The authors have done a good job to address most of the comments. I still have a few outstanding issues that could be resolved.

1) The authors stated in their responses that this paper was not intended to be a comprehensive review of hazards for NYC, but rather presents a new and interesting methodology for DRR. My problem with this response is that at a large portion of the revised manuscript text is focused on developing a new hazard assessment of NYC using novel techniques (Sections 1.3, 2.2, and 3.1, Figures 1 - 3) which is in conflict with the responses provided. If this hazard assessment merely a placeholder that you will refine in a future paper, then why is it worth publishing here? I think if you want the reader to understand your research aim is on the methodology and the hazard assessment is really just a placeholder for a more complete assessment in a future papers, then all of this cataloging of hazards belongs in a supplemental material. In the main manuscript you can then say something like: "We provide a cursory hazard assessment based on the datasets A, B, C, etc. in order to demonstrate our methodology. Multihazard estimates are provided in the supplemntary material." Alternately, if the paper is focused on novel ways to assess hazard, then the authors could do more to address the shortcomings of the hazard assessment.

Thank you for your comment and the specification. This manuscript provides an improved methodology for calculating multi-hazard risk in coastal megacities. It for instance integrate experts opinions in the calculation of final multi-hazard risk improving the accuracy of the high resolution spatial assessment. However, it also advances our understanding of risk specifically in New York City in a multi-hazard context and the conclusions provide relevant information specific to the case of the City of New York. We have added text similar to that suggested by the reviewer to make it clear that New York is a case study for demonstrating the improved multi-hazard risk methodology presented in the manuscript. However, we don't agree that putting all hazards in supplementary material is the best way to present the NYC case or for readers to fully grasp the methods and so have kept case study material in the main manuscript. We have also updated the abstract and other places in the manuscript to make sure the intent of the paper is clearly to present a methodology with NYC as a case study. (See abstract and Lines 101-102; 110-111; 172-177; 743-746; 764-765)

2) Line 371: Your response says that you do not suggest a uniform increase, but the revised text still does not offer enough information to make this clear. I'm not sure about the relevance of changes in annual rainfall totals to the multi-hazards that you're discussing, and I think it's a bit misleading. First, I would choose a temporal scale for precipitation analysis that is relevant to flooding (daily intensity or shorter). Second, since your study specifically focuses on mechanisms, you should disaggregate this into the rainfall mechanisms of interest. For example:

"Recent research using historical data has suggested that for the NYC region, daily precipitation extremes are increasing in the fall with less change in all other seasons (Frei et al 2015; Huang et al 2017; 2018), however, projections from downscaled GCMs provide less clear evidence for a shift in the intensity of flood causing rain events in the Northeast US (Knighton et al 2017; Schoof & Robeson, 2016)."

You do not need to use this text or these references, but saying something like this would help the reader to make the connection between climate change and the hazards you are discussing.

Frei, A., Kunkel, K. E., & Matonse, A. (2015). The seasonal nature of extreme hydrological events in the northeastern United States. Journal of Hydrometeorology, 16(5), 2065-2085.

Huang, H., Winter, J. M., & Osterberg, E. C. (2018). Mechanisms of Abrupt Extreme Precipitation Change Over the Northeastern United States. Journal of Geophysical Research: Atmospheres.

Huang, H., Winter, J. M., Osterberg, E. C., Horton, R. M., & Beckage, B. (2017). Total and extreme precipitation changes over the Northeastern United States. Journal of Hydrometeorology, 18(6), 1783-1798.

Knighton, J., Steinschneider, S., & Walter, M. T. (2017). A Vulnerability-Based, Bottom-up Assessment of Future Riverine Flood Risk Using a Modified Peaks-Over-Threshold Approach and a Physically Based Hydrologic Model. Water Resources Research, 53(12), 10043-10064.

Schoof, J. T., & Robeson, S. M. (2016). Projecting changes in regional temperature and precipitation extremes in the United States. Weather and climate extremes, 11, 28-40.

We agree with this comment which was not properly addressed in the previous version. We inserted the suggested paragraph and references in the paper. Thank you for this very helpful addition and for being specific in the suggested additions. Most reviewers do not take this extra care and we thank you. Lines 321 to 325.

3) I believe my comment on the decision analysis literature was perhaps not entirely clear. A large component of this research is social, in that these frameworks are fundamentally based on the mapping of hazards to risks as a way to reduce the demand placed on the social component of DRR. This is fundamentally the focus of your paper, just from a new point of view. Citing them is certainly not a requirement for publication. I just think the authors might find some relevance in these papers to the work they've presented. I leave it to the authors to decide how to handle this. I only bring it up again because the authors response suggested that I left an ambiguous comment.

Thank you for the specification. We certainly considered and acknowledge the suggestion. However, we thought to narrow the focus of the paper's background and discussion to address principally the body of the literature about risk and vulnerability. The suggested literature is surely a facet of the problem we are addressing but we tried to limit the background of the paper to a specific literature. Nonetheless the suggested literature remains very informative to our case.

4) With respect to the representation of uncertainty in the weights I think my initial comment wasn't entirely clear. As the authors state, experts were given 100 points to allocate between indicators. If I'm understanding this correctly, each indicator has a population of n allocated points, one from each person surveyed, which the authors then average. If you can calculate an average, you also can calculate some measure of the population variance. Simply presenting the standard deviations of the allocated points for each indicator would given readers an idea about how much agreement (or not) there was among the group surveyed. I believe this is a critical piece of information. If there is low variability it says the the social network of experts was highly connected and held similar perceptions of risk. If there is a large variance among points assigned, then it perhaps suggests divergent perceptions of vulnerability and difficulty in lending a broader legitimacy to this approach. If this data was not collected in a way that would allow calculation of population variance, then I think this is a major issue.

Thank you for this comment, this analysis enriches our case and we added the values of the standard deviations for weights of each indicator considered in our analysis. There was high variation in values in some cases which might be linked to the wide variety of background represented in the group of respondents. (see Table 1 and 2 and Lines 460-466). We have updated the tables and results to reflect this in the manuscript. In hindsight, we should have included this from the beginning and thank the reviewer for pointing this out as including this data is important.

Multi-hazards risks in New York City

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Abstract

Megacities are predominantly concentrated along coastlines, making them exposed to a ~~broader mix~~diverse mix of natural hazards. The assessment of climatic hazard risk to cities rarely has capture~~d~~s the multiple interactions that occur in complex urban systems. We present an improved method for urban multi-hazard risk assessment. We then analyze the risk of New York City as a case study to apply enhanced 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 demonstrate the application of multi-hazard risk assessment to a coastal megacity and show that spatial hotspots of multi-hazard risk affect~~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, natural hazards, disaster risk reduction, megacities, multi-hazard risk, social vulnerability, climate change, ~~spatial assessment,~~ New York City

2

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 beis 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 human losses, 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. Heat waves kill on average more persons than any other extreme event in NYC (Depietri and McPhearson, 2018). AdditionallyThen, extreme precipitation can cause havoc in cities. –In NYC 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.

In general, hazards in urban areas also overlap spatially and/or temporally (e.g. high 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., 2012a; 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 adaptation policies and specific interventions and

97   can maximize resilience and adaptation by meeting challenges posed by different sources of natural hazard

98   risk. For example, tree planting or green roof investments to increase stormwater infiltration can also be a

99   synergistic strategy for the reduction of the urban heat island (UHI).

100

101   The objective of this study is to provide an improved multi-hazard risk assessment methodology which is

102   then applied toof NYC as a case study of how megacities in coastal areas are affected by multiple, spatially

103   overlapping hazards. NYC is an important megacity for examining multi-hazard risk given its global

104   prominence, as being the largest city in the U.S. with hundreds of US$ billions in assets and millions of

105   people at risk. It is a coastal city threatened by multiple hydro-meteorological hazards, further exacerbated

106   by climate change. Here we report data on past and future, potential multi-hazards events in NYC and assess

107   the combined socio-economic risks of residents to three different sources of climatic hazards: heat waves,

108   inland flooding and coastal flooding. The analysis is based on the spatial features of hazards and social

109   vulnerability in the city to inform resilience and adaptation planning that typically focuses interventions on

110   single hazards. In this way we intend to provide a scientific basis with context specific and expert based input

111   for improving our understanding of multi-hazard risk in the city, for future planning in the city as well as

112   recommendations for real world implementation of such a multi-hazard assessment for other similarly

113   exposed urban areas.

114

1.1. Vulnerability and risk assessment to natural hazards

116   The study of the impacts of natural hazards on the social-ecological systems has moved from the focus on

117   the geophysical, climatological or hydro-meteorological phenomena by considering first physical

118   vulnerability (i.e. exposure and fragility of the exposed elements) and only later the socio-economic,

119   institutional and cultural factors that increase the exposure, susceptibility and coping capacity of the system

120   (Bankoff et al., 2004; Birkmann, 2006; Cardona, 2004). In this perspective the occurrence of a hazard does

121   not necessarily lead to a disaster. Disasters are socio-cultural constructions mainly driven by the fragilities

122   of the affected social-ecological system, its health and it's management approach, which all contribute in

123   defining risk from hazards (Oliver-Smith, 2004). Risk thus concerns the values, knowledge and actions of a

124   particular society (Cardona, 2004; Wisner et al., 2014). Economic factors also play a role in defining

125   vulnerability and thus risk. For instance, poor populations tend to settle in hazard prone areas where housing

126   costs are lower, a result of past political, economic and cultural legacies that provide them with little

127   alternative, putting them at higher risk (Wisner et al., 2014). The same hazard can cause very different

128   impacts in adjacent areas but which differ for their socio-economic activities and institutional or governance

129   practices. An example from Collins (2010) describes how, in "Paso del Norte" (a city between two countries:

130   El Paso County, USA and Ciudad Juárez, Mexico), the impacts of floods, that occurred between July and

131   September 2006, were overall of an order of greater magnitude in the Mexican part of the city due to unequal

132   power relations expressed through the economic system. Risk is thus a complex concept that encompasses

133   both the features of the hazard and that of the system potentially affected.

134

135

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., 2012b). Some studies have assessed different 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. A 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, but considering the hazards features only and leaving for future investigation the vulnerability component. Most of these case studies 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 wor~~Here,~~k~~ we explore the socio-economic vulnerability and risk spatially and by using an extensive survey amongst local experts and stakeholders to

5

identify sources of multi-hazards risk and derive weights assessing the importance of the different hazards and the vulnerability indicators selected. This is an additional feature of this type of studies that aims at further adapting the study to the local conditions. We thus developed a highly context specific case of multi-hazard risk assessment of in NYC, but with a generalizable multi-hazard risk assessment 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. The methodology, in fact, intends to add to the literature on multi-hazard risk assessment by integrating locally adapted weights derived from expert opinions.

1.2.1 Multi-hazard risk in 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 an 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. (2012a) 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. Overall, few studies have focused on multi-hazard risk assessment with a strong social component to understand vulnerability in coastal megacities of the developed world.

6

210

211 Multi-hazard mapping, which consists of "the totality of relevant hazards in a defined area" (Kappes et al.,

212 2012b), is a fundamental approach for multi-hazard risk assessment in urban areas and relevant for the NYC

213 area. Such an approach allows for the identification of potential hotspots of risk and vulnerability derived

214 from spatial combination of more than one hazard. The effects of the hazards are considered as additive, with

215 overlapping degrees of impacts. In this way, the impacts acting in the same locations, without interacting

216 causally or coinciding contemporaneously, can be considered jointly. The approach facilitates the

217 identification of structural improvements that can lead to the combined reduction of the exposure to two or

218 more hazards in urban areas. The socio-economic determinants of vulnerability, which often lead to the

219 concentration of vulnerable people in certain areas of the city, are examined jointly and help the identification

220 of zones of the city more likely to suffer harm from multiple hazards and in which more resources should be

221 invested for adaptation. Multi-hazard risk is composed of two main steps: the analysis of the hazards and of

222 the vulnerability of the system. Thus it widely refers to the vast literature on disaster risk and vulnerability

223 assessment mentioned above (e.g. Birkmann, 2006; Birkmann et al., 2013; Bogardi and Birkmann, 2004;

224 Cardona, 2004; Pelling, 2003; Turner et al., 2003; Wisner et al., 2014). The vulnerability component

225 expresses the predisposition of the system to suffer harm and it generally expressed through the degree of

226 exposure of the system (or number of subjects or objects potentially affected by the hazard), the susceptibility

227 (or the fragilities of the system exposed such as the health of the population) and the lack of resilience (or

228 the incapacity to be prepared, cope and respond to the hazard) (Birkmann et al., 2013). Here, we analyze

229 how multiple hazard risks overlap spatially in New York City with the goal of supporting planning and policy

230 for three key objectives: 1) to improve risk reduction through multi-purpose strategies, 2) to improve adaptive

231 capacity of the city, and 3) to suggest a potential approach for similar multi-hazard risk assessments in other

232 vulnerabile urban areas and settlements.

233

234 **1.3. New York City and disaster risk**

235 NYC is the largest city in USA and is located on the East coast (see Figure 1), with approximately 8.62

236 million people in 2017 and just in the municipal area with over 10,500 people per km² according to U.S.

237 Census Bureau (2010). The NYC-Newark-New Jersey metropolitan statistical area is much larger, with 20.3

238 Million people living in the region closely connected socially, economically, and infrastructurally to NYC[1].

239 The metropolitan area is also the largest economically the largest city in the U.S. (. in terms of economic

240 activity, this according the U.S. Census Bureau, 2010). Approximately 1.4 million people aged 60 and older

241 live in the city, representing a particularly vulnerable group, especially for heat-related morbidity and

242 mortality. Elderly constitute 17% of the population at present, and this proportion is expected to grow

243 considerably in coming years (Goldman et al., 2014). NYC is also built around a network of rivers, estuaries

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

7

244 and islands with much of the Metropolitan region situated less than 5 m above mean sea level (Colle et al.,
245 2008) which contributes to the hazard context especially in terms of coastal flooding.

246

247 We focus our analysis on three hazards that cause the highest human impacts in NYC (see Depietri and
248 McPhearson, 2018): heat waves, inland flooding and coastal flooding. Heat waves in NYC are defined by
249 the NYC Panel on Climate Change (NPCC) 2015 Report as three consecutive days above 90F (or about 32.2
250 °C) (Horton et al., 2015a). Inland flooding in NYC can be triggered by precipitation of more than 1.5 inches
251 (or 38 mm) of rain per day since the city's drainage system is designed to handle heavy rainfall with
252 intensities of 1.5 inches (about 38 mm) per day in most areas of the city where sewers were built prior to
253 1960, and of 1.75 inches (about 44 mm) per day in locations with sewers were built after 1960 (Llyod and
254 Licata, n.d.). Coastal flooding is primarily driven by storm surge. NYC is affected by changing climate with
255 future projections including probable higher temperatures, increasingly frequent heavy downpours, and a
256 rising sea level that will further increase storm surge and coastal flooding (Garner et al., 2017; Horton et al.,
257 2015a; Lin et al., 2012, 2016; Reed et al., 2015; Rosenzweig and Solecki, 2015). In the next sections, we
258 describe each hazard and its local impacts. Information about multi-hazard risk in the city is scarce in the
259 available literature, consequently we have combined multiple sources of evidence of the occurrence of multi-
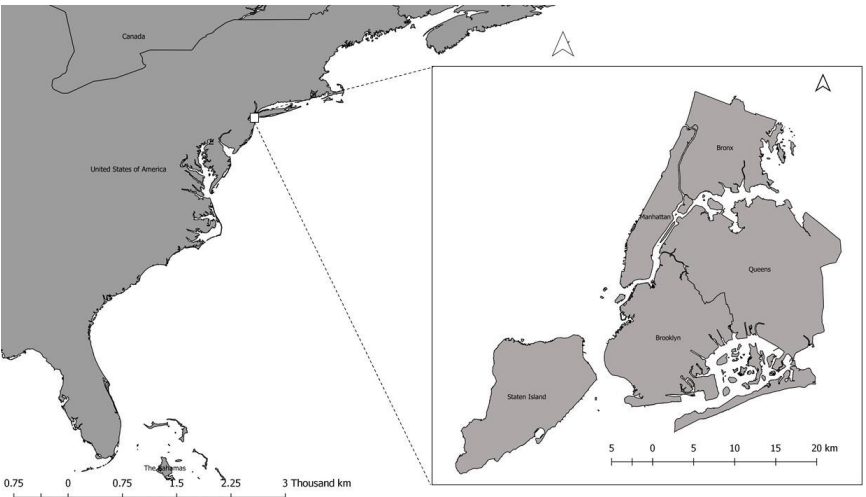260 hazards events in NYC and review them in section 3.1.

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

263

264 **1.3.1. Heat waves**
265 As mentioned above, H heat waves in NYC are the largest cause of death due to socio-natural hazards
266 (Depietri and McPhearson, 2018; NYC, 2014). Past disastrous heat waves include the July 1966 event, where
267 the mortality rate increased by 36% (Schuman, 1972) and the summer 1972 heat wave which caused 253

268 deaths on the 24th of July only (Ellis et al., 1975). According to the NYC Department of Health and Mental

269 Hygiene, 46 heat stroke deaths resulted from two heat waves in July-August 2006 while 26 heat related deaths
270 occurred during the heat wave of July 2013 (NYC, 2006, 2014). Between 2000 and 2011, 447 patients were
271 treated for heat illness and 154 died (CDCP, 2013). A study by Madrigano et al. (2015) reported up to 234
272 heat related excess death for the same period. It has been documented that extreme heat impacts have been
273 increasing at least for the period 1987-2005 (Anderson and Bell, 2011). However, numbers of deaths are
274 significantly less pronounced if compared to the first half of 20th century, showing an evidence of adaptation
275 likely due to the use of air conditioning (Depietri and McPhearson, 2018; Petkova et al., 2014).

276
277 Risk to heat waves is driven by several factors. Those with poor socio-economic status, for example black
278 (non-Hispanic) individuals, and the socially or linguistically isolated are more likely to die during a heat
279 wave (Madrigano et al., 2015). People with chronic physical or mental health illnesses (i.e. cardiovascular
280 disease, obesity, neurologic or psychiatric disease) also account for a large part of the causalities, together
281 with individuals subject to alcohol or drugs abuse (CDCP, 2013; Ellis et al., 1975). The ageing population is

282 the most at risk to suffer heat stroke during a heat wave (Luber and McGeehin, 2008; Oudin Åström et al.,

283 2011). Madrigano et al. (2015) also found that greener neighborhoods were less at risk in NYC, potentially
284 due to decreased urban heat island in those areas of the city. Increased rates of poverty and higher densities
285 of African-American populations were found to be highly correlated with the lack of green spaces in the city
286 (Klein Rosenthal et al., 2014). Low income and crowding where also elements of risk in the 1966 heat waves
287 according to Schuman (1972). Primary indicators of heat vulnerability are relatively consistent across studies
288 with poverty, poor housing conditions, low access to air-conditioning and seniors' hypertension associated
289 with elderly death due to heat stress in NYC between 1997 to 2006 (Klein Rosenthal et al., 2014).
290 Environmental conditions, pervious land cover and aggregated surface temperatures were also found to be
291 positively associated with heat related deaths of elderly (Klein Rosenthal et al., 2014).
292
293 Gedzelman et al. (2003) calculated the UHI of NYC to be on average approximately 4 °C in summer and
294 autumn and 3 °C in winter and spring according to measurement taken between 1997 and 1998 (Gedzelman
295 et al., 2003). Temperatures have been rising in Central Park between 1900 to 2013 (Horton et al., 2015a).
296 More in particular, it has been estimated that the temperature rose by 1.1 °C between 1900 to 1997 in NYC
297 (Knowlton et al., 2007). One third of the total warming of the city since 1900 was attributed to the
298 intensification of the UHI. Projections show that this trend is likely to continue in the future, with warmer
299 temperatures in NYC in the coming decades driven by UHI and increasing temperatures caused by climate
300 change (Horton et al., 2015a). A study by Knowlton et al. (2007) showed that, despite the possibility to adapt
301 to rising temperature, heat related premature deaths are likely to rise in projected future climates and affect
302 regions also beyond the urban core of the city. Spatial and temporal patterns of current risk combined with
303 projections for increasing temperatures and frequency and intensity of heat waves thus suggests the need for
304 extensive planning and management to reduce heat risk in NYC.

1.3.2. Inland floods

In the city, the built environment – dense and heavily paved built up areas 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). 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).

Recent research using historical data has suggested that for the NYC region, daily precipitation extremes are increasing in the fall with less change in all other seasons (Frei et al., 2015; Huang et al., 2017, 2018). However, projections from downscaled Global Climate Models (GCMs) provide less clear evidence for a shift in the intensity of flood caused by rain events in the Northeast US (Knighton et al., 2017; Schoof and Robeson, 2016) ~~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

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

341 (Orton et al., 2012; Rosenzweig et al., 2011). Extratropical first and then tropical cyclones tend to generate
342 the greatest storm surge heights and flooding in NYC (Catalano and Broccoli, 2017; Smith et al., 2010;
343 Towey et al., 2018), which can reach up to 5.12 m according to Lin et al. (2010). Extratropical storms account
344 for 80%–85% of total precipitation from December to May and 93%–100% of extreme precipitation from
345 November to May in the Northeastern coast of the U.S. (Agel et al., 2015). Hurricanes affect NYC more
346 infrequently. However the associated flooding are being exacerbated due to the increase of sea level and the
347 increase in the intensity of the hazard itself (Kemp and Horton, 2013; Reed et al., 2015). Five major
348 hurricanes of category 3 have affected the New York area between 1851 and 2010, mostly in the month of
349 September (Blake et al., 2011) and generally lead to large damages (Rosenzweig et al., 2011). In 2012,
350 Hurricane Sandy made landfall as a post-tropical cyclone in New Jersey with 70-kt maximum sustained
351 winds, droving a catastrophic storm surge into the New Jersey and New York coastlines (Blake et al., 2013).
352 In NYC the storm surge was of 2.81 m and was at the origin of most of the damages and losses (Kemp and
353 Horton, 2013). Hurricane Sandy caused 43 deaths in NYC and nearly half were adults aged 65 or older
354 (Kinney et al., 2015). According to Lane et al. (2013), death was caused most frequently by drowning
355 associated with the storm surge. Other deaths were caused by falling trees, falls, electrocution, and other
356 traumas. Further, Sandy caused at least $19 billion in economic losses to the city (NYC, 2013), left hundreds
357 of thousands without power, some for many weeks (Lane et al., 2013). It was also found that power outages
358 increase risk of death in NYC (Anderson and Bell, 2012). Five hospitals shut down due to Sandy, three of
359 them had to evacuate patients after the storm hit because of flood damage to critical equipment; power losses
360 in these facilities further complicated evacuation operations (Lane et al., 2013). Nearly 70,000 buildings were
361 damaged by the storm or destroyed by related fire especially in south Brooklyn, South Queens and Staten
362 Island; the subway system was seriously affected; roads, railroads and airports were flooded; while the
363 communication system was disrupted in many areas (NYC, 2013).
364
365 Since Hurricane Sandy, the city established a US$20 billion plan to adapt to climate extremes with 257
366 initiatives which span from coastal protection, economic recovery, community preparedness and response,
367 and environmental protection and remediation (NYC, 2013). Additionally, the Mayor's Office of Housing
368 Recovery Operations was established in 2013 to oversee housing recovery in NYC.
369
370 Increasing hurricane intensity over time has been detected (Gornitz et al., 2001; Knutson et al., 2015).
371 Additionally, three of the nine highest recorded water levels in the New York Harbor region have occurred
372 since 2010, and eight of the largest twenty have occurred since 1990 (Talke et al., 2014). 40% of sea level
373 rise in NYC is driven by subsidence and the rest by global climate change, amounting in total to 25,4 mm
374 per decade since 1900 (Horton et al., 2015b). Due to sea level rise, which is projected to accelerate during
375 this century to reach up to 1.2 m in the coming century (Kopp et al., 2014), coastal flooding in NYC is
376 expected to become more frequent and intense, even in absence of changes in intensity and frequency of
377 storms (Colle et al., 2008; Gornitz et al., 2001; Horton et al., 2015b). A recent study has shown that, by 2030-

11

378 2045, the megacity could be affected by significant flooding on average every 5 years (Garner et al., 2017).
379 This is ever more significant when considering the high and increasing concentration of assets and people
380 exposed in the coastal areas of the city (Aerts and Botzen, 2012). According to Aerts et al. (2013), the
381 estimated flood damage to buildings for NYC is between US$ 59 and 129 million/year, while the damage
382 caused by a 100-year storm surge is within a range of US$ 2 to 5 billion.
383
384 **2. Methods**
385 **2.1. Multi-hazards events in New York City and indicators weighting**
386 We present an improved method for multi-hazard risk in cities generally, and applied to the case study of
387 NYC as a coastal megacity. Similar methodologies have been presented by Johnson (2016) and Grieving
388 (2006), however here we integrated of weights derived from local expert opinions. We aassessed past heavy
389 precipitation and extreme high temperatures based on daily precipitation and daily max temperatures
390 recorded in Central Park from 1876 to 2016 and made available by the US National Oceanic and Atmospheric
391 Administration (NOAA) to examine how temporally consecutive events which occur in the city, this as part
392 of a broader study initially presented in Depietri and McPhearson (2018). We carried outconducted an
393 analysis of daily NOAA's meteorological records (including daily precipitation, max and min temperatures)
394 to identify dates in which an event of extreme heat would be immediately followed by a storm (or vice versa),
395 two consecutive heat waves events (happening within 3 days max away from each other's) and consecutive
396 flooding events (two consecutive days of extreme precipitation). We then manually investigated the New
397 York Times database for relevant articles appearing in the edition of the day following the multi-hazard event
398 identified, this to analyze more in depth the occurrence and social, infrastructural and economic impact of
399 cumulative events. We then conducted a survey of local experts and decision-makers with a principal
400 objective to collect weights multi-hazard risk assessment for indicators and sub-indicators selected, but also
401 to collect information of past and future, potential multi-hazards event occurring in the city.
402
403 For the survey, we drafted a comprehensive list of the local authorities' representatives, researchers and other
404 local actors such as NGOs whose daily work is related to different aspects of vulnerability and risk to hazards
405 in NYC. The respondents to the survey were thus identified as being highly knowledgeable and to have
406 experience of the local hazard risks and impacts. The institutional, urban planning, environmental planning,
407 disaster risk reduction, health and social sectors were represented in the survey. A total of 122 invitation e-
408 mails were sent to contact persons belonging to local and federal institutions as well as local NGOs. Of these,
409 10 were no longer valid and we subsequently collected 65 responses with a 58% response rate. The survey
410 was anonymous but almost 60% of the respondents belonged to local jurisdictions, about 15% to NGOs, 10%
411 to local universities, while state agencies, federal agencies, and companies represented less than 5% each.
412 No further information about the respondent identity were collected to ensure anonymity.
413
414 The list of indicators and sub-indicators weighted by the respondent of the questionnaire were derived from
415 the relevant literature. The final list included those indicators able to describe the vulnerability to the three

12

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

Multi-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 15th and 31st 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

454 acquired the air pollution data from New York City Community Air Survey (NYCCAS) carried out by the
455 New York City Department of Health and Mental Hygiene, Queens College Center for the Biology of Natural
456 Systems, and Zev Ross Spatial Analysis. Indicators used to develop the heat hazard map were weighted
457 according to the survey responses (see Table 1 and Equation 1 and 2), and then combined resulting in a raster
458 surface with values ranging from 1 to 5.
459

460 $AP = 0.483\ O + 0.517\ PM$ (Eq. 1)
461 $HW = 0.632\ ST + 0.367\ AP$ (Eq. 2)
462

463 where AP stands for air pollution, O for ozone and PM for particulate matter smaller than 2.5µm. HW stands
464 for heat wave hazard and ST for surface temperature. Additional scenarios for applying weightings could be
465 applied that take into account different priorities amongst diverse stakeholders in the city and here we present
466 a single scenario where the mean weight from all respondents was applied which has proved to be informative
467 about the nuances of the factors determining multi-hazard risk in NYC.
468

469 **Table 1**. Hazard indicators selected, and weights derived from the survey with standard deviations (SD).
470 (The SD are equal due to the weighting method which required the allocation of 100 points amongst the sub-
471 indicators indices).
472

Hazards (H)	Weight	SD	Indicator	Weight	SD	Sub-indicator	Weight	SD
Heat waves (HW)	0.378	0.127	Surface temperature (ST)	0.632	0.156			
			Air pollution (AP)	0.367	0.156	Ozone (O)	0.483	0.156
						Particulate Matter <2.5µm (PM)	0.517	0.156
Inland flooding (IF)	0.205	0.080	311 calls					
Coastal flooding (CF)	0.417	0.132	Hurricane inundation zones					

473
474

475 The inland flooding map was derived through a spatial interpolation of 311 calls for street flooding (data
476 available between January 2010 and December 2015) and basement flooding (data available between July
477 2011 and December 2015). The 311 calls were obtained from a spatial database developed and maintained
478 by the city of New York which comprises of all sorts of complaint calls. When preparing the inland flooding
479 layer, we removed from the dataset the complaint points that had been recorded during or one day after the
480 event of coastal storms, this to maintain differences between precipitation driven inland flooding and coastal

14

481 flooding driven by storm surges. The dates and times of storm surges in NYC coastal area were obtained
482 from NOAA's storm events database[3] under the keywords "coastal flooding", "high surf", "tropical storm",
483 "storm surge/tide". The 311 calls dataset has nonetheless some limitations worth a mention. For instance, it
484 does not account for possible differences in the likelihood of reporting flooding amongst populations (e.g.
485 depending on income). However, this is the only available dataset on inland flood occurrence and allows us
486 to consider one of the most frequent and perennial natural hazards affecting NYC – flooding driven by
487 precipitation. Still, NOAA tide gauge data at the Battery in NYC is a useful source of continuously recorded
488 water surface elevation and therefore could be used as an indicator of storm surge heights, though not
489 included in this analysis.

490

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

496

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

503

504 $\quad H = 0.378\ HW + 0.205\ IF + 0.417\ CF$ $\hspace{4cm}$ (Eq. 3)

505

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

508

509 **2.2.2. Vulnerability and risk maps**
510 To be compatible with computation of hazard layers, we developed raster surfaces of 30m spatial resolution
511 for different socio-economic and demographic variables relevant for the three hazards, describing the three
512 components of vulnerability as listed in Table 2. For this reason, we disaggregated the 2010 census data made
513 available by the US Census bureau at the block group level. Disaggregation of census data using dasymetric
514 approaches to a finer spatial scale follows Mennis and Hultgren (2006). We used the number of residential
515 units, land use type, and building type as ancillary information to convert demographic totals from census
516 block groups to spatially corresponding cadastral lots for each vulnerability indicator. The disaggregated data

---

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

15

517 layers were then resampled to a spatial resolution of 30 m to maintain uniformity with the spatial resolution
518 of hazard data layers. These data were used to derive a vulnerability map based on indicators describing
519 exposure, susceptibility and lack of coping capacity. Selection of these indicators stemmed from the review
520 of available literature covered in sections 1.3.1 to 1.3.3 and the weights derived from the survey are presented
521 in Table 2.

522

523 **Table 2**. Vulnerability indicators and weights derived from the survey with standard deviations (SD). (Note:
524 the SD for the two indicators of Lack of coping capacity are equal due to the weighting method which
525 required the allocation of 100 points amongst the sub-indicators indices).

526

	Component	Indicator	Weight	SD
Vulnerability (V)	*Exposure (E)*	Population (P)		
	Susceptibility (S)	Pop over 65(El)	0.351	0.146
		Children (<18) (C)	0.212	0.098
		1- Median income (I)	0.191	0.112
		African Americans (AA)	0.170	0.085
		No schooling completed (NS)	0.117	0.062
	Lack of coping capacity (CC)	Speak no English (L)	0.516	0.168
		One-person household (HH)	0.484	0.168

527

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

535

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

543

544 $S = 0.351\ EL + 0.212\ C + 0.191\ I + 0.170\ AA + 0.117\ NS$ (Eq. 4)
545 $CC = 0.516\ L + 0.484\ HH$ (Eq. 5)

546

547 where EL stands for elderly, C for children, I for median income, AA for African Americans, NS for no

548 schooling, L speak no English, HH one-person household. We aggregated the indicators as a weighted sum,

549 as each indicator contributes for a fraction of the susceptibility or lack of coping capacity. The S and CC

550 layers thus generated have values ranging between 1 and 5.

551

552 Some indicators (i.e. homes in deteriorated or dilapidated buildings, mold in home, asthma, heart attack

553 hospitalizations, overweight, adults reporting heavy drinking, crowding, air conditioning, adults with

554 personal doctor and adults with health insurance) were considered but excluded in the final list because they

555 were not available at the low scale for NYC or because some were not relevant for the three hazards when

556 jointly considered. Respondents to the survey also suggested some additional indicators to consider and are

557 summarized in the results section.

558 The final vulnerability (V) map was generated by adding exposure (E), susceptibility (S) and lack of coping

559 capacity (CC) layers with equal weights (Equation 6):

560

561 $V = \frac{1}{3}E + \frac{1}{3}S + \frac{1}{3}CC$ (Eq. 6)

562

563 We aggregated the three components of vulnerability by summing equally weighted values, a general

564 approach adopted in the literature due to the difficulty to assigning different weights to these three

565 components (see for instance Welle and Birkmann, 2015). Risk to natural hazards, such as hydro-

566 meteorological, climatological or geophysical hazard, is the combination of the probability or likelihood in

567 time and space of a natural hazard to occur and to affect a vulnerable system (UNISDR, 2015). In the disaster

568 risk reduction literature, risk is commonly defined as the product of hazard and vulnerability. The final

569 aggregated risk map was calculated by multiplying the final aggregated hazard map with the vulnerability

570 map (see Equation 7):

571

572 $R = H * V$ (Eq. 7)

573

574 where R is risk, H is multi-hazards and V vulnerability. We multiplied hazard per vulnerability because,

575 following to the definition of risk, with no hazard or no vulnerabilities there would be no risk. The final risk

576 map thus derived comprises of 16 classes with the values ranging from 1 to 25. As for the hazard and

577 vulnerability maps mentioned above, the final aggregated risk is also displayed using five intensity classes.

578

579 Our method of aggregation, which first quantifies the indicators of hazard and vulnerability into five ordinal

580 categories and then uses weighted linear combination, is drawn from the existing literature hazard and

581 vulnerability assessment. Previous studies on hazard risk mapping have documented the robustness and

582 accuracy of this method (Greiving, 2006; Greiving et al., 2006; Johnson et al., 2016; Michael and Samanta,

583 2016; Zhou et al., 2016).

17

584

585 To compare the plausibility of our results, we also followed an additional method of aggregation, which is

586 collectively described as the fuzzy-defined weighted combination (Aydi et al., 2013; Janke, 2010). We

587 followed the same procedural steps, weights, and aggregation formulae except that the numerical values of

588 each of the hazard and vulnerability layers were standardized between 0 and 1 (i.e. 0-100%) instead of the

589 five ordinal classes. When displayed the final risk layer by reclassifying into five categories based on natural

590 break (Jenks), the map was very similar to the final map generated following the method we describe above.

591

592

593 **3.   Results**

594 **3.1. The qualitative results of the NOAA-NYT search and the survey**

595 Most of the temporally overlapping extreme events identified in NOAA database between 1876 to 2016 were

596 related to multiple heat waves happening at distance of up to 3 or 4 days (13 events), followed by two

597 consecutive days of extreme precipitation (9 events) and days of extreme heat followed by high precipitation

598 (3 events). However, ~~thanks to~~given a broader review carried out on the New York Times and described in

599 Depietri and McPhearson (2018), we were able various additional interrelated multi-hazards incidents in

600 NYC, meaning that multi-hazard events have more interrelated impacts which might not depend only on the

601 high intensity of the hazard alone.

602

603 The stakeholders who compiled the questionnaire were also asked to provide information related to past and

604 present multi-risk events as well as strategies that they would prioritize for the city. In a multi-hazard

605 perspective, the results of the survey indicated that heat waves in NYC would highly positively interact (i.e.

606 increasing their impacts) with droughts, but also with inland and coastal flooding, although these would have

607 opposed interactions too. Inland and coastal flooding can have additive impacts if they occur at the same time

608 or successively. Furthermore, respondents indicated that other interactions between the wider ranges of

609 hazards affecting NYC have occurred in the past and may occur in the future (summarized in Table 3 and 4

610 respectively). In this~~our~~ study we cover many of these situations although further analysis can be envisaged

611 to better understand the interaction between the hazards and infrastructures failures ~~chiefly~~.

612

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

614 questionnaire.

615

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 &

18

	Infrastructure failure

616
617   **Table 4.** List of multi-hazards events that the city should adapt to as these could occur in the future.
618

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

619

620   **3.2. Multi-hazard risk assessment**
621   Figures 2 a, b, and c present the mapped analytical results for each of the three hazards considered. Except

622   for heat stress, which is distributed across the whole city with points of low hazard intensity corresponding

623   to the urban parks, the hazards intensities are mainly concentrated along the coast, especially in Manhattan

624   and in Brooklyn.

19
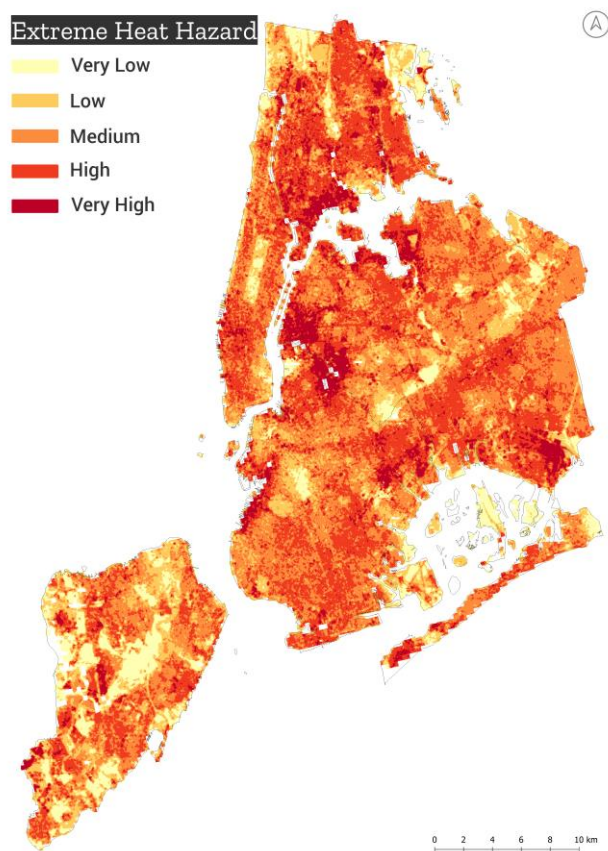
a. Map of the heat stress based on surface temperature and air pollution

625
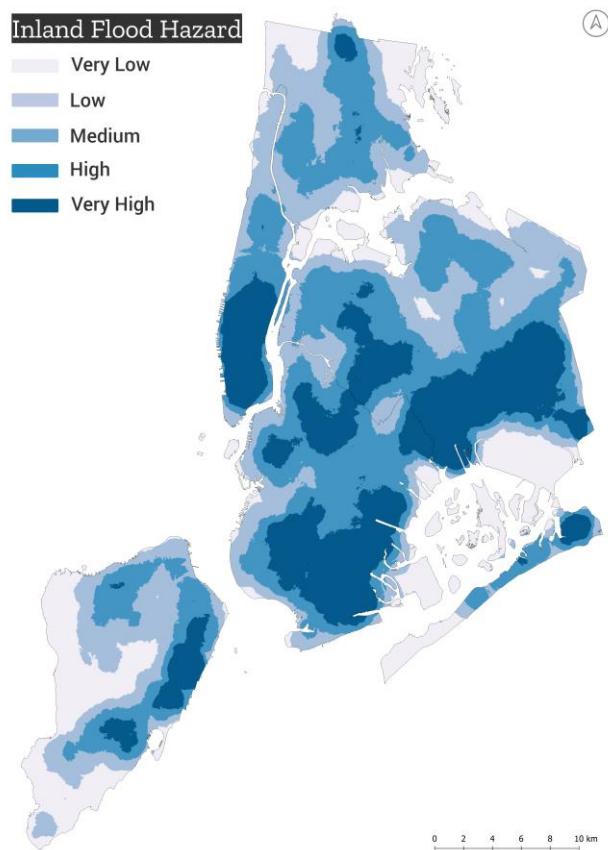
b. Map of the inland flooding based on the 311 calls for street flooding or basement flooding

626
627

21
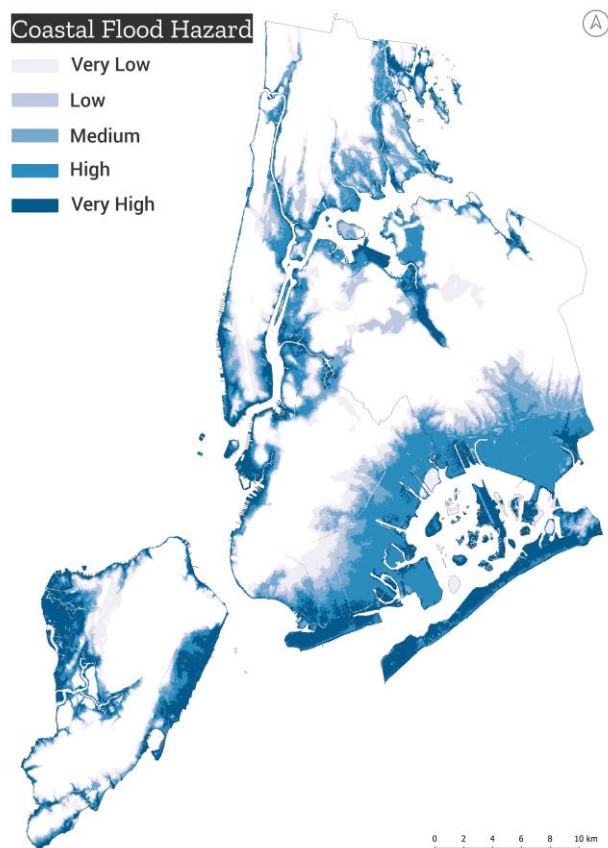
c. Hurricane inundation zones based on the map provided by the Office of
Emergency Management

628
629 **Figure 2 a, b and c.** Spatial variation in heat hazard, inland flooding hazard, and coastal flood hazard for
630 New York City.
631

632
633 Figure 3 displays the joint multi-hazard map with higher intensities in most of the coastal areas. Coastal

634 flooding was assigned a larger weight with respect to the other two hazards based on survey responses, which

635 drives the hotspot analysis somewhat. At present the city is still largely unprepared to cope with flooding and

636 is highly exposed to this type a hazard, a condition that was particularly clear after Hurricane Sandy. Inland

637 flooding was shown to be most intense along the coast, further strengthening the presence of hazards along

638 coastal areas, though further modeling is required to better understand the drivers of inland flood hazards and

639 where they are likely to occur in the future.

22

640

Combined Hazards
- Very Low
- Low
- Medium
- High
- Very High

641
642
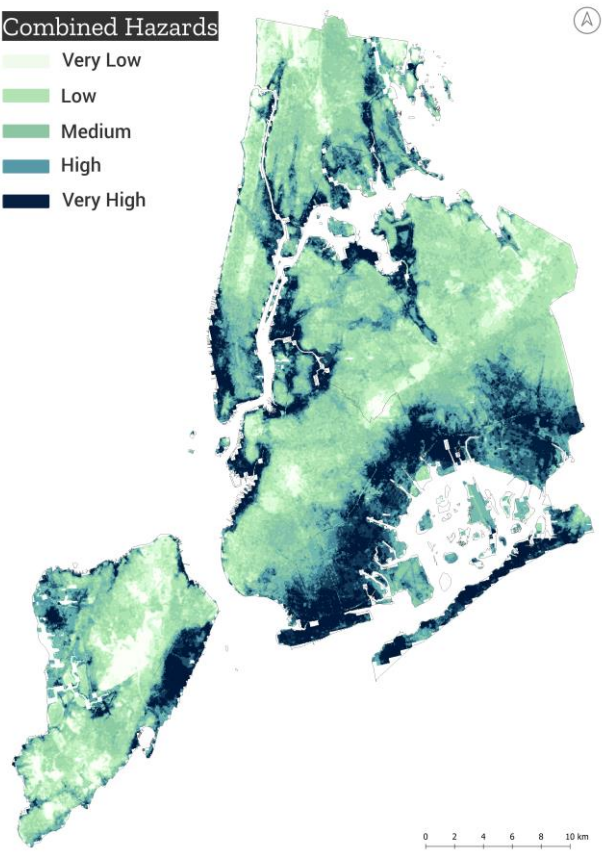
Figure 3. Spatial variation in the combined hazards including weights derived through expert input.

644
645

Exposure
- Very Low
- Low
- Medium
- High
- Very High

646
647

a. Map of exposure

648

24
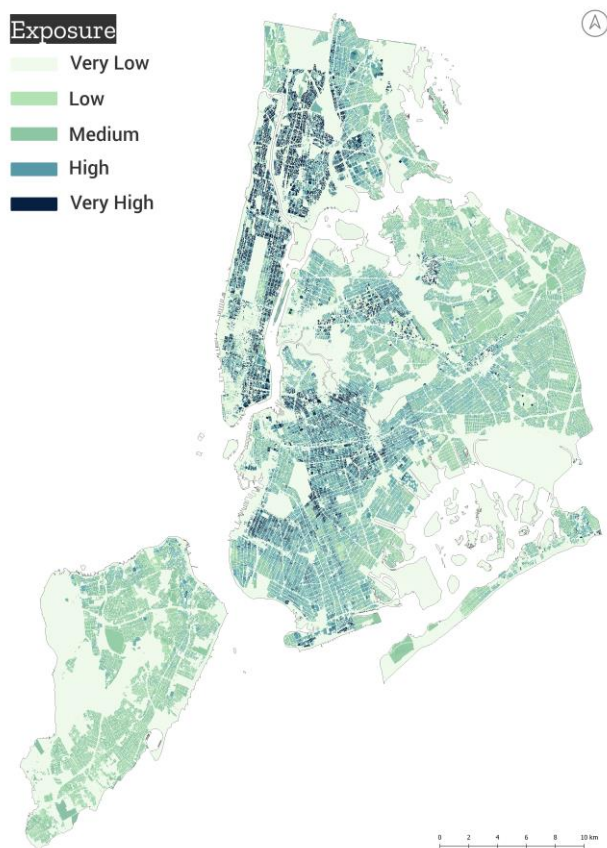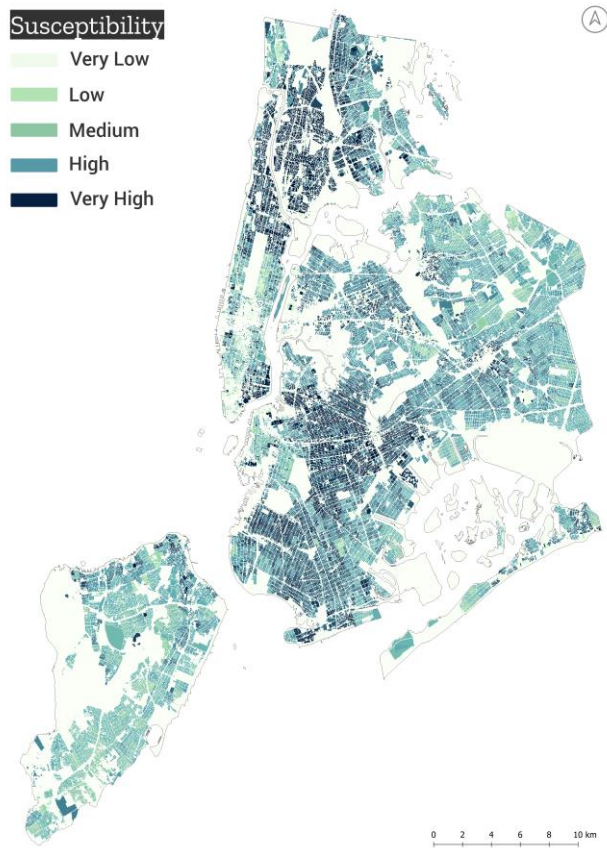
b. Map of susceptibility

649

25
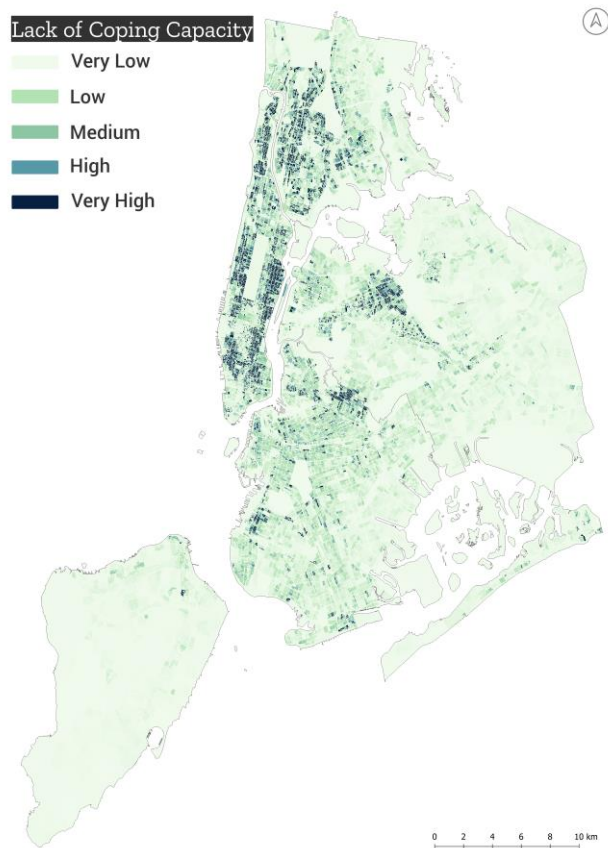
c. Map of lack of coping capacity

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).
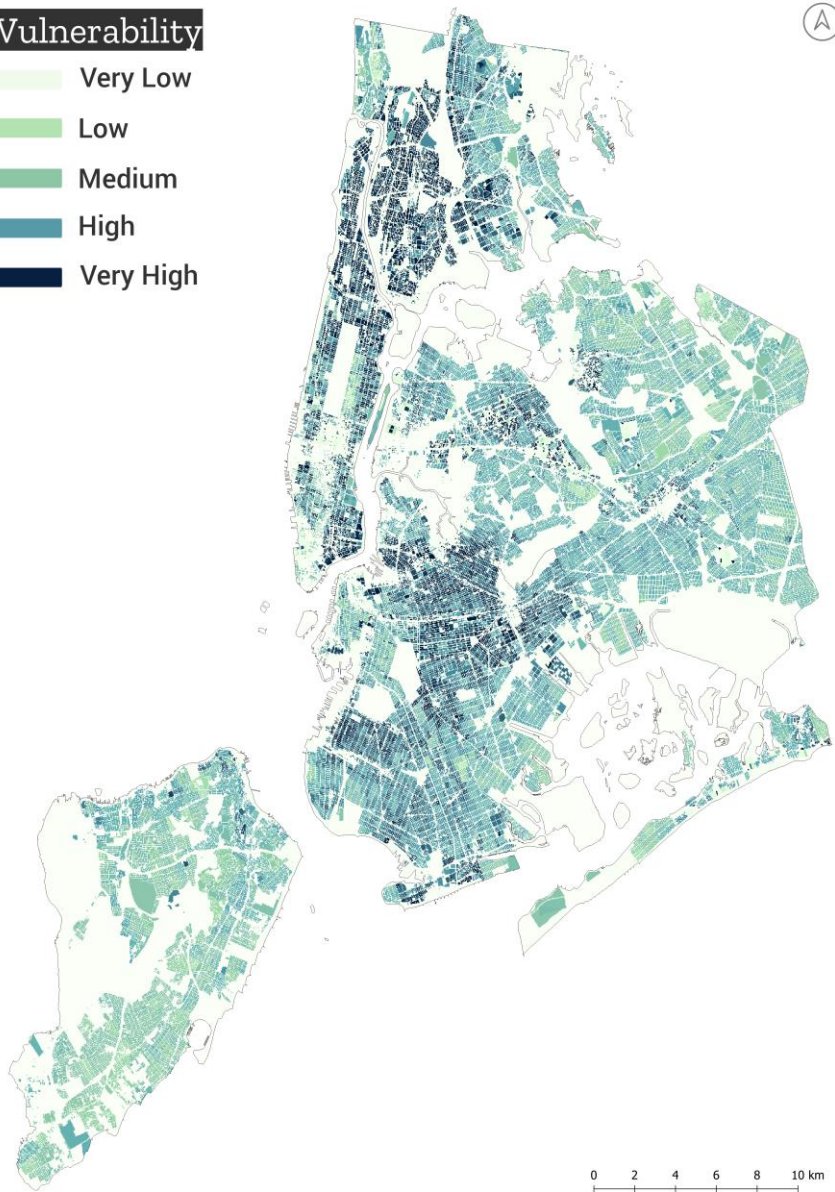
Figure 5. Map of Vulnerability

666   The resultant vulnerability map (Figure 5) shows highly vulnerable populations located mainly in the Bronx,

667   large parts of Brooklyn and some parts of Manhattan (such as Harlem) and the Queens. Staten Island appears

668   as the least vulnerable compared to other parts of the city.

669

670   The survey's respondents suggested other important indicators that can be considered in a vulnerability

671   assessment (see Table 5). These fall into the categories of indicators that we had to exclude either because

672   they were not directly relevant to the three hazards we focused on jointly, or because data were unavailable

673   at the spatial scale we conducted our analysis. Despite their exclusion from the study, we report these results

674   as a useful piece of information for further research.

675

676   **Table 5**. Indicators that have been suggested by the survey and that could be further integrated in this type

677   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

678

679

28

Risk
- Very Low
- Low
- Medium
- High
- Very High

0　2　4　6　8　10 km

a. Multi-hazard risk map

680

29
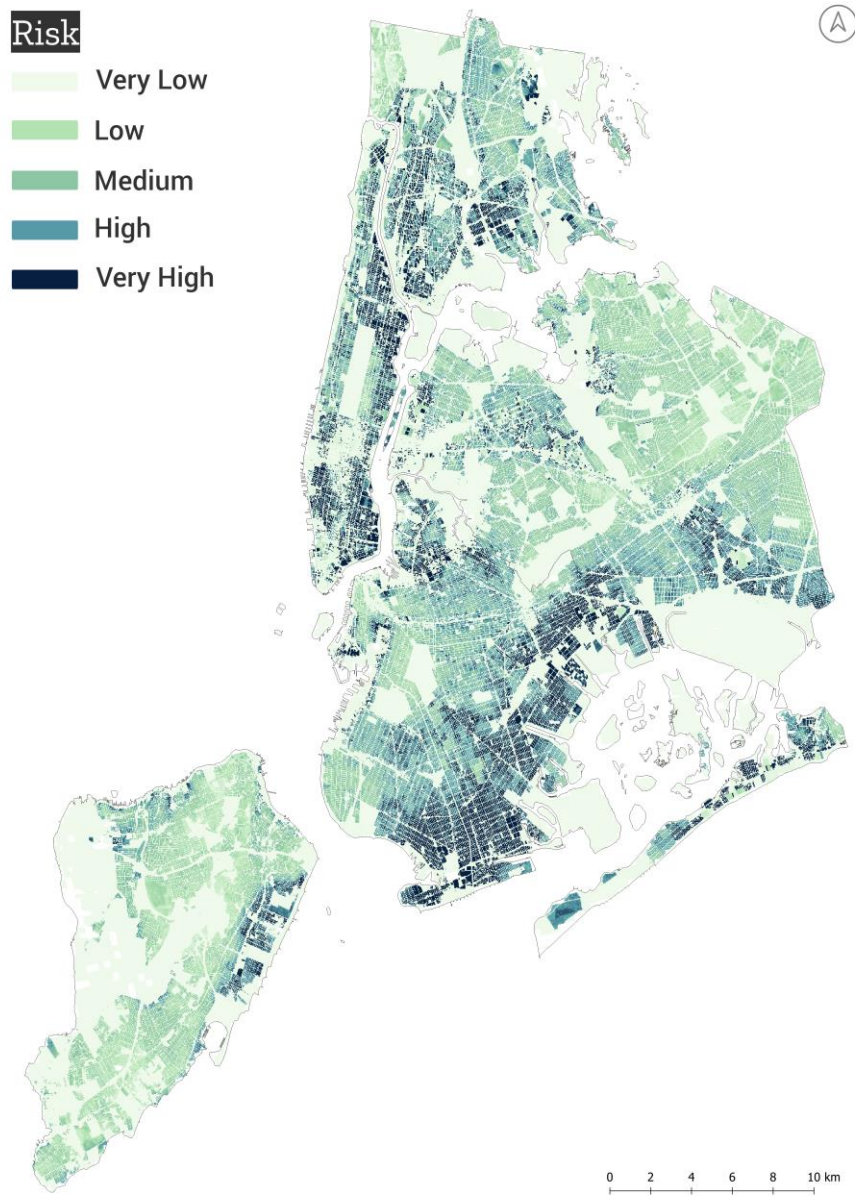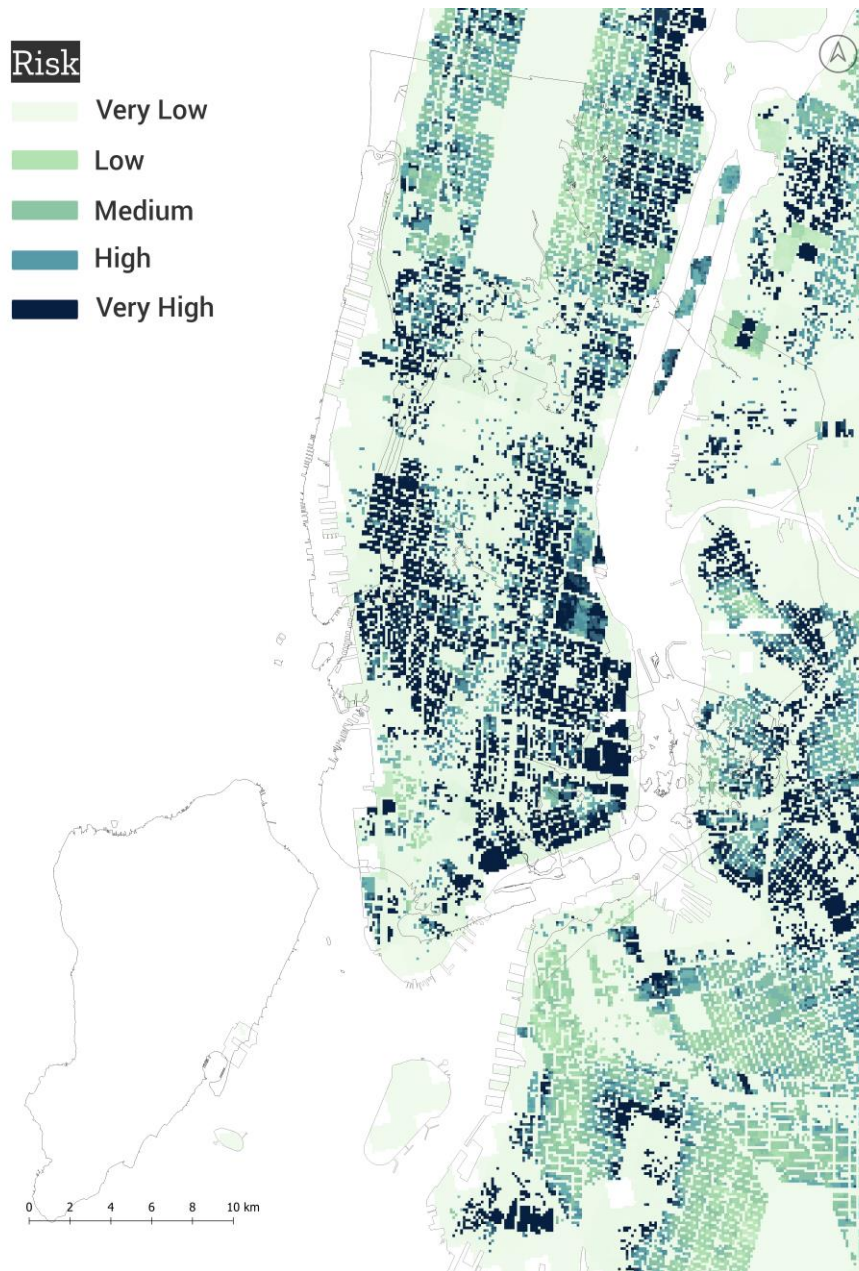
b. Detail of the multi-hazard risk map

681

682 **Figure 6 a and b.** Final multi-hazard risk map and detail of the high spatial resolution risk map for Lower
683 Manhattan and parts of Brooklyn.
684
685 Combining multiple hazards and vulnerability assessment produced final multi-hazard risk assessment map
686 at high resolution for NYC (Figure 6a). We find that the coastal areas of Brooklyn, Manhattan and Harlem
687 are the most at risk from the three hazards considered given the methodological approach and expert input
688 affecting weighted indicators. Figure 6b, shown in detail, demonstrate the relatively high spatial resolution
689 of the analysis and the utility for decision-making for prioritizing investments within neighborhoods and
690 down to building scale for multi-hazard risk reduction.
691
692 Adapting to coastal threats remains a high priority for the city post-Sandy, but results here suggest that coastal
693 areas are also at risk from a multi-hazard perspective. This result is further supported from expert input
694 gathered through the survey of local stakeholders who see the city the least prepared to cope with coastal
695 flooding, second only to earthquakes (see Figure 7). Of note is that some of responses appear to be
696 contradictory, e.g. snowstorms are often associated with nor'easters while hurricanes are associated with
697 coastal flooding with different degree of preparedness. This inconsistency might be explained by the variety
698 of hazards respondents were asked to assess.
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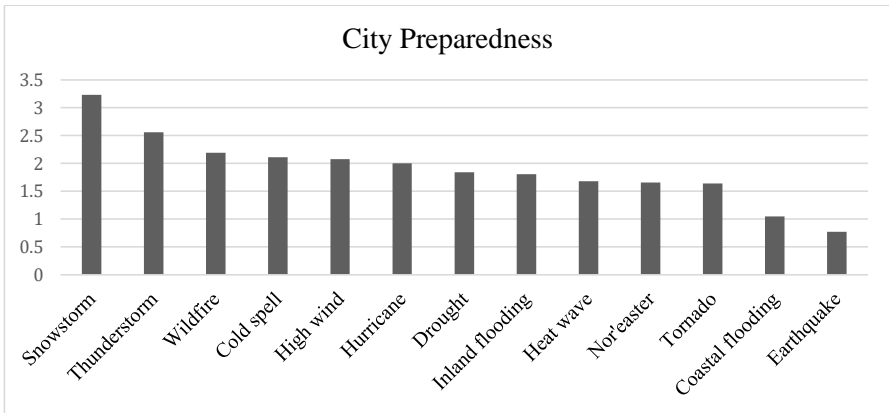
700
701 **Figure 7**. Survey result's regarding the level of city's preparedness to impactful hazards potentially affecting
702 NYC out of a maximum of 5 points.
703
704 **4. Discussion**
705 Based on the NOAA-NYT quali-quantitive assessment of multi-hazard climatic events, the responses of the
706 survey as well as from the analysis carried out for a companion study by Depietri and McPhearson, (2018)(by
707 Depietri and McPhearson, 2018), NYC can be described as at risk from multiple and overlapping
708 hazards, both spatially and temporally. Multi-hazard risk is therefore a reality that is important to further

31

709 understand and plan for in NYC. We also suggest other similar located coastal megacities would benefit from

710 a multi-hazard perspective on planning and policy for climate adaptation and resiliency which integrates

711 context specific weight based on experts opinions. We focused on heat waves, inland and coastal flooding

712 multi-hazard risks and assess how these are spatially distributed leading to overlapping risks. We find that

713 the hazards considered mainly affect the coastal areas while the socio-economic vulnerability is concentrated

714 in central areas of Brooklyn where the poorest segments of the population reside and in the Bronx. Parts of

715 Manhattan are also highly vulnerable, likely due to the concentration of elderly and people living alone in

716 these areas of the city or to the poverty that characterizes certain neighborhoods, such as Harlem. Coastal

717 areas of the city facing the open sea as well as large areas of Manhattan and the Bronx were also the most at

718 risk from the multiple hazards considered. We suggest that adaptation strategies should prioritize these areas.

719 Further soft or hard infrastructures need to be adapted to potential inland flooding and heat waves for instance

720 through enhanced infiltration and reduction of the urban heat island by improving the distribution of green

721 infrastructures. No part of the city is totally devoid of potential impacts from these hazards and synergies and

722 tradeoffs should be carefully evaluated. Coastal flooding also appears to be one of the hazards the city is least

723 prepared to, followed by heat waves and inland flooding, amongst the hazards considered in this study.

724 RThese results support current priorities in the city to invest resources to improve coastal areas, such as

725 Jamaica Bay and its remaining wetlands.

726
727 The quantitative analysis we conducted principally considered the social aspects of vulnerability and risk.

728 We illustrate that parts of the city potentially affected to multiple hazards do not necessarily correspond to

729 the areas with highest densities of vulnerable people live. A further development of this study could include

730 indicators of infrastructural vulnerability especially in reference to inland and coastal flood risk. Some of the

731 indicators that could be used to extend this analysis include: the conditions of exposed buildings; roads,

732 railroads and the subway system; and other critical infrastructures that supply energy, support communication

733 or treat wastewater.

734
735 Multi-hazard risk indicator weights were derived from expert-input through a survey methodology where

736 experts ranked indicators and sub-indicators. This survey approach allowed for the development of an

737 assessment specific to the case of the city of New York. Higher multi-hazard risk in coastal zones is partially

738 driven by weights derived from survey respondents and may depend on the recent awareness raised by

739 disastrous impacts caused by Hurricane Sandy and generally because of the high infrastructural and social

740 impacts these hazards have on the city. We initially calculated risk through all steps described but with equal

741 weighting. The results still showed that the coastal areas of Brooklyn, Harlem and the Bronx were the most

742 at risk to multiple hazards. This suggests that the methodology is robust and would not lead to significantly

743 major different changes in the results with a change of weights. However, at the high resolution the study is

744 carried out, context specific weights become important to the overall understanding of risk from multiple

745 hazards.

746

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

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

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

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

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784 supported by the responses from the survey that emphasize how the city is little prepared to cope with coastal
785 flooding.
786
787 Further research should consider additional indicators of physical vulnerability and cascading effects
788 provoked by climatological hazards and leading to failure of critical infrastructures dangerous for human
789 health (e.g. power outages and exposure to toxic substances). We suggest that it is important for not only
790 NYC, but other coastal megacities, to adopt a multi-hazard approach to understanding climate related risk
791 and for designing and prioritizing action to maximize interventions and investments in ways that reduce risk
792 and build resilience to multiple hazards.
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