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Multi-hazards risks in New York City

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Abstract

Megacities are predominantly concentrated along the coast and are greatly exposed to natural hazards. Generally, the assessment of risk to climatic hazards does not yet fully capture the multiple interactions that occur in these complex urban systems. We analyze the risk of New York City as an example of a coastal megacity exposed to multiple hazards which overlap spatially and, in some cases, temporally. The aim is to identify hotspots of multi-hazard risk to support the prioritization of adaptation strategies. We used socio-economic indicators to assess vulnerabilities and risks to three climate related hazards (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 risk assessment. Results show spatial hotspots of multi-hazard risk principally located in coastal areas. We conclude that New York City is exposed to multiple hazards that interact spatially and temporally and that the city should prioritize adaptation in its coastal areas while considering possible synergies or tradeoffs adapting to spatially overlapping hazards.

Keywords

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

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1. Introduction

Megacities, urban areas exceeding 10 M inhabitants, host 500 M people and thus 6.8 % of the global population, a proportion that is projected to rise to 8.7% in 2030 (UNDESA, 2016). These urban agglomerations are highly interconnected and vibrant centers in which enormous physical and intellectual resources are concentrated. Mainly located in the global South and 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). But large cities also modify the local and regional environment, changing the microclimate (e.g. 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 megacities (Pelling and Blackburn, 2013). New York City is a megacity located in the global North of the world and highly exposed to hydro-meteorological hazards. On the 29th of October 2012, hurricane Sandy made landfall close to Atlantic City, New Jersey (US) with the intensity of a category 3 storm. Located approximately 200 km north, the New York City (NYC) region 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 (CDC and EPA, 2016). Storm water overflows in NYC are driven not only by extreme precipitation. Even precipitation events as low as 38 mm a day are of concern to local authorities as these cause pollution issues in NYC due to the city's combined sewage overflow system (Llyod and Licata, n.d.) and create surface flooding impact residents and infrastructure.

Hazards often overlap spatially or temporally, though this is not well addressed in research and planning. More attention has traditionally been paid to the physical components of risk to hazards, looking at the joint impacts that multiple hazards could have on the infrastructures and buildings within certain sensitive areas or locations (e.g. Kappes et al., 2012b; van Westen et al., 2002). Less has been done to assess the socio-economic components of multi-hazard risk in cities in order to envisage common and more effective plans and policies for disaster risk reduction and climate change adaptation (Johnson et al., 2016). Further, certain policies developed to tackle individual hazards could reduce or even increase vulnerability and risk to other hazards. A multi-hazard assessment plan facilitates identifying these potential synergies or tradeoffs for adapted policies, and specific interventions. For example, tree planting 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 improve decision-making and maximize the multi-functional benefits of interventions to meet complex challenges posed by multiple hazards in New York City. Using a common conceptual framework and methodology for different hazards is critical for identifying hotspots of risk of communities exposed to overlapping hazards. Despite these benefits, we still know little about multi-risk and the occurrence of multi-hazards in urban areas. Here we empirically address this gap by focusing on NYC which 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 billions in assets and millions of people at risk, as well as its place as a coastal city threatened by multiple hydro-meteorological hazards potentially exacerbated by climate change. Exploring NYC as a case study, this paper reports data on past and potential multi-hazards events in NYC and assesses the combined socio-economic risks of residents to three different hazards (i.e. heat waves, inland flooding and coastal flooding).

1.1. 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 consideration of multi-hazard risk 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). Recently, the Sendai Framework for Disaster Risk Reduction 2015-2030, 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 urban area around the world.

There are different ways to look at how multiple hazards affect a same area, 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

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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, and 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, focusing on hazards features only and leaving for future investigation the vulnerability component. Most of these case studies available in the literature 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 our study we explore the socio-economic vulnerability and risk using an extensive survey amongst local experts and stakeholders to identify sources of multi-hazards risk and to derive weights for the different hazards considered and the vulnerability indicators selected. We develop a context specific case of multi-hazard risk assessment which 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), and even more so in megacities 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 city rather than in rural areas (Clarke, 1972; D'Ippoliti et al., 2010). In coastal cities a high number of people is 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 which, by encroaching them, ultimately further increases risk (MA, 2005; Pelling and Blackburn, 2013).

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. Some studies have previously assessed multi-hazard risk in the urban context. A recent study has analyzed the risk to multiple hazards including landslide, typhoon and heat wave in two districts of Hong Kong (Johnson et al., 2016). The study found that, despite socio-economic differences of the two districts, both present comparable levels of risk. van Westen et al. (2002) looked at physical risk (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, 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

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S'Abanell urban and touristic beach of Spain, finding that cultural and regulating 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 vulnerability in coastal megacities of the developed world as we have done in this study.

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. Thus, impacts acting in the same locations, without interacting causally or coinciding contemporaneously, can be considered jointly. This 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.

In this paper we analyze how multiple hazards overlap spatially in New York City to support planning 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.

1.2. New York City and disaster risk

New York City is a megacity, the largest city in USA and is located on the East coast, with approximately 8.2 million people in just the municipal city, with over 10,500 people per km^2 according to U.S. Census Bureau (2010). The New York City-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 US in terms of economic activity according the U.S. Census Bureau. In the city live approximately 1.4 million elderly age 60 and older, representing a particular vulnerable group (especially for heat related morbidity and mortality) which constitute 17% of the population and this proportion is projected to significantly increase (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 (Depietri and McPhearson, 2018): heat waves, inland flooding and coastal flooding. Heat waves are defined in NYC by the NYC Panel on Climate Change (NPCC) 2015 Report as three consecutive days above 90F (or about 32.2

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

°C) (Horton et al., 2015a). Inland, surface flooding can be triggered by precipitation of more than 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 hour in most areas of the city where sewers were built prior to 1960, and of 1.75 inches (about 44 mm) per hour in locations with sewers were built after 1960 (Llyod and Licata, n.d.). Coastal flooding is 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 increase storm surge and coastal flooding (Horton et al., 2015a; 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. However, we have combined multiple sources of evidence of the occurrence of multi-hazards events through this study which are presented in section 3.1.

1.2.1. Heat waves

Heat waves kill approximately 400 people each year in the U.S., and have caused more deaths in since 1998 than any other hazard (Bernard and McGeehin, 2004). Heat waves in NYC are also the largest cause of death due to socio-natural hazards (Depietri and McPhearson, 2018; NYC, 2014). Recent 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). Ageing people were the bulk of reported deaths during the August-September heat wave of 1973 (Ellis et al., 1975) similar to what has been reported for the August 1975 heat wave in which mortality doubled mainly affecting the elderly in poor sections of the society (Ellis and Nelson, 1978). 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). Madrigano et al. (2015) 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). Still, elderly were the most affected in past heat waves episodes in NYC, regardless of race (Ellis et al., 1975; Ellis and Nelson, 1978). 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). Temperature 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). The study by Knowlton et al. (2007) showed that, despite the possibility to adapt or to acclimatize to rising temperature, heat related premature deaths are likely to rise in projected future climates and affect regions beyond the urban core of the city. Spatial and temporal patterns of current risk combined with projects for increasing temperatures and frequency and intensity of heat waves suggests the need for extensive planning and management to reduce heat risk in NYC.

1.2.2. Inland floods

In NYC, the built environment – dense, heavily paved, and built up, 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 little more than one inch 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). 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. On the other hand, flash floods in NYC are rarely life threatening because of 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). To cope with present and future risk the city needs to reduce peak discharges to the sewer system during rain events by requiring greater onsite storage of stormwater runoff and slower release to the sewer system. With this objective, in 2010, 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, these efforts have a limited total stormwater mitigation potential and inland flooding is likely to continue to pose significant risks to urban residents in NYC.

1.2.3. Coastal flooding

Close to 15% of the NYC area lies within 100-year flood zone (Maantay and Maroko, 2009). The most frequent coastal storms affecting NYC are tropical storms and nor'easters (i.e. storms which originate in the Northeast, are usually polar, and not originating from the Gulf Stream where most weather in NYC originates). 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). Hurricanes affect NYC very infrequently. Five major hurricanes of category 3 have affected the New York area between 1851 and 2010, most in the month of September (Blake et al., 2011), but generally lead to large damages (Rosenzweig et al., 2011). In 2012, Hurricane Sandy caused 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 has also been 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 and 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). On the other hand, 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 potentially reach more than 1 m in 2100, 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).

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 overlapping events occur in the city as part of the study presented in Depietri and McPhearson (2018). We carried out an analysis of NOAA's meteorological records cross-referenced with the New York Times database of articles to analyze more in depth the occurrence of cumulative events. Furthermore, we conducted a survey of local experts and decision-makers with a principal objective to collect weights for indicators and sub-indicators selected but also to collect information of past and future multi-hazards risk in the city. The list of indicators and sub-indicators were derived from the literature. To describe vulnerability, the indicators were selected as able to describe the vulnerability to the three hazards considered jointly. Then 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. The respondents to the survey were 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.

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 set of indicators assigning 100 points amongst the listed indicators in each question. Final weights were derived by averaging the scores assigned by each respondent and dividing the means by 100. The weights thus derived were normalized ones and sum to 1 (i.e. 100%) 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 also related more broadly to multi-hazard risk in NYC and the city preparedness to cope with different hazards.

2.2. Multi-hazard risk assessment

Based on the initial search of multi-hazard risk events in the city in the NOAA/NYT search and on the responses of the survey described below, 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. Overall, the methodology consists of generating hazards maps, one for each hazard, a combined multi-hazards map and a common vulnerability map to the three hazards

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that includes socio-economic indicators. We then obtain the final risk map as the product of the combined multi-hazards map and the multi-hazard vulnerability map.

2.2.1. Hazards mapping

Multi-hazard risk assessment consists of an initial study of combined hazards which have overlapped 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.

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

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

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 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[2] under the keywords "coastal flooding", "high surf", "tropical storm",

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

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"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.

In the case of coastal flooding, a map was 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 for 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 more inclined to be compared with the other hazards.

The hazards' weights reported in Table 1 indicate that, according to the respondents, the 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		
			Air pollution (AP)	0.367	Ozone (O)	0.483
					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.

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. In Birkmann et al. (2013, p. 200), vulnerability is described through three components: a) exposure, "the extent to which a unit of assessment falls within the geographical range of a hazard event"; b) susceptibility, referring to the "predisposition of elements at risk (social and ecological) to suffer harm" resulting from the levels of fragilities, disadvantageous conditions and relative weaknesses; and c) lack of resilience or of coping capacity, meaning "limitations in terms of access to and mobilization of the resources of a community or a social-ecological system in responding to an identified hazard".

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). We selected eight different variables (Table 2) from a list of indicators identified with the literature review for mapping vulnerability. Like the hazards mapping described above, we reclassified each of the indicators into five intensity categories represented by the values of 1-5 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 (i.e. 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.

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

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 as we considered each component to equally contribute to the final vulnerability as determined by the definitions presented above.

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 community, risk is 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).

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

Where R is risk, H is multi-hazards and V vulnerability. We multiplied hazard per vulnerability as, according 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 aggregated risk is also displayed using five intensity classes (Figure 8 in results section).

Our method of aggregation, which first quantifies the indicators of hazard and vulnerability into five ordinal categories and then uses weighted linear combination, primarily stems from the existing literature. Previous mainstream 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). The final aggregation (i.e. the risk map), as a product of two composite layers, is based on the actual definition of risk (i.e. the product of hazard and vulnerability).

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 is highly comparable 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

Various interrelated multi-hazards incidents in NYC were reported by the New York Times, especially at the end of the 19th century beginning of the 20th, for example city inhabitants seeking relief from heat in the surrounding forests but were then stricken by lightings as they were taken by surprise by an unexpected thunderstorm. Thousands of people commonly use beaches as a source of cooling (especially Coney Island) and parks. Yet parks used to provide cooling relief, given occurrence of multiple hazards, were also a threat. People caught in the city and that were looking for shelter under a street tree or park trees were hit by a lightning or died because an electric wire broke due to high wind and which struck the residents. Lightning also often caused fires. Other people were taken by surprise on boats or swimming looking for relief in the breeze or the cool water and were injured or died due to by the sudden appearance of a thunderstorm. Power outages have also been caused by storms following a heat wave that cut power for air conditioning and affect the transport system, especially in the more recent times. Thus, relief from heat often comes at the price of human lives.

Another example involves the interaction between hurricanes and coastal flooding. These, if occurring in the winter, have been followed by snowstorms that rendered more difficult rescue and recovery operations, as in the case of the aftermath of hurricane Sandy. Oils spills and the release of other toxic substances have also been caused by a coastal storm or inland flooding event. This was the case of Hurricane Irene in 2011 when heating oil tanks were overturned by flood waters in the basements of houses causing widespread pollution.

Beyond providing weights for our list of indicators, 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 those

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that can occur in the future. These results are summarized in Table 3 and 4 respectively. In our study we cover most 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.

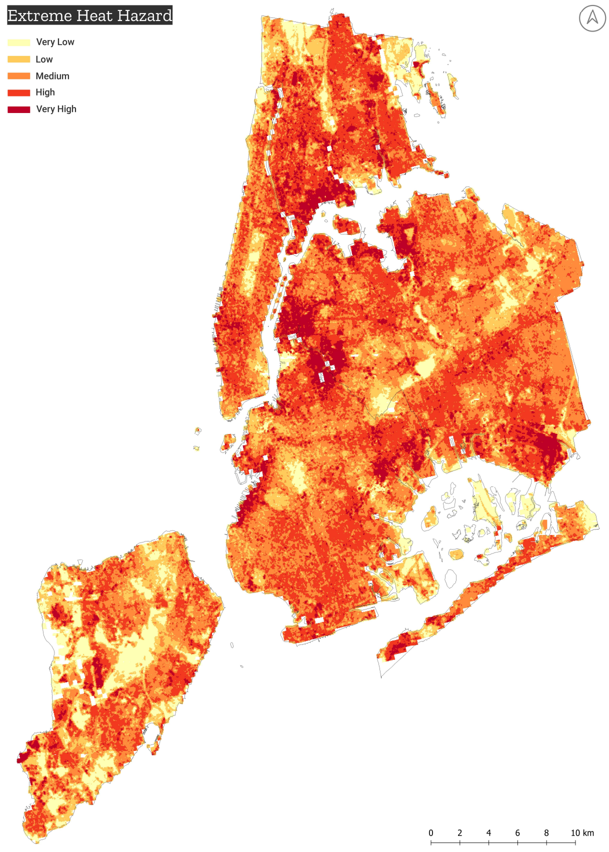
Multi-hazard evets that already occurred in NYC		
Hurricane	Cold spell	Inland flooding
Heat waves	Thunderstorms	Inland flooding
Hurricane	Infrastructure failure	

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

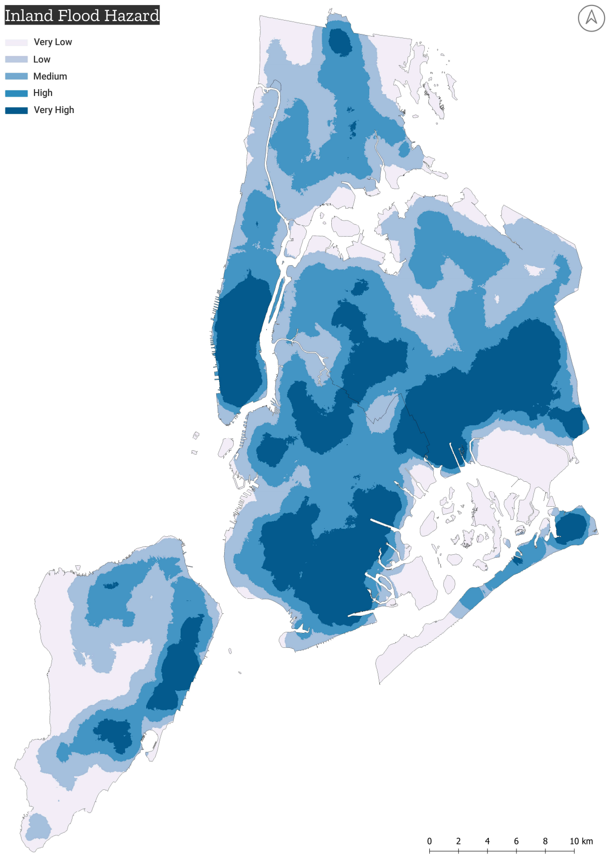
Combinations of events that the city should adapt to	
Coastal flooding	Exposure to toxic substances
Coastal flooding	Inland flooding
Coastal flooding	Cod Spell
Coastal storms	Power outages
Heat waves	Hurricane
Heat waves	Power outages
Heat waves	Severe thunderstorm
Heat waves	Drought

3.2. Multi-hazard risk assessment

Figures 1 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.



542 **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

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

Figure 1 a, b and c. Spatial variation in heat hazard, inland flooding hazard, and coastal flood hazard for New York City.

Figure 2 displays the joint multi-hazard map with higher intensities in most of the coastal areas. The Coastal flooding had in fact been assigned a higher weight with respect to the other two hazards. The city is 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.

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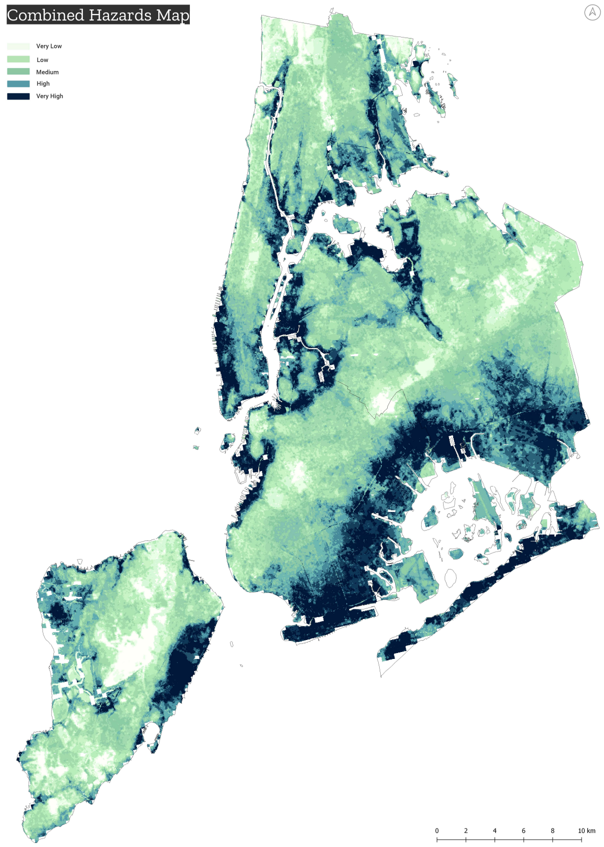
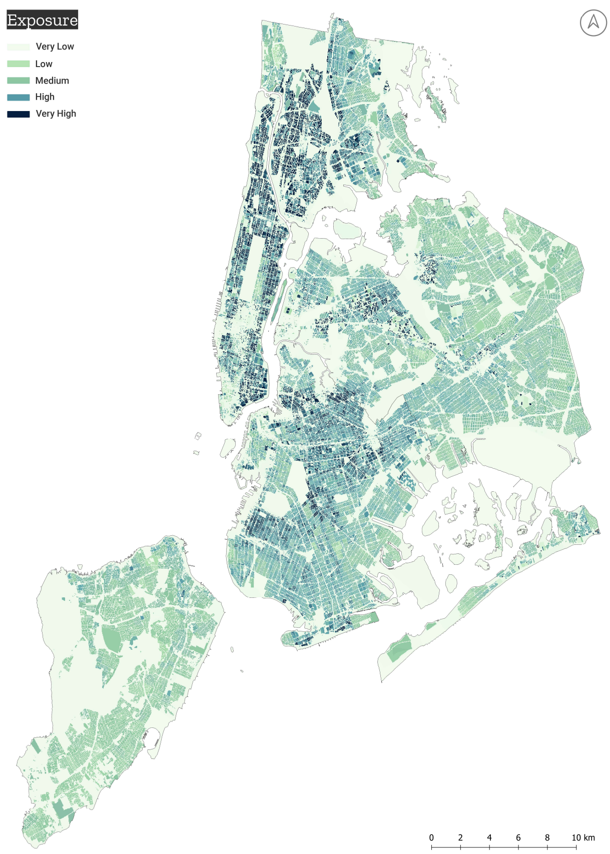


Figure 2. Spatial variation in the combined hazards including weights derived through expert input.



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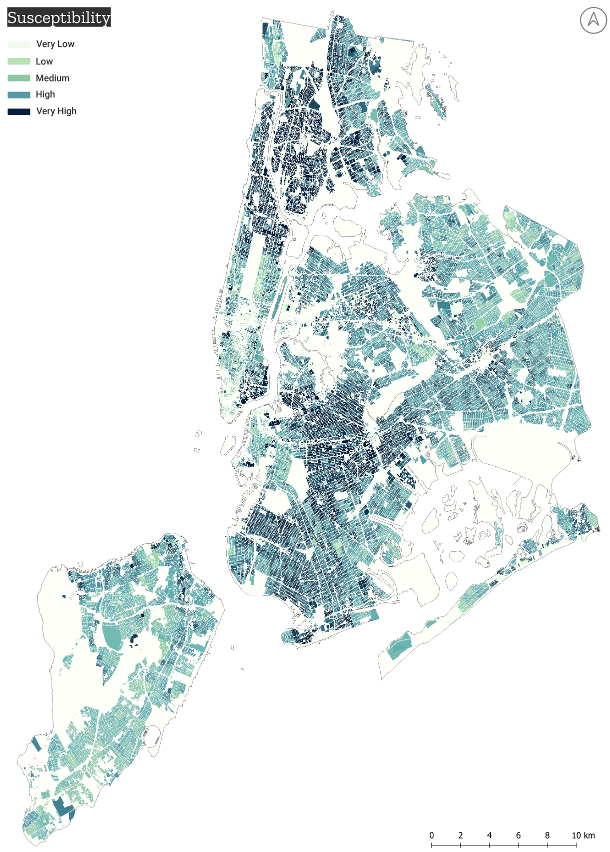
a. Map of exposure



b. Map of susceptibility

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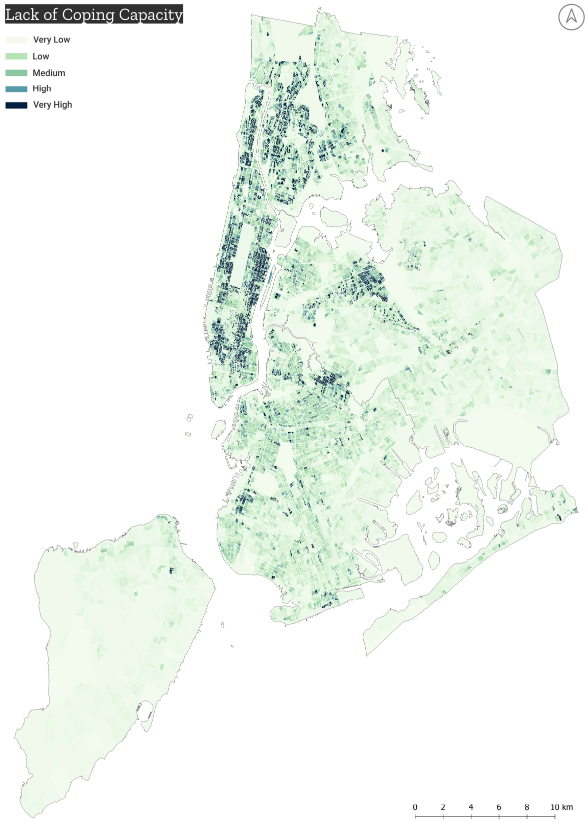

c. Map of lack of coping capacity

Figure 3 a, b and c. Spatial variation in three components of vulnerability (exposure, susceptibility and lack of coping capacity) to multiple hazards.

Figure 3a 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 3b) 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.

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Figure 4. Map of Vulnerability

The resultant vulnerability map (Figure 4) 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 scale we conducted our analysis. Despite their exclusion from the study, we report these results as a useful piece of information for further research on the subject.

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.

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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

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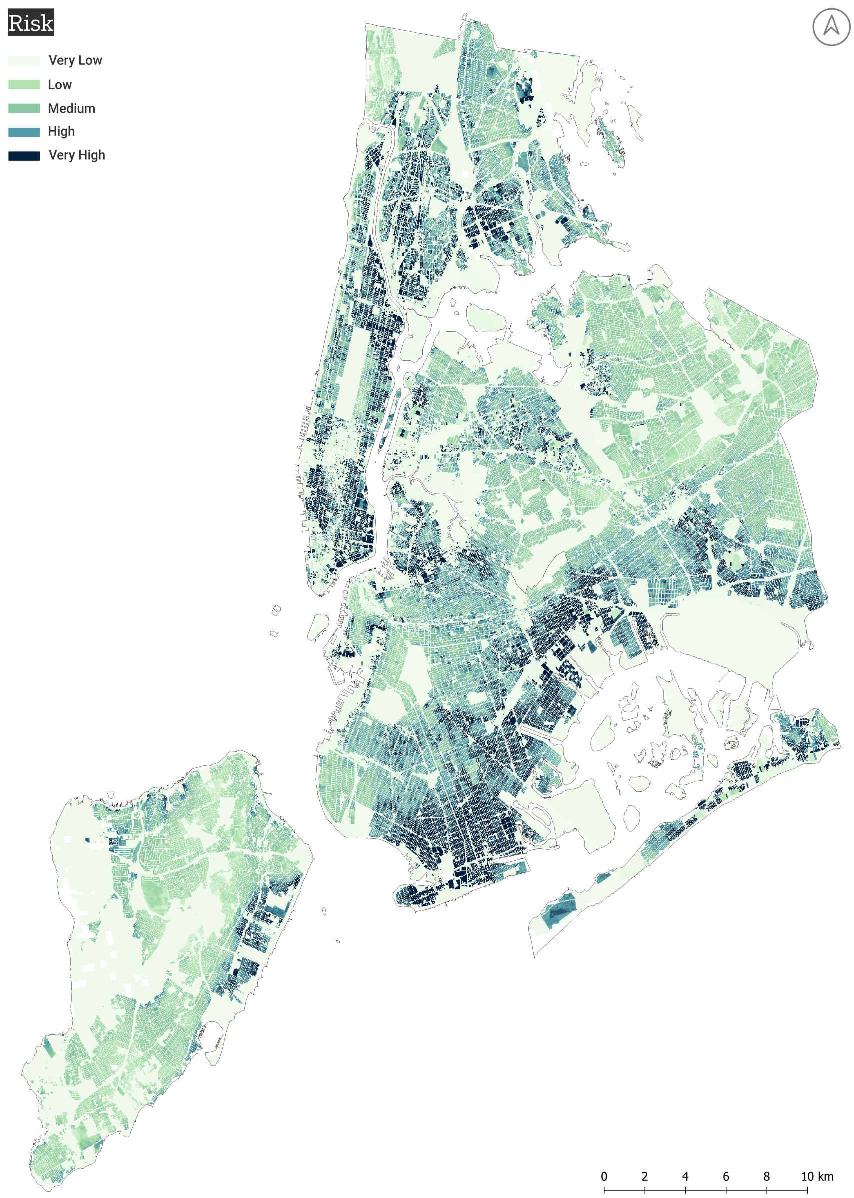

a. Multi-hazard risk map

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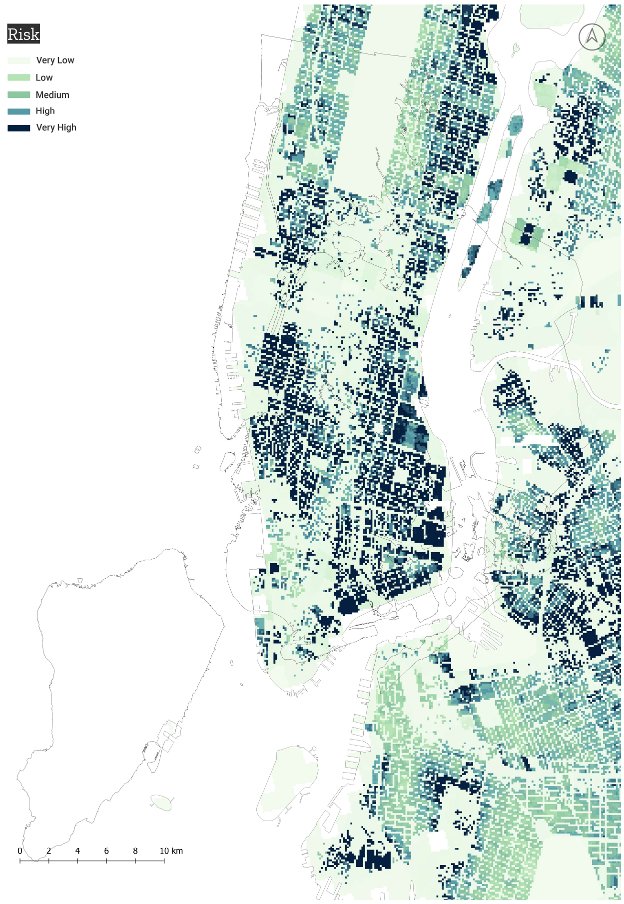

b. Detail of the multi-hazard risk map

Figure 5 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 results in a final multi-hazard risk assessment (Figure 5a). We find that the coastal areas of Brooklyn, Manhattan and Harlem are the most at risk from the three hazards considered. Figure 5b, 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 results to be a priority for the city. An outcome that is made further pressing by the opinions gathered through the survey amongst local stakeholder who see the city the least prepared to cope with coastal flooding, second only to earthquakes (see Figure 6).

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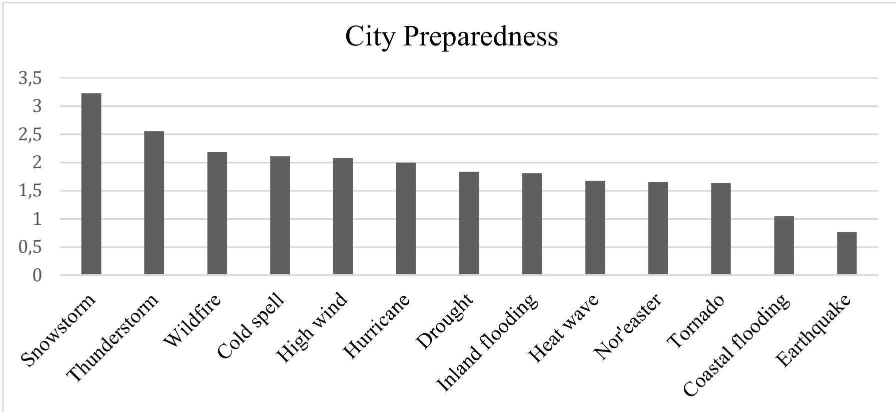

Figure 6. Survey result's regarding the level of city's preparedness to impactful hazards potentially affecting NYC out of a maximum of 5 points.

4. Discussion

From our qualitative analysis and survey responses, NYC is found to be at risk to multiple and overlapping events, spatially and temporally. Multi-hazard risk is therefore a reality that is worth exploring in the city. Hazards interactions were found to have happened or be likely to happen in conjunction with coastal flooding or hurricanes, heat waves and inland flooding. We focused on these three hazards to analyze socio-economic vulnerability and multi-hazard risk and see how these are spatially distributed. 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 also resulted to be highly vulnerable, seemingly due to the concentration of elderly and people living alone in these areas of the city or to poor neighborhoods such as Harlem. These factors, despite the wealth characterizing Manhattan, explain the high level of multi-hazards risk that the neighborhood needs to face. Coastal areas of the city facing the open sea as well as large areas of Manhattan and the Bronx resulted to be also the most at risk from the multiple hazards considered. We suggest that adaptation strategies should prioritize these areas while considering that soft or hard infrastructures put in place need to be adapted also inland and heat waves alleviation for instance through enhanced infiltration and reduction of the urban heat island. No part of the city is in fact 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 the choice of 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 suggest this is a key innovation given that most of the previous studies tended to focus on physical vulnerability (other examples are Greiving, 2006; Johnson et al., 2016). It allowed to show that parts of the city potentially affected to multiple hazards not necessarily correspond to the areas where most of the

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vulnerable people live. However, the reviewed literature and the collected experts' opinions that point to the need to complement with indicators of physical dimension of vulnerability especially when one consi1-*ders risk to flooding. Some of the indicators that could be used are: the conditions of exposed buildings; roads, railroads and the subway system; and other critical infrastructures that supply energy, support communication or treat wastewater.

Furthermore, the weights were derived from expert-input through a survey methodology where experts ranked indicators and sub-indicators. This allowed to develop an assessment specific for the case of the city of New York. For instance, with respect to hazards' weights, these indicated that the higher impacts would be caused by coastal hazards, a result that might depend on the recent awareness raised by disastrous impacts caused by Hurricane Sandy and generally the high impact of these hazards have on the city although if not frequent. Nonetheless, we initially calculated risk through all steps described but with equal weighting. The results still showed how coastal areas of Brooklyn, Harlem and the Bronx are 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 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 components of vulnerability show that high exposure (where most of the people are located) does not correspond to areas where people are the most vulnerable. Also, the final risk map, when compared with the combined hazards maps, shows that the main determinant of risk is the multi-hazard level rather than the vulnerability of the population.

The choice of the 311 calls to represent inland flooding allowed us to include an element of the disaster scape of NYC which has not been explored in previous studies. Despite the drawbacks mentioned, areas identified at high risk of inland flooding varied little with changes in the classification method used but may need further validation.

The methodology can potentially be expanded to accommodate other indicators, for instance to produce hazard-specific vulnerability maps instead of a common assessment. With a broader range of indicators and by conducting hazard specific vulnerability assessments each step of the methodology would be even more relevant.

The detailed spatial resolution of the risk assessment provides decision makers with the possibility to prioritize areas of intervention at the very narrow scale, down to the building and street level. By considering the three hazards jointly, no inhabited area of the city results at no risk, while some present accumulation of risk where to prioritize interventions.

5. Conclusions

This study presents 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.

Through the responses to the questionnaire and the NOAA NYT database search, we show that risk to multiple, temporally and spatially interacting hazards in NYC is substantial. The steps of quantitative assessment 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 combined risk exist in the city. The results showed that the city is significantly most at risk in the coast areas of midtown and downtown Manhattan, Harlem and the coastal areas of Brooklyn, especially those surrounding the Jamaica bay. A predominant role is played by coastal flooding. The analysis of these results suggest that decision makers should prioritize those strategies that protect the city from coastal flooding while considering that those areas are also affected by other hazards and could be jointly addressed. A result validated by the responses from the survey which show how local stakeholders feel that the city is little prepared to cope with coastal flooding.

Further research should consider more indicators of physical vulnerability, if data is available, 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 the city 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 for multiple hazards.

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