Multi-hazards risks in New York City

Yaella Depietri[1], Khila Dahal[1], and Timon McPhearson[1, 2, 3]

[1] Urban Systems Lab, The New School, New York, NY, USA

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

[3] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

Correspondence to: Timon McPhearson (timon.mcphearson@su.se)

Abstract

Megacities are predominantly concentrated along coastlines and making them exposed to a broader mix of natural hazards. The assessment of climatic hazard risk to cities rarely has captures the multiple interactions that occur in complex urban systems. We analyze the risk of New York City as a case study to develop initial methods for multi-hazard risk assessment given the history of exposure to multiple types of natural hazards which overlap spatially and, in some cases, temporally in this coastal megacity. Our aim is to identify hotspots of multi-hazard risk to support the prioritization of adaptation strategies that can address multiple sources of risk to urban residents. We used socio-economic indicators to assess vulnerabilities and risks to three climate related hazards (i.e. heat stress, inland flooding and coastal flooding) at high spatial resolution. The analysis incorporates local experts' opinions to identify sources of multi-hazard risk and to weight indicators used in the multi-hazard risk assessment. Results show spatial hotspots of multi-hazard risk with similar local residential communities along the coastlines that experience risk to multiple hazards. Analyses suggest that New York City should prioritize adaptation in coastal zones and consider possible synergies and/or tradeoffs to maximize impacts of adaptation and resilience interventions in the spatially overlapping areas at risk of impacts from multiple hazards.

Keywords

Adaptation, disaster risk reduction, megacities, multi-hazard risk, social vulnerability, spatial assessment, New York City

1. Introduction

Megacities (i.e. urban areas exceeding 10 M inhabitants) host 500 M people or 6.8 % of the global population, a proportion that is projected to rise to 8.7% by 2030 (UNDESA, 2016). These urban agglomerations are highly interconnected and vibrant centers in which enormous physical and intellectual resources are concentrated. Mainly located along waterways and coastal areas, megacities tend to be more exposed to disasters and suffer higher social and economic losses (UNDESA, 2016). Earthquakes, cyclones and flooding are the major threats to megacities (Philippi, 2016). Large cities themselves modify the local and regional environment, changing the microclimate (e.g. by creating urban heat islands), paving over soil and altering ecosystem processes, and building up infrastructure (e.g. roads, buildings, pipes, wires), which, together with projected impacts of climate change such as sea level rise, contributes to magnifying hazard impacts in coastal inhabited areas (Pelling and Blackburn, 2013). New York City (NYC), a regional megacity, results to be highly exposed to multiple hydro-meteorological hazards. For example, on the 29th of October 2012, hurricane Sandy made landfall close to Atlantic City, New Jersey (US) with the intensity of a category 3 hurricane. Located approximately 200 km north, the NYC area was severely affected by the hurricane, which surprised the city largely unprepared to cope with the magnitude of such an event. The city suffered widespread damage to buildings, power outages, interruptions in utility service and large-scale flooding. In the Metropolitan region 97 people lost their life, thousands were displaced and economic losses amounted to more than US$ 50 billion (Abramson and Redlener, 2012). Hurricane Sandy triggered a series of responses from the local administration. Since then, the NYC Office for Emergency Management has developed multiple initiatives to decrease risk to coastal storms, as described in the 2014 NYC Hazard mitigation plan. Additionally, the city established the Mayor's Office for Recovery and Resilience in 2014. Innovative design approaches lead to the recently approved Big U coastal resilience project that is planned as a fortification of lower Manhattan to protect it from future storm surges and flooding. However, coastal hazards are not the only extreme events that threaten New Yorkers. According to the U.S. Centre for Disease Control and Prevention and the US Environment Protection Agency, heat waves kill on average more persons than any other extreme event in NYC (Depietri and McPhearson, 2018). Then, even precipitation events as low as 38 mm a day are of concern to local authorities because they create surface flooding which impact residents and infrastructures.

Hazards in urban areas often overlap spatially and/or temporally (e.g. rainfalls and storm surges, or heat waves followed by a storm), though these overlaps are rarely adequately captured by research and policy. Attention has traditionally been paid to the physical components of risk to hazards, focusing on the potential joint impacts that multiple hazards could have on the infrastructures and buildings within certain sensitive areas or locations because of their frequency and intensity (e.g. Kappes et al., 2012b; van Westen et al., 2002). There has been less study to assess the socio-economic components of multi-hazard risk in cities in order to design combined plans and policies that can together address multiple sources of vulnerability and risk (Johnson et al., 2016). Policies based on mono-hazard risk assessments could reduce or even increase vulnerability and risk to other hazards affecting the same area. A multi-hazard risk assessment, instead facilitates identifying potential synergies or tradeoffs for adaption policies and specific interventions and can maximize resilience and adaptation by meeting challenges posed by different sources of natural hazard risk. For example, tree planting or green roof investments to increase stormwater infiltration can also be a synergistic strategy for the reduction of the urban heat island (UHI).

The objective of this study is to provide a multi-hazard risk assessment of NYC as a case study of how megacities in coastal areas are affected by multiple, spatially overlapping hazards. NYC is an important megacity for examining multi-hazard risk given its global prominence, as being the largest city in the U.S. with hundreds of US$ billions in assets and millions of people at risk. It is a coastal city threatened by multiple hydro-meteorological hazards, further exacerbated by climate change. Here we report data on past and future, potential multi-hazards events in NYC and assess the combined socio-economic risks of residents to three different sources of climatic hazards: heat waves, inland flooding and coastal flooding. The analysis is based on the spatial features of hazards and social vulnerability in the city to inform resilience and adaptation planning that typically focuses interventions on single hazards. In this way we intend to provide a scientific basis for future planning in the city as well as recommendations for real world implementation of such a multi-hazard assessment for other similarly exposed urban areas.

1.1. Vulnerability and risk assessment to natural hazards

The study of the impacts of natural hazards on the social-ecological systems has moved from the focus on the geophysical, climatological or hydro-meteorological phenomena by considering first physical vulnerability (i.e. exposure and fragility of the exposed elements) and only later the socio-economic, institutional and cultural factors that increase the exposure, susceptibility and coping capacity of the system (Bankoff et al., 2004; Birkmann, 2006; Cardona, 2004). In this perspective the occurrence of a hazard does not necessarily lead to a disaster. Disasters are socio-cultural constructions driven by the features of the affected social-ecological system, its health and it's management which all contribute in defining risk from hazards (Oliver-Smith, 2004). In this sense, risk also concerns the values, knowledge and actions of a particular society (Cardona, 2004; Wisner et al., 2014). Economic factors also play a role in defining vulnerability and thus risk. For instance, poor populations tend to settle in hazard prone areas where housing costs are lower, or through past political, economic and cultural legacies that provide them little alternative, putting them at higher risk (Wisner et al., 2014). The same hazard can cause very different impacts in adjacent areas which differ for their socio-economic activities and institutional or governance practices. An example from Collins (2010) describes how in "Paso del Norte" (a city between two countries: El Paso County, USA and Ciudad Juárez, Mexico) the impacts of floods, that occurred between July and September 2006, were overall of an order of greater magnitude in the Mexican part of the city due to unequal power relations expressed through the economic system. Risk is thus a complex concept that encompasses both the features of the hazard and that of the system potentially affected.

1.2. Multi-hazard risk assessment

A subgroup of hazard risk-assessments that considers more than one hazard at a time are called multi-hazard risk assessments. The UNSIDR glossary of term of 2009 defines multi-hazard as "(1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects". The need for multi-hazard approaches is acknowledged at the local, national and international level. Already in the early 1990s, the multi-hazard risk approach was proposed as a requirement for the development of strategies aiming at sustainable urban development. The need for multi-risk assessment is part of Agenda 21 for sustainable development, formulated during the UN Summit in Rio in 1992, which requests "complete multi-hazard research" as part of human settlement planning and management in disaster-prone areas (UNEP, 1992). This was reaffirmed in the Johannesburg Declaration of Sustainable Development in 2002, which required "[a]n integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery" (UN, 2002, p. 20). The Hyogo Framework of Action 2005-2015 pledged for the introduction of "integrated, multi-hazard approach[es] for disaster risk reduction […] into policies, planning and programming related to sustainable development, relief, rehabilitation, and recovery activities in post-disaster and post-conflict situations in disaster-prone countries" (UNISDR, 2005). The Sendai Framework for Disaster Risk Reduction 2015-2030, which follows the Hyogo Framework of Action, calls for disaster risk reduction practices to be multi-hazard, besides being multi-sectoral and inclusive. And yet, despite decades of attention, we still have little understanding of risks posed by multiple hazards spatially and temporally interacting in sensitive area around the world (Wipulanusat et al., 2011).

There are different ways to look at how multiple hazards affect a same area, or a group of subjects or objects. A hazard can lead to another hazard through cascading effects (e.g. a heavy storm causing landslides) (1); two or more hazards can simultaneously impact a same area (2); or hazards can impact in sequence a same subject or object leading to cumulative effects (3) (Kappes et al., 2012a). Some studies have assessed certain aspects of multi-hazard risk in the recent literature. Bernal et al. (2017), adopt a probabilistic approach to analyze physical risk to earthquakes, landslides, and volcanic eruptions jointly. Similar approach to physical risk was adopted by van Westen (2002). Liu et al. (2015) propose a multi-hazard risk framework, comparable to the one we apply in this study, but show an example of multi-hazard risk focusing on physical vulnerability. Forzieri et al. (2016), look at the multi-hazard assessment in Europe linked to climate change impacts, considering the hazards features only and leaving for future investigation the vulnerability component. Most of these case studies thus look at physical vulnerability and risk and consider potentially cascading hazards. Few studies have looked at the socio-economic component of risk in multi-hazards assessments (Greiving, 2006; Johnson et al., 2016). In this study we explore the socio-economic vulnerability and risk spatially and by using an extensive survey amongst local experts and stakeholders to identify sources of multi-hazards risk and to derive weights assessing the importance of different hazards and the vulnerability indicators selected. We develop a context specific case of multi-hazard risk assessment of NYC, but with a generalizable approach that can be adapted to other regions with variations on the choice of the hazards, vulnerability indicators and weights assigned to the indicators themselves.

1.2.1 Multi-hazard risk in large urban areas

Urban areas worldwide tend to suffer greater fatalities and economic losses when compared to their rural counterparts due to the concentration of people, infrastructures and assets as well as to inadequate management (Dickson et al., 2012). The high concentration of infrastructures in urban areas (water supply network, sewage systems, transportation, subways, roads and railways, energy supply network, telecommunication system, green infrastructures) put them particularly at risk in case of failure or damages of these critical systems (Graham, 2010). Amongst the natural hazards, heat wave is a predominantly a urban hazard, meaning that higher degrees of mortality and morbidity are experienced in cities compared to rural areas (Clarke, 1972; D'Ippoliti et al., 2010). In coastal cities a high number of people are also exposed to storm surges, water intrusion and erosion (Nicholls and Small, 2002). Coastal ecosystems are the most productive as well as the most threatened by human activity and expanding urban development in these zones with increasing concentration of infrastructure and people ultimately further increases risk (MA, 2005; Pelling and Blackburn, 2013). Urbanization and climate change in coastal areas are on a collision course and understanding and planning for multi-hazard risk is an increasingly critical part of climate change resilience and adaptation planning, policy and management.

Different hazards such as floods, heat waves and earthquakes, when concentrated in densely populated urban areas, make multi-hazard assessment an important yet challenging task for decision makers. A recent study analyzed the risk to multiple hazards including landslide, typhoon and heat wave in two districts of Hong Kong and found that, despite socio-economic differences of the two districts, both present comparable levels of risk (Johnson et al., 2016). van Westen et al. (2002) looked at physical risk (i.e. of buildings and infrastructures) in a spatial manner to suggest possible mitigation measures for Turrialba in Costa Rica, a city exposed to flooding, landslides and earthquakes. Kappes et al. (2012b) assessed geo-physical risk of Faucon municipality located in the Barcelonnette basin, in Southern French Alps, to debris flows, shallow landslides and river flooding to support priority settings for users. Likewise, Lozoya et al. (2011) took an ecological perspective to assess risk of multiple hazards such as riverine floods, storm-induced coastal floods and storm-induced erosion in S'Abanell urban and touristic beach of Spain, finding that cultural and regulating ecosystem services were the most affected by hazards in the area. However, few studies have focused on multi-hazard risk assessment with a strong social component to understand vulnerability in coastal megacities of the developed world.

Multi-hazard mapping, which consists of "the totality of relevant hazards in a defined area" (Kappes et al., 2012a), is a fundamental approach for multi-hazard risk assessment in urban areas and relevant for the NYC area. Such an approach allows for the identification of potential hotspots of risk and vulnerability derived from spatial combination of more than one hazard. In this perspective, the effects of the hazards are considered as additive, with overlapping degrees of impacts. In this way, impacts acting in the same locations, without interacting causally or coinciding contemporaneously, can be considered jointly. The approach facilitates the identification of structural improvements that can lead to the combined reduction of the exposure to two or more hazards in urban areas. The socio-economic determinants of vulnerability, which often lead to the concentration of vulnerable people in certain area of the city, are examined jointly and help the identification of zones of the city more likely to suffer harm from multiple hazards and in which more resources should be invested for adaptation. Multi hazard risk is composed of two main steps: the analysis of the hazards and of the vulnerability of the system. Thus it widely refers to the vast literature on disaster risk and vulnerability assessment mentioned above (e.g. Birkmann, 2006; Birkmann et al., 2013; Bogardi and Birkmann, 2004; Cardona, 2004; Pelling, 2003; Turner et al., 2003; Wisner et al., 2014). The vulnerability component expresses the predisposition of the system to suffer harm and it generally expressed through the degree of exposure of the system (or number of subjects or objects potentially affected by the hazard, the susceptibility (or the fragilities of the system exposed such as the health of the population) and the lack of resilience (or the incapacity to be prepared, cope and respond to the hazard) (Birkmann et al., 2013). Here, we analyze how multiple hazard risks overlap spatially in New York City with the goal of supporting planning and policy for three key objectives: 1) to improve risk reduction through multi-purpose strategies, 2) to improve adaptive capacity of the city, and 3) to suggest a potential approach for similar multi-hazard risk assessments in other vulnerability urban areas and settlements.

1.3. New York City and disaster risk

NYC is the largest city in USA and is located on the East coast (see Figure 1), with approximately 8.2 million people in just the municipal area with over 10,500 people per km^2 according to U.S. Census Bureau (2010). The NYC-Newark-New Jersey metropolitan statistical area is much larger, with 20.3 Million people living in the region closely connected socially, economically, and infrastructurally to NYC[1]. The metropolitan area is also the largest city in the U.S. in terms of economic activity, this according the U.S. Census Bureau. Approximately 1.4 million people aged 60 and older live in the city, representing a particularly vulnerable group, especially for heat-related morbidity and mortality. Elderly constitute 17% of the population at present, and this proportion is expected to grow considerably in coming years (Goldman et al., 2014). NYC is also built around a network of rivers, estuaries and islands with much of the Metropolitan region situated less than 5 m above mean sea level (Colle et al., 2008) which contributes to the hazard context especially in terms of coastal flooding.

We focus our analysis on three hazards that cause the highest human impacts in NYC (see Depietri and McPhearson, 2018): heat waves, inland flooding and coastal flooding. Heat waves in NYC are defined by the NYC Panel on Climate Change (NPCC) 2015 Report as three consecutive days above 90F (or about 32.2 °C) (Horton et al., 2015a). Inland flooding in NYC can be triggered by precipitation of more than 1.5 inches

[1] https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk (retrieved on March 25th 2018)

(or 38 mm) of rain per day since the city's drainage system is designed to handle heavy rainfall with intensities of 1.5 inches (about 38 mm) per day in most areas of the city where sewers were built prior to 1960, and of 1.75 inches (about 44 mm) per day in locations with sewers were built after 1960 (Llyod and Licata, n.d.). Coastal flooding is primarily driven by storm surge. NYC is affected by changing climate with future projections including probable higher temperatures, increasingly frequent heavy downpours, and a rising sea level that will further increase storm surge and coastal flooding (Garner et al., 2017; Horton et al., 2015a; Lin et al., 2012, 2016; Reed et al., 2015; Rosenzweig and Solecki, 2015). In the next sections, we describe each hazard and its local impacts. Information about multi-hazard risk in the city is scarce in the available literature, consequently we have combined multiple sources of evidence of the occurrence of multi-hazards events in NYC and review them in section 3.1.

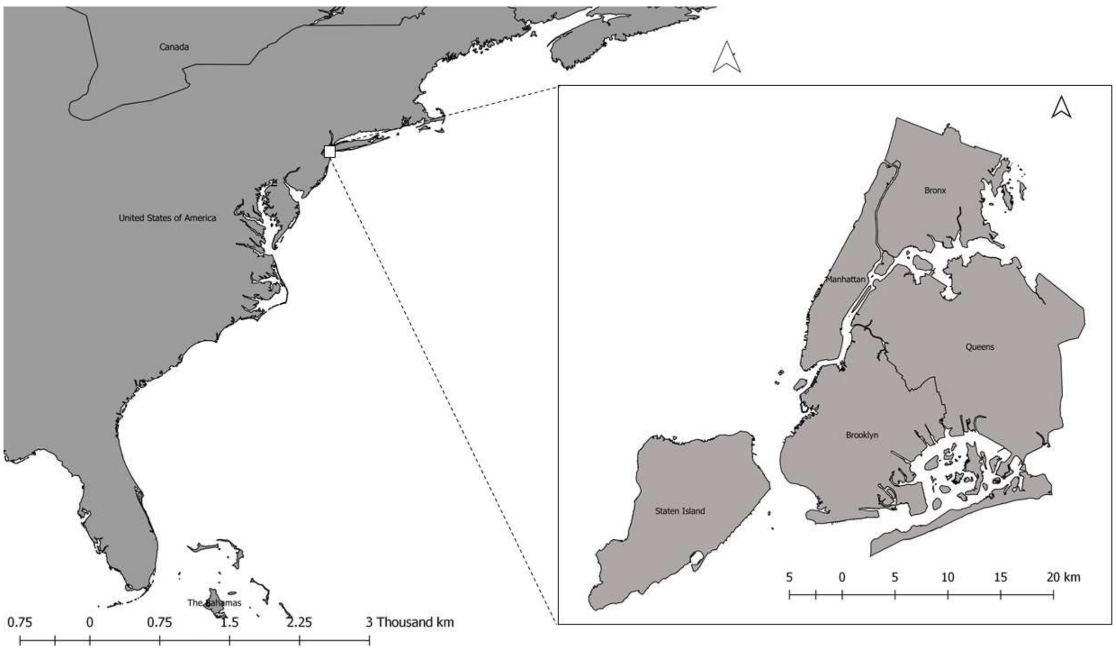


Figure 1. Location of New York City and the map of it boroughs (own elaboration).

1.3.1. Heat waves

As mentioned above, heat waves in NYC are the largest cause of death due to socio-natural hazards (Depietri and McPhearson, 2018; NYC, 2014). Disastrous heat waves include the July 1966 event, where the mortality rate increased by 36% (Schuman, 1972) and the summer 1972 heat wave which caused 253 deaths on the 24th of July only (Ellis et al., 1975). According to the NYC Department of Health and Mental Hygiene, 46 heat stroke deaths resulted from two heat waves in July-August 2006 while 26 heat related deaths occurred during the heat wave of July 2013 (NYC, 2014, 2006). Between 2000 and 2011, 447 patients were treated for heat illness and 154 died (CDCP, 2013). A study by Madrigano et al. (2015) reported up to 234 heat related excess death for the same period. It has been documented that extreme heat impacts have been increasing at least for the period 1987-2005 (Anderson and Bell, 2011). However, numbers of deaths are significantly less pronounced if compared to the first half of 20th century, showing an evidence of adaptation likely due to the use of air conditioning (Depietri and McPhearson, 2018; Petkova et al., 2014).

Risk to heat waves is driven by several factors. Those with poor socio-economic status, for example black (non-Hispanic) individuals, and the socially or linguistically isolated are more likely to die during a heat wave (Madrigano et al., 2015). People with chronic physical or mental health illnesses (i.e. cardiovascular disease, obesity, neurologic or psychiatric disease) also account for a large part of the causalities, together with individuals subject to alcohol or drugs abuse (CDCP, 2013; Ellis et al., 1975). The ageing population is the most at risk to suffer heat stroke during a heat wave (Luber and McGeehin, 2008; Oudin Åström et al., 2011). Madrigano et al. (2015) also found that greener neighborhoods were less at risk in NYC, potentially due to decreased temperatures in those areas of the city. Increased rates of poverty and higher densities of African-American populations were found to be highly correlated with the lack of green spaces in the city (Klein Rosenthal et al., 2014). Low income and crowding where also elements of risk in the 1966 heat waves according to Schuman (1972). Primary indicators of heat vulnerability are relatively consistent across studies with poverty, poor housing conditions, low access to air-conditioning and seniors' hypertension associated with elderly death due to heat stress in NYC between 1997 to 2006 (Klein Rosenthal et al., 2014). Environmental conditions, pervious land cover and aggregated surface temperatures were also found to be positively associated with heat related deaths of elderly (Klein Rosenthal et al., 2014).

Gedzelman et al. (2003) calculated the UHI of NYC to be on average approximately 4 °C warmer than surrounding temperatures in summer and autumn and 3 °C in winter and spring according to measurement taken between 1997 and 1998 (Gedzelman et al., 2003). Temperatures have been rising in Central Park between 1900 to 2013 (Horton et al., 2015a) and it has been estimated that the temperature rose by 1.1 °C between 1900 to 1997 in NYC (Knowlton et al., 2007). One third of the total warming of the city since 1900 was attributed to the intensification of the UHI. Projections show that this trend is likely to continue in the future, with warmer temperatures in NYC in the coming decades driven by UHI and increasing temperatures caused by climate change (Horton et al., 2015a). A study by Knowlton et al. (2007) showed that, despite the possibility to adapt to rising temperature, heat related premature deaths are likely to rise in projected future climates and affect regions also beyond the urban core of the city. Spatial and temporal patterns of current risk combined with projections for increasing temperatures and frequency and intensity of heat waves suggests the need for extensive planning and management to reduce heat risk in NYC.

1.3.2. Inland floods

In NYC, the built environment – dense and heavily paved built up are and reclaimed wetlands – limit the ground's capacity to absorb and drain water, raising the risk of urban or inland surface flooding. Sealed surfaces cover 72% of the NYC areas according to the city Department of Environmental Protection. Much of NYC's infrastructure, especially in low-lying or poor drainage areas, cannot cope with more than 1.5 inches per hour of rainfall (Lane et al., 2013). According to NYC (2014), communities in low-lying areas with limited drainage capacity tend to experience sewer backups, street and basement flooding that can expose them to contaminated storm water and wastewater. Combined sewer overflows, occurring when sewage and storm water are discharged from sewer pipes without treatment, because of the treatments plants are unable to handle flows, are frequent in NYC and are a significant source of environmental pollution (Rosenzweig et al., 2006; Rosenzweig et al. 2018). Excessive rain washes away pollutants from the streets which end up in the surrounding bodies of water. Exposure to contaminated water can have both short and long-term public health effects. Flooded basements and houses increase allergies, asthma and other respiratory illness from exposure to mold and fungus. However, flash floods in NYC are rarely life threatening because of the local topography (Lane et al., 2013).

Precipitation has increased at a rate of approximately 20.3 mm per decade from 1900 to 2013 in Central Park and this trend is likely to continue according to climate projections (Horton et al., 2015a). The city committed to a plan to invest in green infrastructures for storm water management, investing US$ 5.3 billion and saving approx. US$ 1.5 billion by spending a portion of this investment on green infrastructure in combination with traditional pipe and tanks improvements (NYC, 2010). The green infrastructures planned include green and blue roofs, rain gardens, permeable pavements, bioswales and the planting of street trees. However, inland flooding is likely to continue to pose significant risks to the urban residents of NYC.

1.3.3. Coastal flooding

Almost 33 square miles (about 85.5 square km) of NYC are within the equivalent of a 100-year floodplain (close to half of Brooklyn) (NYC, 2013). The most frequent coastal storms affecting NYC are nor'easters (i.e. storms along the East Coast of North America, so called because the winds over the coastal area are typically from the northeast, according to NOAA[2]). Even moderate nor'easters events can cause significant flooding (Colle et al., 2008) and are often associated with extended periods of high winds and high water (Rosenzweig et al., 2011). Extratropical first and then tropical cyclones tend to generate the greatest storm surge heights and flooding in NYC (Catalano and Broccoli, 2017; Smith et al., 2010; Towey et al., 2018), which can reach up to 5.12 m according to Lin et al. (2010). Extratropical storms account for 80%–85% of total precipitation from December to May and 93%–100% of extreme precipitation from November to May in the Northeastern coast of the U.S. (Agel et al., 2015). Hurricanes affect NYC more infrequently. However the associated flooding are being exacerbated due to the increase of sea level and the increase in the intensity of the hazard itself (Kemp and Horton, 2013; Reed et al., 2015b). Five major hurricanes of category 3 have affected the New York area between 1851 and 2010, mostly in the month of September (Blake et al., 2011) and generally lead to large damages (Rosenzweig et al., 2011). In 2012, Hurricane Sandy made landfall as a post-tropical cyclone in New Jersey with 70-kt maximum sustained winds, droving a catastrophic storm surge into the New Jersey and New York coastlines (Blake et al., 2013). In NYC the storm surge was of 2.81 m and was at the origin of most of the damages and losses (Kemp and Horton, 2013). Hurricane Sandy caused

[2] https://www.weather.gov/safety/winter-noreaster (retrieved on the 16th of September 2018)

43 deaths in NYC alone and nearly half were adults aged 65 or older (Kinney et al., 2015). According to Lane et al. (2013), death was caused most frequently by drowning associated with the storm surge. Other deaths were caused by falling trees, falls, electrocution, and other traumas. Further, Sandy caused at least $19 billion in economic losses to the city (NYC, 2013), left hundreds of thousands without power, some for many weeks (Lane et al., 2013). It was also found that power outages increase risk of death in NYC (Anderson and Bell, 2012). Five hospitals shut down due to Sandy, three of them had to evacuate patients after the storm hit because of flood damage to critical equipment; power losses in these facilities further complicated evacuation operations (Lane et al., 2013). Nearly 70,000 buildings were damaged by the storm or destroyed by related fire especially in south Brooklyn, South Queens and Staten Island; the subway system was seriously affected; roads, railroads and airports were flooded; while the communication system was disrupted in many areas (NYC, 2013).

Since Hurricane Sandy, the city established a US$20 billion plan to adapt to climate extremes with 257 initiatives which span from coastal protection, economic recovery, community preparedness and response, and environmental protection and remediation (NYC, 2013). Additionally, the Mayor's Office of Housing Recovery Operations was established in 2013 to oversee housing recovery in NYC.

Increasing hurricane intensity over time has been detected (Gornitz et al., 2001; Knutson et al., 2015). Additionally, three of the nine highest recorded water levels in the New York Harbor region have occurred since 2010, and eight of the largest twenty have occurred since 1990 (Talke et al., 2014). 40% of sea level rise in NYC is driven by subsidence and the rest by global climate change, amounting in total to 25,4 mm per decade since 1900 (Horton et al., 2015b). Due to sea level rise, which is projected to accelerate during this century to reach up to 1.2 m in the coming century (Kopp et al., 2014), coastal flooding in NYC is expected to become more frequent and intense, even in absence of changes in intensity and frequency of storms (Colle et al., 2008; Gornitz et al., 2001; Horton et al., 2015b). A recent study has shown that, by 2030-2045, the megacity could be affected by significant flooding on average every 5 years (Garner et al., 2017). This is ever more significant when considering the high and increasing concentration of assets and people exposed in the coastal areas of the city (Aerts and Botzen, 2012). According to Aerts et al. (2013), the estimated flood damage to buildings for NYC is between US$ 59 and 129 million/year, while the damage caused by a 100-year storm surge is within a range of US$ 2 to 5 billion.

2. Methods

2.1. Multi-hazards events in New York City and indicators weighting

We assessed past heavy precipitation and extreme high temperatures recorded in Central Park from 1876 to date and made available by the US National Oceanic and Atmospheric Administration (NOAA) to examine how temporally consecutive events which occur in the city, this as part of a broader study presented in Depietri and McPhearson (2018). We carried out an analysis of daily NOAA's meteorological records (including daily precipitation, max and min temperatures) to identify dates in which an event of extreme heat would be immediately followed by a storm (or vice versa), two consecutive heat waves events (happening within 3 days from each other's) and consecutive flooding events (two consecutive days of extreme precipitation). We then manually investigated the New York Times database for relevant articles appearing in the edition of the day following the multi-hazard event identified, this to analyze more in depth the occurrence and social, infrastructural and economic impact of cumulative events. We then conducted a survey of local experts and decision-makers with a principal objective to collect weights multi-hazard risk assessment for indicators and sub-indicators selected, but also to collect information of past and future, potential multi-hazards event occurring in the city.

For the survey, we drafted a comprehensive list of the local authorities' representatives, researchers and other local actors such as NGOs whose daily work is related to different aspects of vulnerability and risk to hazards in NYC. The respondents to the survey were thus identified as being highly knowledgeable and have experience of the local hazard risks and impacts. The institutional, urban planning, environmental planning, disaster risk reduction, health and social sectors were represented in the survey. A total of 122 invitation e-mails were sent to contact persons belonging to local and federal institutions as well as local NGOs. Of these, 10 were no longer valid and we subsequently collected 65 responses with a 58% response rate. The survey was anonymous but almost 60% of the respondents belonged to local jurisdictions, about 15% to NGOs, 10% to local universities, while state agencies, federal agencies, and companies represented less than 5% each. No further information about the respondent identity were collected to ensure anonymity.

The list of indicators and sub-indicators weighted by the respondent of the questionnaire were derived from the relevant literature and the final list included those indicators able to describe the vulnerability to the three hazards jointly for which data was available. For the weighting of indicators, we adopted the method of budget allocation, a participatory method (Saisana and Tarantola, 2002). Respondents were asked to rate each indicators by assigning 100 points distributed amongst the set of indicators describing the composite index. Final weights were derived by averaging the scores assigned by each respondent and dividing the means by 100. The weights thus derived were normalized to a fraction of to 1 for each category. Unlike other methods such as analytic hierarchy process (AHP) and Delphi, the technique of budget allocation is intuitive, computationally simple, but accurate, and therefore widely used (Saisana and Tarantola, 2002). The weights obtained are listed in Tables 1 and 2. Additional questions in the survey were related to multi-hazard risk in NYC and the city preparedness to cope with different hazards. The results are presented in section 3.1.

2.2. Multi-hazard risk assessment

We assessed multi-hazard risk to the main three hydro-meteorological hazards affecting NYC described above. In this study, we emphasize the inclusion of social factors of risk by adapting our methodology from Greiving (2006) who carried out a multi-hazard risk assessment at the country level for Europe and from Johnson et al. (2016) who applied a similar methodology to the case of two Hong Kong districts. Overall, the methodology consists of generating hazards maps, one for each hazard (which are then combined in a multi-hazards map) and a common vulnerability map to the three hazards that includes socio-economic indicators. We then obtained the final risk map as the product of the combined multi-hazards map and the common vulnerability map. Note that all variable used have been normalized and expressed as levels, ranging from 1 to 5, of hazards intensity, exposure, susceptibility, lack of coping capacity and then vulnerability and risk This normalization, widely in use in vulnerability and risk assessments, allowed us to conduct analyses across different, otherwise incommensurate, variables.

2.2.1. Hazards mapping

ulti-hazard risk assessment consists of an initial study of combined hazards which overlap temporally and spatially in the megacity. We created a raster surface for each hazard by categorizing the hazard intensity into five ordinal scales of 1 to 5, which are equivalent to standardized hazard levels of very low, low, medium, high and very high. We used Natural Break (Jenks) method of data classification in ESRI's ArcGIS software as the method considers both the span of values and the number of observations for each category (Smith et al., 2007), and is widely used for classification in mapping (Huang et al., 2011).

Especially in the urban context, hazards present a significant social component which magnify impacts due to the high modification of the environment. For creating heat wave hazard surface, we maintained that the hazard affects the entire city with different intensities according to two aggravating factors: surface temperature and air pollution. Surface temperature was derived from thermal band of 2011 Landsat imagery captured on the 15^{th} and 31^{st} of July, while air pollution layer was developed based on raster surfaces of 300-meter resolution for 2010 with annual average values of $PM_{2.5}$ and ozone O_3 concentrations. PM_{10} and O_3 are the main contributors to extreme heat mortality besides heat itself (see Depietri et al., 2011 for a review). We acquired the air pollution data from New York City Community Air Survey (NYCCAS) carried out by the New York City Department of Health and Mental Hygiene, Queens College Center for the Biology of Natural Systems, and Zev Ross Spatial Analysis. Indicators used to develop the heat hazard map were weighted according to the survey responses (see Table 1 and Equation 1 and 2), and then combined resulting in a raster surface with values ranging from 1 to 5.

$$AP = 0.483\, O + 0.517\, PM \qquad \text{(Eq. 1)}$$

$$HW = 0.632\, ST + 0.367\, \text{AP} \qquad \text{(Eq. 2)}$$

where AP stands for air pollution, O for ozone and PM for particulate matter smaller than 2.5µm. HW stands for heat wave hazard and ST for surface temperature.

The inland flooding map was derived through a spatial interpolation of 311 calls for street flooding (data available between January 2010 and December 2015) and basement flooding (data available between July 2011 and December 2015). The 311 calls were obtained from a spatial database developed and maintained by the city of New York which comprises of all sorts of complaint calls. When preparing the inland flooding layer, we removed from the dataset the complaint points that had been recorded during or one day after the event of coastal storms, this to maintain differences between precipitation driven inland flooding and coastal flooding driven by storm surges. The dates and times of storm surges in NYC coastal area were obtained from NOAA's storm events database[3] under the keywords "coastal flooding", "high surf", "tropical storm", "storm surge/tide". The 311 calls dataset has nonetheless some limitations worth a mention. For instance, it does not account for possible differences in the likelihood of reporting flooding amongst populations (e.g. depending on income). However, this is the only available dataset on inland flood occurrence and allows us to consider one of the most frequent and perennial natural hazards affecting NYC – flooding driven by precipitation. Still, NOAA tide gauge data at the Battery in NYC is a useful source of continuously recorded water surface elevation and therefore could be used as an indicator of storm surge heights, though not included in this analysis.

For coastal flood inundation we used the local expert map obtained from the NYC Office of Emergency Management (OEM) with hurricane inundation zones published in 2013. Local authorities suggested that we adopt the hazard map produced after Hurricane Sandy as this would be a more conservative starting point. However, we opted for the general map considering multiple levels of hazard as this had predefined categories of hazard and thus was better able to be compared with the other hazards in a multi-hazard analysis.

The hazards' weights reported in Table 1 indicate that, according to the surveyed respondents, higher impacts would be caused by coastal hazards. This result might be justified by considering the recent occurrence of Hurricane Sandy and its high impacts which triggered high concern amongst local authorities. A final multi-hazard map (H) was generated by adding weighted values of the three hazard layers (IF - inland flooding; CF - coastal flooding), as presented in Equation 3. The resultant composite hazard layer also has values ranging between 1 and 5 to represent the five respective classes of hazard intensity.

$$H = 0.378\,HW + 0.205\,IF + 0.417\,CF \qquad \text{(Eq. 3)}$$

The weighted linear combination of the three hazards intensities considers the hazards to spatially overlap without any additional quantifiable interactions.

Table 1. Hazard indicators selected, and weights derived from the survey.

		Weight	**Indicator**	**Weight**	**Sub-indicator**	**Weight**
Hazards (H)	***Heat waves (HW)***	0.378	Surface temperature (ST)	0.632		
				0.367	Ozone (O)	0.483

[3] https://www.ncdc.noaa.gov/stormevents (retrieved on February 23rd 2017)

		Weight	Indicator	Weight	Sub-indicator	Weight
			Air pollution (AP)		Particulate Matter <2.5μm (PM)	0.517
	Inland flooding (IF)	0.205	311 calls			
	Coastal flooding (CF)	0.417	Hurricane inundation zones			

2.2.2. Vulnerability and risk maps

To be compatible with computation of hazard layers, we developed raster surfaces of 30m spatial resolution for different socio-economic and demographic variables relevant for the three hazards, describing the three components of vulnerability as listed in Table 2. For this reason, we disaggregated the 2010 census data made available by the US Census bureau at the block group level. Disaggregation of census data using dasymetric approaches to a finer spatial scale follows Mennis and Hultgren (2006). We used the number of residential units, land use type, and building type as ancillary information to convert demographic totals from census block groups to spatially corresponding cadastral lots for each vulnerability indicator. The disaggregated data layers were then resampled to a spatial resolution of 30 m to maintain uniformity with the spatial resolution of hazard data layers. These data were used to derive a vulnerability map based on indicators describing exposure, susceptibility and lack of coping capacity. Selection of these indicators stemmed from the review of available literature covered in sections 1.3.1 to 1.3.3 and the weights derived from the survey are presented in Table 2.

Table 2. Vulnerability indicators and weights derived from the survey.

	Component	Indicator	Weight
Vulnerability (V)	***Exposure (E)***	Population (P)	
	Susceptibility (S)	Pop over 65(El)	0.351
		Children (<18) (C)	0.212
		1- Median income (I)	0.191
		African Americans (AA)	0.170
		No schooling completed (NS)	0.117
	Lack of coping capacity (CC)	Speak no English (L)	0.516
		One-person household (HH)	0.484

Vulnerability is defined as the "propensity of exposed elements such as physical or capital assets, as well as human beings and their livelihoods, to experience harm and suffer damage and loss when impacted by single or compound hazard events" (Birkmann et al., 2013, p. 195). This vulnerability perspective in risk reduction particularly looks at the socio-economic, institutional and cultural conditions of people and physical assets which can be affected by a hazard as well as at their capacity to prevent and cope with the impacts of that event. As mentioned, in Birkmann et al. (2013, p. 200), vulnerability is described through three components defined above: exposure, susceptibility and lack of coping capacity.

The first step in the socio-economic vulnerability assessment was to identify the exposed subjects. Exposure (E) was calculated as the number of inhabitants (P) for each 30 x 30 m spatial unit. The other two components of vulnerability are susceptibility (S) and lack of coping capacity (CC). Like the hazards mapping described above, we reclassified each of the indicators into five intensity categories represented by the values of 1 to 5 in such a way that 5 represents the highest level of intensity. For example, smaller values in median income layer represent higher degree of susceptibility and hence were given higher intensity values. The two components of vulnerability (S and CC) were calculated according to Equation 4 and 5:

$$S = 0.351\,EL + 0.212\,C + 0.191\,I + 0.170\,AA + 0.117\,NS \quad \text{(Eq. 4)}$$

$$CC = 0.516\,L + 0.484\,HH \quad \text{(Eq. 5)}$$

where EL stands for elderly, C for children, I for median income, AA for African Americans, NS for no schooling, L speak no English, HH one-person household. We aggregated the indicators as a weighted sum, as each indicator contributes for a fraction of the susceptibility or lack of coping capacity. The S and CC layers thus generated have values ranging between 1 and 5.

Some indicators (i.e. homes in deteriorated or dilapidated buildings, mold in home, asthma, heart attack hospitalizations, overweight, adults reporting heavy drinking, crowding, air conditioning, adults with personal doctor and adults with health insurance) were considered but excluded in the final list because they were not available at the low scale for NYC or because some were not relevant for the three hazards when jointly considered. Respondents to the survey also suggested some additional indicators to consider and are summarized in the results section.

The final vulnerability (V) map was generated by adding exposure (E), susceptibility (S) and lack of coping capacity (CC) layers with equal weights (Equation 6):

$$V = \frac{1}{3}E + \frac{1}{3}\,S + \frac{1}{3}CC \quad \text{(Eq. 6)}$$

We aggregated the three components of vulnerability by summing equally weighted values, a general approach adopted in the literature due to the difficulty to assigning different weights to these three components (see for instance Welle and Birkmann, 2015). Risk to natural hazards, such as hydro-meteorological, climatological or geophysical hazard, is the combination of the probability or likelihood in time and space of a natural hazard to occur and to affect a vulnerable system (UNISDR, 2015). In the disaster risk reduction literature, risk is commonly defined as the product of hazard and vulnerability. The final aggregated risk map was calculated by multiplying the final aggregated hazard map with the vulnerability map (see Equation 7):

$$R = H * V \quad \text{(Eq. 7)}$$

where R is risk, H is multi-hazards and V vulnerability. We multiplied hazard per vulnerability because, following to the definition of risk, with no hazard or no vulnerabilities there would be no risk. The final risk map thus derived comprises of 16 classes with the values ranging from 1 to 25. As for the hazard and vulnerability maps mentioned above, the final aggregated risk is also displayed using five intensity classes.

Our method of aggregation, which first quantifies the indicators of hazard and vulnerability into five ordinal categories and then uses weighted linear combination, is drawn from the existing literature hazard and vulnerability assessment. Previous studies on hazard risk mapping have documented the robustness and accuracy of this method (Greiving, 2006; Greiving et al., 2006; Johnson et al., 2016; Michael and Samanta, 2016; Zhou et al., 2016).

To compare the plausibility of our results, we also followed an additional method of aggregation, which is collectively described as the fuzzy-defined weighted combination (Aydi et al., 2013; Janke, 2010). We followed the same procedural steps, weights, and aggregation formulae except that the numerical values of each of the hazard and vulnerability layers were standardized between 0 and 1 (i.e. 0-100%) instead of the five ordinal classes. When displayed the final risk layer by reclassifying into five categories based on natural break (Jenks), the map was very similar to the final map generated following the method we describe above.

3. Results

3.1. The qualitative results of the NOAA-NYT search and the survey

Most of the temporally overlapping extreme events identified in NOAA database between 1876 to 2016 were related to multiple heat waves happening at distance of up to 3 or 4 days (13 events), followed by two consecutive days of extreme precipitation (9 events) and days of extreme heat followed by high precipitation (3 events). However, thanks to a broader review carried out on the New York Times and described in Depietri and McPhearson (2018), we were able various additional interrelated multi-hazards incidents in NYC, meaning that multi-hazard events have more interrelated impacts which might not depend only on the high intensity of the hazard alone.

The stakeholders who compiled the questionnaire were also asked to provide information related to past and present multi-risk events as well as strategies that they would prioritize for the city. In a multi-hazard perspective, the results of the survey indicated that heat waves in NYC would highly positively interact (i.e. increasing their impacts) with droughts, but also with inland and coastal flooding, although these would have opposed interactions too. Inland and coastal flooding can have additive impacts if they occur at the same time or successively. Furthermore, respondents indicated that other interactions between the wider ranges of hazards affecting NYC have occurred in the past and may occur in the future (summarized in Table 3 and 4 respectively). In our study we cover many of these situations although further analysis can be envisaged to better understand the interaction between the hazards and infrastructures failures chiefly.

Table 3. List of multi-hazard events that happened in the past according to the respondents of the questionnaire.

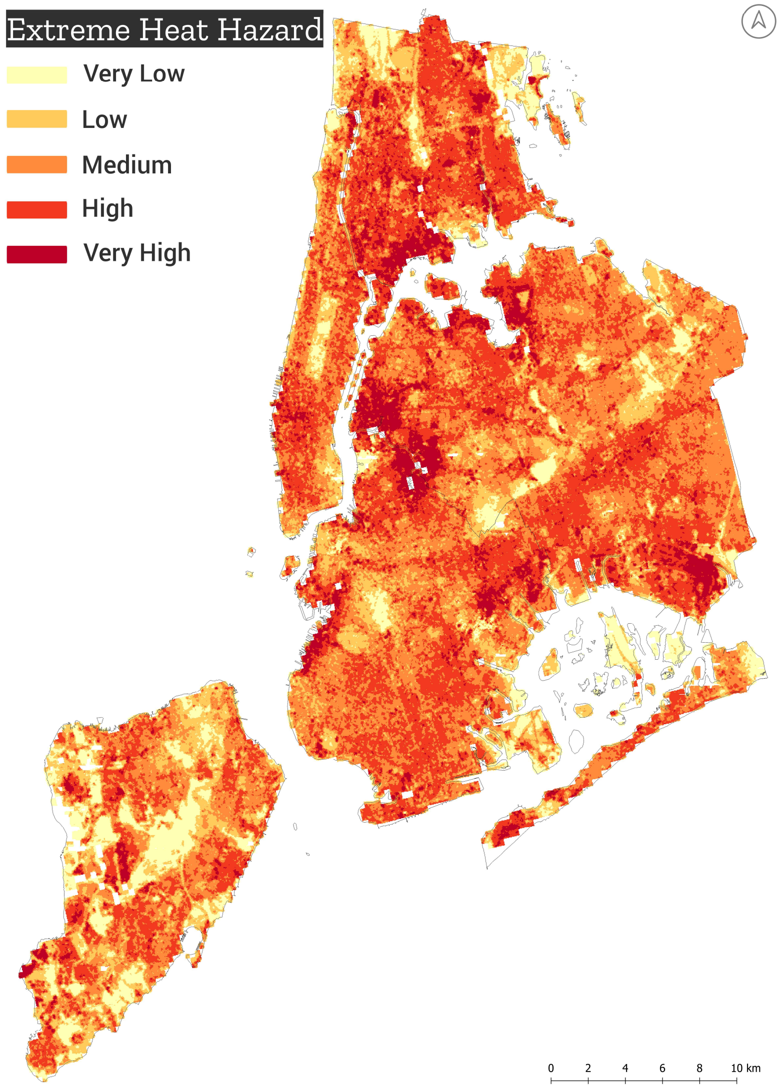
Type	Combination of multi-hazard events that occurred in NYC in the past
1	Hurricane & Cold spell & Inland flooding
2	Heat waves & Thunderstorms & Inland flooding
3	Hurricane & Infrastructure failure

Table 4. List of multi-hazards events that the city should adapt to as these could occur in the future.

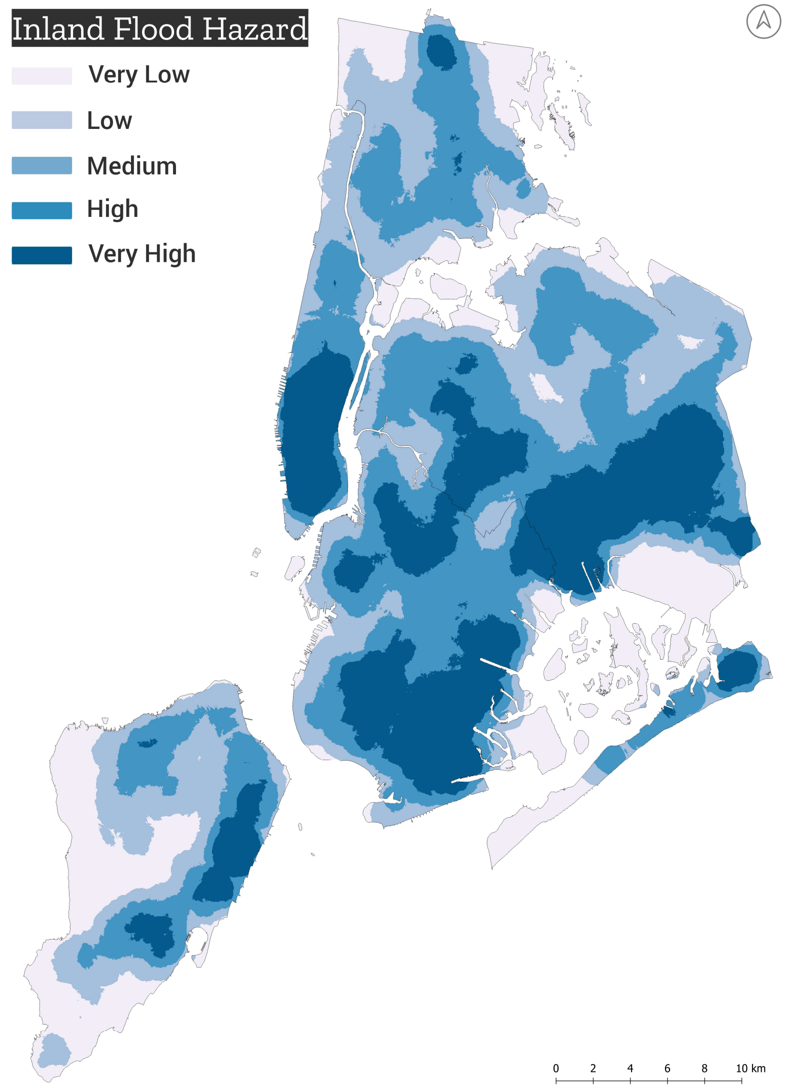
Type	Combinations of multi-hazard events that could occur in NYC
1	Coastal flooding & Exposure to toxic substances
2	Coastal flooding & Inland flooding
3	Coastal flooding & Cod Spell
4	Coastal storms & Power outages
5	Heat waves & Hurricane
6	Heat waves & Power outages
7	Heat waves & Severe thunderstorm
8	Heat waves & Drought

3.2. Multi-hazard risk assessment

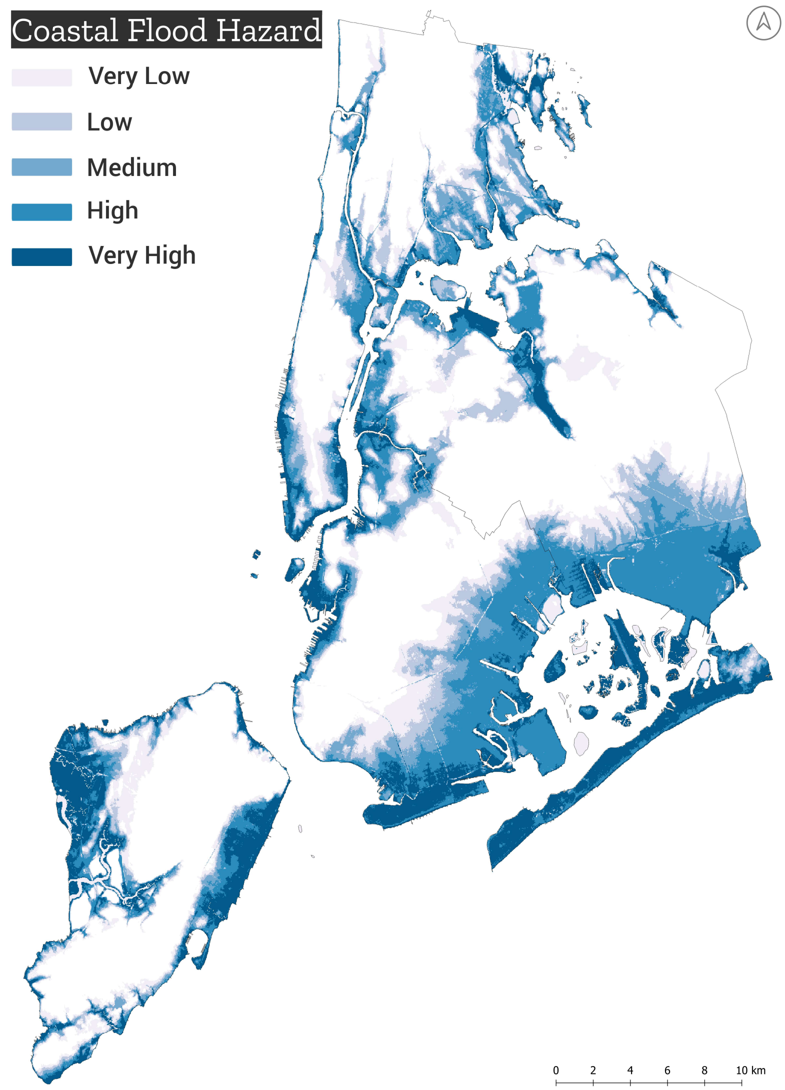
Figures 2 a, b, and c present the mapped analytical results for each of the three hazards considered. Except for heat stress, which is distributed across the whole city with points of low hazard intensity corresponding to the urban parks, the hazards intensities are mainly concentrated along the coast, especially in Manhattan and in Brooklyn.



a. Map of the heat stress based on surface temperature and air pollution



b. Map of the inland flooding based on the 311 calls for street flooding or basement flooding



c. Hurricane inundation zones based on the map provided by the Office of Emergency Management

Figure 2 a, b and c. Spatial variation in heat hazard, inland flooding hazard, and coastal flood hazard for New York City.

Figure 3 displays the joint multi-hazard map with higher intensities in most of the coastal areas. Coastal flooding was assigned a larger weight with respect to the other two hazards based on survey responses, which drives the hotspot analysis somewhat. At present the city is still largely unprepared to cope with flooding and is highly exposed to this type a hazard, a condition that was particularly clear after Hurricane Sandy. Inland flooding was shown to be most intense along the coast, further strengthening the presence of hazards along coastal areas, though further modeling is required to better understand the drivers of inland flood hazards and where they are likely to occur in the future.

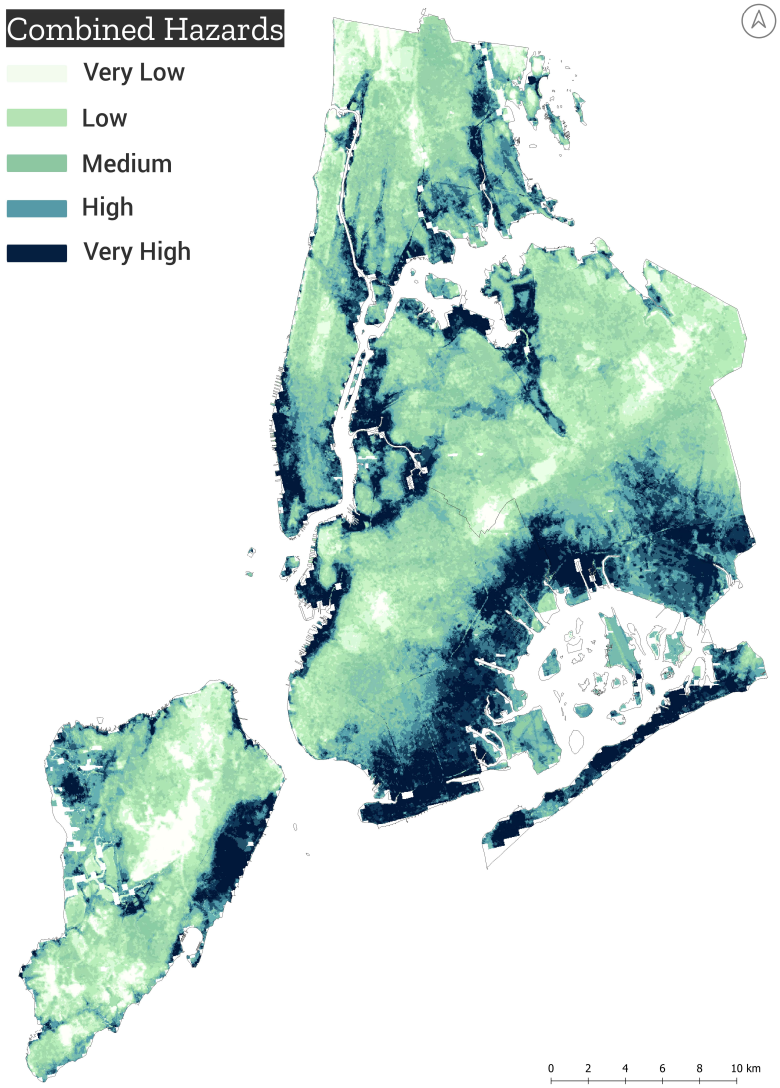
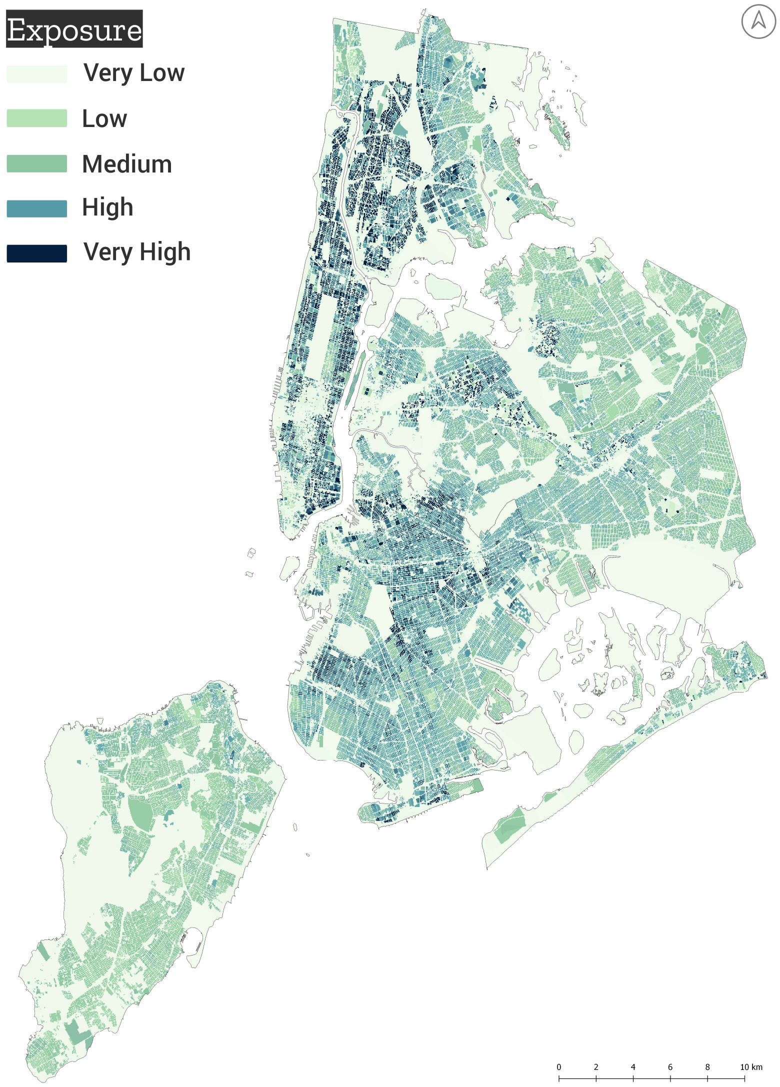
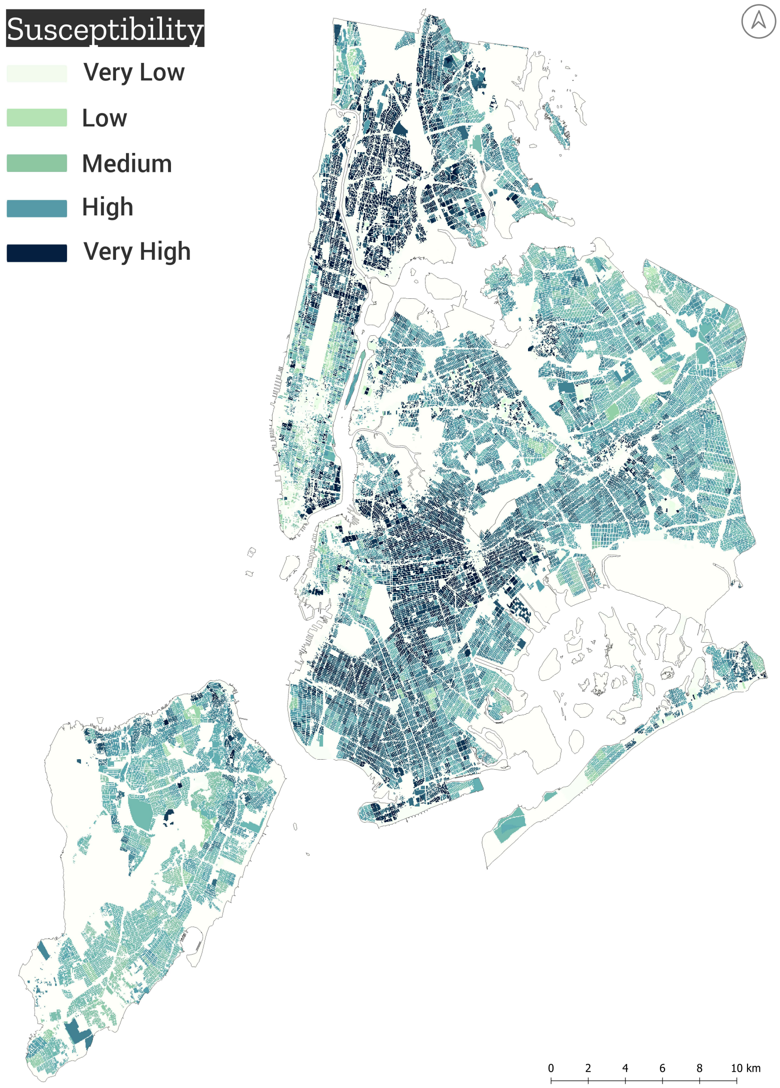


Figure 3. Spatial variation in the combined hazards including weights derived through expert input.

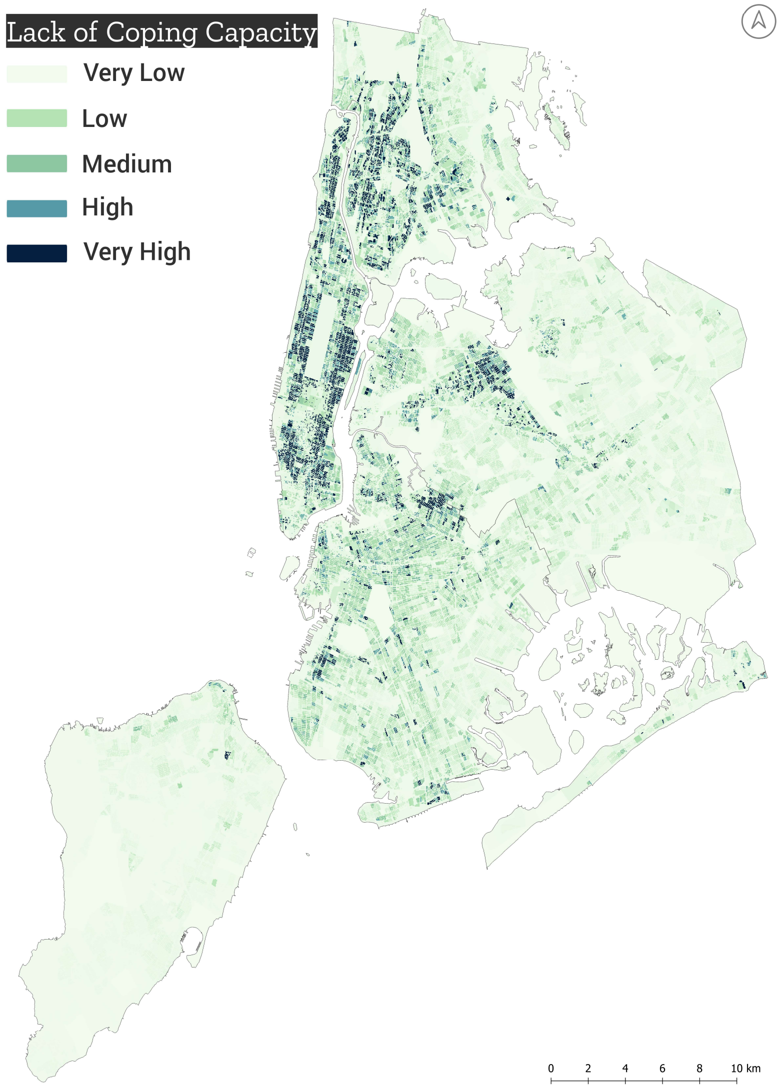


a. Map of exposure



b. Map of susceptibility

622



c. Map of lack of coping capacity

Figure 4 a, b and c. Spatial variation in three components of vulnerability (exposure, susceptibility and lack of coping capacity) to multiple hazards.

Figure 4a shows the exposure of the city based on the population. Since Manhattan has the highest density, it is where the highest exposure values are found. Parts of Brooklyn and the Bronx also have high densities but are overall less concentrated than Manhattan. The susceptibility map of the city (Figure 4b) shows that the most fragile members of the population in socio-economic terms are in some parts of Brooklyn and the Bronx. As most people living alone are in Manhattan, this area shows higher values of lack of coping capacity. While linguistic isolation (non-English speaking) explains some lack of coping capacity in part of Brooklyn and the Bronx (Figure 4c).

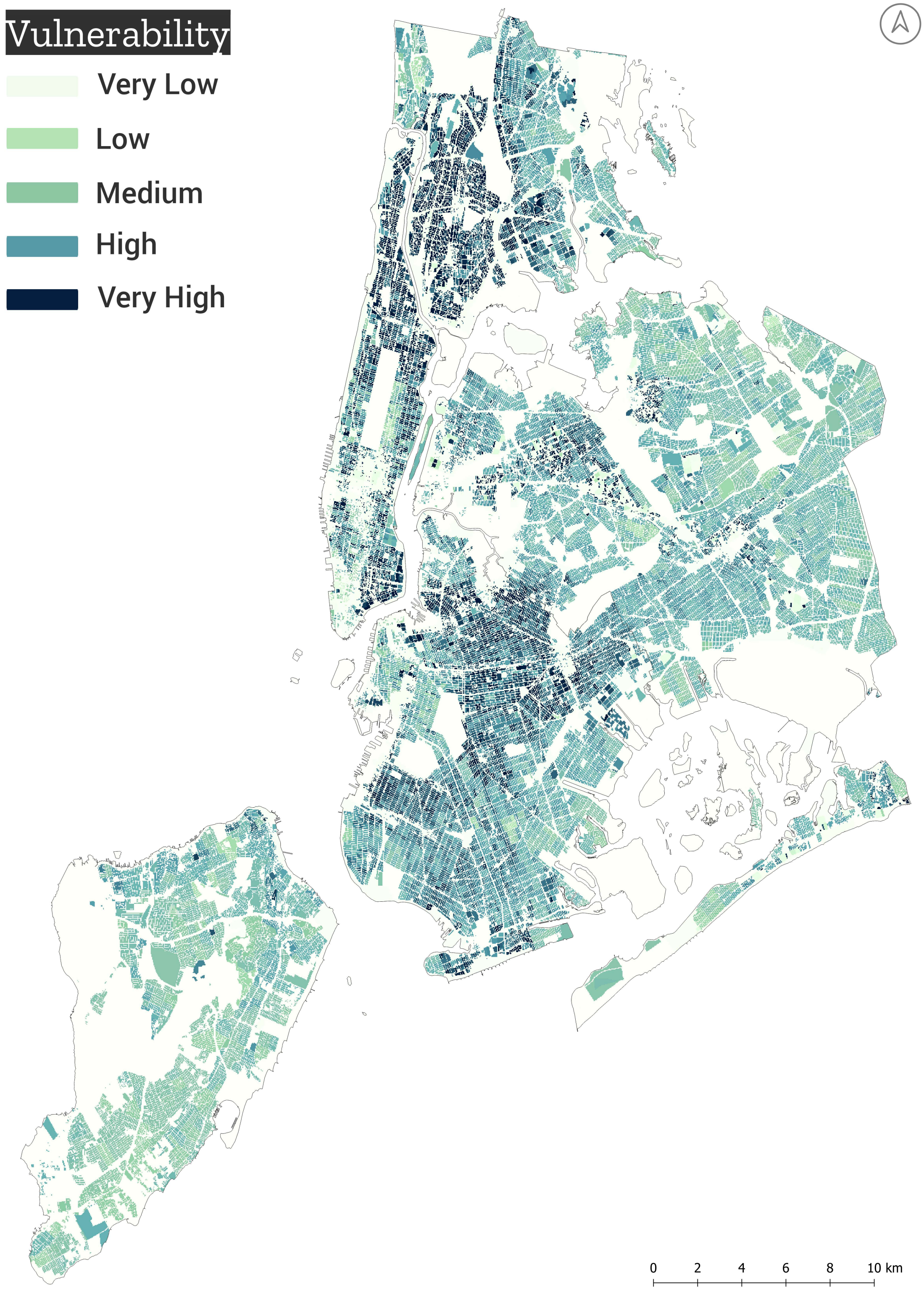


Figure 5. Map of Vulnerability

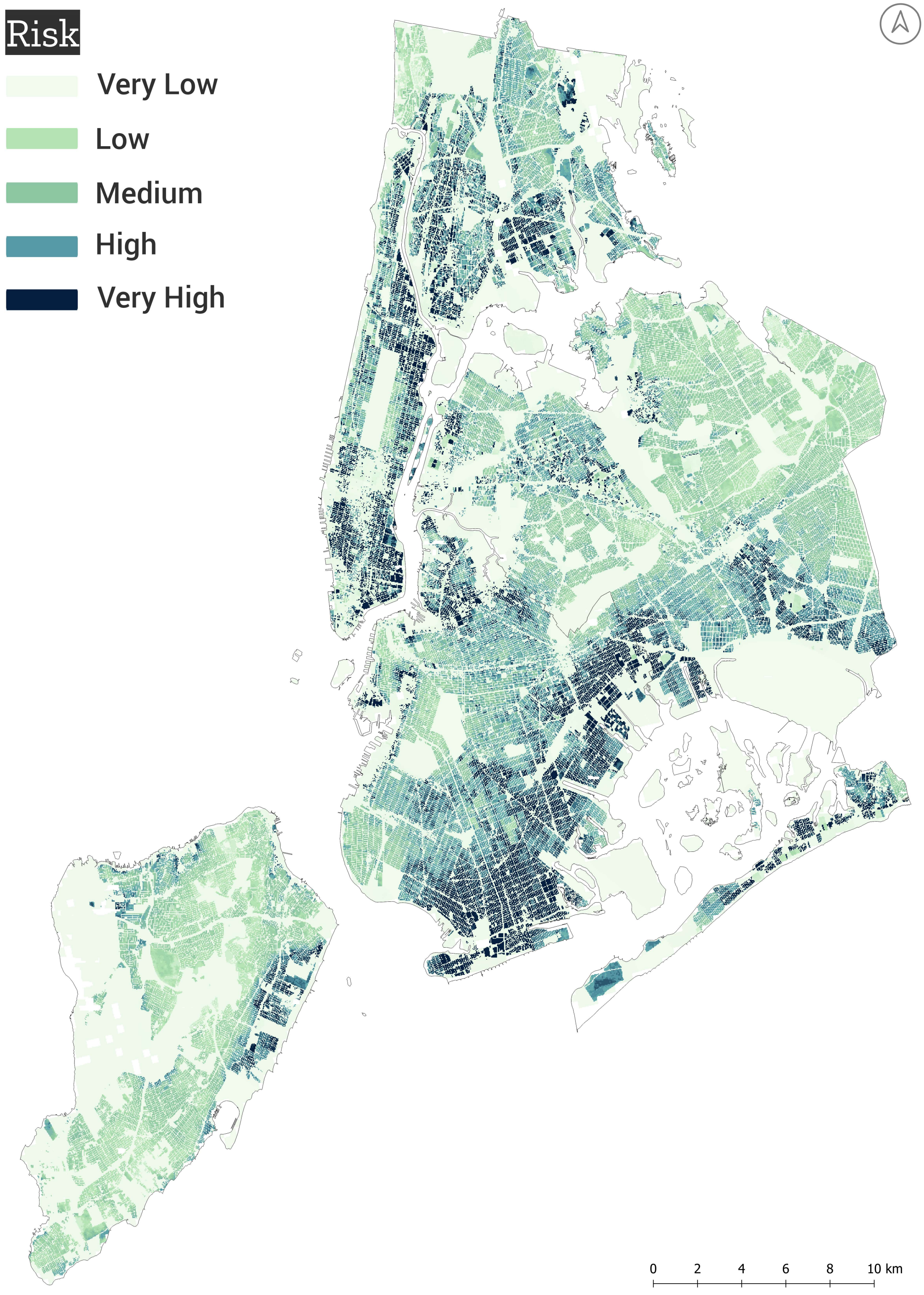
The resultant vulnerability map (Figure 5) shows highly vulnerable populations located mainly in the Bronx, large parts of Brooklyn and some parts of Manhattan (such as Harlem) and the Queens. Staten Island appears as the least vulnerable compared to other parts of the city.

The survey's respondents suggested other important indicators that can be considered in a vulnerability assessment (see Table 5). These fall into the categories of indicators that we had to exclude either because they were not directly relevant to the three hazards we focused on jointly, or because data were unavailable at the spatial scale we conducted our analysis. Despite their exclusion from the study, we report these results as a useful piece of information for further research.

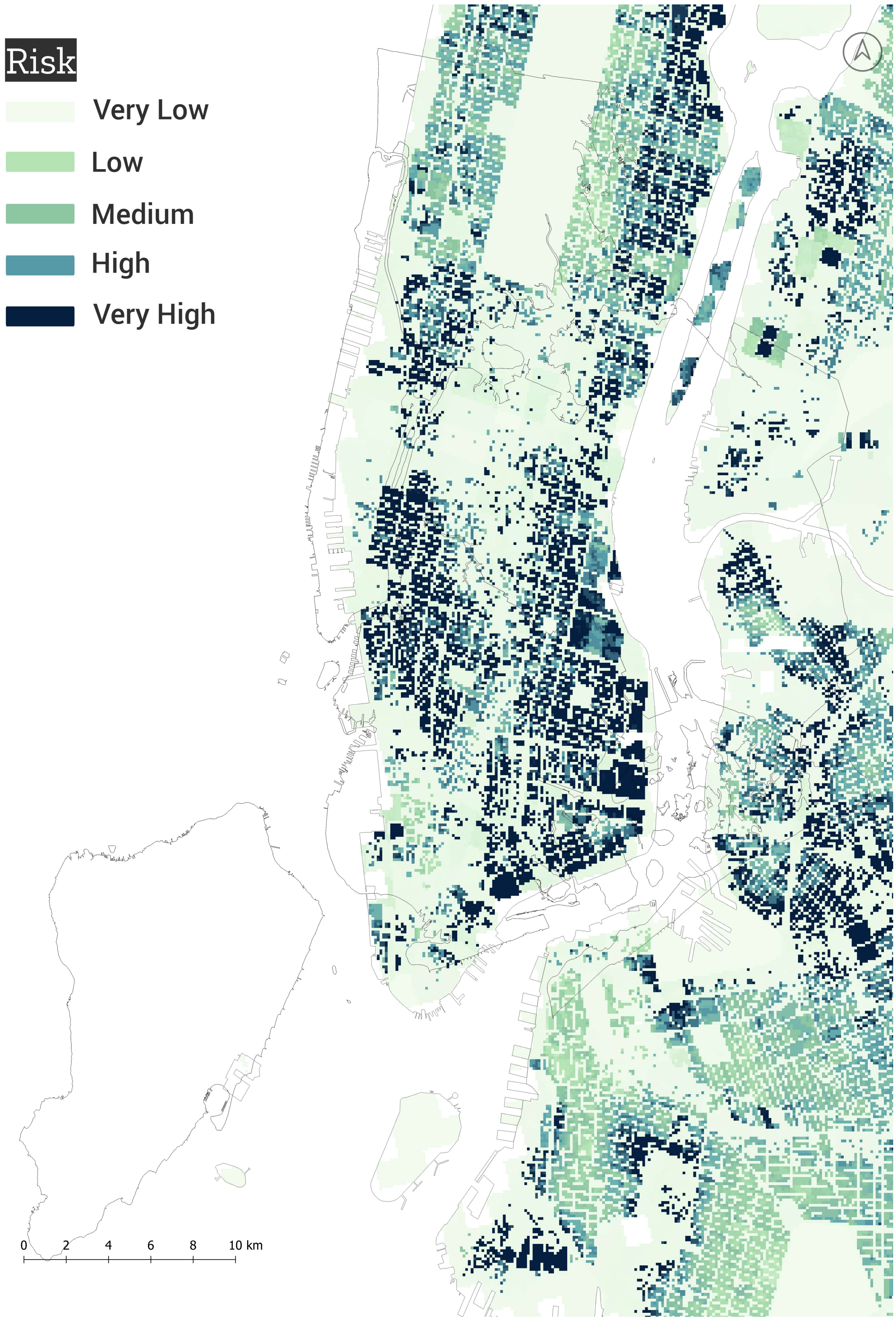
Table 5. Indicators that have been suggested by the survey and that could be further integrated in this type of assessment depending on the availability of the data.

Additional Indicators	
Disabled	Air conditioning and cooling centers
Power housing	Health conditions
Type of housing structure	Proximity to transportation
Political orientation as a measure of awareness	Housing conditions
Family size	Proximity to nuisance flooding
Social isolation	Proximity to industries
Location of the house	Undocumented residents
Home ownership vs rent occupier	Below poverty Status
Social Cohesion	Access of equity capital

653



a. Multi-hazard risk map



b. Detail of the multi-hazard risk map

654

Figure 6 a and b. Final multi-hazard risk map and detail of the high spatial resolution risk map for Lower Manhattan and parts of Brooklyn.

Combining multiple hazards and vulnerability assessment produced final multi-hazard risk assessment map at high resolution for NYC (Figure 6a). We find that the coastal areas of Brooklyn, Manhattan and Harlem are the most at risk from the three hazards considered given the methodological approach and expert input affecting weighted indicators. Figure 6b, shown in detail, demonstrate the relatively high spatial resolution of the analysis and the utility for decision-making for prioritizing investments within neighborhoods and down to building scale for multi-hazard risk reduction.

Adapting to coastal threats remains a high priority for the city post-Sandy, but results here suggest that coastal areas are also at risk from a multi-hazard perspective. This result is further supported from expert input gathered through the survey of local stakeholders who see the city the least prepared to cope with coastal flooding, second only to earthquakes (see Figure 7). Of note is that some of responses appear to be contradictory, e.g. snowstorms are often associated with nor'easters while hurricanes are associated with coastal flooding with different degreed of preparedness. This inconsistency might be explained by the variety of hazards respondents were asked to assess.

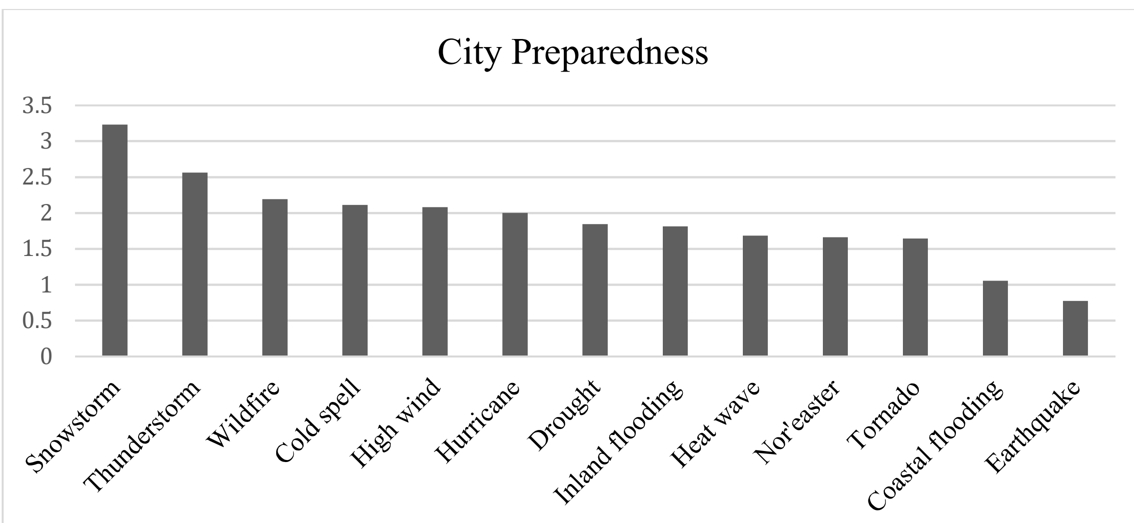


Figure 7. Survey result's regarding the level of city's preparedness to impactful hazards potentially affecting NYC out of a maximum of 5 points.

4. Discussion

Based on the NOAA-NYT quali-quantitive assessment of multi-hazard climatic events, the responses of the survey as well as from the analysis carried out for a companion study (by Depietri and McPhearson, 2018), NYC can be described as at risk from multiple and overlapping hazards, both spatially and temporally. Multi-hazard risk is therefore a reality that is important to further understand and plan for in NYC. We also suggest other similar located coastal megacities would benefit from a multi-hazard perspective on planning and policy for climate adaptation and resiliency. We focused on heat waves, inland and coastal flooding multi-hazard risks and assess how these are spatially distributed leading to overlapping risks. We find that the hazards considered mainly affect the coastal areas while the socio-economic vulnerability is concentrated in central areas of Brooklyn where the poorest segments of the population reside and in the Bronx. Parts of Manhattan are also highly vulnerable, likely due to the concentration of elderly and people living alone in these areas of the city or to the poverty that characterizes certain neighborhoods, such as Harlem. Coastal areas of the city facing the open sea as well as large areas of Manhattan and the Bronx were also the most at risk from the multiple hazards considered. We suggest that adaptation strategies should prioritize these areas. Further soft or hard infrastructures need to be adapted to potential inland flooding and heat waves for instance through enhanced infiltration and reduction of the urban heat island by improving the distribution of green infrastructures. No part of the city is totally devoid of potential impacts from these hazards and synergies and tradeoffs should be carefully evaluated. Coastal flooding also appears to be one of the hazards the city is least prepared to, followed by heat waves and inland flooding, amongst the hazards considered in this study. These results support current priorities in the city to invest resources to improve coastal areas, such as Jamaica Bay and its remaining wetlands.

The quantitative analysis we conducted principally considered the social aspects of vulnerability and risk. We illustrate that parts of the city potentially affected to multiple hazards do not necessarily correspond to the areas with highest densities of vulnerable people live. A further development of this study could include indicators of infrastructural vulnerability especially in reference to inland and coastal flood risk. Some of the indicators that could be used to extend this analysis include: the conditions of exposed buildings; roads, railroads and the subway system; and other critical infrastructures that supply energy, support communication or treat wastewater.

Multi-hazard risk indicator weights were derived from expert-input through a survey methodology where experts ranked indicators and sub-indicators. This survey approach allowed for the development of an assessment specific to the case of the city of New York. Higher multi-hazard risk in coastal zones is partially driven by weights derived from survey respondents and may depend on the recent awareness raised by disastrous impacts caused by Hurricane Sandy and generally because of the high infrastructural and social impacts these hazards have on the city. We initially calculated risk through all steps described but with equal weighting. The results still showed that the coastal areas of Brooklyn, Harlem and the Bronx were the most at risk to multiple hazards. This suggests that the methodology is robust and would not lead to significantly different results with a change of weights.

The choice of the 311 calls to represent inland flooding allowed us to include an element of the disaster scape of NYC which, to our knowledge, has not been explored in previous studies. Despite the potential limitations of the approach, areas identified at high risk of inland flooding varied little with changes in the classification method. The methodology can potentially be expanded to accommodate other indicators, for instance to produce hazard-specific vulnerability maps instead of a common assessment. By including a broader range of vulnerability indicators and by conducting hazard specific vulnerability assessments each step of the methodology would potentially be reinforced and provide additional insights.

The quantitative aspects of this work also show the significance of each step of the methodology. Each map provides valuable information to detecting risk in the city beyond the final aggregated risk map. For instance, the maps of the components of vulnerability show that high exposure (or where most of the people are located) does not correspond to areas where people are the most vulnerable. Further, the final risk map, when compared with the combined hazards maps, shows that the main determinant factor of risk is the level of multi-hazard rather than the vulnerability of the population. The detailed spatial resolution of the risk assessment provides decision makers with the possibility to prioritize areas of intervention at high spatial resolution, down to the building and street level where most planning and development decisions actually occur. By considering the three hazards jointly, no inhabited area of the city is exempt from risk, while other areas show an accumulation of risk and thus locations that should be prioritized for adaptation and mitigation interventions.

5. Conclusions

This study provides a comprehensive assessment of the relevance of a multi-hazard approach in a coastal megacity and its application to three of the main hazards that affect New York City: heat waves, coastal flooding and inland flooding. The results of a NOAA NYT database search and the experts' responses to a questionnaire illustrate the relevance of considering risk in NYC in terms of multi-hazard risk. The quantitative analysis showed that risk to multiple hazards in NYC is mainly driven by the distribution of the hazards rather than by vulnerability. The concentration of people, the susceptibility and the lack of coping capacity play a secondary role in determining risk which is instead dominated by the magnitude and distribution of the hazards combined.

For the three hazards considered, we focus on a significant spatial overlap in where hazards and risk exist in the city. The results showed that the city is most at risk in the coast areas of midtown and downtown Manhattan, Harlem and the coastal areas of Brooklyn, especially those surrounding Jamaica bay. A predominant role is thus played by coastal flooding. The analysis of these results suggest that decision makers should prioritize strategies that protect the city from coastal flooding while considering at the same time that those areas are also affected by other hazards and should be jointly addressed. These considerations are supported by the responses from the survey that emphasize how the city is little prepared to cope with coastal flooding.

Further research should consider additional indicators of physical vulnerability and cascading effects provoked by climatological hazards and leading to failure of critical infrastructures dangerous for human health (e.g. power outages and exposure to toxic substances). We suggest that it is important for not only

NYC, but other coastal megacities to adopt a multi-hazard approach to understanding climate related risk and for designing and prioritizing action to maximize interventions and investments in ways that reduce risk and build resilience to multiple hazards.

Acknowledgements

We thank Jaskirat Randhawa for data visualization assistance, Bill Solecki and Erin Friedman for feedback and local experts for input on weightings. Research was supported by the Urban Resilience to Extreme Weather-Related Events Sustainability Research Network (URExSRN; NSF grant no. SES 1444755) and through the 2015-2016 BiodivERsA COFUND call for research proposals, with the as national funders: the Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning; Swedish Environmental Protection Agency; German aeronotics and space research centre; National Science Centre (Poland); the Research Council of Norway; and Spanish Ministry of Economy and Competitiveness. Yaella Depietri was partially supported by the Zeff fellowship at the Technion, Israel Institute of Technology.

References

Abramson, D.M., Redlener, I., 2012. Hurricane Sandy: lessons learned, again. Disaster Med. Public Health Prep. 6, 328–329.

Aerts, J.C.J.H., Botzen, W.J.W., 2012. Managing exposure to flooding in New York City. Nat. Clim. Change 2, 377. https://doi.org/10.1038/nclimate1487

Aerts, J.C.J.H., Lin, N., Botzen, W., Emanuel, K., de Moel, H., 2013. Low-Probability Flood Risk Modeling for New York City: Low-Probability Flood Risk Modeling for New York City. Risk Anal. 33, 772–788. https://doi.org/10.1111/risa.12008

Agel, L., Barlow, M., Qian, J.-H., Colby, F., Douglas, E., Eichler, T., 2015. Climatology of Daily Precipitation and Extreme Precipitation Events in the Northeast United States. J. Hydrometeorol. 16, 2537–2557. https://doi.org/10.1175/JHM-D-14-0147.1

Anderson, B., Bell, M., 2011. Heat Waves and Mortality in New York, NY. Epidemiology 22, S20. https://doi.org/10.1097/01.ede.0000391719.31370.34

Anderson, G.B., Bell, M.L., 2012. Lights out: Impact of the August 2003 power outage on mortality in New York, NY. Epidemiol. Camb. Mass 23, 189–193. https://doi.org/10.1097/EDE.0b013e318245c61c

Aydi, A., Zairi, M., Dhia, H.B., 2013. Minimization of environmental risk of landfill site using fuzzy logic, analytical hierarchy process, and weighted linear combination methodology in a geographic information system environment. Environ. Earth Sci. 68, 1375–1389. https://doi.org/10.1007/s12665-012-1836-3

Bankoff, G., Frerks, G., Hilhorst, T. (Eds.), 2004. Mapping vulnerability: disasters, development, and people. Earthscan Publications, London ; Sterling, VA.

Bernal, G.A., Salgado-Gálvez, M.A., Zuloaga, D., Tristancho, J., González, D., Cardona, O.-D., 2017. Integration of Probabilistic and Multi-Hazard Risk Assessment Within Urban Development Planning and Emergency Preparedness and Response: Application to Manizales, Colombia. Int. J. Disaster Risk Sci. 8, 270–283. https://doi.org/10.1007/s13753-017-0135-8

Birkmann, J. (Ed.), 2006. Measuring vulnerability to natural hazards: towards disaster resilient societies. United Nations University, Tokyo ; New York.

Birkmann, J., Cardona, O.D., Carreño, M.L., Barbat, A.H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., Welle, T., 2013. Framing vulnerability, risk and societal responses: the MOVE framework. Nat. Hazards 67, 193–211. https://doi.org/10.1007/s11069-013-0558-5

Blake, E.S., Kimberlain, T.B., Berg, R.J., Cangialosi, J.P., Beven, J.L., 2013. Tropical Cyclone Report Hurricane Sandy 22 – 29 October 2012. National Hurricane Center.

Blake, E.S., Lansea, C.W., Gibney, E.J., 2011. The deadliest, costliest, and most intense United States Tropical Cyclones from 1851 to 2100 (and other frequently requested Hurricane facts). National Weather Service, National Hurricane Center, Miami, Florida.

Bogardi, J.J., Birkmann, J., 2004. Vulnerability assessment: the first step towards sustainable risk reduction, in: Malzahn, D., Plapp, T. (Eds.), Disasters and Society - from Hazard Assessment to Risk Reduction. Logos Verlag, Berlin, pp. 75–82.

Cardona, O.D., 2004. The Need for Rethinking the Concepts of Vulnerability and Risk from a Holistic Perspective: A Necessary Review and Criticism for Effective Risk Management, in: Bankoff, G., Frerks, G., Hilhorst, T. (Eds.), Mapping Vulnerability: Disasters, Development, and People. Earthscan Publications, London ; Sterling, VA.

Catalano, A.J., Broccoli, A.J., 2017. Synoptic Characteristics of Surge-Producing Extratropical Cyclones along the Northeast Coast of the United States. J. Appl. Meteorol. Climatol. 57, 171–184. https://doi.org/10.1175/JAMC-D-17-0123.1

CDCP, 2013. Heat Illness and Death - New York City, 2000-2011 (No. Vel. 62, N. 31), Morbidity and Mortality Weekly Report. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention.

Clarke, J.F., 1972. Some effects of the urban structure on heat mortality. Environ. Res. 5, 93–104. https://doi.org/10.1016/0013-9351(72)90023-0

Colle, B.A., Buonaiuto, F., Bowman, M.J., Wilson, R.E., Flood, R., Hunter, R., Mintz, A., Hill, D., 2008. New York City's Vulnerability to Coastal Flooding: Storm Surge Modeling of Past Cyclones. Bull. Am. Meteorol. Soc. 89, 829–841. https://doi.org/10.1175/2007BAMS2401.1

Collins, T.W., 2010. Marginalization, Facilitation, and the Production of Unequal Risk: The 2006 Paso del Norte Floods. Antipode 42, 258–288. https://doi.org/10.1111/j.1467-8330.2009.00755.x

Depietri, Y., McPhearson, T., 2018. Changing urban risk: 140 years of climatic hazards in New York City. Clim. Change 1–14. https://doi.org/10.1007/s10584-018-2194-2

Depietri, Y., Renaud, F.G., Kallis, G., 2011. Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. Sustain. Sci. 7, 95–107. https://doi.org/10.1007/s11625-011-0142-4

Dickson, E., Baker, J.L., Hoornweg, D., Asmita, T., 2012. Urban Risk Assessments: An Approach for Understanding Disaster and Climate Risk in Cities. The World Bank.

D'Ippoliti, D., Michelozzi, P., Marino, C., de'Donato, F., Menne, B., Katsouyanni, K., Kirchmayer, U., Analitis, A., Medina-Ramón, M., Paldy, A., Atkinson, R., Kovats, S., Bisanti, L., Schneider, A., Lefranc, A., Iñiguez, C., Perucci, C.A., 2010. The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. Environ. Health 9, 37. https://doi.org/10.1186/1476-069X-9-37

Ellis, F.P., Nelson, F., Pincus, L., 1975. Mortality during heat waves in New York City July, 1972 and August and September, 1973. Environ. Res. 10, 1–13. https://doi.org/10.1016/0013-9351(75)90069-9

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R., Cid, A., 2016. Multi-hazard assessment in Europe under climate change. Clim. Change 137, 105–119. https://doi.org/10.1007/s10584-016-1661-x

Garner, A.J., Mann, M.E., Emanuel, K.A., Kopp, R.E., Lin, N., Alley, R.B., Horton, B.P., DeConto, R.M., Donnelly, J.P., Pollard, D., 2017. Impact of climate change on New York City's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 CE. Proc. Natl. Acad. Sci. 201703568. https://doi.org/10.1073/pnas.1703568114

Gedzelman, S.D., Austin, S., Cermak, R., Stefano, N., Partridge, S., Quesenberry, S., Robinson, D.A., 2003. Mesoscale aspects of the Urban Heat Island around New York City. Theor. Appl. Climatol. 75, 29–42. https://doi.org/10.1007/s00704-002-0724-2

Goldman, L., Finkelstein, R., Schafer, P., Pugh, T., 2014. Resilient Communities: Empowering Older Adults in Disasters and Daily Life. The New York Accademy of Medicine.

Gornitz, V., Couch, S., Hartig, E.K., 2001. Impacts of sea level rise in the New York City metropolitan area. Glob. Planet. Change 32, 61–88. https://doi.org/10.1016/S0921-8181(01)00150-3

Graham, S., 2010. Disrupted cities: When infrastructure fails. Routledge.

Greiving, S., 2006. Multi-risk assessment of Europe's regions, in: Birkmann, J. (Ed.), Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. pp. 210–26.

Greiving, S., Fleischhauer, M., Lückenkötter, J., 2006. A Methodology for an integrated risk assessment of spatially relevant hazards. J. Environ. Plan. Manag. 49, 1–19. https://doi.org/10.1080/09640560500372800

Horton, R., Bader, D., Kushnir, Y., Little, C., Blake, R., Rosenzweig, C., 2015a. New York City Panel on Climate Change 2015 Report. Chapter 1: Climate

Observations and Projections: NPCC 2015 Report Chapter 1. Ann. N. Y. Acad. Sci. 1336, 18–35. https://doi.org/10.1111/nyas.12586

Horton, R., Little, C., Gornitz, V., Bader, D., Oppenheimer, M., 2015b. New York City Panel on Climate Change 2015 Report. Chapter 2: Sea Level Rise and Coastal Storms: NPCC 2015 Report Chapter 2. Ann. N. Y. Acad. Sci. 1336, 36–44. https://doi.org/10.1111/nyas.12593

Huang, G., Zhou, W., Cadenasso, M.L., 2011. Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhood socioeconomic characteristics in Baltimore, MD. J. Environ. Manage. 92, 1753–1759. https://doi.org/10.1016/j.jenvman.2011.02.006

Janke, J.R., 2010. Multicriteria GIS modeling of wind and solar farms in Colorado. Renew. Energy 35, 2228–2234. https://doi.org/10.1016/j.renene.2010.03.014

Johnson, K., Depietri, Y., Breil, M., 2016. Multi-hazard risk assessment of two Hong Kong districts. Int. J. Disaster Risk Reduct. 19, 311–323. https://doi.org/10.1016/j.ijdrr.2016.08.023

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., 2012a. Challenges of analyzing multi-hazard risk: a review. Nat. Hazards 64, 1925–1958. https://doi.org/10.1007/s11069-012-0294-2

Kappes, M.S., Papathoma-Köhle, M., Keiler, M., 2012b. Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Appl. Geogr. 32, 577–590. https://doi.org/10.1016/j.apgeog.2011.07.002

Kemp, A.C., Horton, B.P., 2013. Contribution of relative sea-level rise to historical hurricane flooding in New York City. J. Quat. Sci. 28, 537–541. https://doi.org/10.1002/jqs.2653

Kinney, P.L., Matte, T., Knowlton, K., Madrigano, J., Petkova, E., Weinberger, K., Quinn, A., Arend, M., Pullen, J., 2015. New York City Panel on Climate Change 2015 ReportChapter 5: Public Health Impacts and Resiliency: NPCC 2015 Report Chapter 5. Ann. N. Y. Acad. Sci. 1336, 67–88. https://doi.org/10.1111/nyas.12588

Klein Rosenthal, J., Kinney, P.L., Metzger, K.B., 2014. Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. Health Place 30, 45–60. https://doi.org/10.1016/j.healthplace.2014.07.014

Knowlton, K., Lynn, B., Goldberg, R.A., Rosenzweig, C., Klein Rosenthal, J., Kinney, P.L., 2007. Projecting heat-related mortality impacts under a changing climate in the New York City region. Am. J. Public Health 97, 2028–34.

Knutson, T.R., Sirutis, J.J., Zhao, M., Tuleya, R.E., Bender, M., Vecchi, G.A., Villarini, G., Chavas, D., 2015. Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. J. Clim. 28, 7203–7224. https://doi.org/10.1175/JCLI-D-15-0129.1

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H., Tebaldi, C., 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earths Future 2, 383–406. https://doi.org/10.1002/2014EF000239

Lane, K., Charles-Guzman, K., Wheeler, K., Abid, Z., Graber, N., Matte, T., 2013. Health Effects of Coastal Storms and Flooding in Urban Areas: A Review and Vulnerability Assessment [WWW Document]. J. Environ. Public Health. https://doi.org/10.1155/2013/913064

Lin, N., Emanuel, K., Oppenheimer, M., Vanmarcke, E., 2012. Physically based assessment of hurricane surge threat under climate change. Nat. Clim. Change 2, 462–467. https://doi.org/10.1038/nclimate1389

Lin, N., Emanuel, K.A., Smith, J.A., Vanmarcke, E., 2010. Risk assessment of hurricane storm surge for New York City. J. Geophys. Res. 115. https://doi.org/10.1029/2009JD013630

Lin, N., Kopp, R.E., Horton, B.P., Donnelly, J.P., 2016. Hurricane Sandy's flood frequency increasing from year 1800 to 2100. Proc. Natl. Acad. Sci. 113, 12071–12075. https://doi.org/10.1073/pnas.1604386113

Liu, Z., Nadim, F., Garcia-Aristizabal, A., Mignan, A., Fleming, K., Luna, B.Q., 2015. A three-level framework for multi-risk assessment. Georisk Assess. Manag. Risk Eng. Syst. Geohazards 9, 59–74. https://doi.org/10.1080/17499518.2015.1041989

Llyod, E., Licata, A., n.d. One New York City: One Water. Sustainable water managemnet for New York City's people and environment.

Lozoya, J.P., Sardá, R., Jiménez, J.A., 2011. A methodological framework for multi-hazard risk assessment in beaches. Environ. Sci. Policy 14, 685–696. https://doi.org/10.1016/j.envsci.2011.05.002

Luber, G., McGeehin, M., 2008. Climate Change and Extreme Heat Events. Am. J. Prev. Med. 35, 429–435. https://doi.org/10.1016/j.amepre.2008.08.021

MA, 2005. Ecosystems and human well-being: current state and trends: findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment, The millennium ecosystem assessment series. Island Press, Washington, DC.

Madrigano, J., Ito, K., Johnson, S., Kinney, P.L., Matte, T., 2015. A Case-Only Study of Vulnerability to Heat Wave–Related Mortality in New York City (2000–2011). Environ. Health Perspect. https://doi.org/10.1289/ehp.1408178

Mennis, J., Hultgren, T., 2006. Intelligent Dasymetric Mapping and Its Application to Areal Interpolation. Cartogr. Geogr. Inf. Sci. 33, 179–194. https://doi.org/10.1559/152304006779077309

Michael, E.A., Samanta, S., 2016. Landslide vulnerability mapping (LVM) using weighted linear combination (WLC) model through remote sensing and GIS techniques. Model. Earth Syst. Environ. 2, 88. https://doi.org/10.1007/s40808-016-0141-7

Nicholls, R.J., Small, C., 2002. Improved estimates of coastal population and exposure to hazards released. Eos Trans. Am. Geophys. Union 83, 301. https://doi.org/10.1029/2002EO000216

NYC, 2014. Heat-related Deaths in New York City, 2013 (No. 47), Epi Data Brief. New York City Department of Health and Mental Hygiene.

NYC, 2013. A stronger more resilient New York. The City of New York.

NYC, 2010. NYC green infrastructure plan: A sustainable strategy for clean waterways. City of New York, New York, USA.

NYC, 2006. Deaths Associated with Heat Waves in 2006 (Special Report), NYC Vital Signs Investigation Report. New York City Department of Health and Mental Hygiene.

NYCEM, 2014. NYC's risk landscape: a guide to hazard mitigation. New York City Emergency Management, Department of City Planning and Mayor Office of Recovery and Resiliency.

Oliver-Smith, A., 2004. Theorizing vulnerability in a globalized world: a political ecological perspective, in: Bankoff, G., Frerks, G., Hilhorst, D. (Eds.), Mapping Vulnerability: Disasters, Development and People. Earthscan, London, pp. 10–24.

Oudin Åström, D., Bertil, F., Joacim, R., 2011. Heat wave impact on morbidity and mortality in the elderly population: A review of recent studies. Maturitas 69, 99–105. https://doi.org/10.1016/j.maturitas.2011.03.008

Pelling, M., 2003. The Vulnerability of Cities: Natural Disasters and Social Resilience. Earthscan.

Pelling, M., Blackburn, S. (Eds.), 2013. Megacities and the coast: risk, resilience, and transformation. Routledge/Taylor & Francis Group, London ; New York.

Petkova, E.P., Gasparrini, A., Kinney, P.L., 2014. Heat and Mortality in New York City Since the Beginning of the 20th Century: Epidemiology 25, 554–560. https://doi.org/10.1097/EDE.0000000000000123

Philippi, C., 2016. Megacities Pushing the Boundaries of our Industry. Risk trends and insurance challenges. Allianz Global Corporate & Specialty.

Reed, A.J., Mann, M.E., Emanuel, K.A., Lin, N., Horton, B.P., Kemp, A.C., Donnelly, J.P., 2015. Increased threat of tropical cyclones and coastal flooding to New York City during the anthropogenic era. Proc. Natl. Acad. Sci. 201513127. https://doi.org/10.1073/pnas.1513127112

Rosenzweig, C., Gaffin, S., Parshall, L. (Eds.), 2006. Green Roofs in the New York Metropolitan Region. Research Report. Columbia University Centre for Climate Systems Reserach and NASA Goddard Institute for Space Studies, New York.

Rosenzweig, C., Solecki, W., 2015. New York City Panel on Climate Change 2015 Report Introduction: NPCC 2015 Report Introduction. Ann. N. Y. Acad. Sci. 1336, 3–5. https://doi.org/10.1111/nyas.12625

Rosenzweig, C., Solecki, W.D., Blake, R., Bowman, M., Faris, C., Gornitz, V., Horton, R., Jacob, K., LeBlanc, A., Leichenko, R., Linkin, M., Major, D., O'Grady, M., Patrick, L., Sussman, E., Yohe, G., Zimmerman, R., 2011. Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies. Clim. Change 106, 93–127. https://doi.org/10.1007/s10584-010-0002-8

Saisana, M., Tarantola, S., 2002. State-of-the-art report on current methodologies and practices for composite indicator development. Citeseer.

Schuman, S.H., 1972. Patterns of urban heat-wave deaths and implications for prevention: Data from New York and St. Louis during July, 1966. Environ. Res. 5, 59–75. https://doi.org/10.1016/0013-9351(72)90020-5

Smith, M.J. de, Goodchild, M.F., Longley, P.A., 2007. Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools, 2nd Revised edition. ed. Matador, Leicester.

Smith, J.A., Villarini, G., Baeck, M.L., 2010. Mixture Distributions and the Hydroclimatology of Extreme Rainfall and Flooding in the Eastern United States. J. Hydrometeorol. 12, 294–309. https://doi.org/10.1175/2010JHM1242.1

Talke, S.A., Orton, P., Jay, D.A., 2014. Increasing storm tides in New York Harbor, 1844–2013. Geophys. Res. Lett. 41, 3149–3155. https://doi.org/10.1002/2014GL059574

Towey, K.L., Booth, J.F., Frei, A., Sinclair, M.R., 2018. Track and Circulation Analysis of Tropical and Extratropical Cyclones that Cause Strong Precipitation and Streamflow Events in the New York City Watershed. J. Hydrometeorol. 19, 1027–1042. https://doi.org/10.1175/JHM-D-17-0199.1

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. 100, 8074–8079. https://doi.org/10.1073/pnas.1231335100

UN, 2002. Johannesburg Declaration on Sustainable Development. Plan of Implementation of the World Summit on Sustainable Development. United Nations; World Summit on Sustainable Development (UN).

UNDESA, 2016. The World’s Cities in 2016: Data Booklet. United Nations, Department of Economic and Social Affairs, Population Division, New York, NY.

UNEP, 1992. Agenda 21. Tech. rep., United Nations Environment Programme.

UNISDR, 2015. Global Assessment Report on Disaster Risk Reduction. Making Development Sustainable: The future of Disasster Risk Management. United Nations Office for Disaster Risk Reduction (UNISDR), Geneva, Switzerland.

UNISDR, 2005. Hyogo Declaration.

van Westen, C.J., Montoya, L., Boerboom, L., Badilla Coto, E., 2002. Multi-hazard risk assessment using GIS in urban areas: a case study for the city of Turrialba, Costa Rica. Presented at the The Regional Workshop on Best Practices in Disaster Mitigation: lessons learned from the Asian urban disaster mitigation program and other initiatives, Bali Indonesia, pp. 120–136.

Welle, T., Birkmann, J., 2015. The World Risk Index – An Approach to Assess Risk and Vulnerability on a Global Scale. J. Extreme Events 02, 1550003. https://doi.org/10.1142/S2345737615500037

Wipulanusat, W., Nakrod, S., Prabnarong, P., 2011. Multi-hazard Risk Assessment Using GIS and RS Applications: A Case Study of Pak Phanang Basin. Walailak J. Sci. Technol. WJST 6, 109–125. https://doi.org/10.2004/wjst.v6i1.76

Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2014. At risk: Natural Hazards, People’s Vulnerability and Disasters. Routledge.

Zhou, S., Chen, G., Fang, L., Nie, Y., 2016. GIS-Based Integration of Subjective and Objective Weighting Methods for Regional Landslides Susceptibility Mapping. Sustainability 8, 334. https://doi.org/10.3390/su8040334