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TECHNICAL REPORT

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NPCC4: Climate change and New York City's flood risk

Bernice Rosenzweig[1] | Franco A. Montalto[2,3] | Philip Orton[4] | Joel Kaatz[5] | Nicole Maher[6] | Jerry Kleyman[5] | Ziyu Chen[4] | Eric Sanderson[7] | Nirajan Adhikari[2,3] | Timon McPhearson[8,9] | Pablo Herreros-Cantis[10]

[1]Environmental Science, Sarah Lawrence College, Bronxville, New York, USA

[2]College of Engineering, Drexel University, Philadelphia, Pennsylvania, USA

[3]eDesign Dynamics LLC, New York, New York, USA

[4]School of Engineering and Science, Stevens Institute of Technology, Hoboken, New Jersey, USA

[5]Arcadis, New York, New York, USA

[6]The Nature Conservancy, Cold Spring Harbor, New York, USA

[7]New York Botanical Garden, New York, New York, USA

[8]Urban Systems Lab, The New School, New York, New York, USA

[9]Cary Institute of Ecosystem Studies, Millbrook, New York, USA

[10]Basque Center for Climate Change, Leioa, Spain

Correspondence
Bernice Rosenzweig, Environmental Science, Sarah Lawrence College, Bronxville, New York, USA.
Email: brosenzweig@sarahlawrence.edu

Franco A. Montalto, College of Engineering, Drexel University, Philadelphia, Pennsylvania, USA.
Email: fam26@drexel.edu

Abstract

This chapter of the New York City Panel on Climate Change 4 (NPCC4) report provides a comprehensive description of the different types of flood hazards (pluvial, fluvial, coastal, groundwater, and compound) facing New York City and provides climatological context that can be utilized, along with climate change projections, to support flood risk management (FRM). Previous NPCC reports documented coastal flood hazards and presented trends in historical and future precipitation and sea level but did not comprehensively assess all the city's flood hazards. Previous NPCC reports also discussed the implications of floods on infrastructure and the city's residents but did not review the impacts of flooding on the city's natural and nature-based systems (NNBSs). This—the NPCC's first report focused on all drivers of flooding—describes and profiles historical examples of each type of flood and summarizes previous and ongoing research regarding exposure, vulnerability, and risk management, including with NNBS and nonstructural measures.

KEYWORDS
climate change, flood hazards, flood risk management, flooding, natural and nature-based systems, NPCC4

CONTENTS

1 | CHAPTER SUMMARY

The purpose of this chapter is to provide a comprehensive description of the different types of flood hazards (pluvial, fluvial, coastal, groundwater, and compound) facing New York City (NYC) and to provide climatological context that can be utilized, along with climate change projections, to support flood risk management (FRM). Previous New York City Panel on Climate Change (NPCC) reports documented coastal flood hazards and presented trends in historical and future precipitation and sea level but did not comprehensively assess all the city's flood hazards. Previous NPCC reports also discussed the implications of floods on infrastructure and the city's residents but did not review the impacts of flooding on the city's natural and nature-based systems (NNBSs). This—the NPCC's first report that considers how climate change will increase risk associated with all types of flooding—describes and profiles historical examples of each type of flood and summarizes previous and ongoing research regarding exposure, vulnerability, and risk management, including with NNBS and nonstructural measures.

1.1 | Key messages

Key Message 1: NYC faces risks from four types of flood hazards: pluvial, fluvial, coastal, and groundwater, each with a unique geography of exposure that will expand in different ways in the future due to climate change. Identifying these four types as separate, but related, hazards is an important step in studying how they impact NYC, what FRM tools are available to address them, and where future research is needed. Climate adaptation planning must consider all four flood hazards and their interactions and potential impacts across a range of magnitudes, including very extreme events.

Key Message 2: Discussions about flooding often focus on risks within the special flood hazard areas (SFHAs) mapped by the US

Federal Emergency Management Agency (FEMA). However, the FEMA SFHA maps characterize fluvial and coastal flood hazards only. The recently released NYC Stormwater Flood Maps represent the City's first attempt to map pluvial and some compound flood hazards, with risks spread out over a much larger fraction of NYC. In the coming year, the US Geological Survey (USGS) and New York City Department of Environmental Protection (NYCDEP) will be embarking on a study to investigate and model groundwater flooding in Queens and Staten Island. In this chapter, we present a preliminary assessment of pluvial and groundwater flood hazard exposure areas that can be utilized to support FRM. Additional work is needed to develop hazard maps that represent a broader range of flooding hazards and their increase in magnitude in response to anthropogenic climate change.

Key Message 3: Much of NYC is exposed to pluvial flooding, which occurs when the intensity of precipitation exceeds the infiltration capacity of the soil and/or when the rate of runoff exceeds the hydraulic or hydrologic capacities of the sewer system. These exceedances often occur during cloudbursts—short-duration periods of intense rainfall that can be embedded within large storm systems or occur as individual, hard-to-forecast thunderstorms. Intense rainfall has already been observed to have become more frequent in NYC since the mid-20th century and is projected to further intensify and occur more frequently with unmitigated climate change. Despite the increasing risk, pluvial flood hazards remain poorly understood. The NYC Floodnet project is beginning to document flood depths, but more monitoring of rainfall, in-sewer flows, and flooding velocities, along with hydrologic and hydraulic (H&H) modeling of pluvial flooding processes and impacts is needed.

Key Message 4: In NYC, fluvial flood risks are spatially localized to the portions of the Bronx, Staten Island, and Eastern Queens where surface stream channels remain. In the remainder of the city, historical surface streams were filled and replaced, with their flow routed to the sewer system. As a result, fluvial flood hazards have largely been replaced by pluvial flood hazards in most of the city. Both fluvial and pluvial flood hazards will increase due to climate change-driven intensification of precipitation and elevation of sea level. Although traditional floodplain management can be an effective strategy in reducing exposure to fluvial floods, a broader, watershed-scale approach that retains, detains, and redirects stormwater is needed to jointly manage pluvial and fluvial flood risks.

Key Message 5: Current and future coastal flood risks are caused by high storm tides, rising sea levels, and historical development on landfill over tidal marshes and nearshore areas. In Jamaica Bay, tides and storm surges have also been significantly elevated by historical dredging and landfilling, worsening chronic and extreme flooding. For example, on December 23, 2022, a major flood event around Jamaica Bay was caused, in part, by dredging that has led to amplified storm tides which were nearly a foot higher there than elsewhere in the harbor. Further improvement of our understanding of future coastal flood hazards is possible through downscaling of climate model data and modeling of multiple compounding flood drivers.

Key Message 6: Many NYC neighborhoods have very shallow groundwater tables and already experience groundwater flooding. These areas include parts of the city that were developed when groundwater levels were substantially lower due to historical pumping of groundwater for municipal water supply. Groundwater flood risk has the potential to be particularly significant in NYC because of the prevalence of subterranean infrastructure. Groundwater flood hazards have not yet been assessed citywide, but preliminary efforts are underway. Sea level rise may cause groundwater levels to rise, resulting in inflow and infiltration of groundwater into sewer pipes and subterranean spaces, and inundation of topographically vulnerable locations from below. Improved characterization of spatially heterogenous aquifer hydraulic properties and sustained monitoring of groundwater levels will be necessary to develop projections for future groundwater flooding.

Key Message 7: Climate change is increasing the frequency of extreme precipitation events and elevating sea levels, increasing the likelihood of compounding either one of these flood drivers by the other. In addition, tropical and post-tropical cyclones (TCs) have caused severe storm surges and extreme rainfall to occur simultaneously. Although assessment is limited by the small number of historical TC events, the limited evidence suggests that TCs can cause low-probability, dangerous compound flooding. Given the importance of TCs and limited historical data, a deeper understanding of compound flood hazards likely requires detailed modeling and downscaling to simulate such storms under the present and future climate.

Key Message 8: NYC's NNBS provides many valuable ecosystem services, including critical water regulation services that can play a role in FRM. However, many of these systems are themselves vulnerable to different flood hazards, especially along the coast. Research into how different types of NNBS are impacted by flood/storm surge events, hydroperiod changes, rising water tables, and salinization is needed to better evaluate future changes in ecosystem services. Opportunities for designing NNBS to mitigate the impacts of various flood hazards need to be further explored.

Key Message 9: Comprehensive FRM plans must eventually be designed to mitigate the full range of flood risks faced by individual communities. Although these plans are being developed, many neighborhoods remain at significant risk, especially due to pluvial flooding. In the short term, FRM should focus on measures that reduce the impacts of floods—for example, by making the city "safe to flood." In the long-term, FRM decisions should be based on sound science and participatory decision-making processes that establish neighborhood-specific levels of acceptable future flood risk. FRM tailored to each community will include combinations of structural and nonstructural approaches, including NNBS, that are implemented in ways that reduce social vulnerability and are also synergistic with community histories, needs, and goals.

2 | INTRODUCTION

2.1 | Chapter scope and context

Located along the Atlantic coast with a year-round humid climate,[1] NYC is subject to multiple types of flood hazards (Figure 1). Even without climate change and independent of the significant anthropogenic

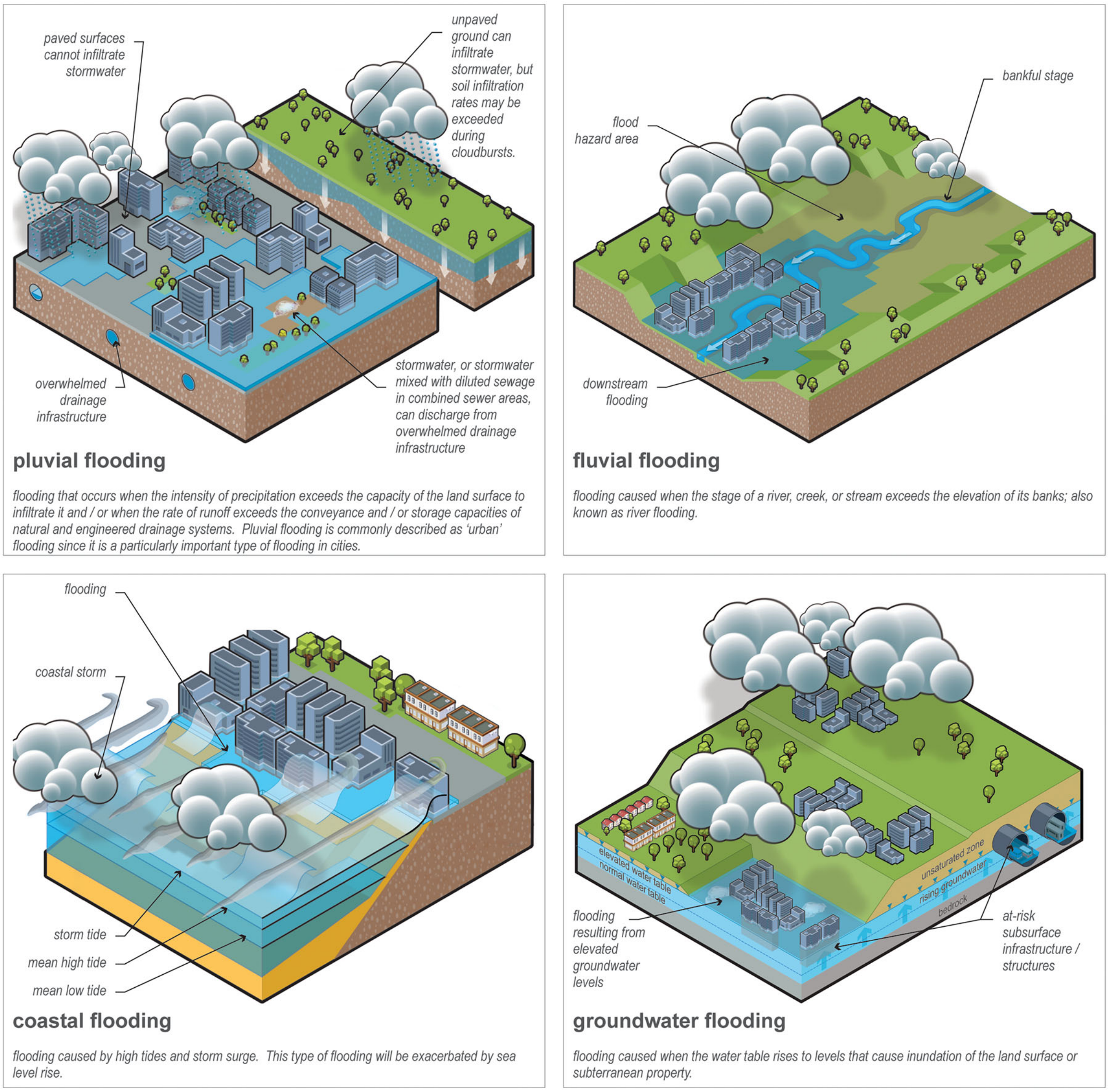

FIGURE 1 The four types of floods that impact New York City (pluvial, fluvial, coastal, and groundwater). The impacts of these four flood types can be compounded when they occur in combination resulting in compound flooding (Section 8). Figure by: Climate Adaptation Partners (adapted from UK Research and Innovation (UKRI) and the Natural Environment Research Council (NERC)/Ben Gilliland under Creative Commons License CC BY-NC 4.0).

morphological changes that have been made to the local geography, floods occur in this region due to extreme precipitation, coastal storm surges and high tides, high groundwater tables, and their co-occurrence (Figure 2). Over four centuries of urbanization, the city's land surface, streams, wetlands, underwater habitats, coasts, and soils have all been radically modified.[2–5] In addition, global climate change has elevated regional sea level, increasing the likelihood of coastal flooding[6] and making it more difficult for sewers, rivers, and streams to drain to the sea. In the absence of significant and rapid reductions in greenhouse gas emissions, sea levels will continue to rise, and extreme precipitation events will become more frequent, more intense, and possibly also larger in areal extent.[6,7] Together these phenomena carry significant implications for future flood severity, frequency, and the resources needed to manage flood risks.

Previous NPCC reports discussed some types of flooding, along with historical and projected changes in their occurrence due to climate change. For example, Gornitz et al.[8] provided projections for future sea level rise, whereas Patrick et al. [9] and Orton et al. [10] mapped static and dynamic coastal flood risks, respectively. Orton et al.[11] updated the projections of storm-driven coastal flood risk considering monthly high tides and storm surge due to a broadened set of sea level rise projections and extreme wind. González et al. [12] analyzed the climatology of heavy precipitation in NYC, including observed heavy rainfall days and trends in subdaily precipitation events at different durations, and their meteorological drivers, evaluated fluvial flooding in regional streams, and assessed the use of 311 to report street flooding. Zimmerman et al.[13] described some of the potential impacts of flooding on critical infrastructure systems. Although this body of knowledge is

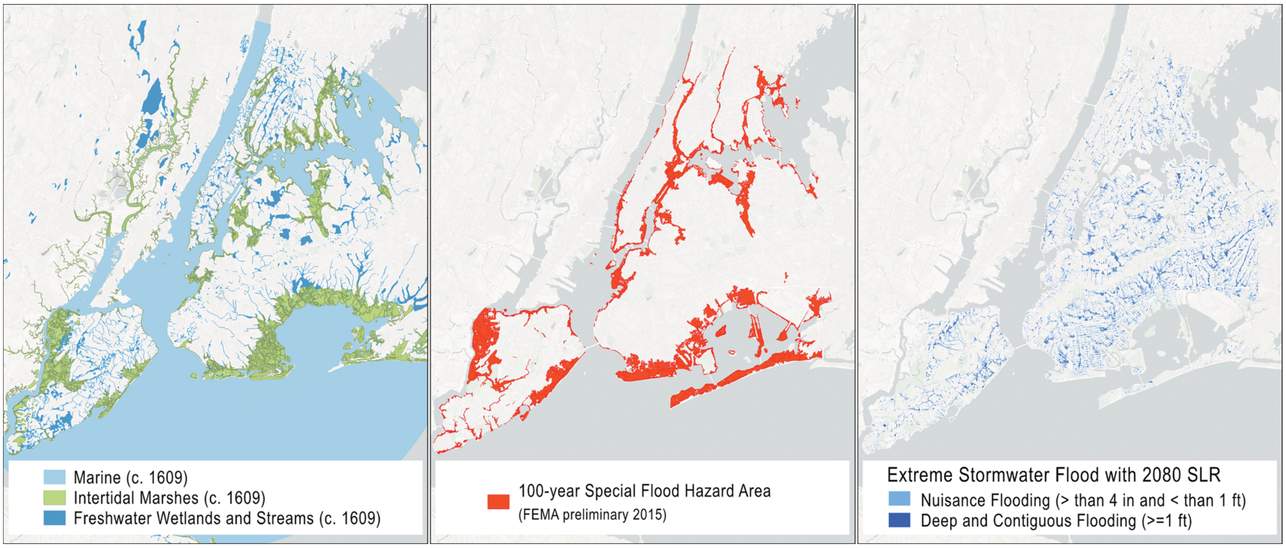

FIGURE 2 Historic streams and wetlands across the city (left), the Federal Emergency Management Agency (FEMA) 100-year Special Flood Hazard Area (center), and pluvial flooding resulting from ~3.5 in. of rain per hour with 58 in of sea level rise (right). Areas where inland streams and coastal wetlands were landfilled for urban development tend now to be topographically low-elevation areas that are exposed to flooding. Areas landfilled to dispose of municipal waste and dredged sediment are now anomalously higher elevation areas, even when located along the coast. Figure by: The map of historic streams and wetlands was provided by Eric Sanderson and Lucinda Royte, New York Botanical Garden. The extreme stormwater flood map was provided by the City of New York.[17]

extensive, none of the prior NPCC reports comprehensively reviewed and/or mapped historical and future trends in all types of NYC flood hazards.

This chapter expands the discussion of climate change impacts on NYC flood hazards, building on prior NPCC assessments. The chapter reviews the current science on how climate change will impact different types of flood hazards and the risks they pose for people and—for the first time—for natural ecosystems. The chapter also presents an introduction to the key dimensions of FRM including the potential applicability of different structural and nonstructural, as well as gray and green, approaches, including NNBS. The relationship of flooding to health is described in Matte et al.,[14] whereas the relationship of flooding to equity is covered in Foster et al.[15] Future changes in population and transitions that may impact flood management are discussed in Balk et al.[16]

2.2 | Chapter organization

The chapter is organized as follows:

- Flood risk
- Types of flooding (including a hazard characterization, a historic example, assessment of exposure and vulnerability, discussion of how climate change is projected to affect this hazard, and identification of persistent knowledge gaps):
  - Pluvial flooding
  - Fluvial flooding
  - Coastal flooding
  - Groundwater flooding
  - Compound flooding (various combinations of the above)
- Flood risk management
- Opportunities and future research

3 | FLOOD RISK

3.1 | Flood risk

In undeveloped landscapes, flooding is a natural hydrologic process that plays an important role in the fate and transport of nutrients and sediment, geomorphological evolution, and the function of ecosystems.[18–20] In heavily developed landscapes like NYC, flooding can have adverse consequences for both human and ecological systems. Floods occur because of dynamic interactions between human, natural, and atmospheric processes. Policies that determine how natural and engineered landscapes are managed; specify specific protocols for the planning, design, and management of infrastructure; and/or influence certain types of human behavior can all significantly influence the occurrence of flooding and associated risks.[21]

A key climate change impact, flood risk is determined by three factors.[22,23]

- The magnitude and frequency of flooding **hazards**.
- The **exposure** of people, real property, natural ecosystems, and critical infrastructure to inundation when flooding occurs.
- A variety of social, ecological, technological, and infrastructure factors[24] that contribute to **vulnerability** to flooding.

These three factors can be exacerbated by **responses** taken to mitigate flooding, as well as any tradeoffs and/or unintended consequences of those responses or any other actions taken to address other societal needs that make flooding worse, commonly referred to as **maladaptation**.

Flooding creates risks when vulnerable people or ecosystems are exposed to flood hazards. Within cities, flood impacts can occur anywhere, for example, within coastal and riverine floodplains but also at interior locations due to precipitation, and can be exacerbated by small-scale differences in topography, drainage system constraints, and building design.[25] Flood risks can also arise as unintended consequences of actions taken to address flooding or any other societal challenge (e.g., the construction of housing in flood hazard areas). FRM includes plans, actions, strategies, or policies taken to reduce the likelihood and/or magnitude of adverse potential consequences based on assessed or perceived risk.[23] FRM can be accomplished by a variety of responses that may be implemented individually or in combination, by public and/or private entities from the Federal government down to individual landowners.[26,27] Effective FRM requires equitable collaboration that is both vertical (e.g., across different governance levels) and horizontal (e.g., among various actors at any given level of governance) and must consider flooding's physical, social, and informational dimensions.[25]

3.2 | Flood hazards

Each of the four principal types of flooding that impact NYC (e.g., pluvial, fluvial, coastal, and groundwater) is triggered by a wide range of associated hazards. For example, coastal flooding can occur due to infrequently occurring, but powerful storm surges that cause deep inundation over one or two tidal cycles; frequently occurring but moderate "sunny day" high water that occurs during the highest astronomic tides each month; as well as by future sea level rise that will result in regular inundation of the lowest lying areas of the city. Flood hazards can be amplified when they occur concurrently. This can include compound flooding (when coastal and rain-driven flooding occurs within the same event) or when multiple hazards with the same driver (such as the co-occurrence of pluvial and groundwater flooding, or pluvial and fluvial flooding, all of which are driven by precipitation) occur.

The magnitude of a flood hazard at any given location is primarily characterized by the maximum depth of water inundation.[28] However, other factors may also strongly contribute to the magnitude of hazard during a flood event.[29,30] These include:

- **Fast-flowing water**: The force associated with flowing water can generate life-threatening conditions, even when floodwaters are only a few inches deep. The force of flowing water can cause pedestrians to be knocked down,[31,32] and vehicles to be floated,[33] and can generate hydrodynamic forces that can destroy solid walls and dislodge buildings.[34] Fast-flowing floodwaters can erode large volumes of soil and sand, undermining vegetation, bridge piers, sea walls, and foundations. The transport and deposition of suspended sand and sediment, along with vehicles and other debris, can contribute to additional flood damages.
- **Waves**: Hydrodynamic forces caused by wave breaking, runup, and slam can cause severe structural damage to buildings and other infrastructure located along the coast.[34,35]
- **Flooding rise time**: The time between the peak of a rain event that causes (pluvial and/or fluvial) flooding and the time of peak inundation.[36] Virtually all pluvial floods and many fluvial floods in NYC are "flash" floods, defined by the US National Weather Service (NWS) as events that have a rise time of less than 6 hours (h).[37] Fluvial floods along the Bronx River may have longer rise time due to the size of its watershed.
- **Inundation duration**: Describes the length of time that the exposed area remains inundated. Along with direct increases in the length of time of disrupted transportation, transport, and utilities service, porous building materials exposed to floodwaters for longer durations have a greater likelihood of mold growth and corrosion.[38]
- **Water chemistry**: Floodwaters can transport dissolved and suspended contaminants, including potentially toxic chemicals or pathogens. The risk of waterborne infectious disease from exposure to floodwaters that have passed through combined and separate sewers is much greater than that associated with surface runoff.[39,40] Corrosion from saline coastal and groundwater inundation can cause additional damage to infrastructure and utilities[41,42] and can impact the health of urban trees and other vegetation that is not salt tolerant.[43–45]
- **Live electric current**: Submerged power lines or other inundated electrical systems can create areas of electrified floodwaters or conditions that allow people to otherwise contact live electric current. Jonkman and Vriling[46] estimated that 3% of global flooding deaths were caused by electrocution, as occurred in College Point, Queens in 2004 (see Table 2).

As a rule, the magnitude of a potentially hazardous weather event is inversely related to its annual probability of occurrence.[47] As a result, the magnitude of floods and the weather events that drive them are often described by their recurrence interval (also known as return interval or return period) (Equation 1), or the inverse of the probability that an event will occur in any given year:

$$R = \frac{1}{p} \tag{1}$$

where R is the recurrence interval (years), also known as the return period; p is the probability of occurrence in any given year (# occurrences/# years analyzed), also known as the annual exceedance probability (AEP).

Although the recurrence interval provides a convenient way to describe the probability of occurrence of a particular hazard, it can be easily misunderstood for several reasons. First, it does not provide information on the timing of actual events. For example, a 100-year precipitation event does not necessarily occur once every 100 years. Rather, this event has a 1% chance of occurrence every year and, statistically, can happen more than once in the same year or not happen for many hundreds of years. Second, precipitation events with the same recurrence interval can imply very different precipitation accumulations (typically measured in inches) and intensities (typically measured in inches/hour). For example, in NYC, a 100-year, 24-h precipitation event implies the accumulation of almost three times the amount of precipitation as would be associated with a 100-year, 1-h event. However, the 1-h event is more than eight times as intense. Third, climate change is altering both the mean and extreme values of climate variables like precipitation accumulations and sea level,[6] creating uncertainty in the estimation of the frequency with which a particular event occurs.

For all the reasons discussed above, event recurrence intervals derived from retrospective analyses of historical climate data may be outdated and inadequate for use in designing FRM strategies. The recurrence intervals associated with certain flood hazards are expected to decrease with climate change through the 21st century, as the climate system accelerates. In 2024, the NYC Climate Vulnerability, Impact, and Adaptation Analysis (VIA) released updated and forecasted future recurrence intervals for NYC precipitation.[48] As such research evolves, effective communication among practitioners, scientists, and the public is necessary to avoid misinterpretation and misuse of recurrence interval terminology in FRM planning.[49]

Despite their shortcomings, recurrence intervals are a convenient descriptor of referring to specific flood hazards, and they are used throughout this chapter. The reader is advised to treat these recurrence intervals with caution, and as a rule, to use the physical characteristics of the event (e.g., its duration, intensity, frequency, and spatial extent) as a more accurate descriptor of a flood hazard.

3.3 | Flood exposure

Exposure describes "the presence (i.e., location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage."[50] For any specific flood hazard, exposure is a descriptor of what areas were affected by the hazard and who and what is in the affected area. The dense, highly built-up environment of NYC means that multiple critical infrastructure systems and thousands of people can be exposed to flooding, even when inundation is only limited to several city blocks.

Potential exposure to different flood hazards is typically evaluated using flood hazard maps. Flood hazard maps visually represent the area over which a specific flood hazard has a defined probability of occurring. The most well-known flood hazard maps are the SFHA maps developed by FEMA. Widely used to support City flood management, the SFHA maps identify geographic areas that have a 1% chance of at least 1 ft of coastal and fluvial flooding each year (i.e., the 100-year recurrence interval base flood elevation). Additional mapped hazard areas provided by FEMA include areas within the SFHA that also experience waves of at least 3 ft in height above the base flood water level, and areas associated with the 0.2% (500-year storm surge or fluvial flood).

The term "floodplain" is commonly used to describe FEMA's SFHA, but only a small fraction of NYC's flood hazard areas are classically defined floodplains—for example, relatively flat alluvial landforms adjacent to rivers that are formed by processes associated with periodic flooding of the river.[18,51] This distinction has important implications for understanding flooding processes, risk, and potential opportunities to enhance the resilience of areas of the city exposed to flooding. To avoid confusion, in this chapter, the more physically representative term SFHA is used to refer to coastal and riverine flood hazard areas identified by FEMA only.

When mapping flood risks, it is also important to be mindful of "what is being exposed to what."[52] Flood hazard maps only represent areal exposure to a specific flood hazard—for example, areas exceeding a specific depth of inundation associated with an event with a specific recurrence interval. Areas outside of this zone may still be highly exposed to flooding from a higher magnitude (e.g., higher recurrence interval) event or from other types of flood hazards. Within any flood hazard area, there is often likely to be a spectrum of exposure—with different locations exposed to different water depths and/or different combinations of flood hazards.

The dense, highly built-up environment of NYC presents unique challenges for providing direct counts of exposed populations. The smallest spatial unit at which population density data are available is the census block, which in NYC can represent several thousand residents.[53] But flood hazard areas are often discontinuous and small relative to the size of census blocks, with boundaries that do not spatially coincide with them. In addition, at any given location in NYC, populations are often distributed vertically, with relevance for the evaluation of flood exposure. Although residents on higher floors may be exposed to significant indirect impacts from flooding (such as loss of utilities or isolation), their exposure is very different from populations in ground-level or subgrade residences that may be exposed directly to deep inundation. Dasymetric mapping techniques can be used to apportion census block populations to flood hazard areas. However, these techniques have not historically been used to represent the vertical distribution of populations. Three-dimensional dasymetric mappings of urban populations have only been introduced recently,[54,55] and, to date, this approach has not been applied in NYC.

Throughout this chapter, maps depicting exposure of NYC's buildings to the flood hazards listed in Table 1 are presented. Because the flood insurance studies[56,57] used to delineate FEMA's SFHA in NYC do not consider pluvial or groundwater flooding, nor the impact of climate change on future flood exposure, this chapter also utilizes the additional hazard layers listed in Table 1. The present-day and future pluvial flood hazard maps were developed by the City of New York. The US Geological Survey (USGS) mapped areas with shallow groundwater tables that may be subject to future groundwater flooding. NPCC researchers developed maps of coastal hazards based on Mean Monthly High Water (MMHW).[11] Spatial data on buildings and subgrade spaces were obtained from the publicly available NYC Building Footprints and *MapPLUTO* cadastral datasets.[58,59]

3.4 | Flood vulnerability

The term "vulnerability" is used broadly in a variety of fields, including natural hazards management and everyday language. In this

TABLE 1 Flood hazard maps used exposure assessment in this chapter.

	Mapped flood hazard	Return interval	Type of flooding	Methods	Source
Current scenarios	Pluvial flooding (inundation depth greater than 4 in.) from 2 in. of rain in 1 h, falling uniformly across the city	Approximately 10-year (10% probability each year)	Pluvial	InfoWorks ICM 1D–2D Hydrologic and Hydraulic (H&H) Hydrologic Modeling	Stormwater Resiliency Study[17]
	Uncompounded (not co-occurring) storm surge and fluvial flooding (inundation depth greater than 1 ft); base flood water depth is provided for most of the flood hazard area	100-year (1% probability each year)	Coastal and fluvial	HEC-RAS modeling of identified water bodies	FEMA NYC Flood Insurance Study[56,57]
	Tidal Mean Monthly High Water (MMHW); base flood depth associated with these tides varies across the hazard area	0.08-year (1250% probability each year) in the 2020s	Coastal	3D dynamic simulations of tides using the SECOM model with the NYHOPS operational setup	NPCC3[11]
	Shallow groundwater areas: areas where the depth-to-water table is estimated to be less than 10 ft below the land surface	n/a	Groundwater	Estimated based on pre-2013 water table observations and the topography of the land surface	Monti et al. [60]
Future scenarios	Pluvial flooding from ~3.5 in. of rain in 1 h falling uniformly across the city, along with 58 in. of sea level rise; inundation depth greater than 4 in. is delineated	2080s 90th percentile sea level rise	Pluvial	InfoWorks ICM 1D–2D Hydraulic and Hydrologic Modeling	Stormwater Resiliency Study[17]
	Tidal Mean Monthly High Water (MMHW with 58 in. of sea level rise); base flood depth associated with these tides varies across the hazard area	2080s 90th percentile sea level rise	Coastal	3D dynamic simulations of tides using the SECOM model with the NYHOPS operational setup	NPCC3[11]

Note: It is important to note that each layer is associated with different probabilities of annual occurrence.
Abbreviation: FEMA, Federal Emergency Management Agency; NYC, New York City.

chapter, the term is defined as "the propensity or predisposition"[23,61] of an individual, community, or natural system to be adversely affected by a flood, referring specifically to their "capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events."[50] Flooding can cause many direct adverse effects in exposed communities, including loss of life (Table 2), injuries, and damage to property and utilities from inundation. It can also cause a variety of indirect adverse effects, including the disruption of transit and transportation, extended loss of electricity, heat, and other utility service, health impacts from mold or pathogen exposure, and stress, and can contribute to the involuntary displacement of individuals and communities.[62–65] Flooding can also disrupt, damage, or destroy NNBS, reducing their innate ability to provide urban ecosystem services, including those needed to buffer the impacts of climate extremes.

3.4.1 | Vulnerability of human communities

Past floods have incurred significant known economic costs, but the true total costs borne by vulnerable NYC residents remain unquantified. In NYC, Post-Tropical Cyclone Sandy (2012) was estimated to have caused over $19 billion dollars of damage to NYC including lost economic activity, with much of this damage attributed to storm surge flooding.[66] In 2021, a cloudburst associated with the remnants of Hurricane Ida (Ida Remnents Cloudburst) triggered just over an estimated $900 million (FEMA IA: ~$158 M, FEMA PA: ~$283 M, FEMA NFIP: ~$28 M, SBA ~$123 M, HUD CDBG-DR: ~$310 M, NYS ONA: ~$1.5 M) in known damages (Personal Communication, NYC Office of Emergency Management). However, it is unlikely that such estimates include the total costs incurred by NYC residents. Nationally, existing flood data have been found inadequate in representing the magnitude of urban flooding impacts.[25] Although typical flood damage estimates are based on flood insurance claims or financial assistance provided by FEMA or other federal agencies following a flooding disaster, most NYC residents, including many who live in areas highly exposed to flooding, do not have flood insurance. Additionally, the FEMA Individual Assistance Program may only cover a fraction of actual property damage costs and is only available during floods that are officially declared disasters by the US President. Many impactful pluvial floods are highly localized and not declared disasters by FEMA,[67] suggesting that the true total costs of flooding to residents of NYC could be substantially higher than published estimates.

A combination of physical and socioeconomic factors contribute to flood vulnerability.[70] To help to evaluate the vulnerability of NYC residents to flooding, a team of academic researchers, working in collaboration with experts from the NYC Inter-agency Climate Assess-

TABLE 2 Flooding events that caused 52 direct deaths in New York City (NYC) since 1987.

Date	Type of flooding	Description	Source
8/12/1993	Pluvial	An infant drowned in her basement when it flooded from heavy rains in Flushing, Queens	NCEI Storm Events Database Episode 342081[68]
8/11/2004	Pluvial	"Flash flooding of roads occurred at College Point, Queens. Two occupants of a vehicle were electrocuted by a fallen power line when they apparently stepped out of their vehicle into several feet of water"	NCEI Storm Events Database Episode 1178433[68]
10/29/2012	Coastal	A total of 36 fatalities were directly attributed to storm surge and high surf (*Staten Island*: 23; *Queens*: 6; *Brooklyn*: 5; *Manhattan*: 2)	NCEI Storm Events Database Episode 70044[68]
9/1/2021	Pluvial	A total of 10 drowning deaths in subgrade apartments and residential offices in Queens 1 drowning death in a subgrade apartment in Brooklyn 1 drowning death outdoors after falling into a body of water during the storm (The body of a pedestrian was found floating in the Gowanus Canal the day after the storm.) 1 direct fatality from asphyxiation resulting from a car fire that was caused by flooding of a vehicle	Yuan et al. [69]

Note: Additional fatalities from vehicle accidents associated with storm conditions are not included in this table.
Abbreviation: NCEI, National Centers for Environmental Information.

TABLE 3 Indicators used in the Preliminary New York City Flood Susceptibility to Harm and Recovery Index (FSHRI).

1. Black, indigenous, people of color (% that identify as any racial category besides "White" and/or ethnically Hispanic/Latino)
2. Income (Per capita)
3. Disability (% with a disability)
4. Language isolation (% speaking English less than "well")
5. Children (% below 5 years old)
6. Elderly (% above 60 years old)
7. Elderly population living alone (% living alone above 65 years old)
8. Healthcare access (% without health insurance)
9. Household income (% households making less than $75,000)
10. Home ownership (% households that are owner-occupied)
11. Cost-burdened households (% households spending 30% or more in their living costs)
12. Rent-burdened households (% households spending 30% or more in their rental costs)

ment Team (ICAT), developed The New York City Flood Susceptibility to Harm and Recovery Index (FSHRI) (Figure 3) as part of the NYC VIA study.[48] The FSHRI is an index of socioeconomic vulnerability (susceptibility to harm and capacity to cope and recover from flooding) based on social demographic indicators (Table 3) provided through the American Community Survey at the census tract level. These indicators were selected based on empirical evidence in the social science literature on socioeconomic parameters that are correlated with measures of flood outcomes.[70–73] The outcomes considered in the empirical analyses include depth of water for exposure; loss of life or injury; amount of damage to a home, loss of employment, and/or loss of access to food or health care for susceptibility to damage; and cost of recovery and length of various aspects of recovery for capacity to recover. The FSHRI is part of a larger effort to develop NYC's first Flood Vulnerability Index (FVI), which includes the FSHRI together with scenarios of exposure to different types of flooding. The FVIs developed to date are available on the NYC Mayor's Office of Climate and Environmental Justice (MOCEJ) mapping tool.[74]

Many unmapped, physical characteristics of the built environment are determinants of flood vulnerability. For example, compared to traditional structures, buildings that have "wet floodproofing" (measures that allow water to safely enter the enclosed areas of a house) or "dry floodproofing" (measures that make a structure watertight below the level that needs protection) may be much less vulnerable even if they are highly exposed.[75] The placement and design of critical utilities, such as electrical, mechanical, and HVAC systems, can also be a key determinant of vulnerability. However, no publicly available datasets documenting which buildings have been flood proofed and which buildings have elevated critical utilities are currently available.

Throughout this report, an initial attempt has been made to evaluate the exposure of two building typologies to flood hazards. These are as follows: 1–2 unit residential buildings with subgrade spaces (e.g., basements or cellars) and NYC Housing Authority (NYCHA) buildings. Residents of 1–2 unit residential buildings and residents of buildings with subgrade basements or cellars are more likely to experience costly and life-threatening flood damages than are residents of large multifamily buildings and buildings without inhabited subgrade space.[34,76] For example, during the Ida Remnants Cloudburst in 2021 (see Section 4.2), 75% of the damaged buildings were small, 1–2 family residential buildings, compared to 52% of buildings citywide.[77]

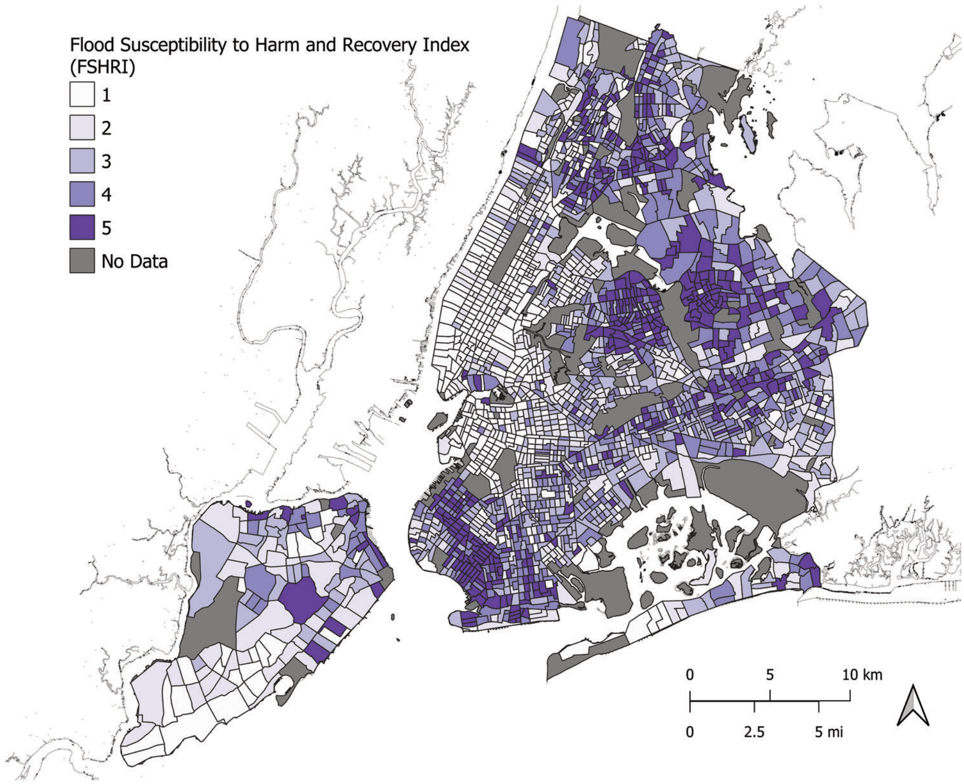

FIGURE 3 The Flood Susceptibility to Harm and Recovery Index (FSHRI), by census tract across New York City (NYC). Areas with higher socioeconomic vulnerability, as indicated by higher numeric values of the Flood Susceptibility to Harm and Recovery Index (FSHRI) (and darker shades of purple), may face more adverse effects if exposed to different types of flooding. The FSHRI does not consider exposure to any particular type of flooding. The NYC Flood Vulnerability Index, which includes the FSHRI and exposure to different types of flooding, is available on the NYC MOCEJ mapping tool. Figure by: New York City Panel on Climate Change 4 (NPCC4) Fellow Fiona Dubay, Sarah Lawrence College.

Based on NFIP claims for Post-Tropical Cyclone Sandy 2012, small residential buildings were also more likely to have experienced structural damage, particularly if built prior to modern flood-resistant construction standards.[75] The presence of basements in older buildings can, itself, contribute to structural damage during floods.[78] Basement apartments often provide a secondary source of income for the landlords of small residential buildings, who often live on-site. Basement apartments in these types of buildings disproportionately serve very low-income households, recent immigrants, and other socioeconomically vulnerable households that lack access to affordable options in the general housing market.[77]

Over 400,000 New Yorkers live in NYCHA residences, which can include many multi-generational communities with internal support structures and kinship networks that can help to reduce vulnerability to flood hazards, especially when compared with communities that lack such social cohesion.[79–82] At the same time, NYCHA residents often face distinct socioeconomic and infrastructure vulnerabilities—they are disproportionately elderly, disabled, and low-income, and from groups that are victims of racism and ethnic marginalization.[83] Moreover, although substantial progress has been made in floodproofing and structurally reinforcing NYCHA buildings located in the FEMA SFHA since Post-Tropical Storm Sandy in 2012[84], and pilot cloudburst management strategies are planned for some NYCHA developments,[84,85] most NYCHA buildings outside the SFHA remain vulnerable to flooding. These vulnerability factors are exacerbated by a legacy of multidecadal deferred maintenance in many NYCHA properties.[86]

3.4.2 | Vulnerability of natural and nature-based systems (NNBSs)

NYC's NNBSs provide a wide range of regulating, provisioning, supporting, and cultural ecosystem services, to which many NYC residents attach significant value.[87] These include water regulating services that can help reduce the impacts of different types of floods, as described in detail in the recently published International Guidelines for Natural and Nature-based Features for FRM.[88] However, NNBSs are also vulnerable to flooding as climate change-induced changes in flood frequency, sediment, salt loading, and temperature can all impact the ecosystem functions that support ecosystem services.

For example, sea level rise and storm surges will raise coastal groundwater tables and cause saltwater to enter coastal aquifers.[89] Changes to soil salinity can trigger complex changes to vegetation composition, ultimately favoring salt-tolerant species.[45] Though salt adversely affects trees at all stages of growth and development, responses vary significantly by species.[90–92] Exposed to salt water, some tree species may have difficulty germinating by seed,[45,93] whereas others may stop producing new leaves, senesce prematurely, fail to recruit new individuals, or die.[94] Analyzing street trees in post-Tropical Cyclone Sandy's inundation zone 3 years after the storm, Hallett et al.[43] found that red maple (*Acer rubrum*) was negatively impacted by saltwater flooding but was able to recover over time. London plane trees (*Platanus* × *acerifolia*), by contrast, showed high mortality and no signs of recovery.

Tidal wetlands are particularly sensitive to changes in both mean sea level and tidal range. Tidal wetlands require regular cycles of surface flooding and exposure, as well as deeper and longer duration episodic flooding that typically occurs during spring tides and storm surges. Some storm events can supply a pulse of sediment that enables wetlands to keep pace with sea level rise and weather future storm events.[95–98] By contrast, some large storms can produce high velocities and can deepen channels and tidal flats, propagating waves further into tidal creeks, causing scouring and long-term erosion, even during subsequent calm conditions.[99,100]

The frequency of wetland inundation, also called its hydroperiod, is determined jointly by sea level and wetland topographic elevation. Wetlands with hydroperiods that are extended due to sea level rise may undergo significant changes in structure and function[101,102] that hinder their ability to provide ecosystem services such as water quality improvement, and wave attenuation, and can eventually lead to their loss.[103] In undeveloped landscapes, wetlands experiencing sea level rise migrate in a landward direction. However, in many parts of NYC, landward migration of tidal wetlands is impossible given the presence of engineered coastal infrastructure (e.g., highways, bulkheads, and buildings), highlighting the importance of protecting existing and potential expansion pathways.[2,104]

Tidal wetlands can also be sensitive to a reduction in hydroperiod, for example, if a tide gate, barrier, or other hydraulic restriction prevents high tide flooding.[2] Less frequent flooding often results in a reduction in sediment delivery to the wetland surface. Wetlands that are sediment starved need active management and restoration to persist in place. Jamaica Bay marshes, for example, are sediment poor[105,106] and extremely high nutrient loading impacts their structural integrity and ability to grow vertically.[107–110] Courtney et al.[111] found that over a recent 20-year period, high tides propagated further into the groundwater aquifer of a brackish Hudson River tidal wetland even though the marsh surface elevation was increasing at a rate that matched sea level rise. This phenomenon was attributed to high tides increasing faster than mean sea level. Such impacts are significant given the importance of NYC wetlands in sustaining biodiversity and many critical and endangered species. Without active management, such wetlands undergo significant ecological changes[112] as outlined in detail in the City's Wetland Management Framework.[113]

Outside NYC and along the eastern Atlantic coast, sea level rise has also been linked to a reduction in the distributional area of lichens,[114] a modification of the position of the marsh–forest interface,[93] reductions in carbon sequestration, above- and below-ground carbon storage potential,[115] and long-term reductions in the radial growth of a coastal pine forest years after coastal inundation.[116] Given the broad range of potential impacts, more research is needed to determine the vulnerability of other NNBS to various flood hazards in NYC.

3.5 | Responses

Flood risks are heavily influenced by the responses that are taken to reduce perceived flood hazards. If these responses result in successful adaptation or transformation, they can reduce flood risks. Responses that inadvertently increase risk or vulnerability to a hazard are referred to as maladaptive. In the flooding context, actions that transfer flood risks from one place to another, reduce flood preparedness, stimulate development in flood hazard areas, cause gentrification, or increase the vulnerability of NNBS can all be considered maladaptive. A thorough exploration of responses that increase and decrease flood risks is provided in Section 9 of this chapter.

4 | PLUVIAL FLOODING

4.1 | Pluvial flood hazard characterization

Pluvial flooding occurs when the intensity of precipitation exceeds the capacity of the land surface to infiltrate it, and/or when the rate of excess precipitation (i.e., runoff) exceeds the stormwater conveyance capacities of natural and engineered drainage systems, resulting in surface ponding.[117] This process dominates the hydrologic cycle of most densely developed cities, which typically have a high percentage of buildings, pavements, and other impervious surfaces that inhibit stormwater infiltration. For this reason, pluvial flooding is often referred to as "urban" flooding.[118]

Although impervious surfaces are the primary driver, pluvial flooding can also occur over pervious surfaces. When the intensity of short-duration precipitation events, commonly referred to as "cloudbursts,"[119] exceeds the infiltration capacity of pervious surfaces, the excess precipitation will accumulate and flow over the surface. This phenomenon is more likely when pervious surfaces are already saturated and/or are covered with snow or ice.[120,121] Alizadehtazi et al.[122] found that the infiltration capacity of urban park soils, tree pits without tree guards, porous pavers, and certain bioretention facilities was frequently below the intensity of the 5 years, 6 min design storm used to design many components of the city's stormwater drainage systems, underscoring the potential of these pervious surfaces to produce runoff.

To reduce pluvial flooding, the city's separate and combined sewer systems were designed to intercept and convey runoff rapidly away from buildings and roads.[123] This approach to urban drainage reduced local flood risks under routine precipitation conditions but transferred pollution loads and flood risks further downstream. Because engineered drainage systems have a finite capacity, they are less effective at reducing local flood risks under extreme precipitation conditions, as brought on by climate change.

Several limitations of the sewer system contribute to contemporary pluvial flood risks. These include (1) the spacing, hydraulic capacity, and maintenance of different types of inlets, (2) hydraulic bottlenecks within the piped collection system, and (3) hydrologic overload. Each of these limitations is described in greater detail as follows:

- ***Inlet conditions***: If stormwater is presented to sewer inlets at rates that exceed inlet hydraulic capacities, the excess runoff will bypass (even if the sewer pipes themselves are not full), causing pluvial flooding further down gradient. In general, grated inlets have higher hydraulic capacities than curb cuts, and curb cuts have greater hydraulic capacity if they are built with higher apron slopes and longer openings. Bypass can be exacerbated by adverse street slopes and/or if snow, leaves, litter, or other debris reduce their interception capacities.[124–127] Bypass of inlets can also be triggered if there are blockages just downstream of the inlet, inhibiting free flow through them. Maintenance of inlets and catchbasins is thus a critical component of pluvial flood risk reduction. The lack of an inlet can also trigger pluvial flooding if runoff accumulates in undrained topographic depressions.
- ***Hydraulic bottlenecks***: Pluvial flooding can occur if the conveyance capacity of a particular segment of the engineered drainage system (e.g., a catch basin hood, a segment of pipe, and a pump) is unable to convey stormwater through the system at the rate at which it is approaching that feature. Under such conditions, stormwater will back up within the system and can ultimately reach the surface through manholes and catch basins (known as a "surcharge") and/or backup into low-lying buildings, subgrade spaces, and other topographically vulnerable areas.
- ***Hydrologic overload***: During extreme precipitation events, some sewer pipes can become filled with water. Under these conditions, any additional rainfall, even at low intensities, will accumulate on the surface. The city's combined sewer system, which serves about 60% of the city and conveys both stormwater and wastewater in the same pipe network, was designed with relief points to reduce the chances of surcharge or backup events. Known as combined sewer overflow points, these features release untreated combined sewage (or CSOs) to the city's surface water bodies, creating significant human and ecological health risks. Climate change could increase hydrologic overload, increasing both flooding and CSOs.

Cloudbursts are a particularly important driver of pluvial flooding.[128] Recent research by the VIA team[48] suggests that many historical pluvial flood episodes were triggered by short-duration (less than 6-h) high-intensity precipitation events. Cloudbursts may occur as highly localized, individual convective (e.g., thunderstorm) cells, or they can be embedded within larger storm systems, including tropical and post-tropical storms, large frontal systems, and Nor'easters. The intense rain associated with any particular cloudburst is usually limited to small areas of the city, but intense rain can also be widespread if thunderstorms are organized into mesoscale storm systems.[129]

The US NWS provides Excessive Rainfall Outlook forecasts, which can identify the large-scale weather and hydrological conditions associated with cloudbursts and flash flooding up to 5 days in advance.[130] These regional forecasts are further enhanced for NYC based on event-specific mesoscale meteorological conditions, but current science is not able to provide forecasts of the exact location, areal extent, intensity, and timing of cloudbursts.[131] Advance warning of imminent potential flooding remains limited to radar-based observations of approaching extreme rainfall and in situ observations of flooding that has already begun, with a nationwide average lead time of 61–68 min.[132] These forecasting challenges make emergency preparations and risk management for pluvial flooding particularly challenging.

4.2 | Historical example: Ida Remnants Cloudburst pluvial flooding

NYC experienced widespread, severe pluvial flooding during a cloudburst on September 1, 2021 (Ida Remnants Cloudburst). Flooding from this event caused 12 drowning fatalities in NYC, which included 11 deaths in subgrade residences and offices. The 13th direct fatality resulted from asphyxiation when the victim's flooded car caught fire.[69] Figure 4 depicts flood-related service requests during the event, along with the location of the residential drowning fatalities. As shown, many of these locations were far outside the most recently developed (Preliminary) SFHA.[57] Flooding from this event was also associated with extensive damage to property and critical infrastructure, displacement due to loss of living quarters, and major disruptions to transit and transportation networks.[76,85]

The extremely intense rainfall associated with this event resulted from three coinciding meteorological factors:[129]

- The remnants of Hurricane Ida, which passed southwest of the city as a post-tropical surface low-pressure system, bringing deep tropical moisture. Precipitable water values peaked at 2.1-2.2 in. (5.3-5.6 cm) over the NYC metropolitan area during this event.
- A large, long-wave trough to the north of the city allowed a deep baroclinic wave to develop along the frontal boundary of the warm air mass associated with the approaching remnant low. This wave created instability and deep convection.
- A powerful, near-zonal jet streak at 250 mb, centered over southeastern Canada. This placed NYC in the right rear entrance quadrant of the jet streak and beneath the area of high upper level divergence. This upper level divergence induced large-scale lift over the region, enhancing persistent, deep convection.

The Ida Remnants Cloudburst was remarkable not only for its extreme rainfall intensity, but also for the large area of the city impacted by it. Most of the city received 2- and 3-h precipitation accumulations that exceeded the 100-year thresholds (Figures 5 and 6). There was a sharp gradient in rainfall from west to east across the city, with the most eastern reaches of the city such as southeast Queens and the Rockaways receiving only moderate rainfall.

Although there are multiple mechanisms through which climate change can increase the intensity of cloudburst events in NYC, these

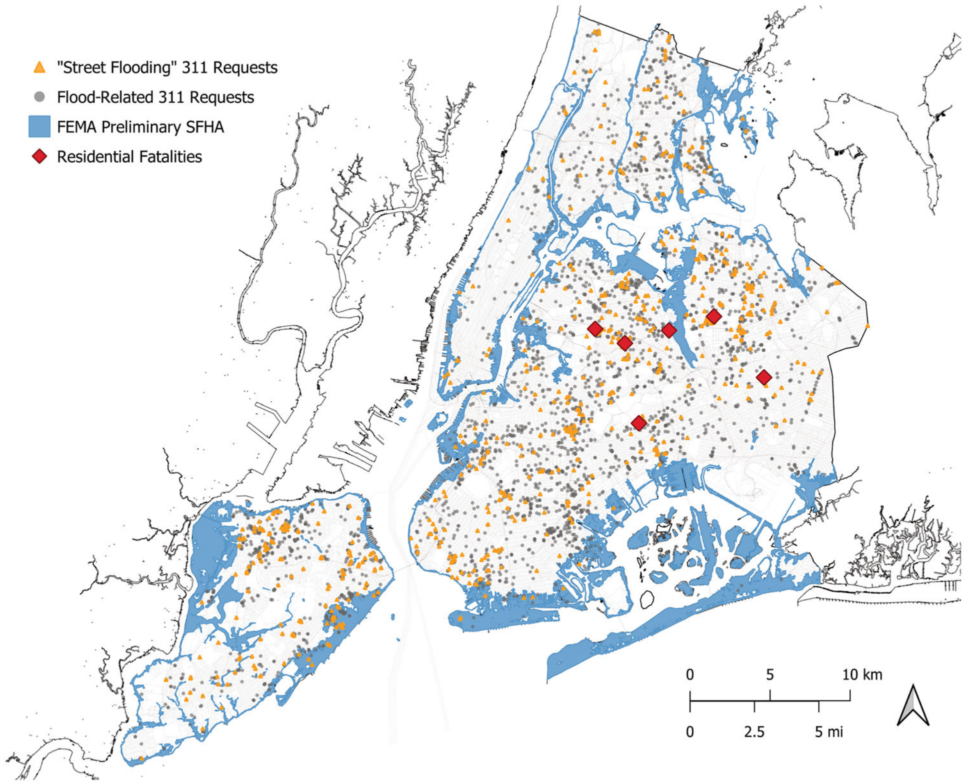

FIGURE 4 Fatalities in subgrade residences/offices, street flooding, and flood-related 311 service requests in New York City (NYC) during the Ida Remnants Cloudburst (September 1–2, 2021). Along with street flooding, flood-related service requests include sewer backup, highway flooding, manhole overflow, possible water main break, catch basin clogged/flooding, and excessive water in basement. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

processes remain poorly represented in global-scale numerical models used to develop climate projections.[133] At present, there is insufficient information to determine if, or to what extent, climate change contributed to the intensity, duration, or areal extent of the Ida Remnants Cloudburst. Attribution studies focused on this and similar events are needed to determine the role that climate change may have had in setting it up and whether more frequent events of similar intensity and spatial extent will occur in NYC in the future.

4.3 | Exposure and vulnerability to pluvial flooding

4.3.1 | Pluvial flood hazard mapping

In 2018, the NYC City Council passed Local Law 172,[137] which required city agencies to develop maps to identify areas of the city that will be most exposed to flooding due to climate change. Because the FEMA's SFHA maps do not include pluvial flood hazard areas, NYCDEP contracted with an academic and consultant team on a Stormwater Resiliency Study,[17] which became the first effort to map pluvial flood hazards in NYC.

As pluvial flooding is caused by hydrologic processes that create runoff rates and volumes that can exceed the limited hydraulic capacity of various components of the surface (e.g., channels, gutters, and inlets) and subsurface (e.g., pipes, pumps, and weirs) sewer systems, mapping pluvial flood hazards requires the use of numerical models that can represent these complex and coupled processes at high spatial and temporal resolution.[138] The Stormwater Resiliency Study involved the development of 13 H&H models using Innovyze's InfoWorks ICM software,[139] each representing a major sewershed that drains into one of NYC's wastewater treatment plants. As detailed in the Stormwater Resiliency Plan,[17] these models utilized a 1D–2D modeling approach. This coupled form of modeling is a recent advance and requires significant computing power and detailed topographic information. Some areas of the city, including large (>100,000 ft^2) parks, large (>250,000 ft^2) nonresidential and noncommercial private lots, and any lots that intersect railway infrastructure were excluded from the resulting pluvial flood hazard maps due to a lack of information regarding their drainage system design.[17]

The Stormwater Resiliency Study models were used to simulate flooding associated with the following three scenarios:

- **Moderate stormwater flood without sea level rise**: ~2 in. of rainfall falling uniformly across the city in 1 h.
- **Moderate stormwater flood with 2050s sea level rise**: ~2 in. of rainfall falling uniformly across the city in 1 h, co-occurring with coastal water levels elevated by 30 in.

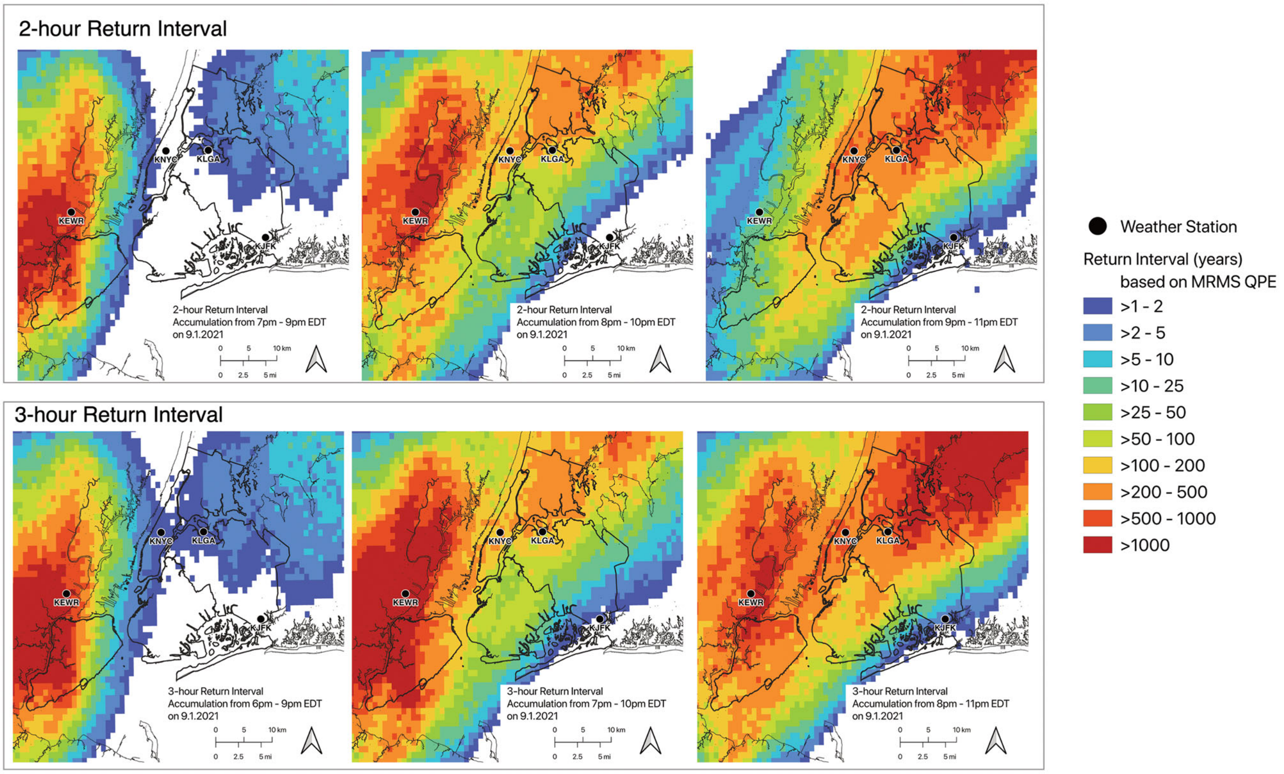

FIGURE 5 Recurrence intervals associated with the 2- and 3-h rainfall accumulations across the city (during Ida) based on National Center for Environmental Prediction (NCEP) Multi-Resolution, Multi-Sensor (MRMS) Hourly Zip Files, 2021 Quantitative Precipitation Estimates (QPE).[134] Recurrence intervals presented in these maps are based on NOAA Atlas 14 Intensity-Duration-Frequency (IDF) curves for the Central Park (KNYC) Weather Station. Extremely intense rain progressed from west to east across the city between 6 and 11 p.m. Time series of precipitation at the area Automated Surface Observing System (ASOS) weather stations (KEWR, Newark Liberty International Airport; KJFK, John F. Kennedy International Airport; KLGA, LaGuardia Airport; KNYC, Central Park Weather Station) are provided in Figure 6. Figure by: BR Rosenzweig.

- **Extreme stormwater flood with 2080s sea level rise**: ~3.5 in. of rainfall, falling uniformly across the city in 1 h, co-occurring with coastal water levels elevated by 58 in.

Each of these scenarios was simulated individually, as a singular event, without consideration of antecedent moisture conditions. Buildings were represented as obstructions. Two of these three scenarios (moderate stormwater flood without SLR and extreme stormwater flood with 2080s SLR) are used in the exposure maps presented in this chapter (Table 1).

The moderate scenario with no sea level rise was used to evaluate present-day pluvial flood exposure. This is the only pluvial flood hazard scenario that evaluates pluvial flooding associated with present-day mean high tide (mean higher high water) levels. This scenario identifies areas that are the most highly exposed to pluvial flooding—that is, those that would experience inundation greater than 4 in. even from a relatively modest rain event of approximately 2 in. in 1 h. Because this precipitation event is roughly associated with a 10-year recurrence interval, exposure cannot be directly compared to that of the FEMA SFHA, which is associated with 100-year (1% AEP) flooding. This scenario also represents less rainfall than occurred during the Ida Remnants Cloudburst which, in most of the city was a much more extreme event than this moderate scenario, was spatially varying and occurred for different durations in different portions of the city. Further, this hazard scenario is a synthetic event and does not capture any operational or environmental conditions, such as catch basins being clogged due to leaves, ice, and/or debris.

To estimate the number of buildings exposed to the moderate pluvial flood scenario, all buildings located within a 1 ft buffer of the simulated pluvial flood hazard area were identified. The 1 ft buffer was used to associate flooding with adjacent buildings and is not an indicator of the model accuracy; it should be noted that the model does not contain property-level information such as curb lines, private walls, fences, or other surface features that may impact localized flooding. Under this moderate scenario, 30,690 buildings would be exposed to stormwater inundation depths of greater than 4 in. Of these exposed buildings, 16.7% (i.e., 5113) are single-story buildings and 41.7% (i.e., 12,796) of the exposed buildings have basements, cellars, or subgrade spaces. Of the exposed buildings, 30.7% (i.e., 9413) are 1–2 residential unit buildings with subgrade spaces, and 0.36% (i.e., 112) of the exposed buildings are part of NYCHA developments (Figure 8). In the interpretation of these results, it is important to note that the Stormwater Resiliency modeling assumes that ~2 in. of rain fall uniformly over the entire city. Such a scenario is unlikely to occur during an actual rain event.

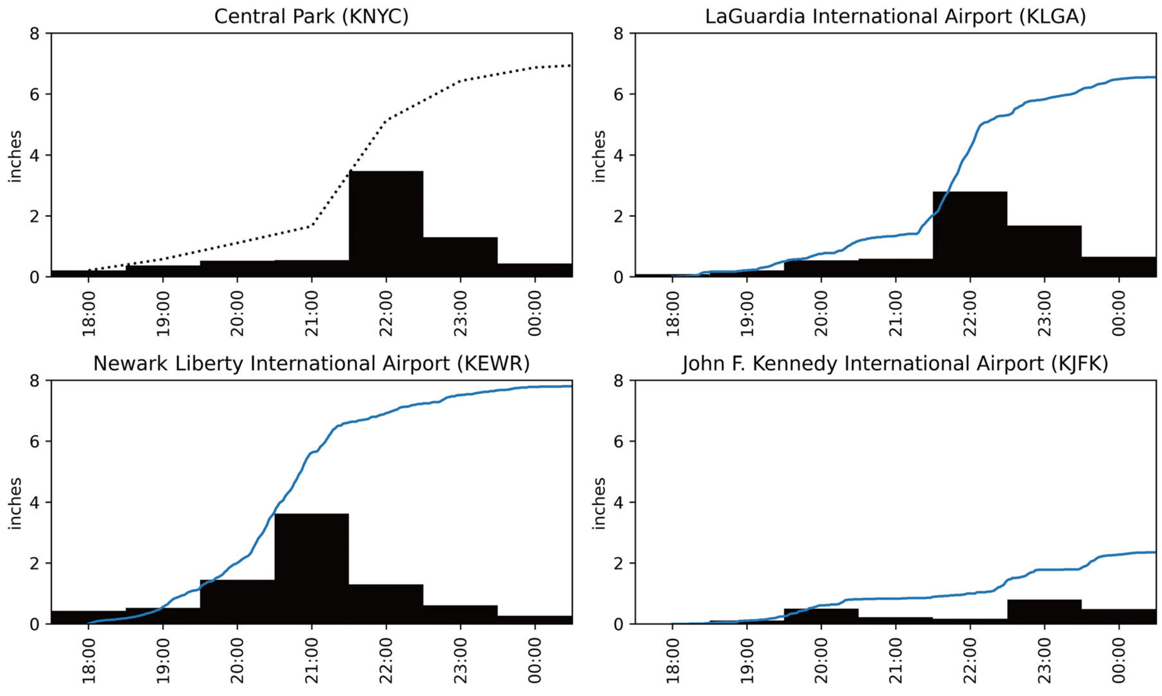

FIGURE 6 Hourly (black bars) and cumulative precipitation during the Ida Remnants Cloudburst on September 1, 2021 (EDT) Cumulative precipitation was determined using 1-min Automated Surface Observing System (ASOS) observations (blue lines). One-minute data were not transmitted from the Central Park Station during this event. Cumulative precipitation was calculated based on hourly measurements (black dotted line) for that station. One-minute data allow for the evaluation of extreme accumulations that do not correspond with hourly measurement intervals. For example, 3.76 in. of rain fell in the 60-min period between 21:18 and 22:18 at LaGuardia Airport. Figure by: BR Rosenzweig.

TABLE 4 Sixty-minute rainfall accumulation in inches at selected annual exceedance probabilities (AEPs) (recurrence intervals).

	2 Year (50% AEP)	10 Year (10% AEP)	50 Year (2% AEP)	100 Year (1% AEP)
Contemporary: NOAA Atlas 14	1.28 (1.04–1.58)	1.89 (1.52–2.36)	2.57 (1.93–3.41)	2.87 (2.08–3.95)
SSP245 (2050s–2090s)	1.56 (1.27–1.93)	2.43 (1.95–3.02)	3.19 (2.39–4.23)	3.62 (2.62–4.98)
SSP585 (2050s–2090s)	1.64 (1.33–2.02)	2.55 (2.05–3.19)	3.34 (2.51–4.43)	3.73 (2.7–5.14)

Note: Contemporary precipitation values are from NOAA Atlas 14 at the Central Park Weather Station. Future precipitation projections are based on the mean citywide delta change factors derived from an ensemble of climate models using the LOCA2 downscaling method for SSP245 (mid-century greenhouse emissions reduction) and SSP585 (unmitigated climate change). Values in parentheses represent the 10th and 90th percentile values at Central Park and their projections based on the citywide mean change factor.
Abbreviation: AEP, annual exceedance probability.

4.4 | Climate change and future pluvial flooding

Pluvial flooding is already a significant hazard for NYC, and it will be exacerbated by human-caused climate change throughout the 21st century, especially if global efforts to reduce greenhouse gas emissions are delayed. Climate change is expected to increase the probability of extremely intense, short-duration precipitation.[140,141] Table 4 presents projected changes in the 10-year (10% AEP) and 100-year (1% AEP) precipitation accumulation falling in 1 hour. The relatively moderate (10-year) cloudbursts that already cause pluvial flooding in some inland areas of the city (Figure 9) are projected to become 19%–24% more intense. Greater potential increases are projected for more extreme (100-year) storms, with 1-h accumulations increasing by 20%, even if global emissions of heat-trapping gases are reduced by mid-century, and by 30% under scenarios of unmitigated climate change. There is greater scientific uncertainty associated with these short-duration precipitation projections, compared with projections of future daily rainfall extremes.[142] This consistent uncertainty presents a significant challenge for the design of stormwater infrastructure for pluvial flood resilience.[143]

Along with projected increases in rainfall rates at any given location, recent studies have identified mechanisms that can result in increases in the areal extent over which intense rain falls with global warming.[140,144,145] Most cloudbursts are highly localized and result in flooding only in small areas of the city at once, though these localized impacts can be severe and associated with life-threatening conditions

FIGURE 7 A total of 83 high water marks (HWMs), such as seed lines, mud, and debris, were surveyed by the US Geological Survey in the weeks following the Ida Remnants Cloudburst.[135,136] Using these observations, land surface inundation was estimated within an 820.2 ft (250 m) buffer of each observed HWM. During the Ida cloudburst, deep inundation from pluvial flooding occurred in areas that were far from the water bodies used as the basis of Federal Emergency Management Agency Special Flood Hazard Areas (FEMA SFHA) modeling. Flooding from this event was not limited to areas where HWMs were obtained and occurred in areas of the city that were not surveyed or where HWMs could not be identified. Several inundated areas are highlighted here, and all HWM data from this survey can be viewed at: https://stn.wim.usgs.gov/fev/#2021Ida. Figure by: BR Rosenzweig.

in affected communities.[117] However, two of the most impactful historic pluvial flood events at the city-scale—the Ida Remnants Cloudburst and a cloudburst on August 8, 2007 that caused the unplanned shutdown of much of the subway system—were associated with organized systems of thunderstorms that resulted in extreme rainfall rates falling over widespread areas of the city.[129,146] A potential increase in the size and organization of future cloudbursts would have significant implications for the citywide impacts of pluvial flood events,[147] but scientific understanding of this topic remains in the earliest stages.

Pluvial flooding may also be exacerbated in areas where groundwater tables rise in response to sea level rise (Section 7.4). In these areas, the ability for storm sewers to convey stormwater may be reduced

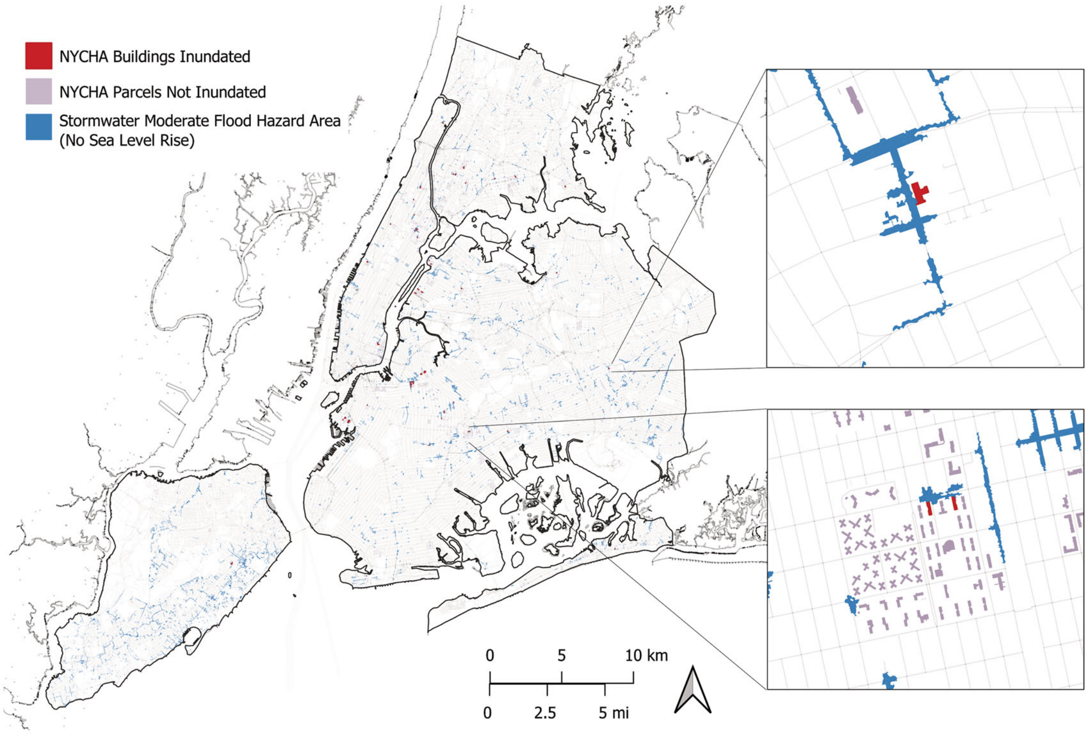

FIGURE 8 New York City Housing Authority (NYCHA) developments with buildings that would be exposed to pluvial flooding from a moderately intense (∼2 in. in 1 h) rain event. NYCHA buildings represent less than 1% of the total buildings inundated under this scenario. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

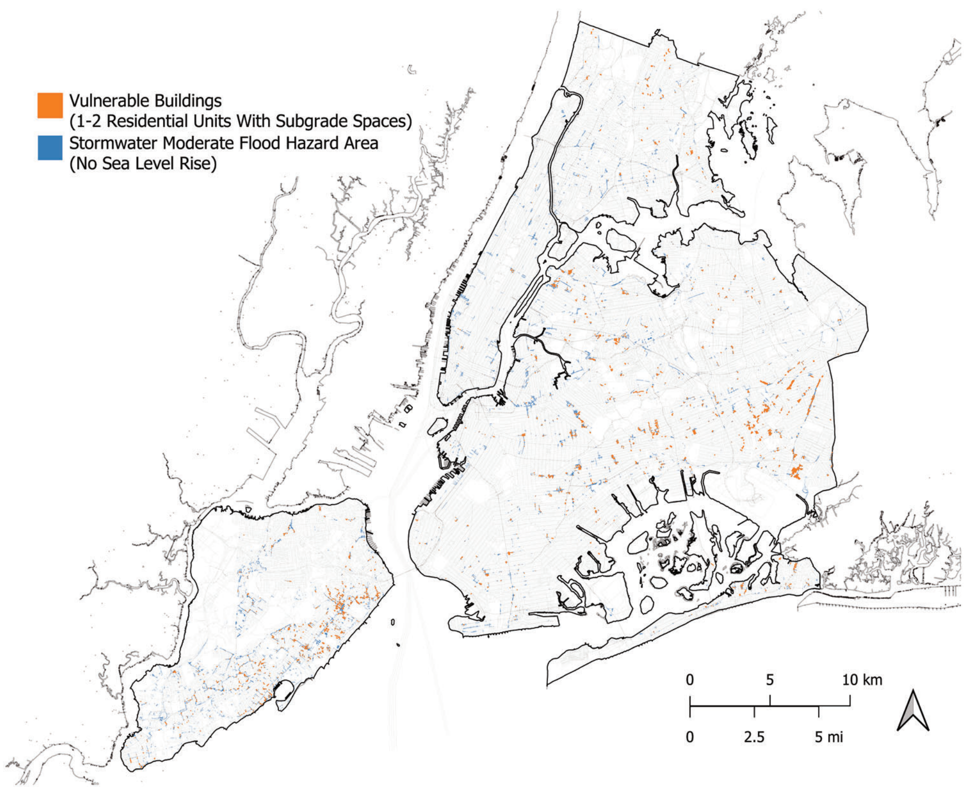

FIGURE 9 1-2 family family residential buildings with basements that would be exposed to pluvial flooding from a moderately intense (∼2 in. in 1 h) rain event. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

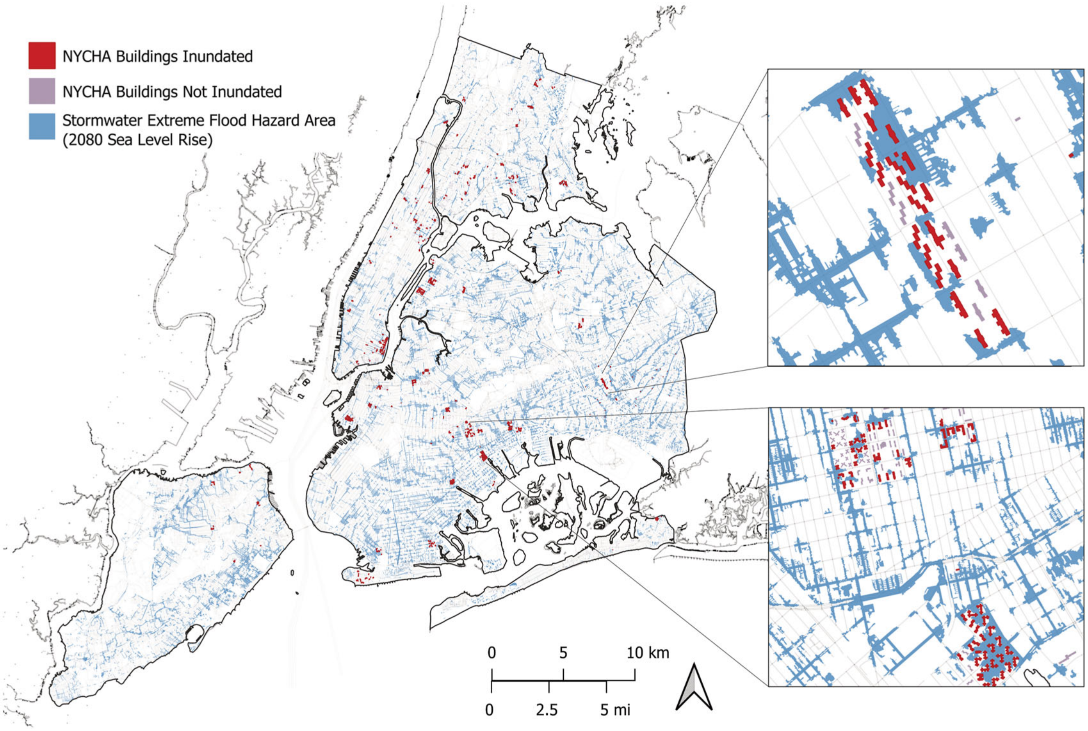

FIGURE 10 New York City Housing Authority (NYCHA) developments that would be exposed to pluvial flooding during an extreme rain event (~3.5 in. per hour) with 58 in. of sea level rise, as modeled for the Stormwater Resiliency Plan (City of New York Mayor's Office of Resiliency, 2021). The inundated NYCHA buildings represent less than 1% of the total buildings inundated under this scenario, but nearly a third (30.1%) of NYCHA affordable public housing buildings. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

by increased infiltration of groundwater into sewers,[117,148] leading to hydrologic overload (see above). Stormwater green infrastructure that utilizes infiltration may also be less effective as rising water tables reduce the volume of available unsaturated subsurface.[149]

Figure 10 presents the area that would be inundated greater than 4 in. under the Stormwater Resiliency Study Extreme Scenario. In this scenario, 206,859 of currently existing buildings would be exposed to pluvial flooding. For comparison, 88,700 buildings were in the area inundated by Post-Tropical Cyclone Sandy of 2012.[66] However, as discussed previously, it is important to note that the Stormwater Resiliency modeling assumes that rainfall is uniform across the entire city, meaning this figure represents the ceiling of exposed buildings for a rainfall of this magnitude. A total of 16% (i.e., 32,918) of the buildings exposed in such a scenario are single-story buildings, and nearly half (i.e., 45.6% or 93,528) of these exposed buildings have subgrade spaces. The overwhelming majority (i.e., 70,970) of the exposed buildings with subgrade spaces are 1–2 unit residential buildings (Figure 9). Of the exposed buildings, 0.43% (i.e., 897) are part of NYCHA developments, which are highlighted in Figure 10.

4.5 | Persistent knowledge gaps: Pluvial flooding

Along with remaining scientific uncertainty on future short-duration precipitation, there remain critical knowledge gaps that limit our understanding of how future precipitation intensification with climate change will impact flood risk:

- **Monitoring of the H&H response and impacts of cloudbursts**: There is currently very limited direct observational data on the H&H response to cloudbursts. Following the Ida Remnants Cloudburst, the US Geological Survey mapped inundation depths by surveying high-water marks in several severely impacted communities in NYC (Figure 7), but observational data on flooding in response to extreme rain remain very limited. The collection of direct, in situ monitoring of street flooding is being piloted through the NYC FloodNet project[150] (discussed in Section 10), but a sustained monitoring network of flooding depths, in-sewer water depths and flow rates, and in situ rainfall rates is needed to understand the H&H response to extreme rain in NYC. There may also be opportunities to develop methods to assimilate existing monitoring data that is collected for other purposes, such as traffic cameras.
- **Pluvial hazard mapping**: The pluvial flood hazard maps developed through the Stormwater Resiliency Study[17] provide novel and critical information to support flood risk assessment. However, currently available maps only represent a very small selection of potential precipitation scenarios, and these maps are only able to identify areas where inundation exceeds depth thresholds (4 in. or 1 ft) at some point during the flood event. Additional hazard maps that represent a broader range of plausible cloudburst scenarios and pro-

vide information on flood rise time, fast-flowing water, exposure to toxic chemicals and pathogens, and inundation duration are needed to support emergency response, flood management planning, and climate adaptation. The development of these additional hazard scenarios remains limited by the computational resources needed for this type of modeling and the limited availability of observational data on flooding in NYC, also described further in Section 10.

- **Pluvial flood vulnerability**: As described in Section 3.4.1, the true costs of pluvial flooding to NYC residents remain poorly characterized. Additional work is needed to improve understanding of who is impacted by pluvial floods, in which ways, and incurring what tangible and intangible costs.

5 | FLUVIAL FLOODING

5.1 | Fluvial flood hazard characterization

Fluvial flood risks (also referred to as riverine flood risks) are caused when the stage of a river, creek, or stream exceeds the elevation of its banks. NYC's inland areas were historically drained by a dense network of streams, nearly all of which were filled, with their flow redirected to subterranean stormwater sewers by the mid-20th century (Figure 1). Remaining freshwater stream channels include the Bronx River, Valley Stream (which flows along the eastern edge of the city and is the head of Jamaica Bay), and small inland creeks in Staten Island and eastern Queens. These streams provide critical freshwater habitat within the city but can cause flooding when their water levels rise above bank full stage (e.g., the water level in a creek or stream at which flooding of the banks begins to occur) during both cloudbursts and longer duration rain events. Fluvial flood risks within the city are mapped in the SFHA (100-year floodplain) maps provided by FEMA, along with coastal flood hazards.[56,57]

Fluvial flooding can be monitored directly using stream gauges, which provide in situ measurements of stream water levels. Bankfull water levels are associated with inundation of the adjacent floodplain and can cause minimal societal impacts (if the floodplain is undeveloped) to moderate/major impacts if buildings, infrastructure, or other assets are located there. NPCC3 presented an assessment of fluvial flooding in regional streams outside the border of NYC with long-term gauge record. Additional research is needed to characterize fluvial flood risks within the city, especially in areas of the Bronx, Queens, and Staten Island.

5.2 | Historical example: Ida Remnants Cloudburst fluvial flooding

At the time of writing, the only active stream gauge located within NYC is along the Bronx River at New York Botanical Garden, which provides observations from 2007 to present.[151] Over this period, 24 minor floods, 7 moderate flood events, and 7 major floods were observed through 2022 at this site (Table 5). In addition, a flood on July 19, 2022

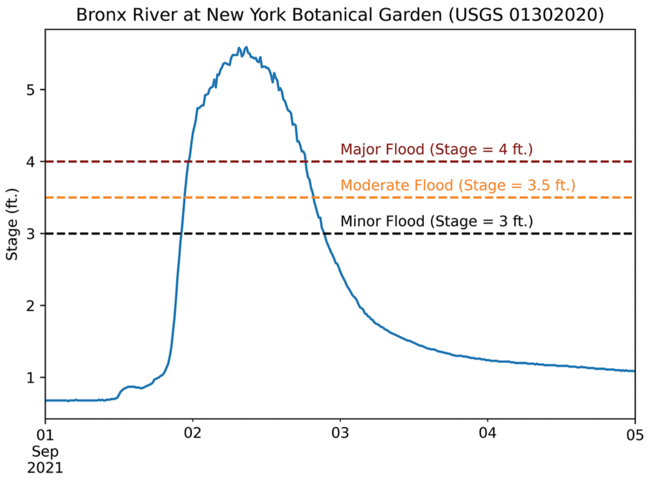

FIGURE 11 Stream stage in the Bronx River during the Ida Remnants Cloudburst. The river remained above major flood stage for over 18 h (from 11:30 p.m. EDT on September 1, 2021, to 6:15 p.m. EDT on September 1, 2021). *Source*: Bronx River at NY Botanical Garden Stream Gauge.[152] Figure by: BR Rosenzweig.

damaged the stream gauge such that the peak flood stage could not be recorded. Figure 11 illustrates the stream stage in the Bronx River during the Ida-Remnants Cloudburst. The river remained above major flood stage for over 18 h.

5.3 | Fluvial flooding exposure and vulnerability

5.3.1 | Buildings and critical infrastructure exposed to fluvial flooding

Exposure to fluvial flooding was evaluated utilizing areas delineated in the FEMA SFHA that are adjacent to remaining inland water bodies. The FEMA SFHA excludes areas that would be flooded with depths less than 1 ft (0.3 m), even though such shallow flooding could result in inundation of ground-floor and subgrade spaces. Based on this available hazard data, only 388 buildings are in areas that have a 1% AEP (100-year return interval) of flooding from inland streams and rivers (Figure 12). Of these buildings, 32.4% (126) are single-story buildings, and 28.6% (111) of the total exposed buildings have identified subgrade spaces, which is somewhat lower than the percentage of buildings with subgrade spaces across the city. A total of 25.5% of the exposed buildings are 1–2 unit residential units with subgrade spaces. No NYCHA buildings are located in this inland fluvial hazard area.

5.4 | Climate change and future fluvial flooding

As with pluvial flooding (Section 4.4), the projected amplification of precipitation with climate change will increase the frequency and magnitude of fluvial floods in the future. Fluvial flooding will also be exacerbated by sea level rise as NYC's rivers and streams are tidal

TABLE 5 Historic major flood events (stage above 4 ft) observed at the Bronx River Stream Gauge at New York (NY) Botanical Garden (2007–2023).

Rank	Dates	Peak stage	Description
1	4/16/2007	6.05 ft (03:00 EDT on April 16, 2007)	Heavy rains from a Nor'Easter (a storm total rainfall of 8.41 in. was observed at Central Park (Storm Events Database Episode 5088[153])
2	9/1–2/2021	5.59 ft (8:45 a.m. EDT on September 2, 2021)	Cloudburst associated with the remnants of Hurricane Ida (described in Section 4.2)
3	8/27–28/2011	5.18 ft (8:15 p.m. EDT on August 28, 2011)	Tropical Storm Irene (described in Section 8.2)
4	3/11/2011	4.34 ft (12:15 p.m. EDT on March 11, 2011)	Fronts associated with a slow-moving low-pressure system west of the city brought heavy rain[154])
5	4/16/2018	4.24 ft (5:00 p.m. EDT on April 16, 2018)	Heavy rainfall from a slow-moving warm front. Most rain occurred within a 3–4 h period (Storm Events Database Episode 125008[155])
6	9/25/2018	4.16 ft (9:30 p.m. EDT on September 25, 2018)	Heavy rainfall preceding a slow-moving warm front (Storm Events Database Episode 131100[156])
7	4/17/2011	4.06 ft (5:45 a.m. EDT on April 17, 2011)	A cold front associated with a low-pressure system brought heavy rain[154])

Source: US Geological Survey (USGS) Bronx River Stream Gauge.[152]

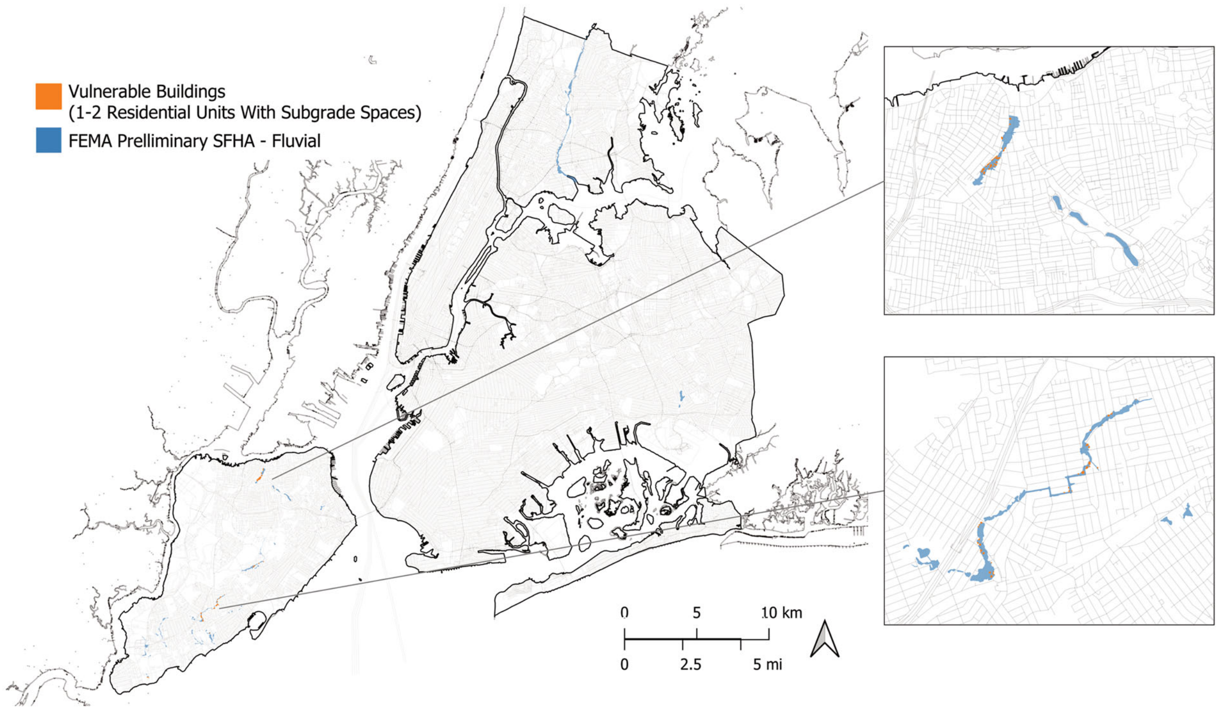

FIGURE 12 1-2 family residential buildings with basements in areas of the city that would be exposed to fluvial flooding during a storm with a 100-year return interval (1% annual probability). As a result of the historic filling of most of New York City (NYC)'s natural streams, exposure to fluvial flooding has largely been replaced by exposure to pluvial flooding and is now very limited compared to other types of flooding. However, areas adjacent to the Bronx River and small surface streams in Staten Island are exposed. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

and drain to the harbor. Rising seas will impede this drainage and may increase groundwater levels and, in turn, stream baseflow, resulting in an increased frequency of stages that exceed flood thresholds.[157,158] FEMA flood insurance studies do not consider changing precipitation patterns or groundwater levels with climate change and do not represent the increased fluvial flood hazard that will result from unmitigated climate change.

5.5 | Persistent knowledge gaps: Fluvial flooding

Understanding of NYC's fluvial flood risk and potential future changes is limited by the same gaps in short-duration precipitation data discussed for pluvial flooding (Section 4.5). In addition, most of the residences exposed to fluvial flooding are in the flood hazard area of streams in Staten Island that are currently ungauged. The reactivation or installation of stream gauges along these high-exposure streams would support enhanced characterization of fluvial flood risk and the development of optimized strategies for fluvial flood resilience. As discussed in Section 4, an estimate of the annual cost of damages due to fluvial flooding on NYC residents is currently not available. However, as the chances of residents of floodplains having FEMA flood insurance are higher, estimates based on FEMA claims may be better estimates than for other flood hazard types.

6 | COASTAL FLOODING

6.1 | Coastal flood hazard characterization

With 520 mi of shoreline,[159] NYC is exposed to severe coastal flooding resulting from high tides and storm surge, as demonstrated during Post-Tropical Cyclone Sandy in 2012. Severe coastal floods are caused by two types of storms, predominantly TCs in warm seasons (June through October) and extratropical cyclones in cooler seasons (November through May).[160,161] Major factors influencing the occurrence of severe coastal floods include the timing of the wind- and pressure-driven storm surge relative to high tide,[162] and amplification of storm surges due to winds that blow into the concave coastline of the New York Bight.[163] Chronic high-tide flooding is also a problem for some NYC neighborhoods, due to sea level rise, dredging, and landfilling of wetlands.[164] Present-day coastal flooding for monthly high tides was mapped for NYC by NPCC3 and includes some localized areas around Jamaica Bay.[11] Coastal extreme floods are mapped in the SFHA maps provided by FEMA, which represent coastal or fluvial flood hazards only.[56,57]

6.2 | Historical example: Coastal flooding on December 23, 2022

Extreme historical events such as Post-Tropical Cyclone Sandy and the 1821 Category 3 hurricane that struck NYC, with storm tides of 11.1 and 9.8 ft (relative to the year's mean sea level) at the Battery, respectively, have been a focus of widespread research in recent years.[161,165,166] However, NWS designated "major floods" (Table 5) from less extreme storms have a factor of 10–20 higher annual probability of occurrence than these two historical extreme events today and even higher in future decades (see water-level recurrence interval curves in Orton et al.).[161] The recent coastal flood highlighted here is included to raise awareness of these far more common but nevertheless dangerous and damaging events.

In December 2022, a powerful, inland extratropical cyclone located over the Great Lakes Region caused winter storm impacts across the Midwest and northeastern United States. Although the storm was located hundreds of miles west of NYC, it generated powerful southeasterly winds that generated a storm surge along the coast. Early on the morning of December 23, a moderate 3-ft storm surge peaked simultaneously with one of the year's highest tides to cause substantial flooding around NYC. Water levels across most of the city exceeded the moderate flood threshold of the NWS (see Figure 13), with those at the Battery peaking at 5.9 ft NAVD88, which is an approximately 3-year recurrence interval event. Water levels in Jamaica Bay (Figure 14), however, exceeded NWS major flood thresholds there and peaked at 6.7 ft above NAVD88 (Inwood, USGS gauge; Figure 13)[167] which is an 8-year recurrence interval water level[3] and the second highest in the bay's 20-year data record, behind (but ~3.9 ft below) Post-Tropical Cyclone Sandy. The likely cause of Jamaica Bay's high peak water levels relative to those elsewhere around NYC was local tide amplification which has raised perigean-spring ("king") high tides by about 0.7 ft, due to a combination of historical dredging and urban development of wetlands surrounding the bay.[164] Flood depths in some areas surrounding Jamaica Bay were observed by FloodNet sensors to be about 3 ft, whereas only shallow nuisance flooding was observed in the harbor areas (typically well below 1 ft). The relative sea level rise around NYC of ~1.3 ft since 1900 was also clearly a contributor to these water elevations and flood depths.

6.3 | Coastal flooding exposure and vulnerability

Based on FEMA's last completed Flood Insurance Study (FIS)[57] 67,255 buildings are located in coastal areas that have a 100-year return interval (1% AEP) of flooding in the contemporary climate. About 30% (i.e., 20,197) of these buildings are single-story buildings and 33.1% (i.e., 22,242) of the total exposed buildings have identified subgrade spaces. Of the exposed buildings, 27.0% (i.e., 18,176) are 1–2 unit residential units with subgrade spaces. Figures 15 and 16 illustrate the extent of this exposure to NYC's vulnerable populations by highlighting the NYCHA developments and 1–2 residential unit buildings with subgrade spaces in coastal areas threatened by inundation during a 100-year storm-surge event. Along with storm surge, coastal high-tide (e.g., "sunny day") flooding will increase with sea level rise. Figure 17 highlights vulnerable 1–2 unit residential buildings that are exposed to present-day flooding when tide levels reach the MMHW level. No NYCHA buildings are in this current hazard area. For comparison, Figures 18 and 19 present NYCHA buildings and 1–2 unit residential buildings with basements that will be exposed to approximately monthly (MMHW) tidal flooding with 58 in. (1.47 m) of sea level rise (NPCC 2080 Scenario) in the absence of adaptive FRM efforts.

6.4 | Climate change and future coastal flooding

It is well-established that SLR will continue to increase the frequency and magnitude of NYC coastal floods,[11] but the potential role of changing storms is an area of high uncertainty and active research.[6] Present-day and future coastal flood risks with sea level rise have been extensively described in previous NPCC reports. Patrick et al.[9] and Orton et al.[11] applied static and dynamic flood modeling to map coastal flood hazards, respectively. Orton et al.[11] also updated the projections of future coastal flood risk considering monthly high tides

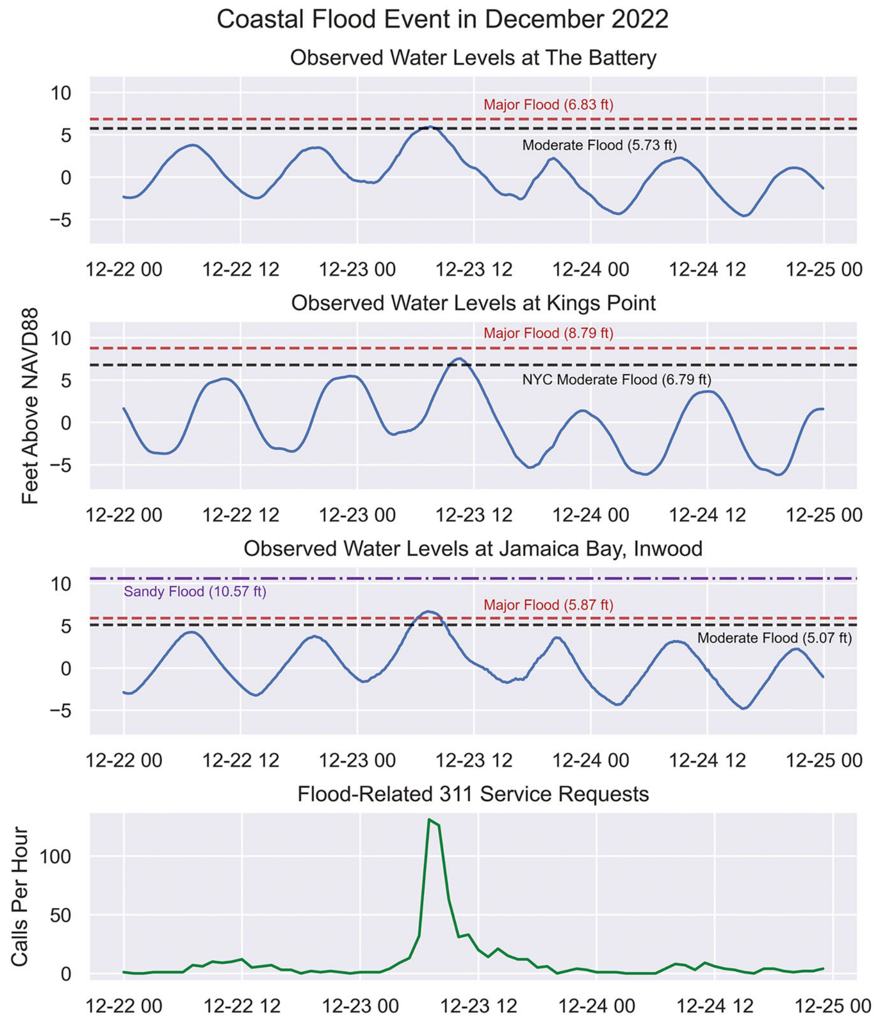

FIGURE 13 Observed water levels and 311 service requests related to flooding (bottom panel) around New York City (NYC) from December 22 to 24, 2022. Tide gauge locations are provided in Figure 14. National Weather Service flood thresholds and Post-Tropical Cyclone Sandy are shown as horizontal lines for comparison. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

and extreme storm surges across a broadened set of sea level rise projections. Although there is consensus that atmospheric warming will likely intensify TCs in the future, cyclogenesis, storm frequency, and storm tracks are also likely to shift. As a result, there is considerable uncertainty and spatial variability in projections of future changes to storm surge and it remains an active research area that has not yet been incorporated into NPCC flood maps.

6.5 | Persistent knowledge gaps

There continues to be a need for deeper research into coastal storms, storm surges, and climate change impacts in the NYC region. There remain persistent cross-study differences in estimates of present-day storm tide hazards,[161,168,169] as well as future changes to hurricane-driven storm surge. Hybrid storms like Post-Tropical Cyclone Sandy are poorly understood, as are the influences of climate change on such storms. These have all previously been noted as key uncertainties.[11]

Secondary or periodic maxima in nontidal anomalies after a storm surge event have been referred to under the general term of "resurgences" or "edge waves"[170] but are relatively poorly understood. What is known is that these resurgences cause extremely rapid drawdowns of water levels on the tail end of a storm surge event, then a resurgence of as much as 3.5 ft in water levels that can cause flooding about 7–8 h later if it coincides with high tide.[170,171] A broader concern is that a storm could cause an initial surge followed by a surprising resurgence into highly populated neighborhoods. Research is needed to assess the associated risk from such events, including flood modeling of extreme historical and potential future cases of resurgence.

Post-Tropical Cyclone Sandy's flooding predominantly affected New York Harbor (southern and western areas of NYC), and the coincidence of peak storm surge with low tide spared areas of South Bronx and Northern Queens from more severe flooding.[172] Extreme storm surges and flooding can affect these areas of NYC when hurricanes cross Long Island, causing extreme east winds and storm surges funneling down Long Island Sound and into the East River, the relatively narrow but potentially important connection between Long Island Sound and New York Harbor. For example, the 1938 "Long Island Express" Hurricane set the historical record for water level in the upper East River (at Willets and Kings Points). Hurricane and extratropical cyclone coastal flood prediction models run by NOAA[173] have poor resolution in the East River. The hydrodynamic model applied in the last FEMA study and now again in a current study showed its worst performance and widespread low-biased water levels for this storm event in the East

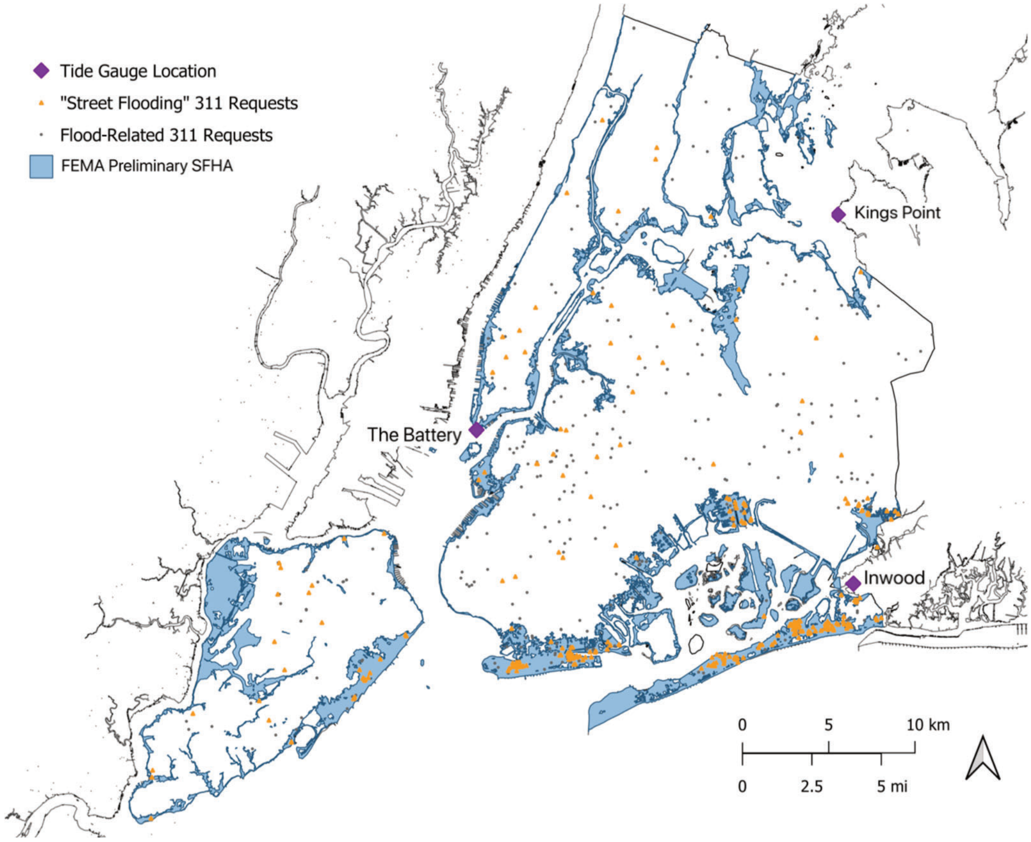

FIGURE 14 Street flooding and flood-related 311 service requests in New York City (NYC) on December 23, 2022. Along with "street flooding," flood-related service requests include "sewer backup," "highway flooding," "manhole overflow," "possible water main break," "catch basin clogged/flooding," and "excessive water in basement." During this event, street flooding requests are concentrated in coastal areas, particularly along Jamaica Bay. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

River.[57] Potential deficiencies in modeling the East River may be undermining our understanding of coastal flood risk, as well as forecasting and emergency management, and should be further investigated.

In the post-Sandy period, many adaptation policies and strategies have been put into operation. Studies to evaluate these strategies are ongoing, and the city has incorporated lessons learned from their experiences with Post-Tropical Cyclone Sandy in guidance for future coastal FRM projects.[174] But more research is needed to fully document lessons learned 10 years after Sandy, listing benefits and limits of coastal flood adaptation strategies that were adopted in response to that event.

7 | GROUNDWATER FLOODING

7.1 | Groundwater flood hazard characterization

Groundwater flooding occurs when the elevation of the water table—a surface that can be used to represent the level at which the subsurface is saturated with water—is higher than that of the land surface or subterranean infrastructure, resulting in the inflow and/or infiltration of groundwater into these spaces.[157,175] Groundwater flooding can occur in the absence of human activities, during very wet seasons or years when recharge rates greatly exceed evapotranspiration, resulting in a rise in the water table that inundates areas that are typically dry. Groundwater flooding has also become a globally significant issue for cities that transition from the use of groundwater supply to other sources.[176,177] As the water table rebounds from the lowered level induced by historical groundwater pumping, land areas that had previously been dry could more frequently become wet or waterlogged.

The elevation of the water table is determined by the interaction of weather and climate, water extraction and management activities, local topography, and subsurface hydrogeology. The subsurface structure of NYC is complex and varies across the city.[178] NYC is underlain by inclined crystalline basement rock that dips from northwest to southeast. Following this incline, the bedrock outcrops in parts of the Bronx and northern Manhattan, with generally thin overlying unconsolidated deposits in much of the Bronx, Manhattan, Staten Island, and northwest Queens. Much of the remainder of Queens and Brooklyn are underlain by sand and gravel glacial deposits that increase in thickness with the sloped bedrock from nearly zero in northwest Queens to over 1100 ft at the southeast edge of the city.[179] These aquifers were historically pumped extensively for municipal supply, with pumping in the easternmost parts of the city continuing through the 1990s.[180] This pumping, over a period of many decades, contributed to a decrease in

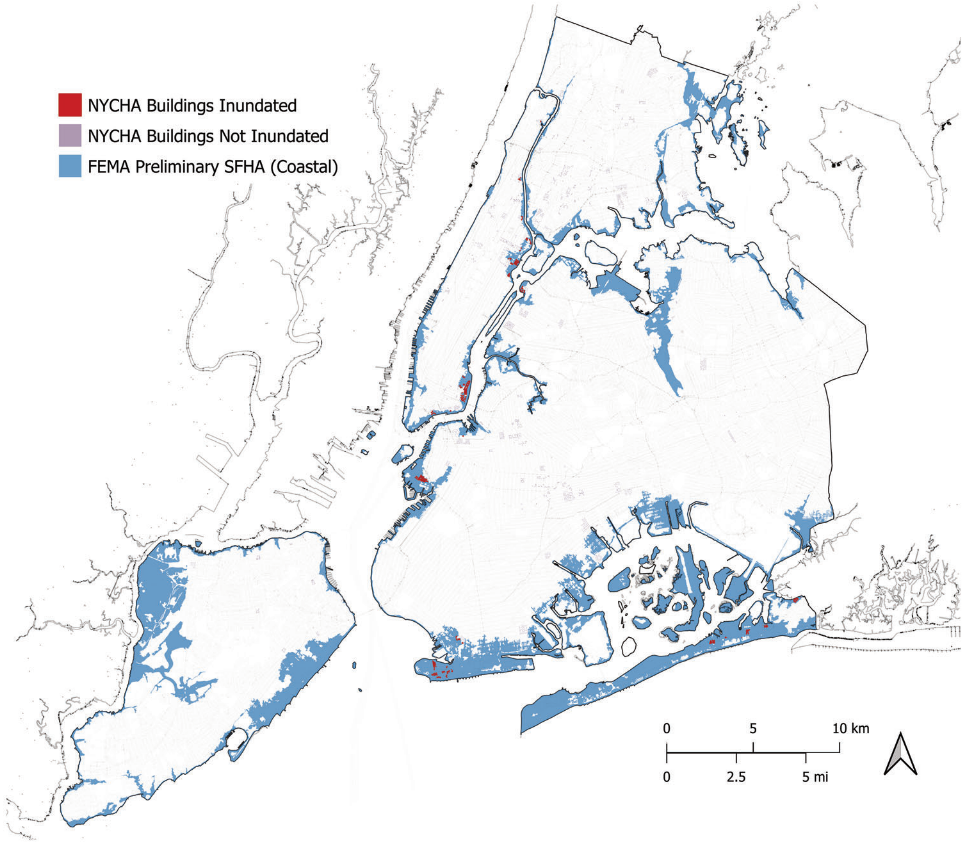

FIGURE 15 New York City Housing Authority (NYCHA) buildings in coastal areas exposed to 100-year (1% annual probability) storm surge flooding. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

groundwater flow to streams and drying out of coastal and remaining inland wetlands in the urban area.

In addition, many of the city's tidal creeks and coastal wetlands were extensively landfilled from the 18th through the 20th centuries.[4,179] Today, many of the city's coastal communities are underlain by urban fill materials, which are highly variable in thickness and composition across the city.[5,181] In many of these areas, the hydrographic legacy of the historic stream corridors remains, and these areas are underlain by very shallow groundwater. The hydraulic properties of historic landfill materials also remain poorly characterized, with implications for the ability to predict groundwater levels and flow using numerical groundwater models.

Areas underlain by shallow water tables (the surface representing the approximate depth to saturation with groundwater) may experience groundwater flooding during atypically wet seasons when the water table rises above the elevation of subterranean infrastructure or the land surface. Extensive areas of Brooklyn and Queens have an estimated depth of groundwater of less than 10 ft (see Ref. 60). Groundwater levels in other parts of NYC are very poorly characterized due to the more complex fractured bedrock geology and the lack of historic groundwater utilization and monitoring in these parts of the city.

Groundwater flooding is an issue of particular concern in areas of the city that were developed during times when groundwater levels were artificially lowered through municipal groundwater pumping. This includes several neighborhoods in eastern Brooklyn and southern Queens that were developed in the mid- to late 20th centuries, when the surficial, Upper Glacial Aquifer was extensively pumped by the Flatbush, Woodhaven, and Jamaica Franchise Areas of the New York Municipal Water Supply Company.[180] Many buildings and other infrastructure in these areas were constructed by builders who were unaware that the water table was depressed by intensive pumping or who assumed that pumping would continue indefinitely. When municipal pumping was discontinued due to saltwater intrusion and other water quality concerns, the water table rebounded, rising above the level of subterranean infrastructure such as basements and subway tunnels that had been constructed when groundwater levels were depressed through pumping.[182] Many of these communities now require continuous groundwater pumping of basements and tunnels to prevent inundation and may face enhanced risk of groundwater flooding during wet seasons.

7.2 | Historical example: Groundwater flooding in Lindenwood

Located at the border of Brooklyn and Queens, the Lindenwood section of East New York is one of several communities across the city that is particularly exposed to groundwater flooding due to its development, topography, and location near the coast of Jamaica Bay (Figure 20). Like many Jamaica Bay coastal communities, the depth

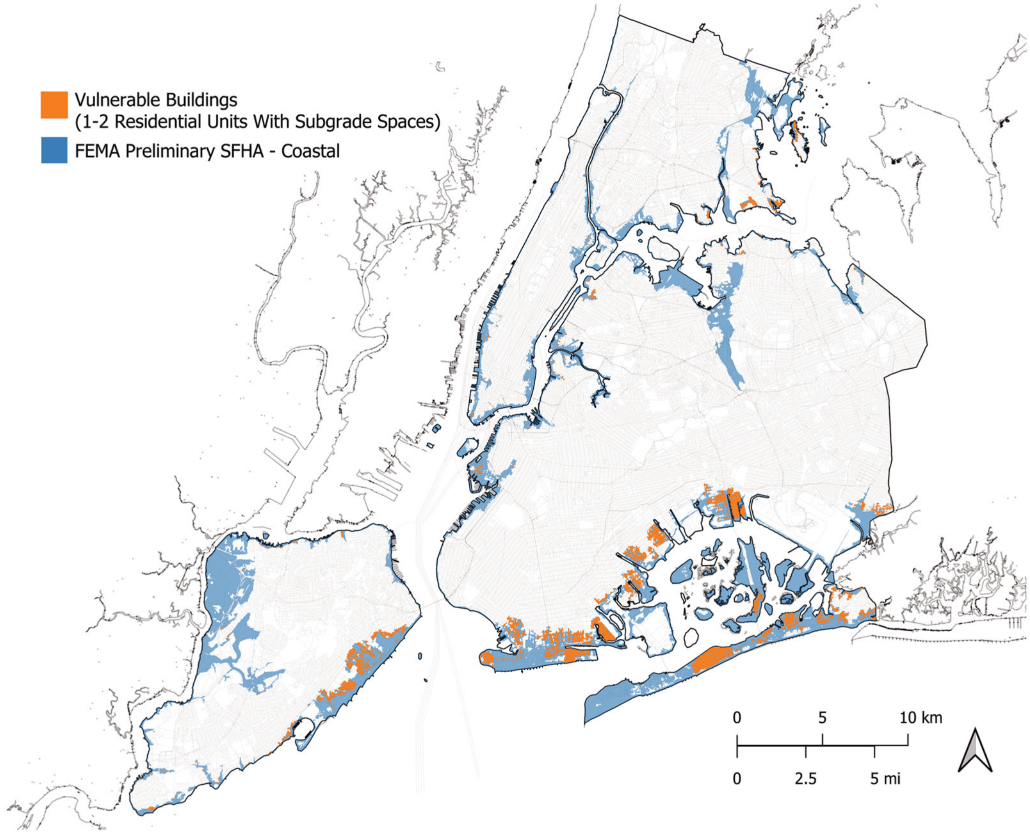

FIGURE 16 1-2 family residential unit buildings with basements located in the Preliminary Federal Emergency Management Agency (FEMA) Special Flood Hazard Area adjacent to the coast. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

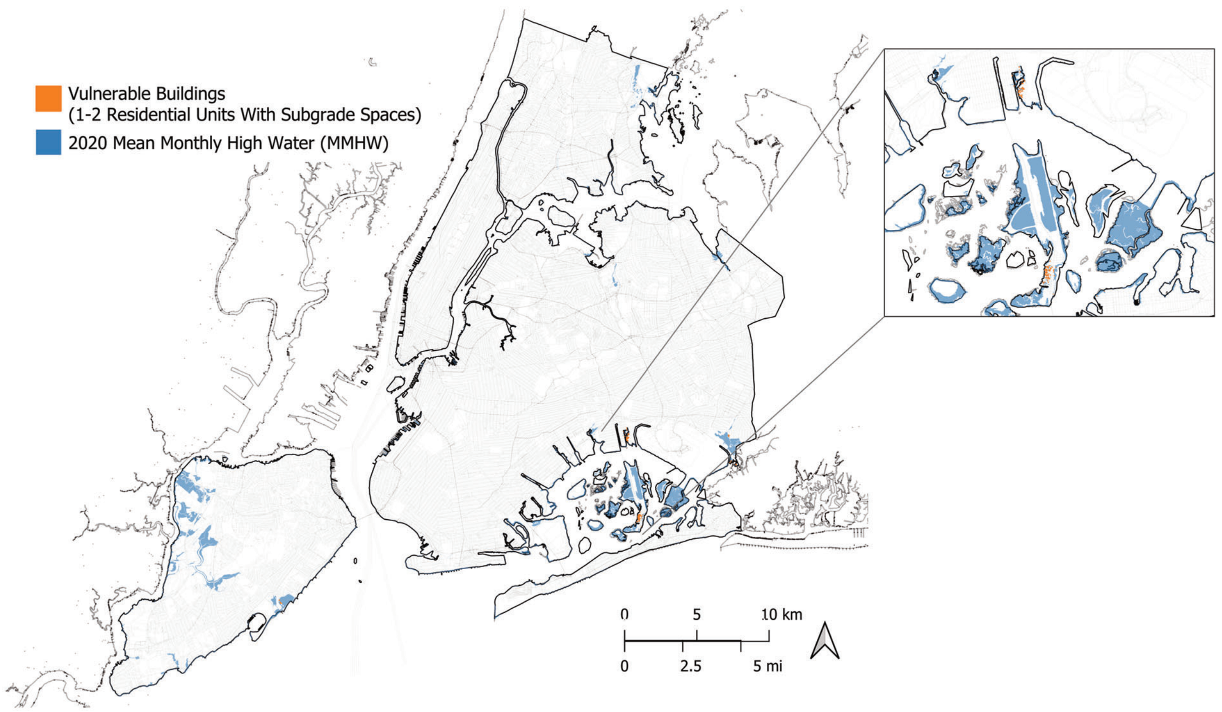

FIGURE 17 1–2 residential unit buildings with subgrade spaces in coastal areas exposed to present-day flooding from tide levels at the Mean Monthly High Water (MMHW). Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

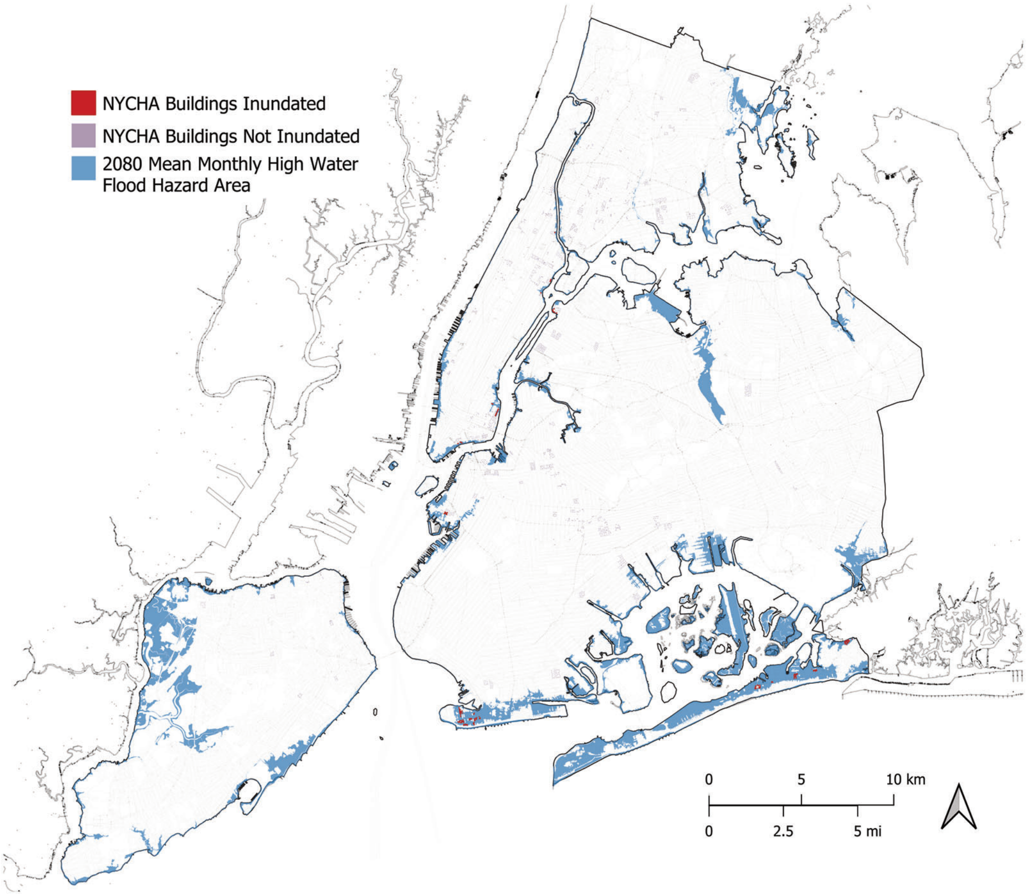

FIGURE 18 New York City Housing Authority (NYCHA) buildings in coastal areas that are projected to be exposed to flooding from the Mean Monthly High Water (MMHW) with 58 in. (1.47 m) of sea level rise (NPCC3 2080 Scenario). Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

to the water table underlying much of the Lindenwood area was estimated to be less than 10 ft in 2013.[60] Some areas of this community are located on landfilled historic riparian wetlands of Spring Creek and are particularly low in elevation.

Groundwater flooding has been a documented issue in East New York—Lindenwood since the 1970s, following the cessation of municipal pumping in the adjacent Woodhaven Franchise Area.[182] This includes basement flooding and damage to building foundations due to the elevated water tables. In addition, a 311 service request for street flooding in this area was attributed to a groundwater flooding condition.[183]

7.3 | Groundwater flooding exposure and vulnerability

7.3.1 | Buildings and critical infrastructure exposed to groundwater flooding

No groundwater flood hazard maps are currently available for the city. As an alternative, for this assessment, we use areas where the depth to the water table has been mapped as shallow as a proxy for areas that may be exposed to groundwater flooding in the future. The USGS conducts an annual synoptic survey of groundwater levels observed in monitoring wells on Long Island each April and May. These surveyed data of the water table elevation are used to develop a map of "depth-to-water"—the distance from the land surface to the water table. When observational data were available, this survey included groundwater levels in the NYC boroughs of Brooklyn and Queens, which are located on Long Island. At present, April–May 2013 is the most recent period for which groundwater monitoring data are available for these two boroughs, although the USGS and NYCDEP are planning to reestablish groundwater monitoring in these two boroughs and across the city for future assessment of groundwater hazard.

The 2013 depth-to-water layer was used to identify areas of Brooklyn and Queens where the depth to the water table was less than 10 ft. (3m) below the land surface—this threshold was determined based on the accuracy of the depth-to-water layer.[184] In these two boroughs, 83,800 buildings are located in areas where the depth to the water table is less than 10 ft. Of these buildings, 33,996 (i.e., 40.6%) have subgrade spaces and of the exposed buildings, 28,411 (i.e., 33.9%) are 1–2 residential unit buildings.

Figures 21 and 22 illustrate the extent of shallow groundwater in NYC's boroughs of Brooklyn and Queens, and locations of vulnerable buildings (e.g., NYCHA developments and 1–2 story residential buildings with subgrade spaces).

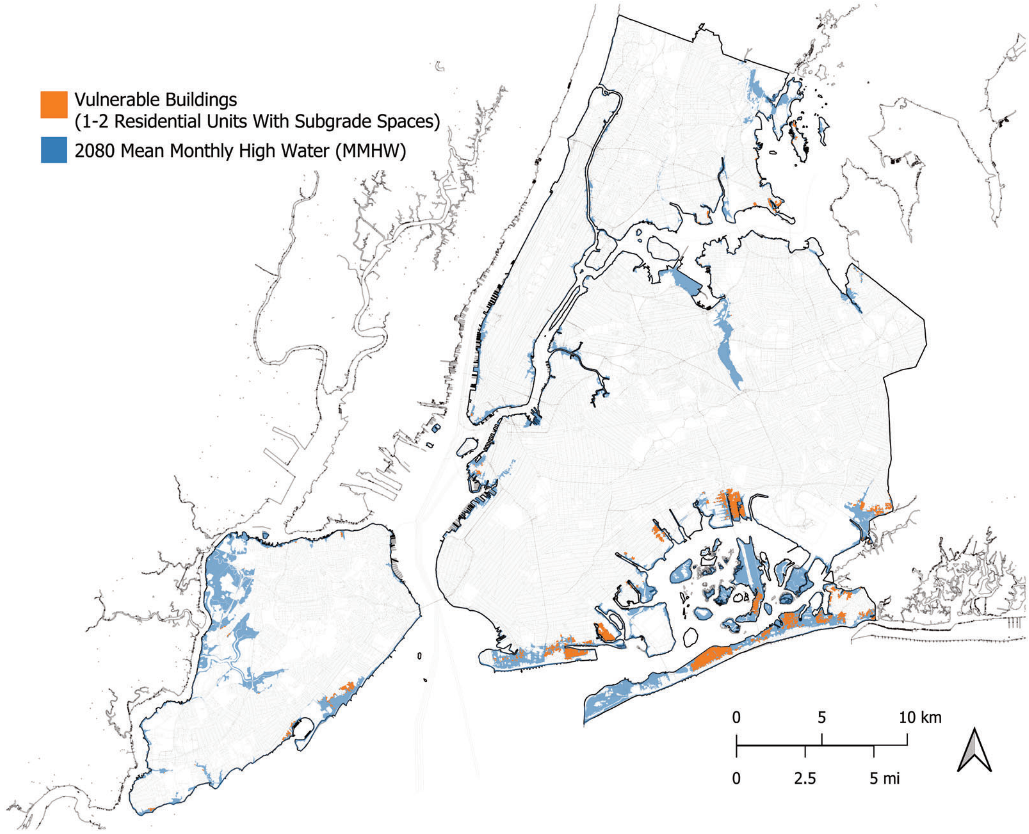

FIGURE 19 1-2 family residential unit buildings with subgrade spaces in coastal areas that are projected to be exposed to flooding from the Mean Monthly High Water (MMHW) with 58 in. (1.47 m) of sea level rise (NPCC3 2080 Scenario). Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

7.4 | Climate change and future groundwater flooding

Climate change can potentially exacerbate existing groundwater flood hazards through two mechanisms. First, the projected increases in annual precipitation with climate change[6] may result in a net increase in recharge to the city's surficial aquifers, elevating the water table. However, when the water table is near the land surface, the impact of increased precipitation may be partially mitigated by concomitant increases in evapotranspiration with warmer temperatures.[185] Predicting climate change impacts on groundwater recharge will be particularly challenging in NYC, where leakage to and from sewers significantly contributes to the subsurface water balance.[180,186]

The second mechanism results from the impacts of sea level rise on groundwater elevation and flow (Figure 23). At the coast, seawater and groundwater function as a system, coupled through the flow of fresh groundwater toward the sea and the intrusion of dense, saline seawater into coastal aquifers. Close to the shore and assuming uniform soil properties, the water table will stabilize to an elevation that is just above the increased local mean sea level at steady-state,[187,188] resulting in emergence at the surface and inundation of areas with shallower water tables—even if they were otherwise protected from direct coastal inundation by floodwalls or dunes at the shore.[157,189] In relatively flat, humid areas such as NYC, this water table rise will be limited by surface drainage once the water table emerges at the lowest elevation areas, a process described as "topography-limitation."[190] For example, in a numerical modeling study, Befus et al.[191] found that surface drainage at topographic low areas significantly limited the areal extent of water table rise in response to rising sea levels across the state of California. However, in NYC, this topography-limitation effect could actually lead to concentrated groundwater flooding in populated, low-elevation areas of the city where groundwater drains at the surface—even if changes in the depth-to-water in other parts of the city are stabilized through this process. Communities developed in the legacy valleys of filled streams would be particularly exposed to risk through this mechanism. In addition, once the water table rise is stabilized by groundwater emergence at the surface, the groundwater freshwater-saline interface will begin advancing inland,[187,192] a process known as saltwater intrusion that would exacerbate corrosion damage of subterranean infrastructure located below the water table and harm to inland NNBS that are not adapted for saltwater as described previously.[42] Courtney et al.[111] found evidence that tidal fluctuations are propagating further into a Hudson River tidal wetland today more so than they were 20 years ago.

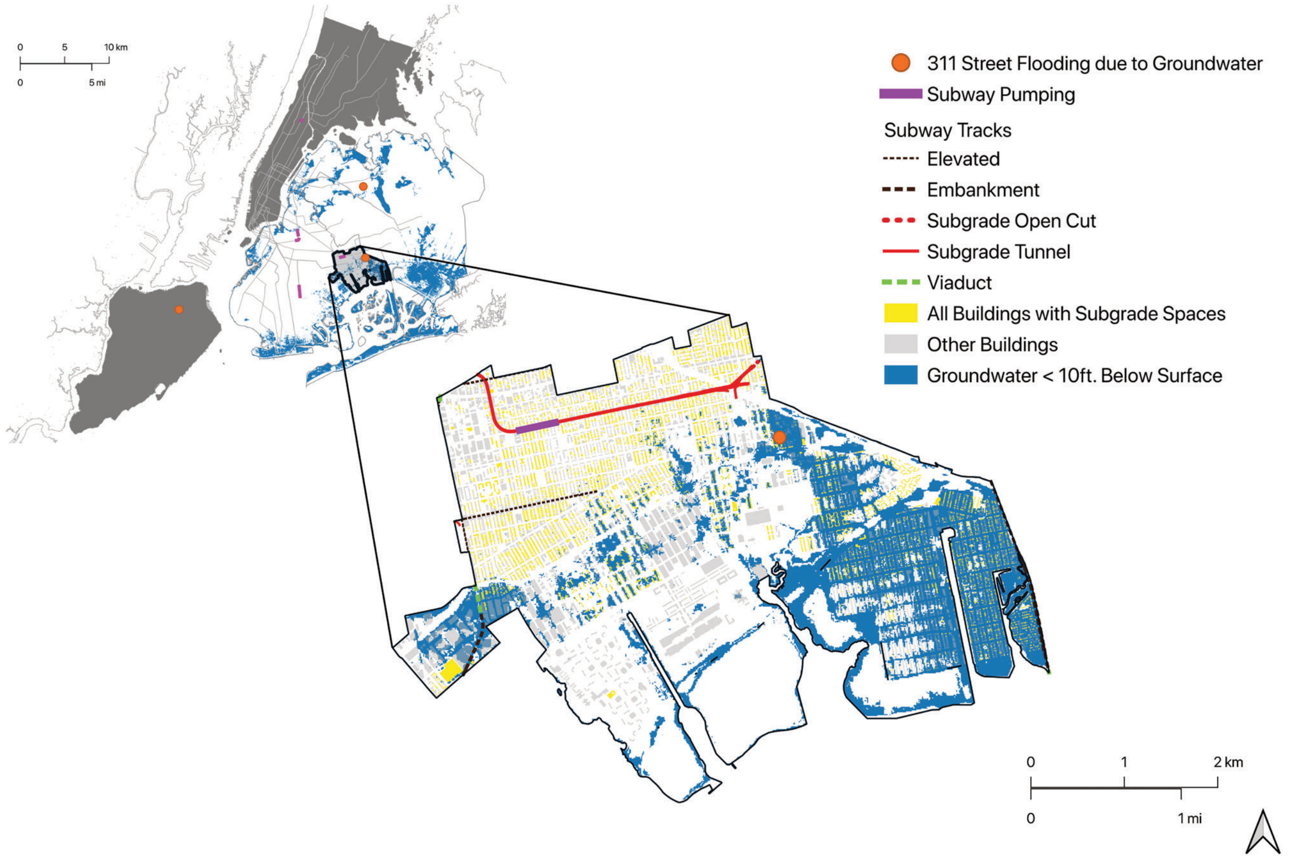

FIGURE 20 Shallow groundwater and subgrade infrastructure in East New York–Lindenwood. Subgrade subway tracks in this area already require pumping due to shallow groundwater. In 2010, the New York City Department of Environmental Protection reported groundwater flooding in response to a street flooding service request in this area. Figure by: BR Rosenzweig.

7.5 | Persistent knowledge gaps: Groundwater flooding

The idealized case of a uniform groundwater aquifer at steady state described above provides a useful first assessment of the potential magnitude of water table rise due to sea level rise, and this proxy has been utilized in previous studies of climate change and urban groundwater flooding.[189,193] However, actual groundwater conditions and the response to sea level rise in NYC will be jointly determined by local aquifer and infrastructure conditions.[194,195] As such, care should be taken in drawing conclusions from studies completed for different locales and spatial scales. In NYC, groundwater conditions are not idealized in that water table elevations will be influenced by sewers[148,196,197] and site-scale groundwater pumping for dewatering, which may mitigate the amount of water table change due to sea level rise but exacerbate saltwater intrusion. Furthermore, changes to historic shorelines and low-lying areas that were filled as the NYC area was developed will also influence groundwater response to sea level rise and groundwater recharge.[198] Nonetheless, these initial, available studies are useful in identifying *potential* risks and considerations for evaluating NYC's groundwater flooding hazards.

In addition, the steady-state assumption does not allow for the assessment of the timing of the groundwater response to sea level rise. Numerical models that can simulate the transient water table response in heterogenous aquifer systems can provide enhanced understanding of groundwater flood hazard under different scenarios of sea level rise,[199] but the predictive skill of these models is highly dependent on the availability of data on spatially distributed aquifer properties, the location and depth of sewers and subterranean groundwater drainage systems, and on observations of groundwater levels for model calibration and validation.[200]

Understanding sea level rise impacts on the shallow groundwater system in NYC in light of anthropogenic influences (e.g., urban drainage systems) is the subject of an upcoming USGS study (*Personal Communication, March 8, 2024*). The USGS has signed an agreement with NYCDEP to reestablish, operate, and maintain a hydrologic-monitoring network program in NYC designed to focus on groundwater-flooding assessment, resiliency efforts, and hazards mitigation.

As the groundwater monitoring wells are reactivated, the USGS-NYCDEP study will focus on the following elements:

- Conducting applied research to aid in the efficient and economical implementation of groundwater flooding abatement systems.

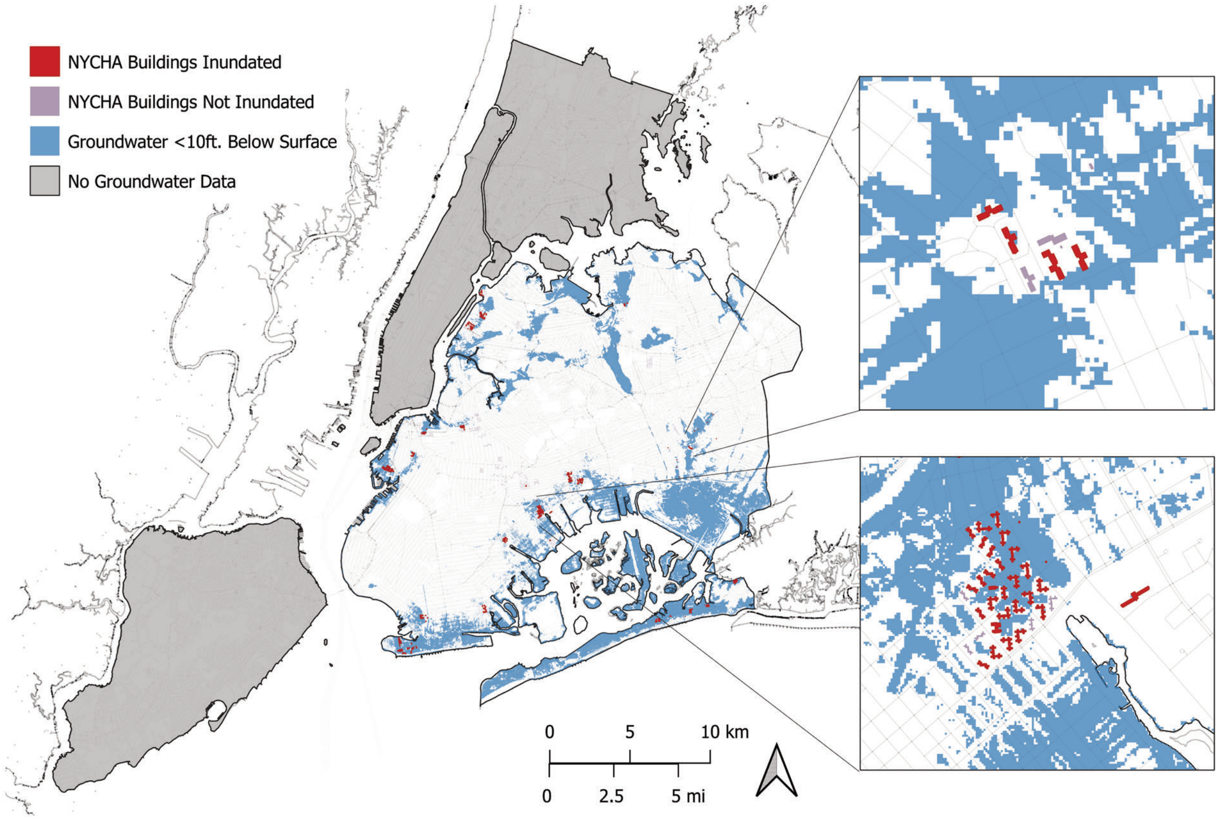

FIGURE 21 New York City Housing Authority (NYCHA) buildings located in areas underlain by shallow (< 10 ft) groundwater. Depth-to-water data are currently only available for the NYC boroughs of Brooklyn and Queens. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

- Developing a groundwater map for Staten Island to inform current and future design of vegetated Bluebelt stormwater management corridors.
- Investigating and modeling the effects of sea level rise and saltwater intrusion upon the groundwater system and Bluebelts in Queens and Staten Island.
- Investigating and modeling potential ground subsidence resulting from a lowered groundwater table due to future dewatering.

Additional research is needed to improve understanding of how sea level rise could increase groundwater flood hazards and associated impacts on the city's infrastructure systems on a site-by-site basis. A higher water table could increase the need for pumping to mitigate the inundation of subways, tunnels, utility vaults, and other subterranean infrastructure by infiltrating groundwater. Increased pumping will require increased electricity demands. In addition, if the pumped water is discharged directly into nearby waterways, this could also result in increased loading of nutrients or other groundwater contaminants to these water bodies. For example, Benotti et al.[201] estimated that contemporary subway dewatering measurably contributes to nitrogen loading in NYC's Jamaica Bay.

Rising water tables could also reduce the conveyance capacity of sanitary and stormwater drainage systems and limit exfiltration of stormwater from the base of green stormwater infrastructure facilities,[148,149] potentially exacerbating pluvial flooding (Section 4.1). At higher elevations, groundwater can also infiltrate into septic systems[157] and reduce the service life of pavements.[202,203] Limited information is available regarding the impact of rising groundwater levels on shoreline flood protection infrastructure such as sea walls and levees, and specifically the potential for groundwater flooding inland of these systems that could reduce their overall effectiveness.[157,189,204]

8 | COMPOUND FLOODING

8.1 | Compound flooding hazard characterization

The impacts of NYC's four flood hazards (coastal, fluvial, pluvial, and groundwater) can be compounded when they occur in combination. For example, a TC that brings both heavy rain and storm surge could result in coastal, fluvial, and pluvial flooding. An intense rainstorm that occurs in the spring or during a very wet season when groundwater tables are elevated could result in both groundwater and pluvial flooding.[205] Future climate change and sea level rise could aggravate the effects of compound floods by increasing their frequency[206] or altering the co-occurrence of flood drivers.[207] An initial analysis of historical observations found that the likelihood of joint occurrence of extreme rainfall and storm surge within a given storm system (defined as a 3-day window) has increased over the past century, possibly due to climate change.[208]

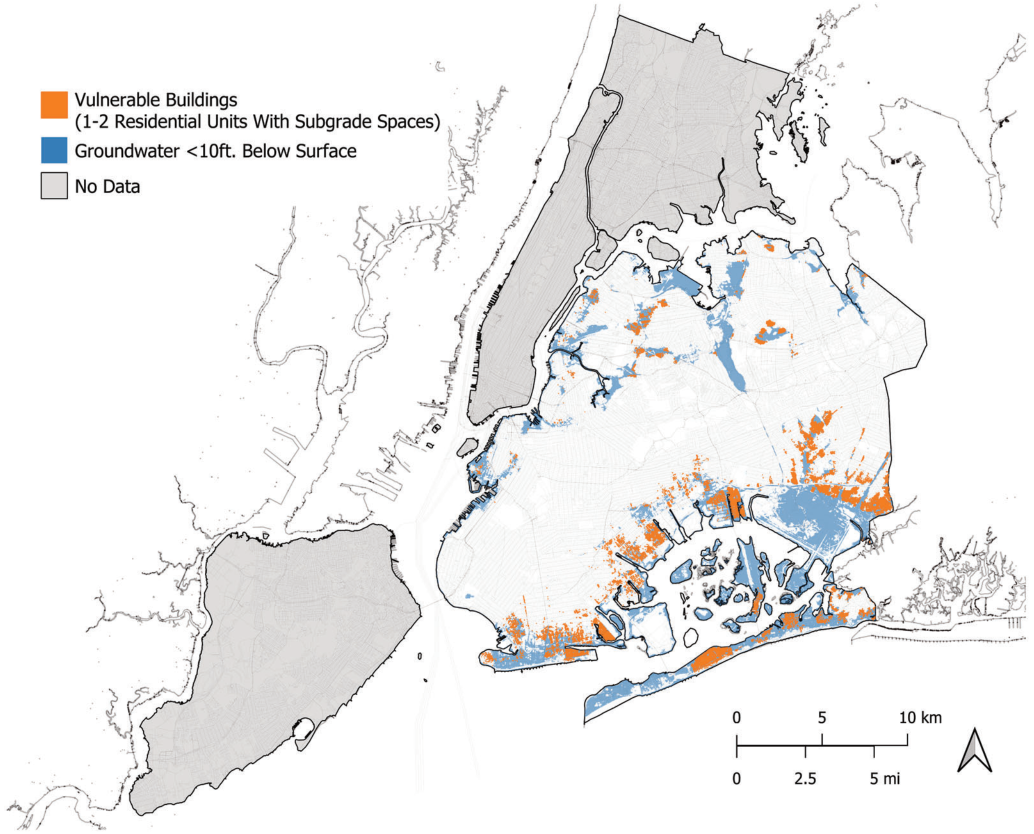

FIGURE 22 1-2 family residential unit buildings with subgrade spaces located in areas underlain by shallow (<10 ft) groundwater. Figure by: NPCC4 Fellow Fiona Dubay, Sarah Lawrence College.

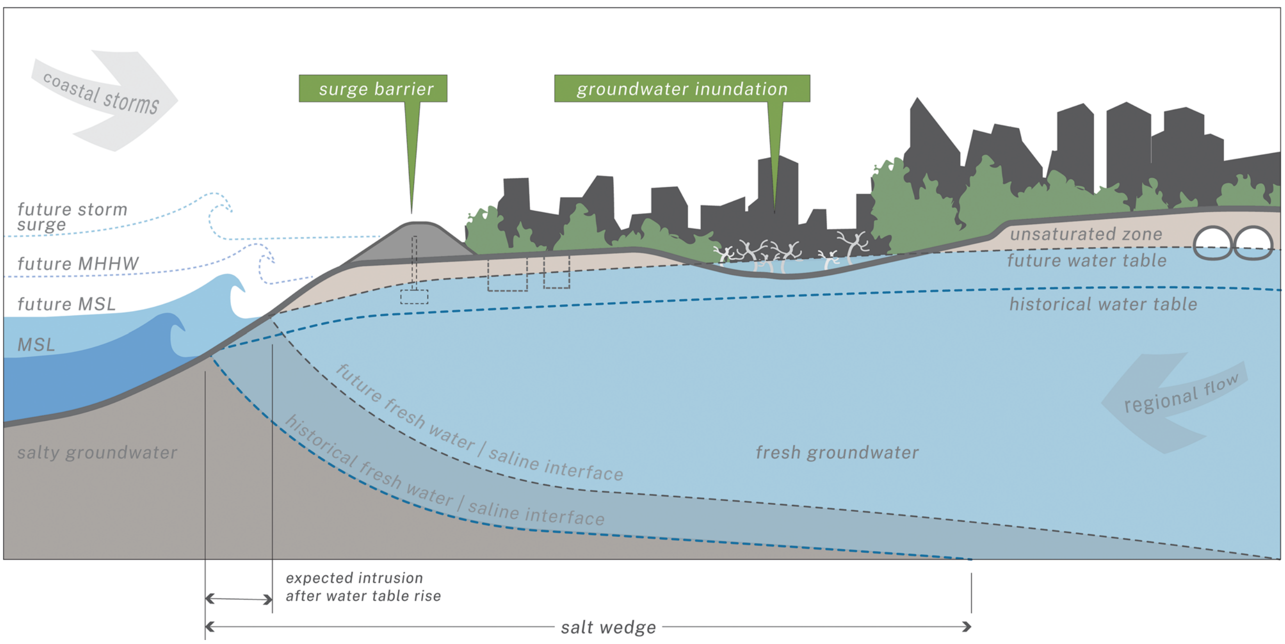

FIGURE 23 Sea level rise and surficial groundwater at an idealized shoreline. Figure by: Climate Adaptation Partners.

Federal risk assessment and forecasting have, however, rarely incorporated multiple flood hazards into flood modeling due to the limited capabilities of existing models and lack of statistical assessments of compounding factors.[209] Compounding of floodwater sources has not been incorporated into flood hazard mapping from FEMA (e.g., flood insurance rate maps) or NOAA (e.g., SLOSH Maps).[210,211] This deficiency is gradually being addressed, with new models being developed and methods applied to better assess compounding. For example, the USGS New York Water Science Center is assessing compound flood risk from the combined effects of sea level rise on storm surge, tidal and groundwater flooding, and stormwater.[212] This research project is exploring and mapping vulnerability to individual and co-occurring flood drivers across the project study area, which includes NYC. The study also includes developing a coupled model framework that links coastal, groundwater, and stormwater models to better understand the dynamics connecting surface stormwater, coastal ocean, and groundwater.

The most widespread compound flood hazard for NYC is likely to compound hazard from rain and storm surge, given that coastal and pluvial flooding commonly co-occur during coastal storms. Analyses of historical data under the NYC VIA project[48] quantify the baseline present-day hazard from co-occurrence of these two drivers.[213] The research focuses on simultaneous and near-simultaneous rain and storm surge. The analyses utilize hourly data because NYC consists of small, heavily urbanized watersheds, with short travel times, in which rain and surge must be nearly simultaneous to cause compounding. This is an improvement upon prior assessments that analyzed daily rain totals and looked at 3-day windows for assessing co-occurrences.[206,208] The new analyses include ranked correlations of rain and surge and joint recurrence interval analyses. Storm types are separated into TCs, extratropical cyclones, and “neither” events (e.g., localized convective thunderstorms) using historical storm track datasets.

The results of this new research reveal nonzero correlations between rain and storm surge, suggesting that there is a higher probability of one variable being extreme when the other is extreme. When all storm types are merged together, rain and surge have a low, but nonzero rank correlation. However, for TC data alone, their correlation can be high. Assessing extreme (50- and 100-year) joint rain-surge events from TCs gives a worse rain and surge hazard than assessing all events combined. As a result, TCs require separate hazard assessments to avoid underestimation of extreme compound flood hazards.[213] The timing of the joint flood drivers, measured as lag time between their peaks, is also important to their potential compounding; when the peak rain and surge come at the same time, they can merge together to create a deeper flood, whereas when they come a day apart, compound flooding is less likely. For TCs, lag times are relatively small, and the most intense TC rain and surge events (e.g., 100-year) have the most potential for compounding. These results are for New York Harbor (the Battery) but a paired assessment of Kings Point tide gauge data addresses compound flood hazard for South Bronx and Northern Queens. The peak surge at Kings Point typically has 2–6 h of lag time behind the peak rain rate during TCs, which reduces the risk of pluvial-coastal compound flood hazard but raises the risk of fluvial-coastal compound flood in nearby Bronx River.[213]

8.2 | Historical example: Tropical Storm Irene

In 2011, Tropical Storm Irene produced a large storm surge (4.2 ft at the Battery), high coastal water levels, and simultaneous heavy rainfall in NYC. The compounding by rain and river streamflow increased peak water levels only very slightly (2%) in New York Harbor.[209] No street flood sensor observations or flood modeling existed for NYC during that storm, but the combination of “moderate” to “major” NWS coastal flood levels along shorelines of NYC and heavy rainfall (as much as 1.3 in. (3.3cm) in 1 h; 5.67 in. (14.4cm) in 12 h) may have caused compound flooding. This lack of quantitative evidence has motivated efforts to deploy hundreds of real-time flood sensors on streets[150,214] and to develop H&H models of the city,[17] both of which can be used to quantify compound flooding and better understand the potential efficacy of mitigation strategies.

8.3 | Compound flooding exposure and vulnerability

Although very little detailed quantification of on-the-ground compound flooding has been possible until recently, areas believed to experience compound flooding are typically in coastal flood zones and include locations like East New York, The Rockaways, and Gowanus. In situ observation efforts like FloodNet[150] are poised to greatly expand the data available to quantify the City’s flooding.

8.4 | Climate change and future compound flooding

Given the relatively new science of compound flooding, relatively little research has quantified future trends. However, rising sea levels alone are likely to cause worsened compounding of pluvial flooding in coastal areas, and any intensification of rainfall extremes could similarly compound coastal floods. Recent work by Gori et al.[215] showed that extreme rain and surge correlations could rise by up to 25% by 2100 due to climate change, and both SLR and storm climatology changes are important to the rainfall-surge joint hazard at the NY/NJ area. The recent Stormwater Resiliency Study[17] assessed future rain intensity change and SLR impacts on pluvial flooding. Research prior to that study used global climate model results for changes to extreme rainfall and used simplified conservative (high-end flooding) modeling approaches by assuming it is always during the high tide for all the extreme rainfall scenarios.[216]

8.5 | Persistent knowledge gaps: Compound flooding

Completed recent research[17,216] has mainly focused on pluvial flooding and sea level rise, but more comprehensive research on all flood hazard types, including groundwater and Bronx River-fluvial compound flooding, is needed. Moreover, rain-surge compounding is also increased by tides, and thus quantification of the joint rain-surge-tide probabilities is important for determining the compound flooding. Although most research to date has focused on less-frequent, extreme compound events, more research on the chronic flooding that will result from more-frequently occurring high tides and the infiltration of groundwater into storm sewers is needed.

A critical next step will be compound flood modeling and analyses of street flood observations alongside the results of statistical assessments like those summarized above, to translate these data into an understanding of actual on-the-ground impacts; two drivers can co-occur, but their combined flood depth is often less than their sum.

Further use of 311 flood-related service requests and NYC FloodNet Street Flooding observations[150] can greatly aid these research endeavors. The impact of climate change on compound flooding is another area of future research. The improved understanding of past- and present-day compound flood hazards presented above helps identify the factors needed to study future changes in compound flooding. For example, tropical and post-TCs are an important area of study for the most extreme compounding events, and the climatological changes to these storms are an important area for future research.

9 | FLOOD RISK MANAGEMENT (FRM)

9.1 | Context for FRM

As discussed throughout this chapter, NYC's natural environment and development history both play important roles in determining the geography of the city's contemporary flood risks. Many of today's flood hazard areas were historically natural streams, wetlands, and other coastal ecosystems (Figure 1) that flooded regularly. This historical flooding presented low risk as the ecological communities found in these pre-urbanization landscapes were well-adapted to these conditions, and human population densities were relatively low. Contextually, this pre-urbanization level of flood risk can be viewed as an **unavoidable floor** (Figure 24, left), below which risk cannot be reduced. It is worth noting that even if no urbanization had occurred, flood hazards—and in turn, flood risks—in this predevelopment NYC would have increased over the last century, due to the effects of global climate change on sea level and precipitation patterns (as represented by the yellow box on the first column).

But the city did urbanize. As streams were filled, natural areas were replaced with impervious surfaces, and the human population skyrocketed, the potentially exposed population grew into the millions and flood risks greatly increased (Figure 24, middle). Each flood exposed more people and more infrastructure systems to flood hazards, without the natural buffering that would have been provided by the natural systems of the pre-urbanization landscape. As in cities across the country,[25,217] flooding became more frequent with impacts experienced differently across different demographic groups. As evidenced by the severity of flood impacts documented throughout this chapter, these **existing** flood risks are already high and climate change (e.g., yellow box, middle column) will elevate them further. Given the extensive work by NPCC and other researchers to quantify the potential effects of climate change on the city, and the growing attention being given to FRM locally, these current flood risks ought to represent a **ceiling**, above which future flood risks are never allowed to rise.

Acknowledging that current risk levels are too high, there is now an urgent need for open, public, inclusive, multi-stakeholder deliberation about the range of future flood risks that are **acceptable** to NYC residents. This deliberation is a necessary precursor to inherently political, value laden FRM decisions about what to preserve, what to change, and what to allow to evolve in an un-managed fashion.[218] FRM decisions will have long-term, legacy implications and will create path dependencies that cut off future options,[219] especially in the neighborhoods directly impacted by them. At this important turning point in the city's dynamic development, sound science and collaboration need to guide decisions regarding which of many possible adaptation pathways (e.g., unique combination of FRM approaches) to pursue both across the city, and in individual neighborhoods. An overview of some leading approaches to FRM options is provided in the next section.

9.2 | Scope of FRM

FRM is an evolving term used to describe a variety of structural and nonstructural approaches—or responses—(Figure 25) that seek to decrease the human and ecological impacts of floods. As defined here, following UNDRR[220] and Wasley et al.,[217] structural measures include some form of physical infrastructure, or the application of engineering, including nature-based engineering, to reduce flood risks. Nonstructural measures use knowledge, practice, agreements, laws, policies, capacity building, financing, and public awareness raising and educational campaigns to accomplish the same goals. FRM can be planned by government agencies with a responsibility for water or flood management but can also be undertaken by flood-exposed populations themselves.

Ideally, FRM strategies reduce flood exposure,[221–223] reduce flood vulnerability factors,[73,224] or accomplish both goals simultaneously. However, when FRM actions result in objectionable tradeoffs; have the unintended consequence of increasing flood risk, for example, in another geographic area; create other environmental (e.g., water quality) or social problems; or negatively impact NNBS, they may be considered maladaptive (see Section 3.5 for definition and Section 9.3 for examples of how maladaptation could arise).

Selection of the most appropriate FRM measures to implement in a particular community is complex because neither governmental decision-makers, nor residents can make these decisions alone. Together, empowered multi-stakeholder teams must deliberate to

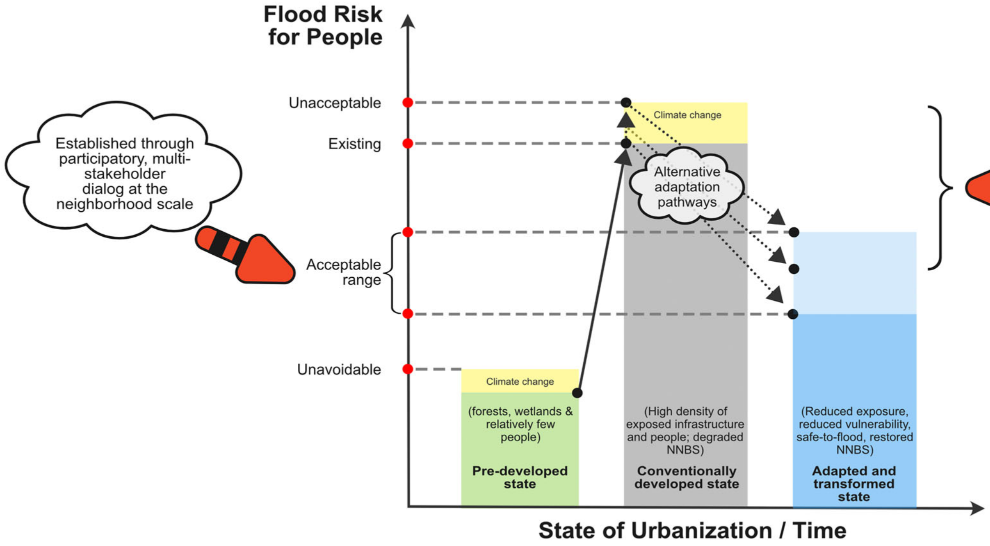

FIGURE 24 Evolution of flood risks for people as a function of urbanization, climate change, and adaptation pathways. The yellow boxes represent increases in flood risk due to climate change. The heights of the green, gray, and blue bars represent New York City (NYC) flood risks in pre-developed, conventionally developed, and adapted/transformed states, respectively. The solid black arrow represents the increase in flood risk due to historical urbanization. The dotted-line black arrows represent alternative adaptation pathways that could emerge through participatory, multi-stakeholder decision-making processes used to plan flood risk management (FRM). Figure by: FA Montalto.

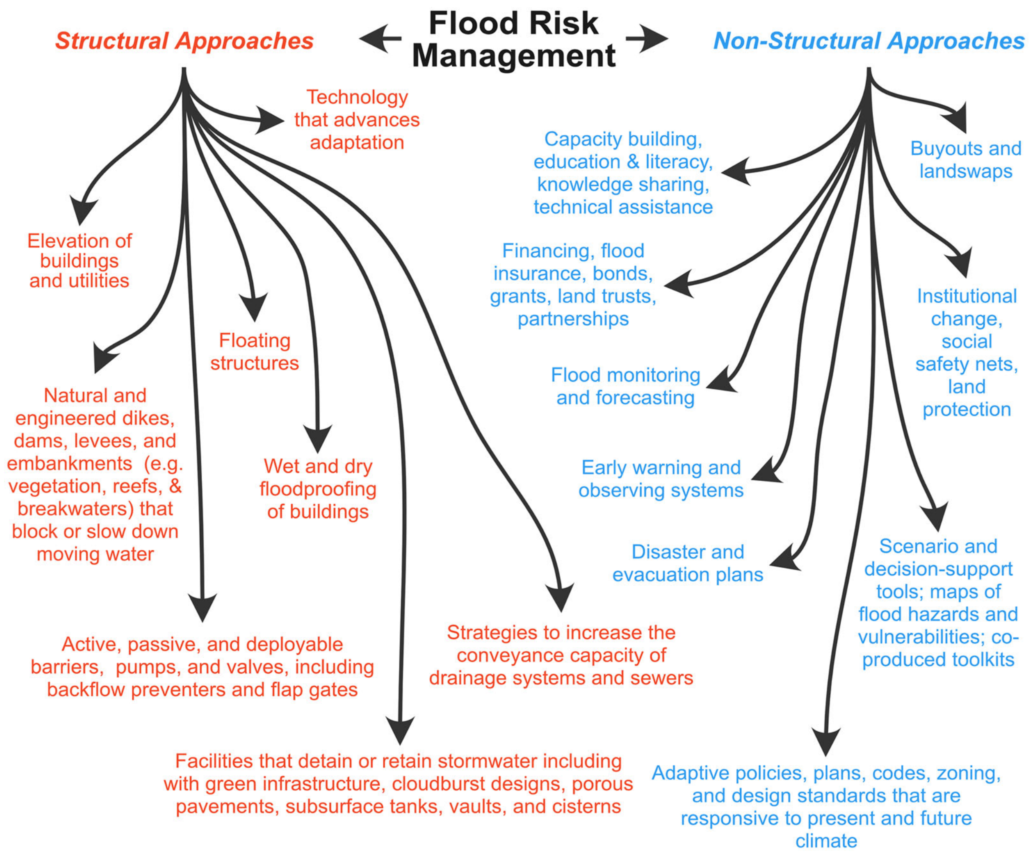

FIGURE 25 Structural and non-structural approaches for addressing the human and ecological impacts of floods. *Source*: Some portions of this figure were adapted from Wasley et al.[217] Figure by: FA Montalto.

select the best suited combinations of responses. Before selecting any specific measure, however, these teams must develop a deep understanding of (1) the types and potential severity of flood hazards faced by the subject community; (2) which segments of the human population are most vulnerable; and (3) what impacts unmitigated flooding might have on local NNBS (all of which are informed by the information provided in this chapter). A collective understanding of these issues can help to develop consensus around the most appropriate FRM strategies to consider, and the spatial scales (e.g., building, block, neighborhood, and city), and time horizons (e.g., immediate, near term, long term, and post-disaster) over which to implement them. These deliberations must also consider whether the impacts of these measures on NNBS are acceptable and identify realistic strategies both to fund and to maintain the final combined strategy.

Deliberation is necessary because individual FRM strategies differ significantly in goals, implications regarding implementation, and impacts. Around the nation and world, the principles guiding FRM decisions have evolved rapidly over the last two decades. Specifically, there has been a noteworthy shift from responses that sought principally to control floods, to responses that made it easier to live with them, to responses derived from visionary long-term changes that seek to transform communities to reduce long-term risk.[225,226] Prior to this century, FRM responses were predominantly reactive, structural, and undertaken after a flood occurred. Today, increasingly—though perhaps not fast or widely enough—FRM is understood in the context of ongoing climate change and urbanization; it is viewed as a critical component of a multifaceted, proactive strategy that seeks to reduce the vulnerability and increase the livability of flood-prone communities before, during, and after flooding events.[227,228]

Martin-Breen and Anderies[229] introduced a helpful taxonomy that can be used to classify different approaches. This schema differentiates between *Resistance*-based responses that seek to "bounce back" to pre-flood "normal" conditions (e.g., the Resistance Approach),[230,231] and *Resilience*-based responses that can either involve an incremental adaptation to a new post-flood "normal" state (e.g., the Adaptive Approach), or a fundamental transformation of the social and ecological conditions that determine flood risk (e.g., the Transformative Approach).[229]

The Resistance Approach to FRM fundamentally seeks to preserve the status quo in the exposed community by "fighting with water" in different ways to keep it away from where it can have negative impacts. It is typically applied at larger spatial scales, for example, by building a levee, floodwall, or flood gate.[232] The two Resilience Approaches involve decentralized actions inside communities but at different scales and for different purposes, as described in the following:

- Because it recognizes the need for exposed communities to "live with water," the Adaptive Approach may incentivize property retrofits (e.g., various forms of floodproofing and/or elevation of buildings or utilities) or other measures that prepare that community for a specific future condition.
- Recognizing the same need, the Transformation Approach does not adopt any fixed end point (e.g., either a historical or future normal condition) as the goal for FRM. Rather, it accepts that climate change (and other social and ecological processes) is creating a dynamic, evolving context in which continuous societal change and transformation will be needed. Like the Adaptive Resilience Approach, these changes can be decentralized and small-scale. But like the Resistance Approach, these changes could also drastically modify how entire communities look and feel and whether their natural ecosystems remain and continue to function.

All three FRM classes can include combinations of structural and nonstructural measures, but with significantly different end goals governing how they are applied.

9.3 | Pros, cons, and caveats of different FRM strategies

It is important that decision-makers, community members, and others be cognizant of the challenges and tradeoffs associated with different FRM responses, as they collaborate to design comprehensive FRM strategies for specific neighborhoods, communities, or properties in NYC. An overview of these factors is provided below.

9.3.1 | Resistance responses

Resistance responses can be among the fastest and easiest ways to provide immediate protection to existing communities, though recent reviews[228,232] point to a range of pros and cons specifically of the engineered components of this approach:

- Resistance strategies can cost-effectively reduce flood frequency and associated impacts and can also be designed to protect vulnerable NNBS.
- However, Resistance strategies have frequently prioritized flood control over the need to conserve, restore, and/or create NNBS. Historical investments in engineered flood control measures nationwide have often negatively impacted NNBS,[232] reducing their ability to provide ecosystem services including water regulating services that can reduce flood risk. In part, these negative impacts arose because of a lack of understanding about where and how to protect or expand natural systems in the built environment. Negative impacts on NNBS include changes in sedimentation patterns, water column and water quality stratification, animal migration, and habitat connectivity.[233] Tognin et al.[234] documented how operation of the Venice storm surge barrier can reduce episodic sediment supply to tidal wetlands inside the lagoon. As documented in Section 3.4.2, unacceptable impacts on NNBS are a form of maladaptation.
- Among Resistance strategies, gated storm surge barriers are being closed with increasing frequency due to sea level rise, reflecting the potential for their overuse,[233] and setting up difficult long-term choices between natural system function and human welfare. Barriers can transfer flood hazards and other environmental risks from one location to another. For example, floodwalls and barriers can,

under some conditions, increase water levels and induce flooding both upstream and downstream of them.[235] If a barrier closing traps water in a bay or impoundment that is also receiving a significant volume of CSO discharges, the action could result in water quality impairment. These opposing positive and negative impacts of the same barrier on different human and ecological communities could be difficult to predict, and contentious to juxtapose, rendering equitable operation of this kind of infrastructure challenging.

- Once built, Resistance designs can be difficult to retrofit and adapt. This obduracy[236] can result in their eventual failure and obsolescence as the climate and other conditions continue to change around them. The possibility that these assets may need to be stranded in the long term must be compared carefully against their short-term protective value.
- Resistance strategies can cause a false sense of security ("the levee effect") among residents in the protected community who may believe that the risk of flooding has been eliminated. If this perception results in less flood preparedness, canceled insurance policies, or if it leads to more development in these communities, it can increase long-term risk,[237] even if risk is initially reduced, and especially if future sea level rise turns out to be greater than the rates assumed by the levee designers.[238]
- When such systems fail, the consequences can be worse than would arise without protection, especially if other flood preparation measures have not been put in place.[239]
- By controlling floods, Resistance strategies can reduce the capacity of communities for episodic adaptation and learning, compounding vulnerability over time. By reducing personal experiences of flooding, Resistance strategies can also reduce public understanding of floods, and the need for FRM, increasing latent risks.

9.3.2 | Resilience responses

By adapting and/or transforming communities, resilience responses reduce flood vulnerability. However, as synthesized by McClymont et al.[232] and Rözer et al.,[225] resilience responses also present several key tradeoffs:

- As broached in Balk et al., [16] Resilience strategies that require individual actions (e.g., moving a car, downloading an app) require that local stakeholders have access to information and resources about flooding. For Resilience strategies to be effective, local stakeholders need agency in FRM decision-making, and the ability and resources to self-organize if they are to have the capacity to implement these measures.
- By prioritizing decentralized local measures, Resilience strategies can have the unintended consequence of shifting flood management responsibility from government to flood-vulnerable groups who may not have the knowledge or resources to design, implement, and maintain FRM in the long term.
- These strategies can be logistically, socially, and institutionally complex to implement as they must modify a large fraction of the flood-vulnerable area to meaningfully reduce overall risks. This is one reason that resilience requires deep collaboration among multiple stakeholders.
- The Transformative Approach can also imply significant demographic, socioeconomic, and cultural changes, with potential implications for environmental and climate justice—both positive and negative—that must be carefully considered.

9.3.3 | NNBSs responses

FRM can be provided by conserving, restoring, creating, or enhancing historical NNBS, or by engineering new ones. Collectively, these NNBSs include salt marshes, beaches, dunes, natural streams, and other aquatic systems, as well as various forms of green stormwater infrastructure. A discussion about the opportunities and limitations of these systems follows.

Storm surge attenuation

High elevation and continuous salt marshes can reduce storm surges by 1.08-15.84 in/mi (1.7-25 cm/km)[100,240] However, the large area of salt marsh that would be required to significantly reduce coastal flooding does not exist in NYC due to its natural deep harbor and the landfilling and development over historical wetlands.[223] Full restoration of the city's historic mantle of salt marshes would involve significant displacement of people and infrastructure.

Though opportunities for creation of large, continuous new salt marshes are limited, the restoration of shallow water habitat can also reduce storm surges by increasing frictional resistance. It is estimated that 75% of the city's shallow water habitat has been lost since the 1870s,[3] underscoring the potential opportunity for restoration. Research studies suggest that by shallowing estuarine bathymetry, coastal flooding around Jamaica Bay could be significantly reduced.[223, 241, 242] Although it is well-established that historical dredging, landfill, and wetland loss in the Bay have exacerbated coastal flood hazards,[3,164,242] only limited research has been conducted into the potential for this type of NNBS to be used solely or in combination with hard infrastructure or nonstructural approaches for mitigating flooding for mitigating Jamaica Bay flooding. More research is needed in this promising application of NNBS to reduce coastal flood risks.

Wave attenuation and reduction in erosion

Even salt marshes that are too small to significantly reduce storm surges can be an effective means of attenuating storm-driven wind waves, reducing wave-related flooding, and erosion.[241] Depending on the density and condition of marsh vegetation, these systems can attenuate up to 95% reduction in wave energy over just 100 m of marsh with 50% vegetation cover; this same level of attenuation can occur over even shorter distances with denser vegetation.[243] This finding supports the continued incorporation of coastal wetland fringes into waterfront redevelopment projects throughout the city.

Dissipation of fluvial floodwaters

Stream restoration and stream daylighting can help spread out and dissipate stream flow,[113] reducing flow velocity, flow depth, and associated fluvial flood hazards. FRM was cited as one justification for daylighting sections of Saw Mill Creek in Yonkers, NY; for Tibbetts Brook in the Bronx, NY; and for continued expansion of NYC DEP's Bluebelt program.

Mitigation of soil erosion through enhanced vegetation canopies

Terrestrial vegetation canopies intercept the kinetic energy associated with falling rain drops, which could otherwise break up soil particles and/or create a surface crust that can accelerate soil erosion, reduce infiltration, and/or increase runoff.[244] As called for in the NYC Urban Forest Agenda,[a] a coordinated, long-term citywide plan to care for and expand NYC's public and private urban forest could intercept small quantities of precipitation, while also helping to protect urban soils from erosion and loss during pluvial hazards.

Stormwater management

NYCDEP has committed billions of dollars in investment in green infrastructure (GI) across all five boroughs. Standard right-of-way bioswales, infiltration basins, urban parks,[245] vegetated urban yards,[246] and Stormwater Capture Greenstreets[247] can all attenuate a significant fraction of runoff during routine (e.g., not extreme) storms. Green roofs[248] and various kinds of permeable urban surfaces (both vegetated and unvegetated) also will not yield runoff during moderate rain events that occur in NYC.[122]

The ability of GI systems to capture stormwater is contingent upon the criteria used to design and site them. GI facilities like the ones mentioned above are most frequently designed for water quality improvement or CSO management. These systems are typically sized to capture only the first 1-2 in. (2.5-5.1 cm). of rainfall over their tributary drainage area (TDA) because that "design storm"[249] generates a volume of stormwater (e.g., the "water quality volume") that is greater than the volume of runoff produced by 80%–90% of all annual rain events. It is also believed to contain the "first flush" of pollutants from the TDA. From a water quality improvement perspective, facilities that are sized to capture more than the water quality volume are often considered overdesigned and prohibitively expensive.[143]

GI facilities designed to capture the traditional water quality volume are individually too small to reduce pluvial flood hazards associated with the most extreme events. For example, Figure 26 compares the NYCDEP design storm depths associated with site and house connections in combined sewer districts to the total accumulation of precipitation during some recent storm events. GI facilities designed to comply with NYCDEP code would have been unable to attenuate significant fractions of the precipitation during all but one of the storm events shown in the figure (Post-Tropical Cyclone Sandy, which was not associated with extreme precipitation).

Field monitoring indicates that the stormwater capture performance of GI facilities designed for water quality improvement is negatively correlated with the amount, duration, and intensity of event precipitation.[126,127,247,248] The greater the rate of runoff applied to a GI facility, the greater the chances of that runoff bypassing its inlet or causing the facility to overflow. Bigger and more intense storms which are projected to increase in frequency due to climate change will increase runoff loading. Loading is also elevated at higher hydraulic loading ratios (e.g., HLR—the ratio of the tributary catchment area to the GI facility area). A Queens Stormwater Capture Greenstreet with a relatively low HLR of 3.8 was able to capture 60% of all runoff generated in its TDA for events exceeding 1.3 in. (3.3 cm) of total rain and/or 0.7 in./h4 (1.8 cm/hr) of peak intensity, compared to 77% of the smaller and less intense monitored events.[247] Most GI facilities in NYC have much higher HLRs.

Field monitoring also suggests that the stormwater capture performance of GI facilities is determined by inlet characteristics and maintenance. Inlets that are clogged with debris or sediment are less efficient, especially under intense rainfall conditions,[126] causing runoff to bypass these facilities. Such observations underscore the importance of GI maintenance activities in maximizing the value of the city's investment in GI to date for FRM.

However, a few recent studies[250,251] suggest that GI facilities designed for water quality improvement can provide FRM when they are installed at high density as part of a comprehensive, watershed-level stormwater management approach. An analysis conducted by the Regional Plan Association[251] for example, asserts that GI application rates in a section of Central Queens would need to be 40× greater than current levels to fully eliminate flood accumulations of 12 in. (30.48 cm). or more caused by 3.5 in. (8.89 cm). of rain over an hour, and 60× more to fully eliminate flooding. To achieve such higher levels of GI application, creative new strategies for resolving a wide range of nontrivial surface (e.g., driveways) and subsurface (e.g., infrastructure, utilities, contaminated soils, and bedrock) constraints would need to be devised. To date, these types of obstacles have been a major impediment to GI implementation across the city.[252,253]

Although GI and other onsite stormwater management practices have, to date, been strategically sited in areas where they can have the greatest water quality benefits, NYCDEP is piloting a variety of strategies for managing larger quantities of stormwater using curbside porous pavements and stormwater retention sites located in Cloudburst Hubs established in some of the city's most flood-prone areas.[254] Planning and design of projects in the Citywide Cloudburst Program are still in the early stages.

Green gentrification

Some concern over the potential for NNBS to lead to gentrification has also been expressed. Various forms of NNBS which, in the right configurations, can detain stormwater, reduce waves, and otherwise help to reduce some kinds of flood risks can also increase property values and housing prices, ultimately resulting in the displacement of working-class residents and racialized groups and cultures ("the greenspace

[a] For more information about the NYC Urban Forest Agenda, see https://forestforall.nyc/nyc-urban-forest-agenda/

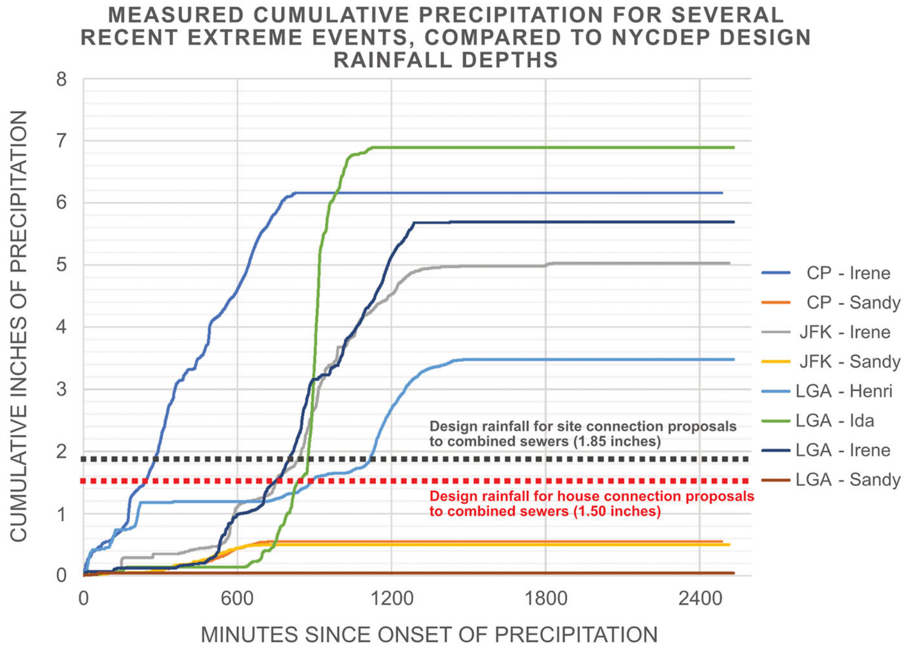

FIGURE 26 Precipitation accumulations of recent extreme events and NYCDEP design storm depths. CP, JFK, and LGA refer to 1-min precipitation data obtained from the gauges at Central Park, John F. Kennedy Airport, and LaGuardia Airport, respectively. The horizontal dotted black and red lines refer to the design rainfall depths used to design stormwater management practices for sites and houses, respectively, when they are connected to combined sewers. House connections apply to 1, 2, or 3 family dwellings less than 20,000 ft^2 in total site area that connect to a sewer that fronts the house. Site connections refer to all other connections to combined sewers. Figure by: FA Montalto.

paradox").[255] Parks have been positively associated with gentrification processes in mid-sized cities across North America and Western Europe.[256] In NYC, research into this maladaptive role of green spaces is limited. Li[257] found that the Million Trees initiative raised housing values and attracted more white, educated, and young households but did not lead to significant gentrification. By contrast, Black and Richards[258] found that The High Line increased housing values closest to it by 35.3%, exacerbating ongoing gentrification forces in the Chelsea section of Manhattan. Nonstructural responses can include managed retreat and flood forecasting and early-warning systems, along with policy measures to support recovery when floods occur.

Managed retreat

Though it is often framed as a single response, managed retreat can be implemented gradually and strategically as part of a multidecadal sequence of actions that may include many of the approaches shown in Figure 25, accompanied by iterative community engagement, vulnerability assessments, planning, and equitable compensation for those who are eventually resettled.[219] Managed retreat projects that have been implemented across the globe have involved mandatory relocation, along with projects that are community-supported or community-led.[259]

Strategies used to operationalize managed retreat include voluntary buyouts, restrictions on post-flood rebuilding, setbacks of future development from flood hazard areas, conservation easements, and downzoning. Buyouts are a common nonstructural approach to flood prevention in the United States. In a buyout, property-owners are offered compensation for the value of their homes if they relocate.[260,261] A buyout requires the government's willingness to buy a property, and the property owner's decision to voluntarily move—a decision that may be precipitated by a flood. Buyouts may be helpful for homeowners but do not resolve the hardship that flooding poses on renters.

Following Post-Tropical Cyclone Sandy, property owners in severely impacted NYC communities were offered buyouts through the NYC Build It Back and state-level New York Rising Buyout and Acquisition programs.[262,263] Homeowners in central Queens requested buyouts again after the Ida Remnants Cloudburst.[264] Through PlaNYC, the City is currently working to develop a "blue-sky" program that will work with households interested in moving away from high-risk areas, by providing housing/financial counseling services to facilitate moving and to minimize long-term displacement from NYC, and then through robust public engagement, converting these properties to sustainable/resilient end uses. Buyouts are discussed more fully in Foster et al.[15]

Another approach, land swaps, involves owners of flood-prone low-lying properties swapping title with the owner of less flood-prone and typically vacant properties within the same community, typically a government agency. Such programs may be spearheaded by residents or led by governmental agencies or nongovernmental organizations in sustained partnership with community members. However, even when programs are voluntary, residents can feel compelled to participate, especially if they lack other means of remaining safely in exposed locations.[265]

In NYC's Edgemere neighborhood, pilot land swaps—some of the first to be implemented for FRM anywhere in the country—were used to allow property-owners whose homes had been damaged during

Post-Tropical Cyclone Sandy to exchange their property titles for city-owned property with newly constructed homes in the neighborhood that were not located in the FEMA SFHA. As part of these efforts, a community-led visioning exercise was conducted so that community members could determine how to best utilize the undeveloped flood-prone properties in a sustainable way that also serves longstanding community needs.[271] The original storm-damaged homes were demolished and converted into city-owned conserved natural lands. But, ultimately, only three land swaps were successfully completed through this program.[272]

Application of such strategies can prevent exposure to flood hazards when sea level rise and other climate-related changes render other forms of FRM ineffectual. But they can also be fraught with a variety of challenges.[265,269,270] Objectors to managed retreat often express concerns about a lack of transparency and community participation in decisions regarding when and where governments make this option available, a lack of fairness and equity specifically as pertains to community impact in historically marginalized communities, and concerns about the fate of ecological resources.[218] Given that all of NYC is subject to some kind of flood risk, uniform application of managed retreat would imply abandoning large portions of NYC permanently. Advocates suggest that if global climate change continues at its current rate, retreat from low-lying coastal area "is an inevitable adaptation action," better planned in advance.[219] But for FRM decisions related to flood exposure, it is important to consider potential inequities. Although the wealthy may deliberately accept flood risks, housing options are often more limited for other groups. Decisions regarding where to discourage development and where to protect it are intrinsically related to class, race, and ethnicity[266–268] and thus directly related to issues of equity.

Flood forecasting and warning systems

Flood forecasting and warning systems are also examples of nonstructural strategies for FRM. They can provide the advanced lead time needed for evacuations, the deployment of active floodproofing barriers, and other emergency planning needed to reduce exposure and vulnerability to flooding when a hazard is imminent. Flood forecasting and warning systems require accurate forecasts of the extreme meteorological events that can cause flooding, numerical models to develop predictions of the extent and magnitude of the resulting flood hazard, and the dissemination of warnings in a manner that is accurate, timely, and can support taking protective actions to reduce flood exposure and vulnerability.[273] To be useful for risk management, forecasts and warnings must be understood by stakeholders and connected to decision processes. As a result, these systems are reliant on both robust social sciences, along with accurate physical forecasts.[274]

Key developments in remote-sensing and in situ observation technologies, data assimilation, and numerical weather forecast modeling have enabled advances in the forecasting of many types of weather systems. For example, National Hurricane Center (NHC) forecast errors for Atlantic Basin tropical storms and hurricanes have fallen rapidly in recent decades, and contemporary 72-h predictions of hurricane tracks are more accurate than 24-h forecasts were 40 years ago.[275] There have also been recent improvements in NHC hurricane intensity forecasts.[276] Accurate forecasting of cloudbursts at the longer lead times needed to support emergency preparations remains limited, however.

For the NYC Metropolitan Region, the NWS Weather Forecast Offices release official consensus coastal flood forecasts and warnings when a storm threatens. The Stevens Institute of Technology Flood Advisory System (SFAS) utilizes ensemble meteorological forecasts and numerical hydrologic and hydrodynamic modeling to provide accurate predictions of coastal total water levels.[171,277] These time-dependent predictions include 5th, 50th, and 95th percentile water levels out 4.5 days into the future and are available online where users can also sign up for coastal flood warnings and alerts.[278] These data are also shared with NWS, who combine them with NOAA model data for their official forecasts.

Operational warning systems for urban pluvial flooding remain in development. Recent advances in convection-permitting numerical weather models and ensemble forecasting make real-time pluvial flood warning systems technologically feasible for the first time. Schubert et al.[279] developed a flash flood warning system forced by Quantitative Precipitation Forecasts. This system was able to forecast high water marks with a mean absolute error of 2.2 ft (0.69 m) and to predict flooding distress calls and FEMA damage claims with hit rates of 90% and 73%, demonstrating the potential to operationally forecast urban flash flooding, but also the need for continued research and development. Significant investments in both operational H&H model development and computational resources will be needed to increase prediction lead times even to several hours and to reduce the spatial resolution of predictions to less than ~4mi^2 (10 km^2).[280] Once a flood forecast has been generated, public alert and warning systems provide information to populations at risk of imminent flood hazards, with the goal of "maximizing the probability that people take protective actions and minimize the delay in taking those actions."[281] Alerts and warnings can be issued by various entities, such as local, state, and federal governments, schools, and media stations. These entities can utilize multiple methods to send alerts and warnings to the public, including TV/radio broadcast, phone and email technologies, and short message service. In addition, social media has emerged as a necessary component for public alert and messaging in the last decade.[282] For example, in NYC, NotifyNYC is an opt-in emergency public communications program available in multiple languages.[283] Participants can register to receive alerts about different types of flood-related and other emergencies, through multiple methods of communication such as basement-specific preparedness messaging before expected rain events.

9.3.4 | The need for an integrated response

As recognized in Foster et al., [15] the significant linkages that exist between climate risks, adaptation investments, and socioeconomic inequality means there is no singular approach to equitable flood resilience that is broadly applicable in NYC. Instead, diverse, multiple, and overlapping approaches must be developed with local input crucial in selecting those most suitable to the unique context of each exposed community. Most flood resilience researchers, and various MOCEJ policy documents, now advocate initiating the FRM planning process by considering a diverse, multifaceted, all-of-the-above approach that is gradually tailored to the characteristics, needs, and types of flooding facing each community.

9.4 | FRM in NYC

The following strategies[27,228,232] could be utilized to support integrated FRM planning in NYC communities.

9.4.1 | Improved quantification of evolving hazards with climate change

The flood hazard modeling, climate change projections, and flood risk assessments discussed throughout this chapter represent a robust foundation on which to make scientifically sound decisions regarding FRM in NYC. More work needs to be done to monitor and simulate all four flood hazards under current and future climate change conditions, superimposing exposure areas on top of maps of human and ecological vulnerability. The communities and ecosystems that are most at risk need to be identified and local residents and governmental decision-makers need to work together to select the most appropriate FRM strategies for each neighborhood. Monitoring efforts such as the city's expanding network of FloodNet sensors that are being used to record high tides, storm surges, and runoff during extreme precipitation events need to be expanded.[284]

9.4.2 | Employing safe-to-flood strategies

This chapter describes the ways that climate change will increase flood risks across the city. A variety of FRM projects are underway, but for the immediate future, much of the city remains at risk. Residents need to be aware of the risks, and measures need to be put in place to make the city safe to flood[285] as long-term FRM strategies are planned, designed, and implemented over time. These measures could include flood exposure reduction measures, but also flood forecasting and early-warning systems, and the development of evacuation and disaster management plans to help communities to better understand and prepare for flooding.

9.4.3 | Structural measures to reduce flood exposure

Structural measures to reduce flood exposure include designs and retrofits such as wet and dry floodproofing that reduce the magnitude of the disturbance relative to a threshold, decreasing the consequences of flooding in the exposed area. Examples include structural measures such as blowout panels to allow for safer egress from basements during floods.[286] These could also include building codes that require elevating utilities, installing pumps, reinforced basement walls, and other similar measures, as implemented recently in Venice, Italy.[287]

9.4.4 | Engineered gray and green flood protection measures

These measures include both gray and green measures to prevent flooding from occurring in targeted areas. These could include restoration of shallow water habitats, construction of engineered dunes to protect against high tides and surges such as those that have been installed in the Rockaways, new salt marsh projects to buffer waves, as well as features such as the floodwalls, levees, and storm surge barriers under consideration for the New York-New Jersey Harbor by the US Army Corps of Engineers.[288] Decisions regarding which communities receive engineered flood protection carry significant equity implications and should not be based solely on traditional benefit–cost ratios that only monetize the value of protected real estate assets. The potential for unintended ecological or social consequences (e.g., maladaptation) should also be evaluated and mitigated.

9.4.5 | Leveraged and expanded investments in water quality protection

As mentioned in several places in this chapter, significant investments are being made to improve NYC water quality using both gray and green stormwater management practices which, through enhancement and upscaling, could provide some flood mitigation. Currently, the protocols used to site and design GI limit the value of this investment for FRM. The current GI Program prioritizes watersheds that discharge to waterbodies that do not meet their current water use standards. However, as is clear from the City's Stormwater Resiliency maps, pluvial flood hazards are spatially pervasive and GI facilities intended for FRM would need to be applied virtually city-wide. If higher GI application rates are accompanied by strategic modifications to GI design standards (e.g., the use of more hydraulically efficient inlets, deeper surface depressions that are directly connected to subsurface vaults and stone reservoirs), these investments in water quality could be integrated into a community's unique FRM strategy. In communities with high water tables, soils with low permeability and/or excessively high percentages of fine particles, and/or shallow bedrock, these practices would also likely need to be lined and connected via underdrains to local catchbasins.[149,289]

9.4.6 | Collaboration to manage larger storms

To overcome the perception that enhanced GI facilities are overdesigned, and to justify the additional costs associated with their construction, maintenance, and higher levels of spatial application, the hybrid role intended for this new generation of GI facilities (i.e., water quality improvement and FRM) would need to be recognized formally and encoded in new interagency agreements. Unique and unprecedented cost-sharing strategies would also need to be devised, as these practices would provide a level of service beyond that needed for Clean Water Act regulatory compliance.

9.4.7 | Broad implementation of cloudburst infrastructure designed for higher magnitude events

The NYC Department of Environmental Protection is piloting cloudburst resiliency projects to detain, retain, and store stormwater during moderate cloudbursts in four flood-prone communities in Corona and Kissena Park, Queens; Parkchester, Bronx; and East New York, Brooklyn.[254] This program relies heavily on porous pavements, offline storage, and modified applications of existing GI designs. To support FRM in a climate where very intense cloudbursts occur more frequently, a broader range of Resilience FRM, such as the cloudburst roads, retention roads, retention spaces, and green roads that have been implemented in the City of Copenhagen, Denmark[290] (Figure 27), could be employed. These cloudburst strategies utilize streets and other surface features to manage stormwater associated with the higher magnitude (e.g., present-day 1% AEP/100-year recurrence interval) cloudbursts that are associated with severe pluvial flooding and projected to occur more frequently with climate change.[290]

9.4.8 | Flood recovery measures

These include measures that help to recover and return to normal efficiently after a flood event, for example, emphasizing reconstruction, rebuilding, compensation, or insurance.

9.4.9 | Transformational strategies

These include strategies that a community collectively decides to undertake as it learns about and adapts to a suite of dynamic and evolving conditions that determine flood hazard and exposure. Transformational strategies need to emerge from discussions between community members and governmental decision-makers and help to address multiple local needs and challenges.

9.4.10 | Global knowledge transfer

Globally, a variety of comprehensive strategies have been developed to manage flood risk, and many opportunities for co-learning between NYC and other cities are possible.[128] As one example, the European Floods Directive[291] was established to reduce the negative consequences of flooding on human health, economic activities, the environment, and the cultural heritage of the European Union (EU). This directive requires EU member states to conduct risk assessments to identify Areas of Potential Significant Flood Risk (APSFR); followed by mapping of the potential consequences of floods of different types and magnitudes; and finally, development of FRM plans including specific measures implemented according to the unique hazard and risk characteristics of each APSFR.

9.4.11 | Build and expand on existing FRM projects

Some of these FRM strategies are already built into local FRM plans and policies. The Lower Manhattan Climate Resilience Study[292] and the East Side Coastal Resiliency Projects[293] both aim to reduce coastal flood risks in individual neighborhoods of Manhattan. The City of New York's Climate Resilience Design Guidelines[294] provides guidance on how to reduce the impacts of extreme precipitation, sea level rise, and heat on capital projects (e.g., infrastructure, landscapes, and buildings). These guidelines focus on reducing stormwater inputs to the city's sewer system and selecting appropriate design flood elevations for Capital projects located in current and future coastal floodplains. In its Neighborhood Coastal Flood Protection Project Planning Guidance, the City of New York[174] provided guidance for initial concept planning, feasibility, and design stages of neighborhood-scale coastal flood protection projects that are equitable, resilient, and well designed. This guidance underscores the importance of shaping these projects to address unique neighborhood characteristics, maximize community benefits, and improve the public realm. In its report, *Increasing Stormwater Resilience in the Face of Climate Change: Our Long-term Vision*,[253] NYCDEP describes a multifaceted approach that will involve some upscaling of its implementation of rain gardens, stormwater medians, onsite detention projects, green roofs, Bluebelts, and cloudburst projects to augment drainage capacity while providing valuable community co-benefits. This vision also includes interim measures that will improve communication between residents and the City, better maintain existing drainage infrastructure, and better predict where flooding occurs now and in the future. It is worth noting, however, that these measures do not explicitly address the need to manage higher volumes and intensities of stormwater (e.g., contemporary 100-year or greater rain events), protect the coast, reduce groundwater flooding, or build resilience to compound hazards.

To date, no community-initiated FRM plans have been developed in NYC. However, although none of the case studies reviewed in Foster et al.[15] mention mention the development of any community-scale FRM plans, other community-scale resiliency planning efforts that emphasize anti-displacement, and a just energy transition are underway.[295] PlaNYC and the Climate Strong Communities program will leverage resources to build climate resilience in communities that did not receive Post-Tropical Cyclone Sandy relief funds.[296,297] Examples of individual properties that have developed site-scale FRM plans can also be found throughout the city.

10 | OPPORTUNITIES FOR FUTURE RESEARCH

Though recent City guidelines and vision documents are important and impactful, much more applied research is needed to reduce flood risks

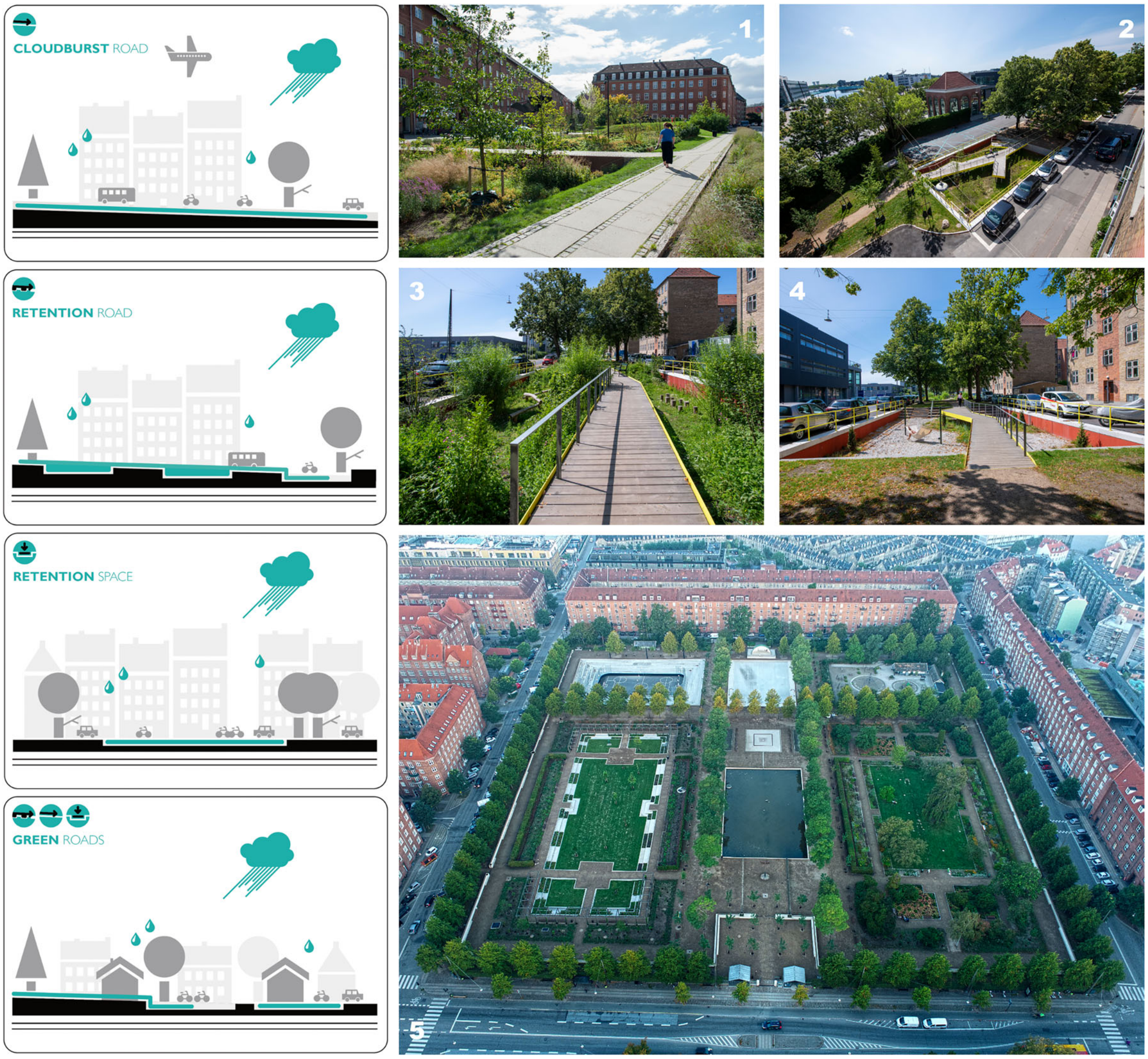

FIGURE 27 Cloudburst roads (starting upper left) are designed to convey runoff generated during extreme events on the surface to places where that can flood safely. Elevated curbs, recontoured street cross sections, and slightly depressed intersections are used to direct the flood waters. Retention roads (second down, left) are designed to retain and detain flood waters in subgrade cisterns, vaults, and curbside planters integrated into the right-of-way. This approach is similar to NYCDEP's current Cloudburst standards. Retention spaces (third down, left) retain and store floodwater in multifunctional urban spaces, such as depressed parking areas, squares, gardens, and recreational fields. Examples from Copenhagen, Denmark: Tåsinge Plads (1), Scandiagade (2–4), and Enghavepark (5). Finally, Green roads (bottom, left) are designed to remove and retain water on smaller roads and alleys. Figure by: Climate Adaptation Partners (Photos 1-4 courtesy of Troels Heien; Photo 5 courtesy of Anders Pedersen. Diagrams courtesy of the City of Copenhagen)

and build flood resilience in NYC. Several key opportunities for future research are summarized below.

10.1 | Monitoring, modeling, and mapping

10.1.1 | Continue to monitor, model, and map all flood hazards, and their interactions, across NYC

Through a collaboration between the city and academic partners known as FloodNet, the city will be deploying a total of 500 ultrasonic surface flood depth sensors around the city by mid-2027.[214] These sensors will be helpful in flood response, namely, by quantifying the real-time depth and duration of different types of flooding. These sensors can also be helpful in calibrating and validating H&H models to historic flood events captured by the sensors, improving model confidence for use in simulating current and future flood hazards. Ideally, the FloodNet sensors will be accompanied by other data acquisition initiatives as described as follows:

- More precipitation gauges that record precipitation accumulations at subhourly temporal resolution.
  - More spatially explicit, subhourly precipitation data are needed to better map spatial variability in extreme precipitation and to drive real-time simulation of pluvial flood hazards. To support FRM, these observations must be accessible to the research and

engineering consulting communities, and the data must be quality controlled. The integration of precipitation observations with community science programs could enhance community understanding of extreme precipitation, climate change, flooding, and FRM, ultimately leading to social transformation.

- More water level and flow gauges throughout the harbor and in local rivers, creeks, and sewers.
  - If planned along with the precipitation gauges and co-located near the FloodNet sensors (applicable for in-sewer gauges), this water level and flow data would improve the accuracy of hydrologic, hydraulic, and hydrodynamic modeling, improving our ability to simulate sewer flows, coastal and fluvial flood risks, and estuarine water quality, supporting flood preparation and ecological transformation. It could also help to design flood-risk prevention and flood protection measures in coastal or fluvial floodplains. The Stevens Institute of Technology has maintained 12 water level gauges in the harbor region for the Port Authority since 2015. Data can be visualized online alongside forecasts (http://stevens.edu/SFAS) but are not available for download.
  - If these gauges were maintained by governmental agencies like NOAA and USGS, working in close collaboration with NYCDEP, community scientists, fishers, and community-based organizations, they could also help advance social transformation.
- More groundwater monitoring wells instrumented with water level loggers and salinity/conductivity probes.
  - Particularly when positioned near the coasts and in topographic depressions, these data could help to improve our understanding of groundwater levels and groundwater flow directions, as well as quantify the extent of saltwater intrusion into coastal artesian aquifers. In this way, the data would help to design groundwater flood-risk prevention and flood protection measures.
- Digitize the geotechnical test results conducted by City as part of its Green Infrastructure Program.
  - The City has invested millions of dollars in geotechnical testing to support its evolving Green Infrastructure program. These data include depth stratified soil texture analysis, and critical information regarding depth to groundwater and depth to bedrock. If these data were digitized, georeferenced, and made open source, it could be helpful in improving groundwater modeling throughout the city.
  - Along with the additional groundwater depth data described above, this geotechnical information could also help to identify subsurface infrastructure and subgrade spaces vulnerable to groundwater flooding, promoting flood preparation, and could also help to design appropriate flood protection measures.

The proposed new datasets could help to improve the City's ability to model pluvial, fluvial, coastal, and groundwater flood hazards. Key to this initiative is a commitment to perpetual data collection at consistent locations, facilitating retrospective analysis of historical trends and helping ensure that the most extreme flooding events are captured for model calibration. Sustained procurement of high-quality and high spatial and temporal resolution data will build a strong flood-related data repository, ensuring that the City can leverage the most recent and future advancements in data-intensive technology (e.g., digital twins and AI).

It is also recommended that the City continue to develop high-resolution models that can be integrated to simulate coastal hydrodynamics, sewer, surface, and groundwater flows. The goal is to develop hazard maps that represent a wide range of current and future flood hazards. For water quality improvement purposes, NYCDEP uses an ensemble of 1D H&H models to simulate separate and combined sewer flows through its major trunk sewers. Development of the recently released Stormwater Resiliency Maps required enhancing portions of these 1D models with higher resolution representation of various elements of the drainage system. The Stormwater Resiliency Study also coupled the 1D model to a 2D model representation of the surface, enabling "rain-on-grid" simulation of pluvial flood patterns. In partnership with NYCDEP, the USGS is developing a transient numerical model of water table response to sea level rise in Queens and Staten Island. The accuracy of these early attempts at model integration could be improved by creating higher resolution data such as digital elevation models, land use cover maps, and other digital representations of the built environment. Integrated modeling can provide more detailed and site-specific results but will require significantly higher computing power. Use of cloud-based computing technology would reduce computation time and facilitate assessment of long-term historical data (requires a substantial simulation period) and near real-time warning systems (requires near-instantaneous model results to issue warnings). Cloud computing may also improve modeling of interacting, compound flood risks across integrated modeling platforms.

Recent statistical and probabilistic assessments of rain and storm surge (see Section 8.1)[213] demonstrate that co-occurrence of these flood drivers can occur during extreme storm events. However, an important next step will be to simulate these scenarios in flood models such as those described above. Given the availability of one or more such flood models, it is recommended that an assessment of actual compound flood risk is initiated.

10.2 | Flood vulnerability indices

10.2.1 | Continue to develop flood vulnerability indices like the FSHRI, which can be used to support the equitable allocation of resources for FRM in priority neighborhoods

As described throughout this chapter, NYC is subject to different flood hazards, each with a unique geography of exposure. Flood hazard geographies are expected to expand in the future as the climate changes. When integrated with or overlayed on top of flood hazard maps, the recently developed FSHRI is an important first step in identifying neighborhoods and populations with greatest need for resources to support FRM. The maps published in this chapter represent an initial attempt to map social vulnerability in areas exposed to flooding where specific hazards have been mapped. Future work could identify socially vulnerable neighborhoods that are exposed to a broader range of types and magnitudes of flooding, including compound flood hazards that have not yet been comprehensively modeled. Additional research could also examine vertical differences in flood vulnerability focusing on residents of multistory buildings. Although many types of flooding have historically been analyzed separately, there are many advantages to holistically analyzing all types of floods, including coastal, pluvial, fluvial, and groundwater hazards.

Along with socioeconomic factors, infrastructure and the built environment features are important contributors to flood vulnerability that should be evaluated in future flood vulnerability assessment. In this chapter, we provide an assessment of exposed buildings with known infrastructure vulnerabilities to flooding that could be mapped using available geospatial data. These included 1–2 unit residential buildings with basements and other subgrade spaces. However, other datasets that would support a more comprehensive assessment of infrastructure vulnerability are currently unavailable. Examples include:

- Citywide data on the elevation of critical building utilities (e.g., boilers and electrical systems);
- Citywide data on infrastructure with/without wet- and dry-floodproofing features.

Efforts to develop these data would provide a valuable opportunity to enhance flood vulnerability assessment research.

10.3 | Decision-making by nongovernmental stakeholders

10.3.1 | Grant decision-making power and resources to nongovernmental stakeholders to develop community-driven, FRM plans at the neighborhood, and/or landscape scale

In NPCC3, Foster et al.[298] reported that representatives of the city's most socially vulnerable communities desire a deeper engagement in climate planning via collaborative co-productive planning processes. However, in the United States, formal responsibility for FRM is distributed across various levels of government from the Federal government to the states, down to the City, and it can be institutionally complex for governmental stakeholders to relinquish meaningful decision-making roles to nongovernmental flooding stakeholders. That said, many strategies for meaningful engagement of community stakeholders in climate decisions have been implemented in different places. To scale-up adaptation efforts and build capacity among multiple stakeholder groups, the Urban Climate Change Research Network has hosted Urban Design Climate Workshops in Paris, Naples, Durban, and NYC.[299] In a study of alternative strategies for implementing green infrastructure in the Bronx, Wong and Montalto[300] demonstrate how incorporation of surveyed community preferences in GI siting decisions can bring about greater long-term economic and social impact from the City's GI program. In the recent NYC Climate Adaptation Scenarios workshop series,[16,301] participants co-imagined scenarios through which NYC residents, provided adequate information and infrastructure, become resilient to extreme precipitation as they self-organize into community land trusts that manage locally generated stormwater in innovative ways.

Multi-stakeholder participation in FRM poses some challenges, such as the possibility of differences of perception and/or conflicts among different stakeholder groups, including both governmental and nongovernmental entities, each of whom have different perceptions, knowledge, values, and needs; and the possibility that ideas that emerge from a deliberative process might be logistically complex to implement. Co-development of FRM plans requires investment of adequate time and resources.[302,303] A broad array of stakeholders should be engaged early in the FRM planning process,[304,305] with open communication allowing stakeholders to express differing views and opinions, and collaborative technology such as remote conferencing tools and online collaboration platforms used throughout the process.[302] Regular meetings, training sessions, and awareness-raising campaigns can be organized to codevelop goals, concepts, and decision-making frameworks, build capacity, reduce conflicts, and promote mutual understanding.[303,304,306,307]

Such methods can be used to engage flooding stakeholders in key decisions regarding equity in FRM, including:

- How are community stakeholders engaged in decisions around flood prevention and protection?
- How will prevention and protection measures change access to, and cultural relevance of, flood hazard areas?
- How does flood prevention influence destination communities and receiving locations?
- Do community stakeholders have the means and capacities to maintain flood-risk reduction measures over time?
- How does prioritization of protection vary across communities?
- Which groups are most likely to experience losses or disruptions because of a particular kind of flood?
- How can resources be allocated to minimize transboundary risks? What additional resources are necessary to protect neighboring communities?

10.4 | Natural and nature-based systems

10.4.1 | Develop incentives, policies, and enable comprehensive transformations of the city emphasizing long-term flood resilience, sustainability, and equity, highlighting the role of NNBS

Flood risk prevention, protection, mitigation, and preparedness measures can help to reduce near-term flood vulnerability. Due to its role in changing precipitation patterns and raising sea levels, climate change contributes to NYC's current hazards and will further increase NYC's future flood hazards in the absence of rapid reductions of global greenhouse gas emissions. However, as described throughout this chapter, flood risk is also determined by the historical destruction of, and modifications made to, local ecosystems. Flood exposure and vulnerability are the result of climate change superimposed on top of historical land use, infrastructure, and social policies that dramatically transformed the ecology of NYC (see also Section 3 in Foster et al.[15]). Transformation of the city toward resilience, sustainability, and equity will emerge from deliberation and collaboration among multiple stakeholders about how to advance both ecological and social justice goals through FRM.

11 | TRACEABLE ACCOUNTS

Key Message 1: NYC faces risks from four types of flood hazards: pluvial, fluvial, coastal, and groundwater, each with a unique geography of exposure that will expand in different ways in the future due to climate change. Identifying these four types as separate, but related, hazards is an important step in studying how they impact NYC, what FRM tools are available to address them, and where future research is needed. Climate adaptation planning must consider all four of these types of flood hazard and their potential impacts across a range of magnitudes, including very extreme events.

- **Description of evidence**: The risks associated with coastal and fluvial flooding have been evaluated through flood insurance studies by FEMA (see https://msc.fema.gov/portal/home). Projections of sea level rise with climate change and its impacts on coastal flooding have also been evaluated in previous NPCC reports.[308,309] Projections of amplified precipitation due to climate are provided in Ortiz et al.[310] In this assessment, we also conduct a review of the scientific literature, technical reports, and government agency databases on risks associated with pluvial and groundwater flooding.
- **New Information and remaining uncertainties**: Significant uncertainties remain regarding the risks of associated flood hazard types that have not yet been mapped (e.g., fast-moving water, daytime, and residential exposure of populations at the spatial scales relevant to flooding in NYC), and the tangible and intangible cost of flooding when it occurs. There are also high remaining uncertainties on how climate change will impact short-duration, intense rainfall events associated with pluvial and fluvial flooding. These uncertainties are discussed in Braneon et al. [6] and Ortiz et al.[310] In addition, observations of shallow groundwater levels in Brooklyn and Queens are available through 2012, but continuous observations along the coast are not available to allow for an analysis of trends with sea level rise. There is also very limited observational data available on aquifer properties and shallow groundwater levels in Manhattan, The Bronx, and Staten Island.
- **Assessment of confidence based on the evidence**: Based on the available evidence and the authors' expert judgment, there is high confidence that pluvial and fluvial flooding will increase due to climate change if flood hazard mitigation efforts are not implemented. Given the trajectory and projections of sea level rise, it is virtually certain that coastal flooding will increase. Confidence on both the magnitude, spatial distribution, and timing of the groundwater table rise in response to sea level response—and resulting groundwater flooding in the absence of mitigation efforts—remains very low.

Key Message 2: Discussions about flooding often focus on risks within the SFHAs mapped by FEMA. However, the FEMA SFHA maps present fluvial and coastal flood hazards only. The recently released NYC Stormwater Flood Maps represent the city's first attempt to map pluvial and some compound flood hazard with risks spread out over a much larger fraction of NYC. In this chapter, we present a preliminary assessment of pluvial and groundwater flood hazard exposure areas that can be utilized to support FRM. Additional research is necessary to develop hazard maps that represent a broader range of flooding hazards and their increase in magnitude in response to anthropogenic climate change.

- **Description of evidence**: The assessment of building exposure to flooding was conducted through overlay analysis of existing flood hazard[17,57] and depth-to-water table[60] layers with geospatial datasets on the location of building footprints,[58] NYCHA Public Housing Development Map Data,[311] and a one-time data layer of Building Elevation and Subgrade Spaces in February, 2022. Analyses were conducted using Python 3 and QGIS 3.22 software.
- **New information and remaining uncertainties**: In this assessment, we provide new information on the exposure of two types of buildings associated with increased vulnerability: NYCHA residences and 1–2 family residential buildings with basements or other subgrade space. Uncertainties associated with each data layer used in the exposure assessment are described in their respective sources.
- **Assessment of confidence based on the evidence**: Confidence is high in the overall trends exhibited by the H&H models used to map pluvial flooding exposure, showing that more intense rainfall will produce more flooding because the drainage system is not sized to convey the recurrence interval events that were simulated. Confidence is medium regarding the exact extents and depths of predicted flooding at the street/property-scale due to stated model resolution. The water table elevation map for Brooklyn and Queens used to map potential groundwater flooding exposure was developed through a synoptic survey of observational and supply wells across Long Island conducted by the USGS in 2012.[60] Depth-to-water estimates were developed using this layer and a Digital Elevation Model created by NOAA and the USGS through the Disaster Relief Appropriations Act of 2013. The resulting depth-to-water layer has a vertical accuracy of 10 ft.[184] Although confidence in the overall spatial patterns provided by this layer is high, this layer may not represent finer-scale variation in the water table or changes that may have occurred since 2012. Groundwater data in Manhattan, The Bronx, and Staten Island remain very limited, and no depth-to-water table layer is currently available for these boroughs.

Key Message 3: Much of NYC is exposed to pluvial flooding, which occurs when the intensity of precipitation exceeds the infiltration capacity of the soil and runoff exceeds the hydraulic capacity of the sewer system. These conditions often occur during cloudbursts, short-duration periods of intense rainfall that can be embedded within large storm systems or occur as individual, hard-to-forecast thunderstorms. Intense rainfall has already been observed to have become more frequent in NYC since the mid-20th century and is projected to further intensify and occur more frequently with unmitigated climate change. Despite the increasing risk, pluvial flood hazards remain poorly understood. The NYC Floodnet project is beginning to collect observations of flooding when it occurs, but more monitoring of rainfall, in-sewer flows, and flooding, along with H&H modeling of pluvial flooding processes and impacts is needed.

- **Description of evidence**: In this assessment we utilize the outputs of H&H modeling[17] to evaluate the areal extent of potential pluvial flooding in NYC during moderate and extreme rain events. 311 service requests were used to map the locations across the city where community members have been impacted by street flooding during intense rain events. Narrative data provided through the National Center for Environmental Information's Storm Events Database and *Storm Data* publication also provide insight on severe impacts of historical pluvial flooding across the city and their associated meteorological conditions. Future precipitation projections are based on the mean citywide delta change factors derived from on an ensemble of climate models using the LOCA2 downscaling method for SSP245 (mid-century greenhouse emissions reduction) and SSP585 (unmitigated climate change). These analyses are described in McPhearson et al.[48]
- **New information and remaining uncertainties**: In this assessment, we provide a literature review on impactful pluvial flooding in NYC, and an exposure assessment of vulnerable buildings to pluvial flooding. Although there are multiple mechanisms through which climate change can increase the intensity of cloudburst events in NYC, these processes remain poorly represented in global-scale numerical models used to develop climate projections. We also provide a detailed case study of a cloudburst associated with the remnants of Hurricane Ida in 2021, which resulted in 13 direct fatalities, severe disruptions, and extensive damage in many parts of the city. This case study includes a literature review, an assessment of rainfall rates and recurrence intervals associated with this event, and mapping of 311 service requests of street flooding and other flood-associated complaints. Attribution studies focused on this and similar events are needed to determine the role that climate change may have had in setting it up and how frequently events of similar intensity and spatial extent will occur in NYC in the future. Significant uncertainties remain in quantitative projections for extreme precipitation as the processes associated with short-duration intense precipitation events remain poorly represented in the global-scale numerical models used to develop climate projections.[7] Significant uncertainties also remain regarding rainfall intensity and areal extent thresholds for pluvial flooding and with hazards associated with pluvial flooding such as fast-flowing water and exposure to pathogens.
- **Assessment of confidence based on the evidence**: Based on the available evidence in the scientific literature and the authors' expert judgment, there is high confidence that short-duration, intense precipitation events will continue to increase in frequency and magnitude in the absence of rapid mitigation of global climate change. As a result, pluvial flooding will occur more frequently due to climate change if flood hazard mitigation efforts are not implemented. At the same time, there is only medium confidence in the quantitative projections of these increases, due to remaining uncertainties in the representation of short-duration precipitation processes in global climate models.

Key Message 4: In NYC, fluvial flood risks are spatially localized to areas of the Bronx and Staten Island where surface stream channels remain. In the remainder of the city, historical surface streams were filled and replaced, with their flow routed to the sewer system. As a result, fluvial flood hazard has largely been replaced by pluvial flood hazard in most of the city. Both fluvial and pluvial flood hazards will increase due to climate-change-driven intensification of precipitation and elevation of sea level. While traditional floodplain management can be an effective strategy in reducing exposure to fluvial floods, a broader, watershed-scale approach that retains, details, and redirects stormwater is needed to jointly manage pluvial and fluvial flood risks.

- **Description of evidence**: The locations of remaining inland streams and rivers in NYC were assessed in the FEMA 2013 FIS.[57]
- **New information and remaining uncertainties**: There are high remaining uncertainties on how climate change will impact short-duration, intense rainfall events associated with pluvial and fluvial flooding. These uncertainties are discussed in Braneon et al.[6] and Ortiz et al.[310]
- **Assessment of confidence based on the evidence**: Based on the available evidence and the authors' expert judgment, there is high confidence that fluvial flooding will increase along with pluvial flooding due to climate change if flood hazard mitigation efforts are not implemented.

Key Message 5: Current and future coastal flood risks are caused by high storm tides, rising sea levels, and historical development on landfill over tidal marshes and nearshore areas. In Jamaica Bay, tides and storm surges have also been significantly elevated by historical dredging and landfilling, worsening chronic and extreme flooding. On December 23, 2022, a major flood event around Jamaica Bay was caused, in part, by dredging that has led to amplified storm tides which were nearly a foot higher there than elsewhere in the harbor. Further improvement of our understanding of future coastal flood hazard is possible through downscaling of climate model data and modeling of multiple compounding flood drivers.

- **Description of evidence**: Recent research has demonstrated that Jamaica Bay landscape changes have made tides larger and worsened storm tides, playing a similar role to past sea level rise in worsening flooding.[3,164]
- **New information and remaining uncertainties**: Important remaining uncertainties for coastal flood hazard are baseline storm

climatology and climate change effects on storms. Moreover, a case is made (Section 6.4) that coastal storm surge models used for risk assessment and forecasting may have inaccuracies due to the challenge of simulating flow through the narrow and sharply curving areas of East River.

- **Assessment of confidence based on the evidence**: There is very high confidence that sea level rise will continue to worsen monthly and extreme coastal flooding, but large uncertainties remain in the exact amounts, as reflected in NPCC projections. Confidence is high that landscape change has worsened flooding for Jamaica Bay, given that the finding is based both on contrasting models and observations from the 1870s and modern era. Confidence is low in the effects of future storm changes on coastal flooding.

Key Message 6: Many NYC neighborhoods have very shallow groundwater tables and already experience groundwater flooding. These areas include parts of the city that were developed when groundwater levels were substantially lower due to historical pumping of groundwater for municipal water supply. Groundwater flood risk has the potential to be particularly significant in NYC because of the prevalence of subterranean infrastructure. Groundwater flood hazards have not yet been assessed citywide, but preliminary efforts are underway. Sea level rise may cause groundwater levels to rise, resulting in inflow and infiltration of groundwater into sewer pipes and subterranean spaces and inundation of topographically vulnerable locations from below. Improved characterization of spatially heterogenous aquifer hydraulic properties and sustained monitoring of groundwater levels will be necessary to develop projections for future groundwater flooding.

- **Description of evidence**: Observations of shallow groundwater levels in Brooklyn and Queens are available through 2012, but continuous observations along the coast are not available to allow for an analysis of trends with sea level rise. There is also very limited observational data available on aquifer properties and shallow groundwater levels in Manhattan, The Bronx, and Staten Island so exposure assessment could not be conducted for these boroughs.
- **New information and remaining uncertainties**: There are remaining uncertainties about the rate of sea level rise and substantial remaining uncertainties associated with the hydrogeology of NYC's complex subsurface, both of which will determine the transient response of the groundwater table to sea level rise. There are also remaining uncertainties associated with the rate and distribution of groundwater pumping to dewater subgrade spaces and tunnels and its potential impacts on the water table and receiving water quality.
- **Assessment of confidence based on the evidence**: Confidence on both the magnitude, spatial distribution, and timing of the groundwater table rise in response to sea level response—and resulting groundwater flooding in the absence of mitigation efforts—remains very low.

Key Message 7: Climate change is increasing the frequency of extreme precipitation events and elevating sea levels, increasing the likelihood of compounding of either one of these flood drivers by the other. In addition, tropical and post-TCs have caused severe storm surges and extreme rainfall to occur simultaneously. Although assessment is limited by the small number of historical TC events, the limited evidence suggests that TCs can cause low-probability, dangerous compound flooding. Given the importance of TCs and limited historical data, a deeper understanding of compound flood hazard likely requires detailed modeling and downscaling to simulate such storms under the present and future climate.

- **Description of evidence**: Sea levels have risen 1.5 ft since 1860 and are accelerating, with projections of 25–65 in. by 2100 (~2 to ~5.5 ft; 80% confidence range).[6] Significant increases have been observed in the frequency of extreme (95th and 99th percentile) rain events and in the magnitude of all rain events in the NYC Metropolitan Area since the mid-20th century.[6] Further increases are projected through the 21st century.[6] These separate changes alone can increase the potential for compound flooding.
- **New information and remaining uncertainties**: Analyses of historical data under the Climate VIA project (Section 8) have quantified the baseline present-day flood hazard from co-occurrence of rain and storm surge. The research focused on simultaneous and near-simultaneous rain and storm surge through analysis of hourly historical data because NYC is located on several small, heavily urbanized watersheds, where timescales of drainage are short, and rain and surge must be nearly simultaneous to cause compounding. The results reveal nonzero correlations between rain and storm surge and that there is a higher probability of one variable being extreme when the other is extreme. For all storm type data merged together, rain and surge have a low, but nonzero rank correlation. However, for TC data alone, their correlation can be high. In addition, when one of the two flood drivers is extreme (the "primary" driver), the magnitude of the secondary flood driver during TCs is much higher than for other storm types. More comprehensive research on all flood hazard types, including groundwater and Bronx River-fluvial compound flooding, is needed. Although most research to date has focused on less-frequent, extreme compound events, more research on the chronic flooding that will result from more-frequently occurring high tides and the infiltration of groundwater into storm drains sewers is needed for NYC. Moreover, a critical next step will be compound flood modeling and analyses of street flood observations alongside the results of statistical assessments like those summarized above, to translate these data into an understanding of actual on-the-ground impacts; two drivers can co-occur, but their combined flood depth is often less than their sum.
- **Assessment of confidence based on the evidence**: The limited historical record of TCs affecting NYC limits our confidence in NYCs potential for joint occurrences of heavy or extreme rain and surge, which we understand with medium confidence. We have high confidence that there will be increased chronic compound flooding from rainfall and higher sea levels unless flood mitigation efforts are undertaken.

Key Message 8: NYC's NNBS provide many valuable ecosystem services, including critical water regulation services that can play a role in FRM. However, many of these systems are themselves vulnerable to different flood hazards, especially along the coast. Research into how different types of NNBS are impacted by flood/storm surge events, hydroperiod changes, rising water tables, and salinization is needed to better evaluate future changes in ecosystem services. Opportunities for designing NNBS to mitigate the impacts of various flood hazards need to be further explored.

- **Description of evidence**: Intensive development of NYC has significantly reduced the area and functionality of its natural systems, replacing them with developed surfaces. Research into the impact of climate change on natural systems is underway in NYC and throughout the region but more work is needed to examine how specific changes are impacting specific systems and what can be done to mitigate negative impacts.
- **New Information and remaining uncertainties**: More research is needed to understand how NNBS responds to climatic changes including changes in precipitation patterns, temperature, and tidal flood frequency.
- **Assessment of confidence based on the evidence**: We have great confidence that climate change and historical development have negatively impacted natural systems.

Key Message 9: Comprehensive FRM plans must be designed to address the full range of flood hazards faced by individual communities. Planning must begin with participatory decision-making processes that establish neighborhood-specific levels of acceptable future flood risk. To reduce risks from current levels, FRM tailored to each community will include combinations of structural and nonstructural approaches, including NNBS, that are implemented in ways that reduce social vulnerability and are also synergistic with community histories, needs, and goals.

- **Description of evidence**: A large body of research has been published recently on FRM locally, nationally, and internationally. This research includes peer-reviewed journal papers, gray literature, and practitioner reports focusing on the physical effectiveness of these responses and the logistical, governance, and socioeconomic factors that constrain their implementation.
- **New Information and remaining uncertainties**: Much of the research on FRM is nascent. Very few long-term studies exist.
- **Assessment of confidence based on the evidence**: We are very confident that successful FRM strategies will both respond to the unique set of local flood risks and be synergistic with community needs.

12 | SUSTAINED ASSESSMENT

NYC's flood risks vary across the four types of flooding presented herein and in the ways in which they may compound. Moreover, these risks require watershed-scale understanding of stormwater for pluvial and fluvial flood risks, improved characterization of, and monitoring of groundwater levels and potential for future groundwater flooding, and more holistic approaches to capture coastal flooding impacts alongside more comprehensive understanding of existing systemic adaptive capacities.

Although NYC's NNBSs provide many valuable ecosystem services, they too are at risk from climate change, especially along the coast, and so researching how different types of NNBS are impacted by flood/storm surge events, hydroperiod changes, rising water tables and salinization is needed to better evaluate ecosystem services. Given increasing opportunities to work with NNBS to reduce risks while improving NY's public realm, understanding how such systems might adapt given expected climate changes and how to build into such systems more adaptive capacity remains an ongoing area of research.

Beyond the technical analyses needed, sustained assessment offers New Yorkers the opportunity to deepen their understanding of NYC's flood risks while simultaneously improving individual and organizational capacities to address those risks. While technical experts continue risk assessments, broader collaborations between governmental, institutional, business, and community-based organizations could help New Yorkers to better understand these risks and the implications to the households and economies of New York.

Future assessments could consider how recently launched activities, such as Rainproof NY or the Climate Knowledge Exchange Flood Series, improve community awareness of the ability to cope with, and the opportunities to adapt to, these risks. Moreover, these could be further leveraged to couple technical analyses and community preparedness in mutually supportive ways wherein community readiness becomes a recognized criterion, particularly for communities where planned investments in flood risk reduction measures are underway or are in planning.

Recognizing that sustained assessment sets the stage for ongoing dialogue within these communities and across various groups of stakeholders while also emphasizing shared growth, setting agenda specific to sustained assessment and NYC's flood risks could enable a whole of community approach, similar to the approaches well underway in Copenhagen and Amsterdam.

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NPCC Member Flooding Workgroup Co-chairs

- Bernice Rosenzweig, PhD (Workgroup co-chair), Sarah Lawrence College, Bronxville, NY.
- Franco Montalto, PhD (Workgroup co-chair), Drexel University, Philadelphia, PA and eDesign Dynamics LLC (NYC).

NPCC Flooding Workgroup Panel Members and Scientific Contributors

- Nicole Maher, PhD (NPCC panel member) The Nature Conservancy, Cold Spring Harbor, NY.

- Timon McPhearson, PhD (NPCC F&T Workgroup co-chair) Urban Systems Lab, The New School, New York, NY and Cary Institute of Ecosystem Studies, Millbrook, NY.
- Philip Orton, PhD (NPCC panel member) Stevens Institute of Technology, Hoboken, NJ.
- Eric Sanderson, PhD (Scientific contributor), New York Botanical Garden, New York, NY.
- Pablo Herreros-Cantis (Scientific contributor), PhD candidate, Basque Center for Climate Change, Leioa, ES.

Fellows and Interns

- Fiona Dubay (Sarah Lawrence College NPCC Fellow 2022–2023) conducted analyses and created graphics presented in this chapter.
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- Post-doctoral researcher Ziyu Chen, Stevens Institute of Technology, Hoboken, NJ.

Interagency Climate Assessment Team (ICAT) Members

- Alan Olmsted, City Planner, Office of Resiliency Planning & Management, New York City Department of Transportation, New York, NY.
- Erika Jozwiak, Senior Program Manager, Infrastructure, Mayor's Office of Climate and Environmental Justice, New York, NY.
- Mallory Rutigliano, Supervising Analyst, Mayor's Office of Management and Budget, New York, NY.
- Carrie Grassi, Deputy Director, Waterfront Resiliency, Mayor's Office of Climate and Environmental Justice, New York, NY.
- Melissa Umberger, Executive Director of Risk Analysis and Recovery, NYC Emergency Management, New York, NY.
- Jessica Colon, Senior Policy Advisor/Planning, Mayor's Office of Climate and Environmental Justice, New York, NY.
- Tallant Burley, Senior Policy Advisor, Mayor's Office of Climate and Environmental Justice, New York, NY.

Other Contributors

- Hayley Elszasz, PhD, Climate Science Advisor, Mayor's Office of Climate and Environmental Justice, New York, NY.
- Janice Barnes, PhD, Managing Partner, Climate Adaptation Partners, New York, NY.
- Leo Temko, MSc, General Partner, Climate Adaptation Partners, New York, NY.
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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Bernice Rosenzweig https://orcid.org/0000-0002-4888-3653
Franco A. Montalto https://orcid.org/0000-0001-8920-1834
Philip Orton https://orcid.org/0000-0003-3708-5661
Nicole Maher https://orcid.org/0000-0002-7698-7484
Ziyu Chen https://orcid.org/0000-0002-5977-5287
Eric Sanderson https://orcid.org/0000-0002-7477-0193
Timon McPhearson https://orcid.org/0000-0002-9499-0791
Pablo Herreros-Cantis https://orcid.org/0000-0002-2278-0648

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