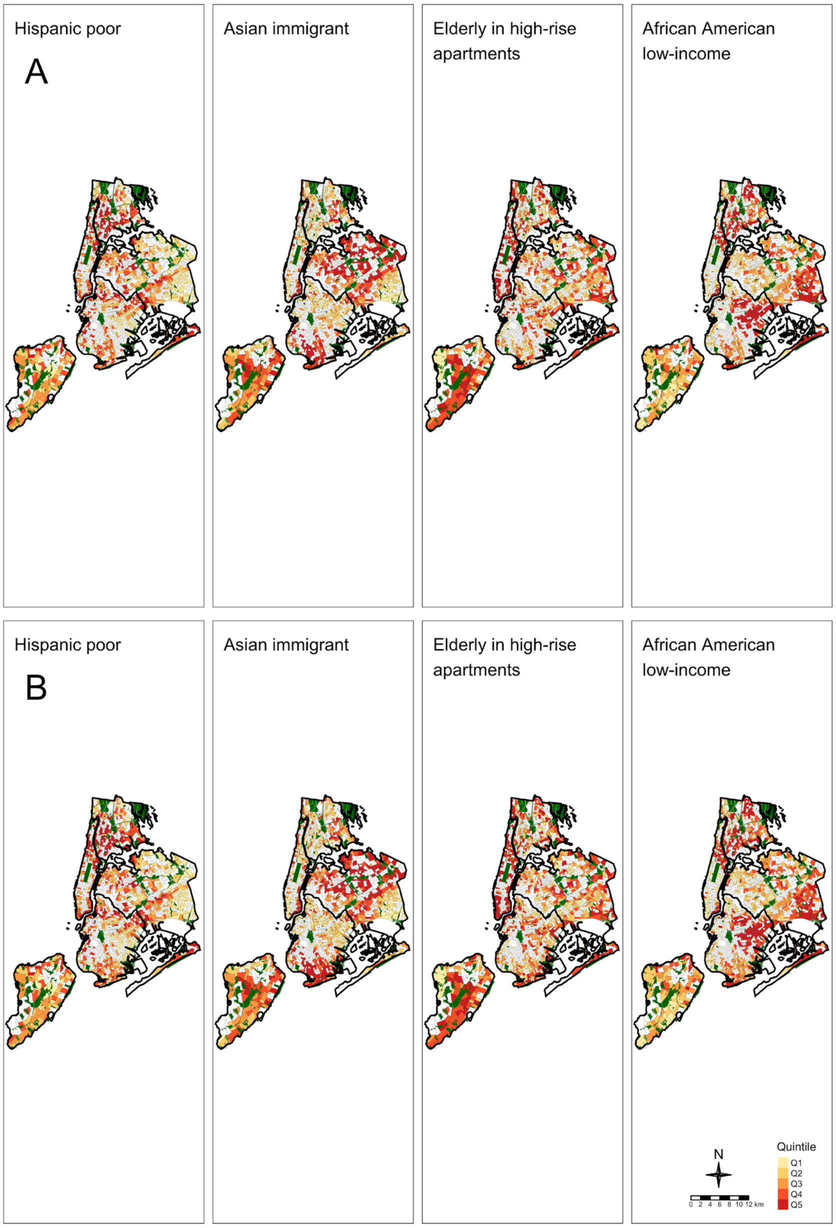

Figure S5 Hazard-sensitive populations by quintiles, that are exposed to moderate (A) and extreme (B) pluvial flooding in New York City.

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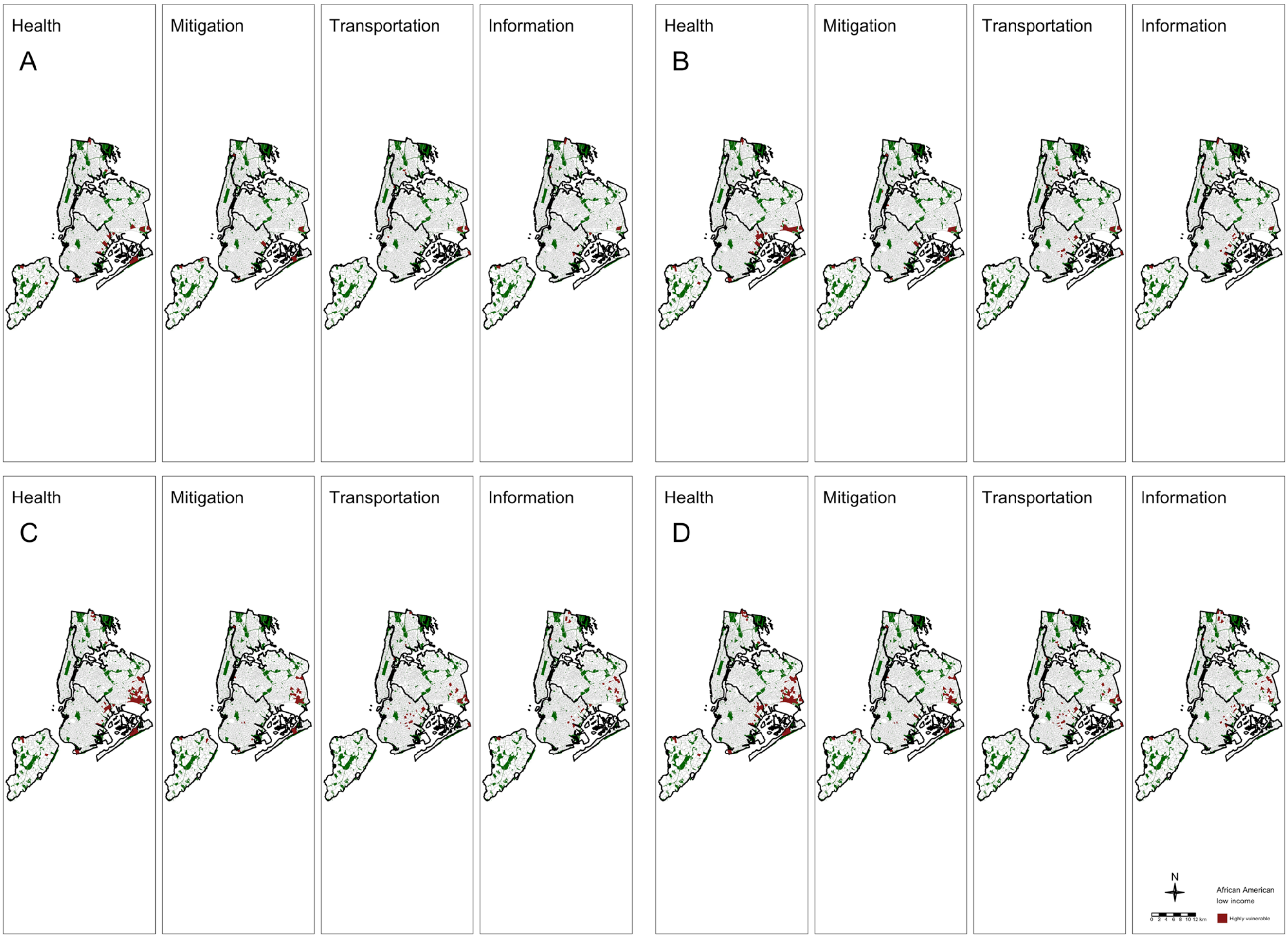

Figure S6 Areas of highly flood-vulnerable African American populations. Dark red areas designate locations of African American populations that are highly sensitive and have low adaptive capacity for community resources. (A) Moderate coastal flooding. (B) Extreme coastal flooding. (C) Moderate pluvial flooding. (D) Extreme pluvial flooding.

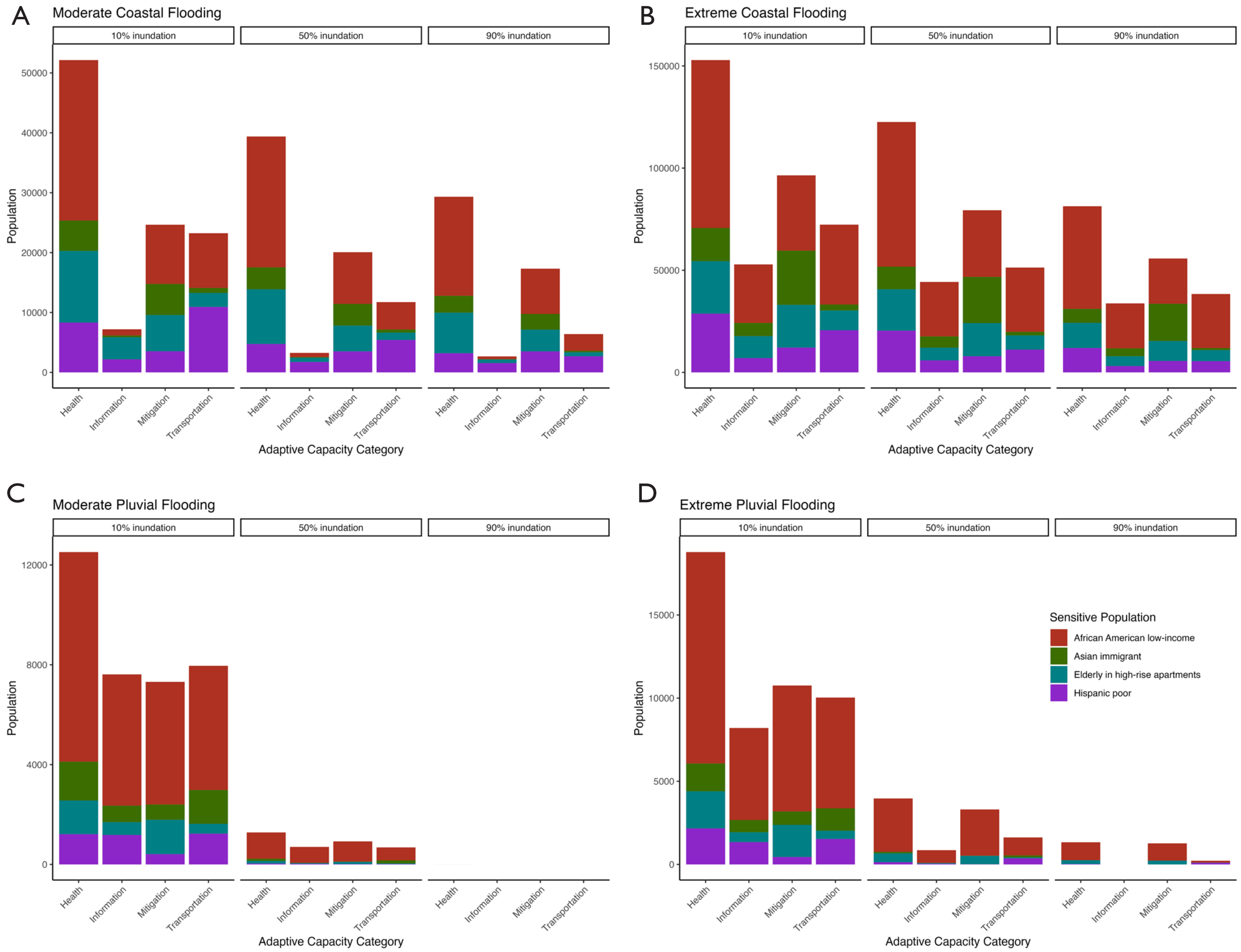

Figure S7 Sensitive populations in areas of high vulnerability to coastal and pluvial flooding in New York City.

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