Nature's integration in cities' hydrologies, ecologies and societies

D3.1 Inland flooding and water quality community vulnerability maps

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Summary of the deliverable

This report, Deliverable D3.1, titled 'Inland Flooding and Water Quality Community Vulnerability Maps,' outlines the methodology and theoretical framework for assessing vulnerability in the communities of the three NICHES core cities: Barcelona, Boston, and Rotterdam. It is designed to complement T2.1 by mapping social-hydrological vulnerabilities within socio-ecological-technological systems. For each city, socio-economic, ecosystem quality characteristics, and sewer system configurations, as well as critical areas for unfiltered discharges, have been studied to define key residential, commercial, and infrastructural zones crucial for mitigating inland flooding and CSO vulnerability.

List of abbreviations

CSO	Combined Sewer Overflow
ES	Ecosystem Services
GIS	Geographic Information System
NBS	Nature-Based Solutions
SET	Social-Ecological-Technological
IPCC	Intergovernmental Panel on Climate Change
AR	Assessment Report
WWTP	Wastewater Treatment Plants
CSSs	Combined Sewer Systems
RCP	Representative Concentration Pathway
RD	Royal Decree
MAB	Metropolitan Area of Barcelona
MWRA	Massachusetts Water Resources Authority
PO	Pumped Overflows

1 Introduction

Humanity faces a wide variety of challenges, including the depletion and destruction of natural resources and ecosystem services, climate change, and the resulting rise in the risk of natural disasters (Cosgrove and Loucks, 2015, UN 2016, Rockström et al. 2023). With a projected 68% of the global population expected to reside in urban areas by 2050 (UN 2019), cities will experience escalating pressure and confront the challenges associated with population growth. Cities hold a dual role, contributing to climate change while remaining susceptible to its repercussions. In the face of increasing intense precipitation and urbanization (Barceló, 2010; Keupers & Willems, 2013; Cutter et al., 2018), water hazards in urban areas intensify. Simulations under Representative Concentration Pathway (RCP) scenarios reveal a direct correlation: a 10% rise in impervious surfaces leads to a 10% increase in flooding across European cities (Kaspersen et al., 2017). Urban flooding is a complicated issue with rapidly changing flow patterns. Water flow exacerbated by obstacles like buildings, presents complex dynamics in streets, crossroads, and underground spaces (Martínez-Gomariz et al., 2018; Mignot and Dewals, 2022). Complicity added interplay between the drainage system and surface flow. The symbiotic relationship between combined sewer overflows (CSOs) and pluvial flooding in urban areas is a pressing concern addressed in this discourse. At its core lies the inherent vulnerability stemming from the constrained capacity of sewer systems. When confronted with intense rainfall, these systems often reach their operational limits, creating a cascade effect leading to flooded urban areas and CSOs. CSOs remain a major cause of water pollution (Rizzo et al., 2020; Botturi et al., 2021; Van der Werf et al., 2021). This pollution leads to algal blooms, affecting water quality and ecological balance (Rucinski et al., 2014; Stow et al., 2015; Steffen et al., 2014; Watson et al., 2016). The repercussions of these ecological transformations reverberate through society. Access to water bodies, a pivotal resource for recreational and communal activities, becomes constrained, with communities confronting the prospect of enduring either temporary or permanent loss of these invaluable aquatic assets (Locatelli et al. 2020). Moreover, the health risks associated with contact with pollutants and pathogens become pronounced, posing a direct threat to human well-being (Polo et al. 2004, Ashbolt et al. 2010, Colford et al. 2012, McBride et al. 2012, Drayna et al. 2010). Waterborne diseases, facilitated by the compromised water quality, emerge as a significant concern, impacting the health of individuals dependent on these water sources for bathing and other purposes. In the aftermath of CSOs and flooding events, the ecosystem grapples with the arduous task of recovery, while society contends with the enduring ramifications of compromised environmental integrity.

The NICHES project addresses this by promoting nature-based solutions (NBS) tailored to urban vulnerabilities. The examples of NBS can vary from vegetation as a big park at the scale of entire neighborhood to green roofs and walls at the scale of single buildings. High-level vulnerability mapping is essential to comprehend and navigate the multifaceted nature of these issues, offering a strategic vantage point from which to deploy nature-based solutions (NBS). The adoption of such innovative planning tools is vital in not only mitigating the immediate impacts of CSO and flooding but also in laying the groundwork for a more resilient and sustainable urban future. Despite NBS potential, awareness is low among key stakeholders, hindering urban water management. This lack of awareness poses a significant challenge to unlocking the full benefits of NBS in urban water management. Without active engagement and understanding among key stakeholders, the potential for sustainable and effective solutions remains largely untapped. It's not just about the technology; it's about fostering a collective consciousness that recognizes the importance of nature-based solutions in creating resilient and environmentally friendly urban water systems. By employing vulnerability mapping, strategic planning for Nature-Based Solutions (NBS) can emerge as a fundamental aspect of urban policy, effectively allocating resources in an equitable manner to strengthen our cities against the escalating challenges of climate-induced water management. This report confronting the urgency of integrating detailed vulnerability assessments with strategic NBS planning, aiming to address the disparity between current urban water management approaches and the evolving demands of environmental resilience and societal well-being. It seeks to establish a comprehensive framework for considering climate-change induced hydrological vulnerabilities, gathering evidence, and offering guidance to decision-makers.

2 Analytical framework

2.1 Urban vulnerability as an overarching assessment framework

The understanding of vulnerability within the realms of climate change and disaster management has garnered significant attention in research. Extensive research has been conducted in the field of urban vulnerability (McCarthy et al., 2001). Vulnerability studies consider factors like exposure to hazards, infrastructure sensitivity, and community resilience. However, there is an ongoing debate regarding the terminology and methodology to be applied. Vulnerability is often conceptualized as a function of exposure and sensitivity, where adaptive capacity is regarded as a component of sensitivity (Cutter, 2011) or as encompassing exposure, sensitivity, and adaptive capacity (IPCC, 2001; IPCC, 2007; Khajehei et al., 2020; Cheng, 2019, Chang et al., 2021). Notably, research has highlighted that socially and economically disadvantaged groups often face a disproportionate burden of flood hazards in urban settings, highlighting the need for holistic vulnerability assessments (Collins et al., 2019). In response, researchers have employed indicator-based approaches, integrating social, technological, or physical, and ecological or environmental variables to capture the spatial variability of flood vulnerability at the urban scale (Nasiri et al., 2019; Salazar-Briones et al., 2020).

Despite the progress made in addressing vulnerability to climate change, there are several research challenges and gaps that remain in the context of water management. Firstly, research on vulnerability often lacks the integration of statistical approaches with the normalization, weighting, and aggregation methods used in constructing an index, which ultimately leads to inadequate validation of results (Moreira et al. 2021). This problem is further worsened by a disregard for temporal dynamics. Secondly, research on vulnerability in the context of water management has not fully explored the perspective of socio-ecological-technical (SETs) systems. Often, substitutability studies typically focus on a single social, ecological, or technological dimension, thereby missing the opportunity to comprehensively understand the substitutability of services across different dimensions of a system (McPhearson et al. 2022). This gap in understanding hampers our ability to develop holistic adaptation strategies that consider the interconnections between the different dimensions of the SETs system, which can have a cascading effect. The explicit examination of ecological and technological vulnerability in relation to floods remains limited, despite their significant impact on understanding the full extent of flood risks (Römer et al., 2012; Weisshuhn et al., 2018, Chang et al., 2021). The exponential acceleration of complexity across various systems and domains has reached a point where the singular advancement of individual domains is unable to match its tempo. (Chester eta l. 2023, Rammelt et al. 2023) Consequently, the imperative for interdisciplinary research, as exemplified by the framework of Social-Ecological-Technological Systems (SETs), emerges as pivotal in adeptly navigating and resolving these intricate challenges. Therefore, a more holistic approach is required, integrating the social, ecological, and technological dimensions to comprehensively assess flood vulnerability and enhance resilience planning (Cheng et al., 2017). By adopting the SETS framework and considering exposure, sensitivity, and adaptive capacity, a nuanced understanding of urban flood vulnerability can be achieved, aligning with principles of sustainable development and strengthening urban sustainability (Grimm et al., 2017; McPhearson et al., 2016; Markolf et al., 2018). Thus, further investigations are warranted, employing the SETS framework to facilitate comparative analyses of flood risk management and enhance our understanding of the complex dynamics within urban systems (Iwaniec et al., 2020, Chang et al., 2021).

2.2 SETS

The study will focus on examining the interplay among distinct Social-Ecological-Technological (SET) domains concerning social vulnerability. Its objective is to comprehend how interactions within social-ecological (S-E), social-technological (S-T), and ecological-technological (E-T) couplings could potentially undermine the sustained well-being of urban communities over the long term. Social domains encompass individuals, households, neighborhoods, communities, and government. Ecological components involve organisms, their populations, and the physical environment, such as soil, air, water, and climate. Technological components comprise infrastructure, including roads, buildings, water systems. The idea posits that vulnerability is not merely a product of physical exposure to hazards but is also shaped by spatially explicit social, ecological, and technological factors that influence how different systems and populations are impacted by environmental hazards (McPhearson et al., 2022).

Indicators that encompass social, ecological, and technological aspects within a specific area have diverse impacts, shaping social vulnerability in both intentional and unintended ways. The social dimension is taking a central role and represents urban communities that might be affected during hazards; the interaction of SETs dimensions refers to factors that will influence the level urban communities will be affected.

For example, if individuals follow guidelines and avoid using washing machines to prevent additional pressure on the sewer system (S-T), it impacts the social vulnerability of local communities. The success of the government in implementing early warning systems and adaptation policies (S) affects how urban communities are impacted by hazards (S).

Numerous interconnections exist among these dimensions, underscoring the potential emphasis on the social-ecological (S-E) coupling and modifications in ecosystem services (ES) provision. For example, water bodies, during hot weather conditions, provide a cooling effect for communities. Simultaneously, the quality of the ecosystem (E) plays a role in determining its retention and detention capacity during heavy rainstorms, influencing the amount of water entering impervious urban areas and the sewer system (S-E).

Additionally, ecological-technological (E-T) interactions may come into play, such as diverting contaminated water from the sewer system when it reaches capacity during intense rainstorm events. These effects often demonstrate interlinkages among the domains; for instance, an expanded green area not only retains stormwater, reducing the strain on the sewer system but also decreases the likelihood of contaminated water from the overloaded sewer system reaching water bodies during combined sewer overflow events and provides safe bathing water for local communities (S-E-T) (Fig 1).

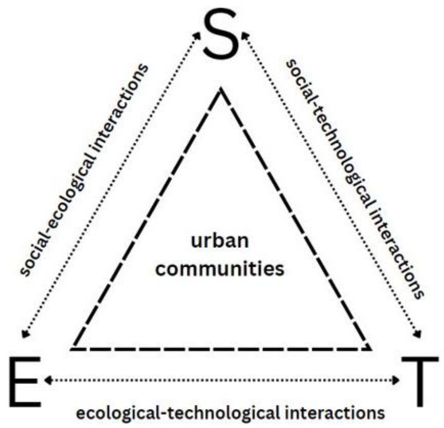


Figure 1: SETS Framework in Social vulnerability (based on McPhearson et al. 2022)

These dynamics induce changes across the three dimensions, tightly interconnected with one another. To comprehend this intricate web of connections, it is imperative to understand how these dimensions collectively influence the urban community's vulnerability from a spatially explicit perspective.

Understanding the dynamics of influence on local communities in the face of hazards like CSOs and flooding can be facilitated by separating the concepts of vulnerability and exposure. In the case of CSOs, where the overflow points into receiving water bodies (e.g., Barcelona's main CSO located near public beaches), it is important to recognize that the impact on communities may vary. Simply overlapping population density with CSO location does not provide a comprehensive understanding. It requires a deeper analysis to identify which social groups are more likely to visit the public beaches, taking into consideration factors such as access to transportation and economic resources. For instance, residents with limited financial resources may have fewer alternatives and be more dependent on public beaches for leisure activities.

3 Case studies

3.1 Metropolitan Area of Barcelona

The Metropolitan Area of Barcelona (MAB) comprises the city of Barcelona and 35 adjacent municipalities, spanning over an urban and peri-urban area of 636 km^2. The population of this region is 3,239,337 people (2016), with half of the population concentrated in the municipality of Barcelona, which houses 1,608,746 people (2016). The city is situated between the rivers Besos and Llobregat, flanked by the Littoral Range and the Mediterranean Sea. Although the rivers have witnessed catastrophic flood events with return periods higher than 100 years, minor flood events occur frequently every year, primarily as a result of convective and local precipitation in late summer and autumn. These events caused by drainage and runoff problems affect both urban and rural areas. (Llasat et al.2013; del Moral et al.2016, Cortes et al.2017).

Within the MAB, similar to a significant proportion of cities in Spain, there is operation under combined sewer systems (CSSs). (Montserrat, 2015). The majority of CSSs are not designed to collectively manage stormwater and wastewater during heavy rainfall periods. This leads to the discharge of the sewer network exceeding its capacity, which leads to overflows into the environment. The environmental impact of urban drainage in Barcelona is primarily attributed to CSOs that occur in both the sea and rivers.

The closure of beaches due to high pollutant levels results in economic losses, which is particularly significant for a city like Barcelona, where tourism and leisure play a vital role in the local economy. Barcelona boasts nine beaches along its 4.5 km stretch of the Mediterranean coast, attracting approximately 5 million visitors between May and September each bathing season. With Barcelona's urban beaches being a popular attraction for both residents and tourists, Barcelona City Council has undertaken an impact assessment to evaluate the health effects on individuals due to the inadequate quality of bathing water caused by CSO. The criteria for insufficient bathing water quality are based on concentrations of E. Coli exceeding 500 cfu/100 ml. To assess the impact, a seawater quality model is employed for continuous simulation of E. Coli concentrations throughout the bathing seasons. The evaluation focuses on quantifying the duration of poor water quality during a representative bathing season. Analysis of the 2009 time series simulations reveals that, on average, at all beaches in Barcelona, exceedances of E. Coli was observed for 3.22 days, which is 2.82% of the entire bathing season (Departament de Territori i Sostenibilitat. Generalitat de Catalunya, 2019; Departament d’Interior. Generalitat de Catalunya, 2015, Ribas, Olcina and Saur, 2020. Beyond tangible impacts, surveys conducted by Martínez-Gomariz et al. in 2021 shed light on the indirect effects on the city's image. Users exhibit a lack of awareness about beach conditions, risks associated with CSO, and responsibility for beach closures. Notably, more than half of the sample (58.3%) of interviewed residents change their plans if there is a red flag, indicating potential revenue loss for businesses in the area.

Additionally, the Barcelona City Council applied the RD (Royal Decree) 849/1986 Regulation of the Public Hydraulic Domain methodology to evaluate environmental damage caused by CSO. The calculated damages for the year 2009 amount to €39M, emphasizing the substantial economic consequences of inadequate water quality management.

3.2 City of Boston

Boston, the capital city of Massachusetts in the United States, spans approximately 125 km^2. Its 76 km long coastline features a mix of public and private shoreline stabilization structures such as bulkheads, seawalls, and revetments (City of Boston, 2014). Notably, about 21 km2 of Boston's shoreline constitutes 'made land,' formed by filling tidal flats and marshes around the original Shawmut Peninsula (Seasholes, 2003). This reclaimed land is notably low-lying (Douglas et al., 2013), compounded by the broader issue of coastal Massachusetts sinking at a rate of approximately 1.5 mm per year, equating to nearly 15 cm over the past century (Nucci Vine Associates and GEO/Plan Associates, 1992).
Historically, Boston has grappled with harbor pollution, earning the reputation for having one of the most polluted harbors in the US (The Boston Harbor Association, 2014). Key contributors to this issue include wastewater treatment plant (WWTP) effluent discharges and CSOs that have persisted for decades, detrimentally impacting water quality (Taylor, 2010). To combat this, the Massachusetts Water Resources Authority (MWRA) was established in 1985, initiating capital improvements and expanding wastewater treatment systems. A significant milestone was reached in 2000 with the opening of a 14 km long tunnel, effectively halting long-term effluent releases into the harbor by redirecting wastewater discharges to Massachusetts Bay. These infrastructure upgrades have successfully reduced CSO discharge volume by over 86% in the past 27 years (BWSC, 2015). Despite these efforts, the challenge of CSO remains relevant, underlining the ongoing need for comprehensive solutions. In late May 2023, a recent public health warning was issued in Boston regarding a CSO event. The Boston Water and Sewer Commission reported untreated overflows at two locations. Additionally, the Massachusetts Water Resources Authority reported a treated discharge at Outflow. The public is urged to refrain from contact with affected water bodies for at least 48 hours post-overflow due to potential health risks associated with bacteria and pollutants.

3.3 City of Rotterdam

Situated in the south-western quadrant of the Netherlands, Rotterdam encompasses an expanse of approximately 200 km^2. As of 2017, the city accommodates a population of 633,471, making it the second-largest urban center in the Netherlands. Beyond the urban facade lies a hydrological discourse of notable complexity. While water supply security constitutes a prevailing concern, the paramount hydrological challenge confronting Rotterdam emanates from river flooding dynamics. This intricate hydrodynamic phenomenon is precipitated by the confluence of upstream rainfall patterns and the consequential impact of downstream sea level rise. It is noteworthy that a significant 80% of Rotterdam's topographic area lies below sea level, therefore the city is mostly built behind dykes (RCI, 2013). The city of Rotterdam experiences CSOs approximately three times per year. CSOs and stagnant water contribute to a dismal quality of urban surface water. The roots of this issue trace back to the 1950s and 1960s post-war reconstruction, with much of the sewer infrastructure reflecting that era. Groundwater leakage adds to the complexity, adding a substantial flow to the WWTP. In attempts at progress, new urban and renewal areas deploy separate sewer systems. These systems aim to channel runoff to the urban surface water and wastewater to the treatment plant. However, a significant 70% of the annual runoff volume still finds its way to the WWTP. Further complexities arise with the pumping of CSO discharge to the river through a pressurized pipe system, known as `pumped overflows' (PO). Despite their contribution to system controllability, these PO operations are limited to around ten times a year on average. In the face of excessive rainfall, even the strategic use of PO fails to prevent CSOs into the city's surface waters.

The key observation here is the contrast between Rotterdam, Barcelona, and Boston. Unlike Barcelona and Boston, Rotterdam lacks public beaches. However, it compensates with urban canals and lakes that people utilize for recreational activities, involving direct contact with potentially contaminated water.

4 Methodology

The initial phase involved the measurement of the vulnerability index using an indicator-based approach, focusing on indicators derived from a comprehensive literature review. Approximately 40 potential indicators underwent evaluation, and an inductive methodology was applied to identify the most suitable ones based on the conceptual framework, geographical specificity, and data availability. Subsequently, an assessment of exposure to CSOs and floods was conducted. Finally, the outputs were overlapped to derive the final score. (Fig. 2).

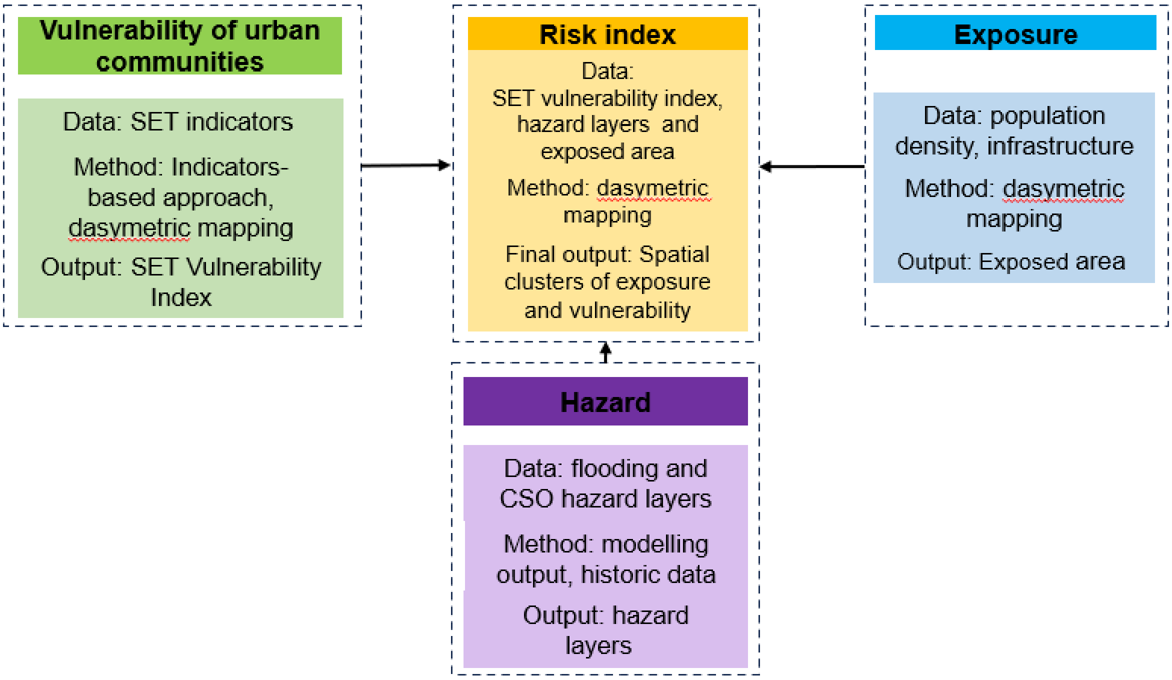


Figure 2: Methodological framework.

4.1 Indicators selection

To elucidate the interplay between hazard and urban communities, an essential first step entails establishing the criteria for impact, focusing particularly on potential vulnerability linked to hazard within the framework of Social-Ecological-Technical Systems (SETs). Moreover, this procedure pinpoints the objects or entities prone to specific impacts. This initial phase lays the groundwork for identifying communities displaying vulnerability. By amalgamating social, environmental, and technological realms, this methodology facilitates a comprehensive evaluation of social vulnerability, enriching our comprehension of the intricate dynamics in motion. Table 2 lays out the selected indicators crucial for the comprehensive assessment of risk. Indicators are organized into three distinct domains—Social (S), Environmental (E), and Technological (T)—and further stratified into groups representing Sensitivity and Adaptive Capacity. This strategic classification aligns seamlessly with the previously outlined framework. Each indicator within its respective group carries equal weight, reflecting a balanced consideration of their collective importance. The justification and supporting literature for each indicator are provided, offering a transparent rationale for their inclusion in the risk assessment. To enhance interpretability, each indicator is accompanied by a directional sign indicating its impact on the final vulnerability score—whether contributing positively or exacerbating vulnerability. More detailed descriptions of each indicator, along with visualizations and explanations, can be found in Annex 1.

Table 2 Indicators selection

DOMAIN	CRITERIA	INDICATORS	RESOLUTION	JUSTIFICATION	References	Sign
Social sensitivity	**Age**	% senior population	Census tract	Older people more sensitive health conditions	Polo et al. 2004, Martínez-Gomariz et al. 2021	neg
		% minor population	Census tract	Children are more vulnerable due to their developing physiological systems, higher rates of ingestion relative to body weight, and time spent outdoors. They are more likely to be exposed to pollutants	Polo et al. 2004, Ashbolt et al. 2010, Colford et al. 2012, McBride et al. 2012, Drayna et al. 2010,	neg
	Language skills and unfamiliarity with local system	% of population	Census tract	Language barriers and unfamiliarity with local water sources can hinder understanding of water quality and safety measures, leaving them at risk of exposure to contaminated water.	Pollack, Blackford, and Herring, 2019, Garrido and Codó 2017, Creese and Wiebe 2012	neg
Social adaptive capacity	**Socio-economic**	% of population with income above of the median	Census tract	Higher income people have more means to cope	Angerville et al. 2013, Del Rıo et al., 2013; Montserrat et al., 2013; Passerat et al., 2011, Pollacket al. 2019, Miller, Ebelt, and Levy 2022	pos
		% of population with income below average	Census tract	People in low-income areas might lack access to safe bathing water and rely on contaminated water due to inability to go to other public beaches due to the lack of personal car. Limited financial resources could hinder their ability to address health issues arising from water, have fewer resources to cope		neg
		% of population rely on government support	Census tract	People in low-income areas might lack access to safe bathing water and rely on contaminated water due to inability to go to other public beaches due to the lack of personal car. Limited financial resources could hinder their ability to address health issues arising from water, have fewer resources to cope, rely on government support		neg
Ecological adaptive capacity		Ecological connectivity	20m	CSO events can exacerbate urban flooding in areas where the combined sewer systems are overwhelmed, which will affect terrestrial ecosystems by changing a threshold in parameters	Passerat et al. 2011	pos
Ecological sensitivity		Wetlands	20m	Act as natural sponges, absorbing excess floodwater and providing vital water filtration and habitat preservation benefits.	Chan et al. 2018	pos
		% of GI	30m	Higher ability to retain rainwater and reduces peak flow	Fahy and Chang 2019	pos
Technological adaptive capacity		Impervious surface	30m	Impervious surface area increases direct runoff	Palla and Gnecco 2015	neg
		Deficit of sewer capacity	20m	Deficit lead to higher chance of the overflow and reaching capacity of the sewer system		neg
Technological sensitivity		Slope more than 20%	20m	Influences its collection efficiency	Pratt and Chang 2012	neg
Exposure		Proximity to public beaches		Losing colling effect of public beaches		
		Population density	20m	More densely populated area more affected	Martínez-Gomariz et al. 2021	
		Critical infrastructure (water/wastewater, power plant, roads, agricultural land)	20m	Critical infrastructure that could be damaged during flooding and have negative impacts on urban communities	Wilbanks and Fernandez (2014); Guidotti et al. (2016)	

4.2 Hazard Indicators

In the context of CSOs, hazard factors encompass the introduction of elevated concentrations of microbial pathogens and other pollutants into receiving waters. Our approach at the basin scale integrates hydrological and hydraulic modeling techniques (PDISBA, 2019) with historical observations to estimate the locations of sewer overflow points (PECIA, 2023). The data derived from the model includes instances of CSOs discharging into receiving water bodies, as well as sewer back-ups occurring when combined sewer water exits the system through manholes onto "dry-land," both of which have direct connections to pluvial flooding. The indicators have been mapped in QGIS version 3.32.

4.3 Exposure

Exposure to contaminated water might occur through inhalation of aerosols near CSO discharge points or direct contact during activities such as bathing and other recreational uses of public beaches. To evaluate the potential exposure to toxic release of CSO, buffers of varying distances around CSO points have been employed. Specifically, buffers of 250m, 500m, and 750m were applied to overflow locations (PECIA, 2023), aligning with the methodology established by Brokamp et al. (2017). Subsequently, these buffers were overlaid with population density data, which had been pre-sorted using a threshold of 0.01 people per square meter, enabling us to discern potential areas of heightened presence of people. The overlaid has been made by utilizing the Raster Calculator with a mean function.

In an endeavor to comprehensively assess the exposure of public beaches to contaminated water resulting from combined sewer overflow (CSO) events, we expanded our methodology to encompass a multi-faceted approach. This involved the application of buffers at varying distances (1km, 2km, 5km, 8km, and 10km) around public beach locations. To enhance our analysis, particularly in discerning the most visited beaches, we incorporated crowdsourced photographic data (Raslan, 2023) from the Flickr platform. The study focused on extracting photos with URLs tagged in the public beaches of AMB, utilizing modified MCSC land cover categories. The data collection spanned from 2004 to 2021, resulting in 180,806 photographs contributed by 13,557 distinct users. The point cloud of sorted post tags was converted into a raster using QGIS' density analysis plugin with heatmap algorithms, enabling the examination of areas with the highest concentrations of points. This raster was then overlaid with the same pre-sorted population density data and the buffers surrounding public beaches by raster calculator tool.

4.4 Social Domain Vulnerability Indicators

Social indicators have been selected based on their potential vulnerability during a flood and CSOs event, with certain groups being more adversely affected and potentially experiencing prolonged recovery periods. Older individuals, due to existing health conditions, may be more sensitive (Martínez-Gomariz et al., 2021), while children, with developing physiological systems and increased outdoor activity, are inherently more vulnerable and prone to exposure to pollutants (Ashbolt et al., 2010, McBride et al., 2013). Language barriers and unfamiliarity with local water sources among refugee and immigrant communities may impede understanding of water quality and safety measures, putting them at risk of exposure to contaminated water (Pollack et al., 2019). Additionally, individuals with vulnerable socio-economic status, particularly those in low-income areas or reliant on government support, may face heightened impacts from a CSO and pluvial flood events. Limited financial resources could hinder the ability of certain communities to recover after flooding, access safe bathing water, and address health issues arising from these threats. In contrast, wealthier individuals may have a broader range of bathing options and greater resources to address health-related concerns (Angerville et al., 2013; Passerat et al., 2011; Miller et al., 2022).

The indicators have been mapped in QGIS version 3.32. Given the substantial variation in census block group sizes, indicators are processed to represent percentages over each geography's total population. Subsequently, the converted indicator values were normalized within a 0 to 1 range using the provided minimum-maximum rescaling formula (1). Different normalization techniques were tested to evaluate the sensitivity of choosing one of them, and only marginal differences were identified.

$$Yin = \frac{x_{in} - min\ (x_{in})}{max(x_{in}) - min\ (x_{in})} \quad (1)$$

Where Yin is normalized value of indicator Xin, min(Xin), and max(Xin) represent the minimum and maximum values of a specific indicator i, respectively.

The next step was estimating vulnerability score (Vs) using normalized values with the following formula:

$$\mathrm{Vs} = \sum_{i=1}^{q} w_i I_i \quad (2)$$

Where Vs is vulnerability score, $\sum_{i=1}^{n} w_i$ =1 and $0 \le w_i \le 1$, for all i=1,. . .,n, and w is the weight (Table 2) associated with a normalized value (I) for the indicator i, and q is the number of indicators.

The next step involves rescaling the vulnerability score to ensure it falls within the specified range of 0 to 1 by applying geometric mean formula (3). In this score, a value of 0 denotes minimal vulnerability, while a value of 1 signifies the utmost vulnerability.

$$Vs(R) = \sqrt[n]{x1 * x2 * x3 \ldots Xn} \quad (3)$$

Where Vs(R) is recalibrating vulnerability score, and $x1 * x2 * x3 \ldots Xn$ - vulnerability score range for block groups.

The final step was converted into raster format for seamless integration into ecological and technological domains vulnerability. With rescaled vulnerability score is translated into a spatial representation and categorized ranging from "low" to " high."

4.5 Ecological and Technological Domains Vulnerability Indicators

Ecological indicators are integral to risk assessment, defined as characteristics of ecosystems that determine their capacity to retain and detain rainwater, thereby influencing the volume of water entering the urban environment and impacting local communities. The selected indicators, such as ecological connectivity, biodiversity, the presence of wetlands, and the percentage of green areas, provide a comprehensive measure of ecosystem quality, affecting water retention and runoff mitigation. As well as during CSO events, particularly in areas with overwhelmed combined sewer systems, there is a potential exacerbation of urban flooding, triggering changes in threshold parameters within terrestrial ecosystems. The intricate interplay between functional biodiversity and challenges posed by CSO and pluvial flood, as highlighted by Passerat et al., 2011, underscores the significance of ecological indicators in understanding and mitigating these impacts.

The selection of technological indicators is based on landscape characteristics that significantly impact the efficacy of engineered constructions in collecting rainwater. The underlying principle is that increased water collection by these engineered constructions results in reduced water entering the urban environment, thereby influencing local communities. Key indicators, such as impervious surface area, play a crucial role in the direct runoff in the area, exacerbating the challenges during heavy rainstorms (Palla et al., 2015). A study conducted in Barcelona has specifically identified areas with a deficit in sewer capacity, characterized by lower elevation within the city, experiencing heightened pressure during intense rainstorms (PDISBA,2019). This deficit increases the likelihood of overflow and reaching the sewer system's capacity. Additionally, the higher slope of the landscape further influences the collection efficiency of engineered constructions, highlighting the importance of technological indicators in assessing and managing the risks associated with rainwater management in urban environments (Palla et al., 2015).

The indicators have been mapped in QGIS version 3.32. The data, initially presented in vector format, was converted into raster format for seamless integration, ensuring the incorporation of values where needed. For instance, in the wetland group, values were assigned based on wetland area (e.g., a value of 1 for wetland locations and 0 for the remaining areas). Finally, all indicators were rescaled from 0 to 1, facilitating integration across different scales and units through the application of formula (1):

$$yi\ scaled\ = \frac{x_i\ -\ min\ (x_i)}{max(x_i)\ -\ min\ (x_i)}$$

where y$i\ scaled$ is the rescaled value of the indicator X at cell i, min (Xi) is the minimum and max (Xi) is the maximum value of the indicator X within the study area.

Subsequently, for each dimension group, we calculated the sum value, assigning equal weight to indicators. This was achieved using the cell statistic function to identify values for each pixel.

4.6 Final score

To determine the comprehensive final score associated with combined sewer overflows (CSO) and flood, the final score was calculated by integrating vulnerability and exposure. Vulnerability maps and exposure maps, representing the Social-Ecological-Technological (SET) vulnerabilities and the proximity to CSO events or flood exposure area, were combined to generate a unified risk score. The calculation of the final score was executed through the Raster Calculator using multiply formula (5):

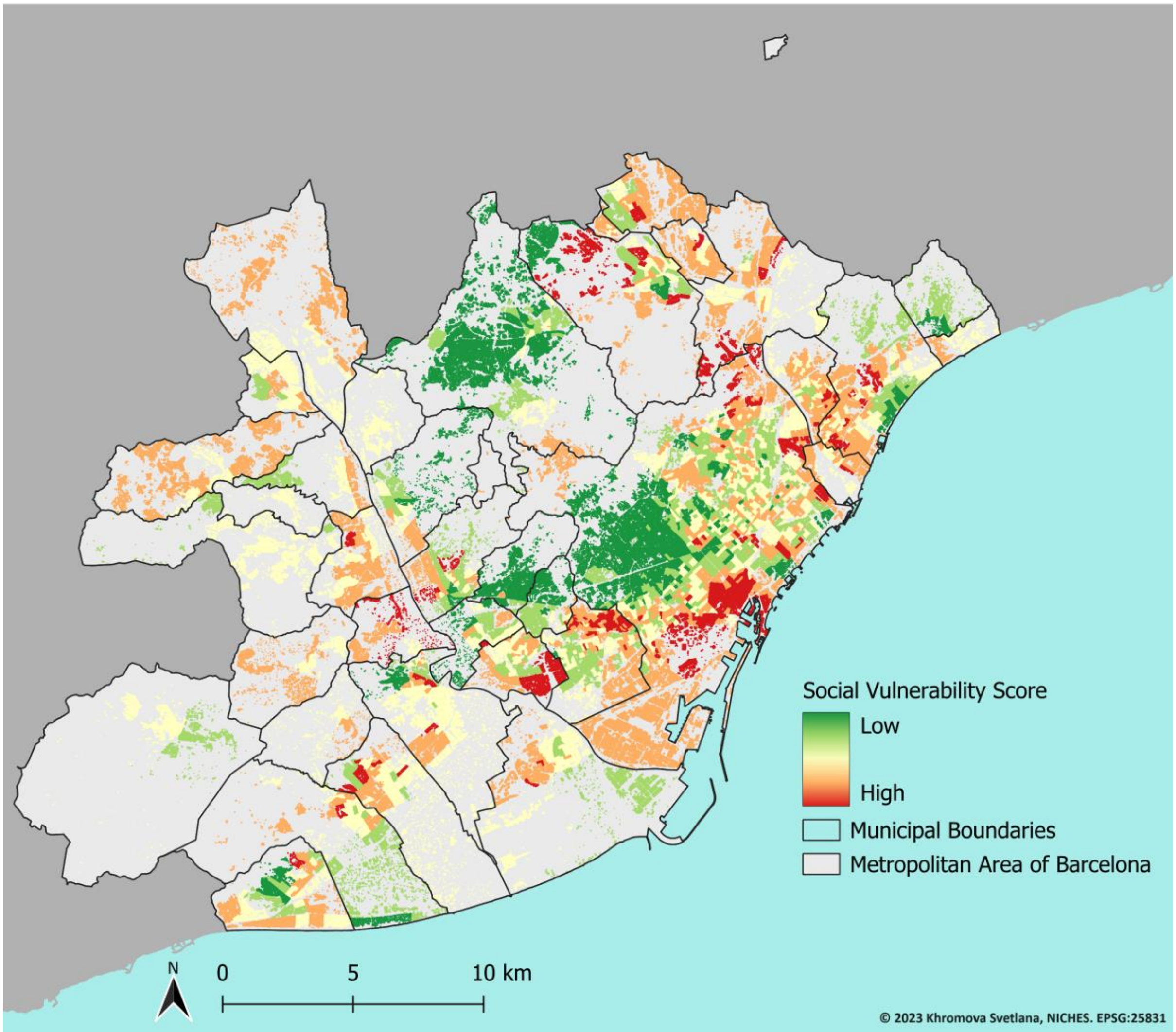
$$Final\ \ score = \ vulnerability * exposure * hazard \quad (5)$$

This approach ensures a balanced consideration of both vulnerability and exposure factors in the final score. The resulting maps provide a spatially explicit representation of the combined influence of vulnerability and exposure.

5 Results

5.1 Social vulnerability map

Map of Social Domain of Social Vulnerability for Metropolitan Area of Barcelona

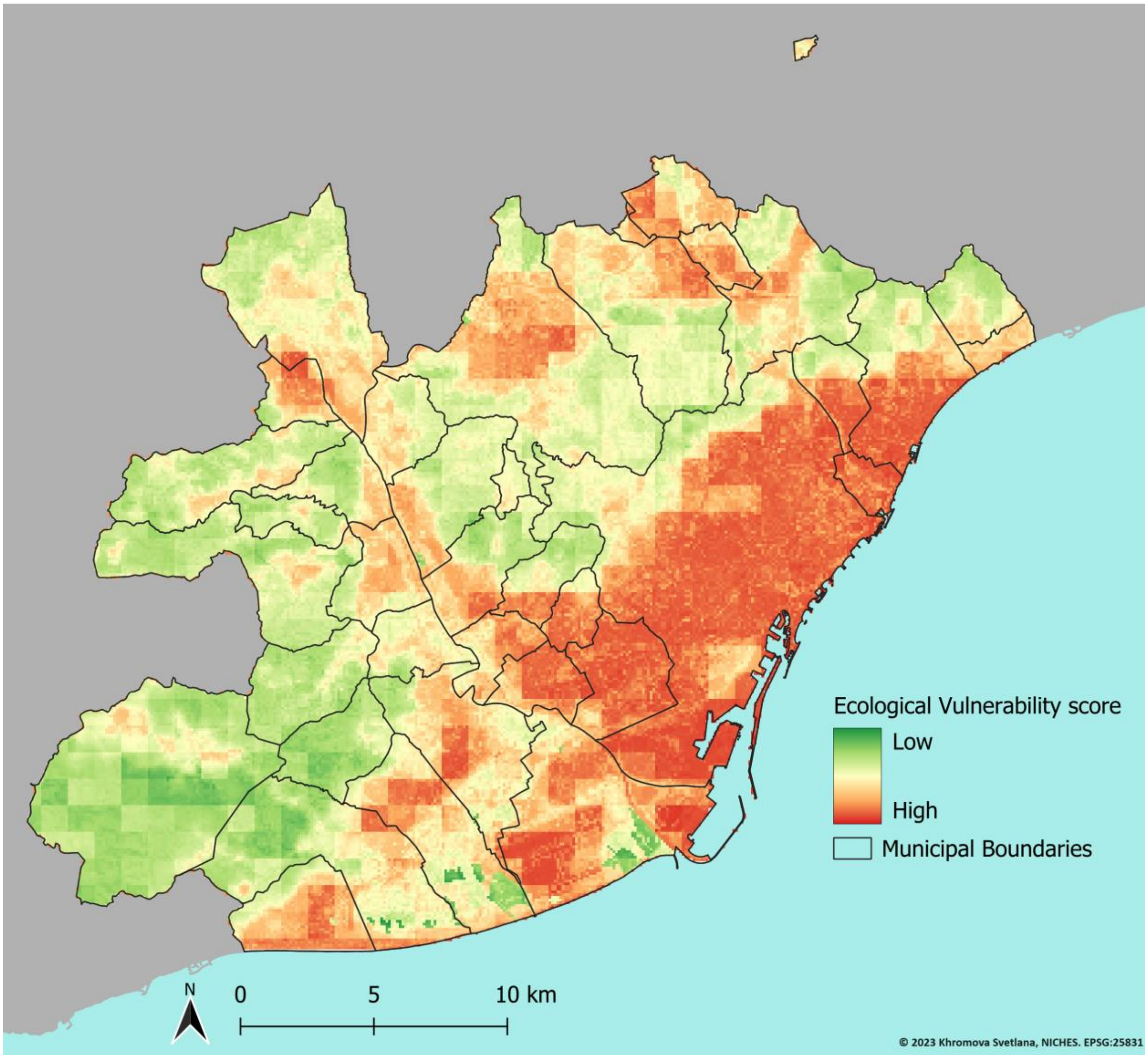


The social vulnerability within the Barcelona metropolitan area is intricately woven into the fabric of its diverse neighborhoods, each telling a distinct story of economic and demographic disparities. Analyzing various factors such as unemployment rates, income distribution, immigrant and refugee communities and minors and majors age groups provides a nuanced understanding of the challenges faced by different communities (see annex 1).

When examining the socio-economic landscape, it becomes evident that vulnerable populations are concentrated in specific regions. Areas characterized by lower income levels, such as the border regions of Santa Coloma de Gramenet and Badalona, neighborhoods in Cornellà de Llobregat, and sections of l'Hospitalet de Llobregat, exhibit heightened social vulnerability. Even within Barcelona itself, certain neighborhoods like Nou Barris, the bordering areas with Sant Adrià de Besòs, and districts within Ciutat Vella face significant socio-economic challenges.

5.2 Ecological vulnerability map

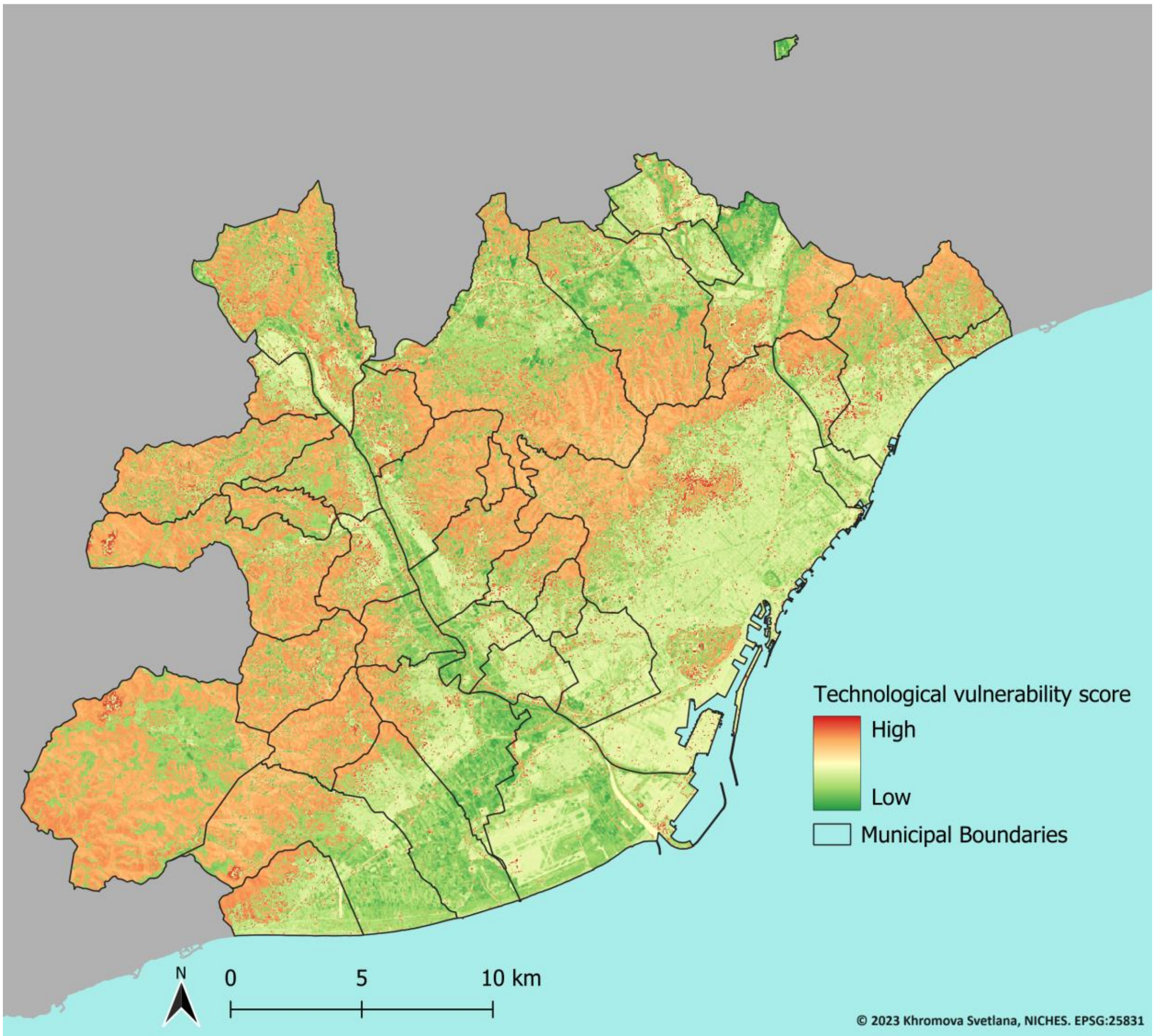
Map of Ecological Domain of Social Vulnerability for Metropolitan Area of Barcelona



In our thorough investigation into ecological vulnerability, we utilize a diverse set of indicators, encompassing ecological connectivity, the presence of wetlands, and the percentage of green space (see annex 1). This systematic approach enables us to depict a detailed picture of the intricate ecological dynamics within the regions under scrutiny. The core focus of our analysis reveals characteristics which might influence the retention/ detention capacity of ecosystems. This distinctive pattern is most pronounced in the highly urbanized expanse encompassing Barcelona, L'Hospitalet de Llobregat, Cornellà de Llobregat, and Badalona. Within this densely populated and urban landscape, a significant prevalence of impervious surfaces becomes evident—an unmistakable signifier of the profound impact of urban development on the local ecology. In addition to less urbanized regions, municipalities such as Sant Andreu de la Barca, Castelldefels, El Prat de Llobregat, Sant Cugat del Vallès, Ripollet, and Cerdanyola del Vallès emerge as exemplars of a low ecological vulnerability score.

5.3 Technological vulnerability map

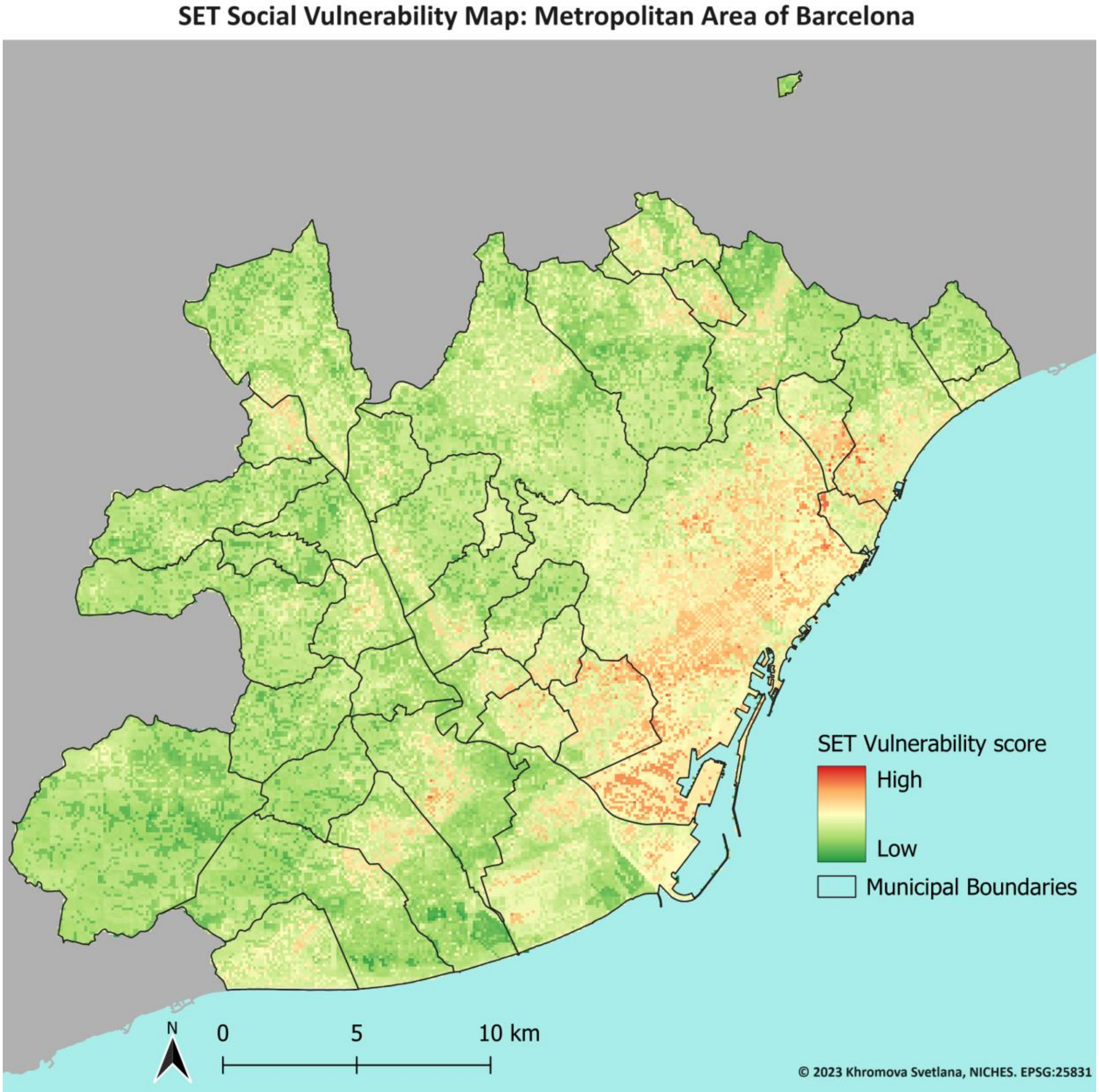
Map of Technological Domain of Social Vulnerability for Metropolitan Area of Barcelona



Technological vulnerability, a key aspect of our analysis, is assessed based on several critical parameters. These include the extent of impervious surfaces, the deficit in sewer capacity (with specific relevance to Barcelona city), and the presence of slopes exceeding 20% (see annex 1). In examining this vulnerability, a notable pattern emerges—higher vulnerability is often associated with a combination of steeper slopes and extensive impervious urbanized areas. This is vividly exemplified in Singuerlín, situated in the northern region of Barcelona city, as well as in the distinctive landscape of Distrito de Sants-Montjuïc within Barcelona city.

It's important to highlight that our approach includes an additional indicator, focusing on sewer deficit per district. However, this specific metric is applied exclusively to Barcelona city due to limitations in data availability for other municipalities. This targeted use of indicators within Barcelona city may, in turn, affect the clarity and comprehensiveness of the technological vulnerability assessment for areas beyond the city limits. As we delve into this research, recognizing and addressing these nuances becomes crucial for a comprehensive understanding of technological vulnerability across various urban landscapes.

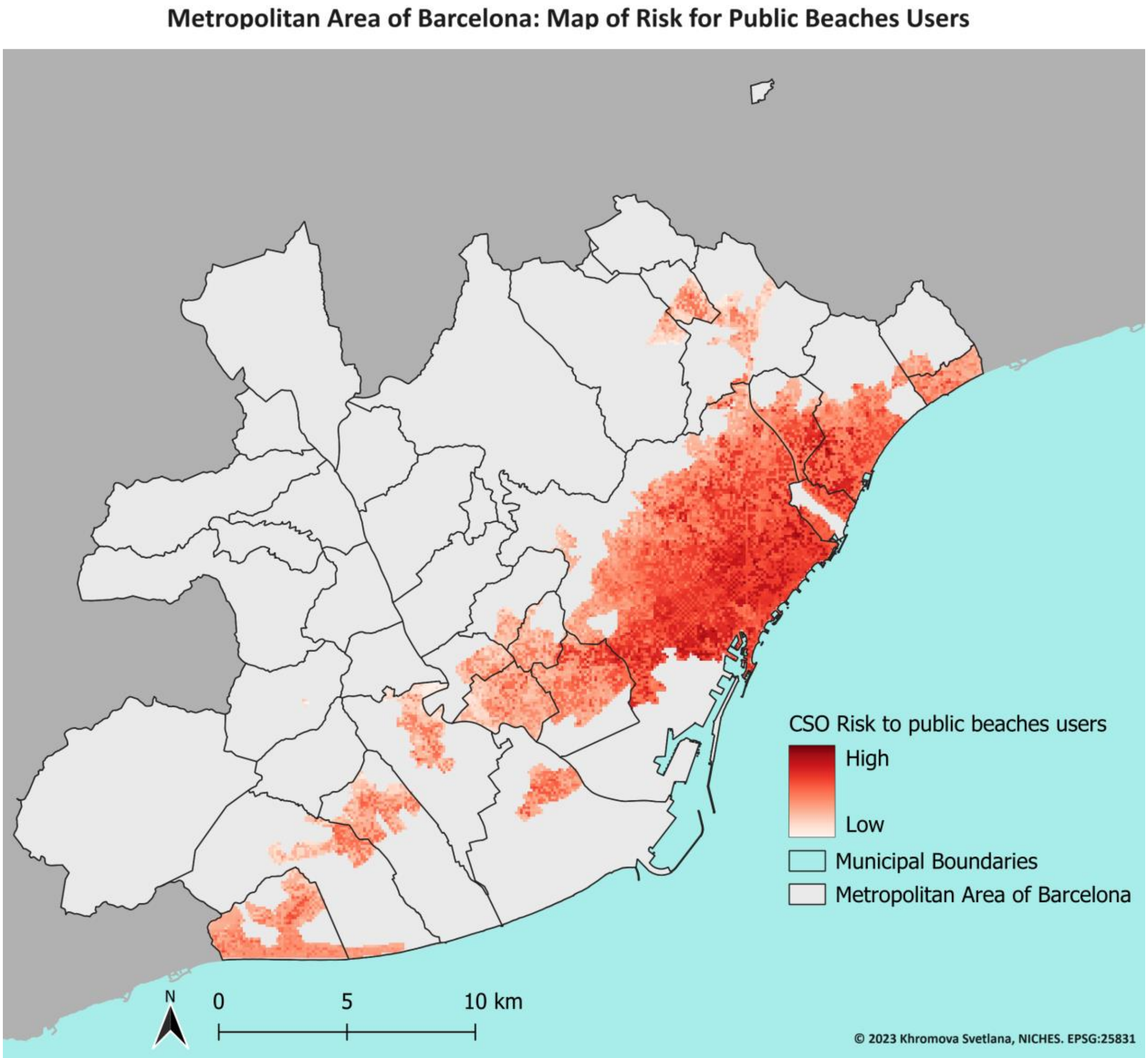
5.4 SET Vulnerability



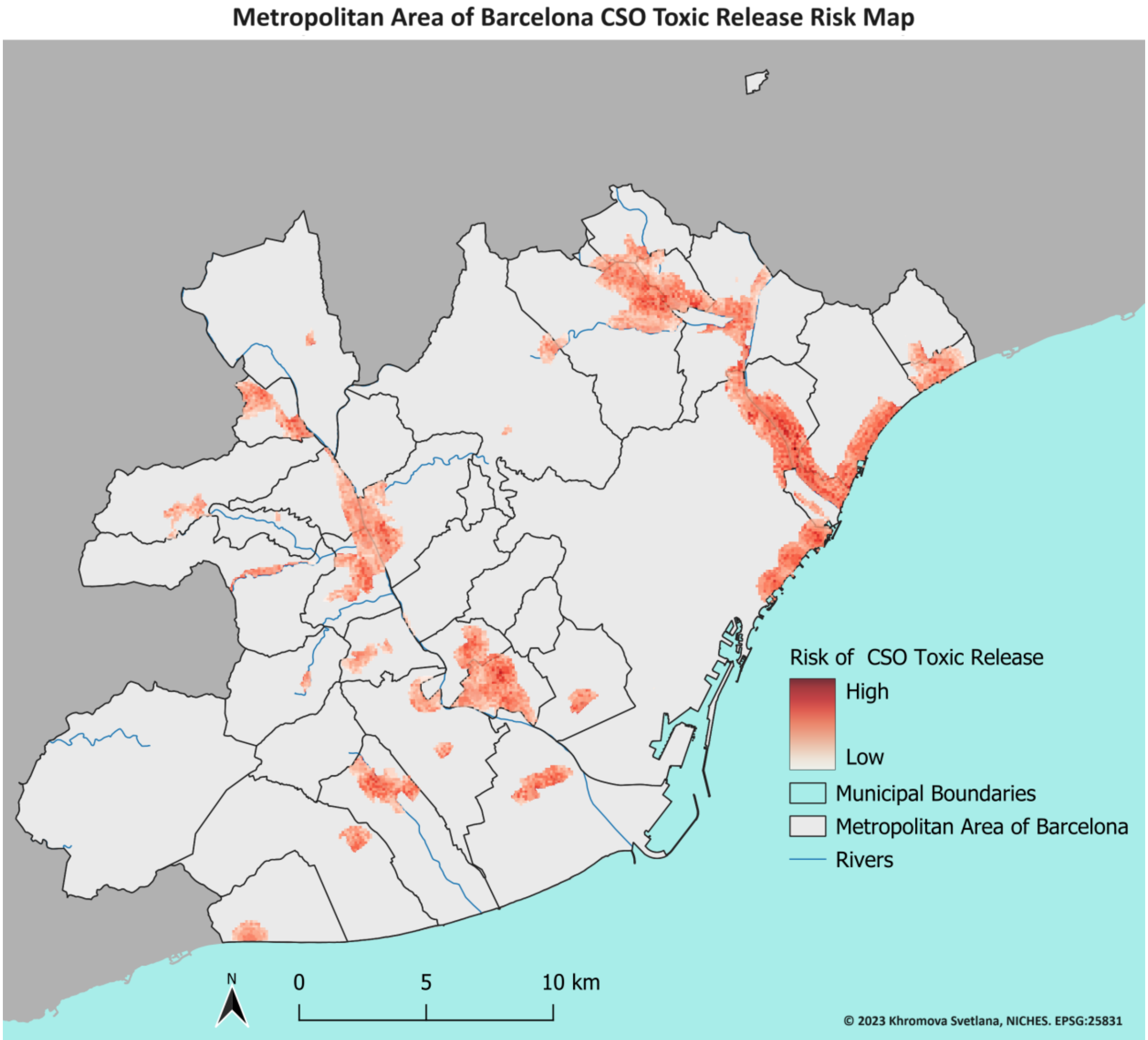
The combination of all three SET dominations, highlighted urban areas still can be seen patterns of social vulnerability Santa Coloma de Gramenet and Badalona, neighborhoods in Cornellà de Llobregat, and sections of l'Hospitalet de Llobregat, Barcelona's neighborhoods like Nou Barris, the bordering areas with Sant Adrià de Besòs, and districts within Ciutat Vella

5.5 Final score

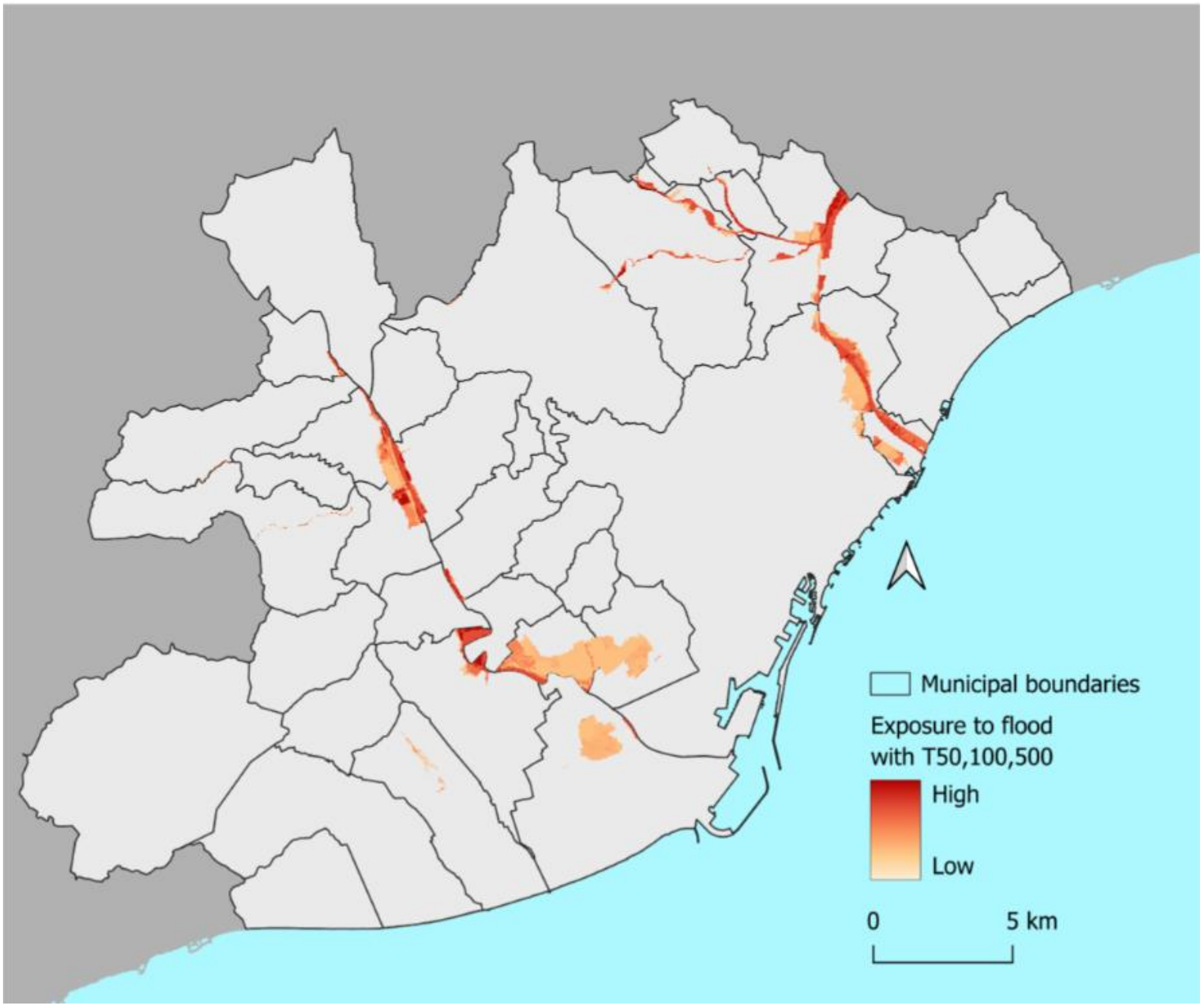
5.5.1 Vulnerability + exposure for public beaches users



5.5.2 Vulnerability + exposure of Toxic Release from CSOs



5.5.3 Vulnerability + exposure of Fluvial Flooding



6 Discussion

The application of the SETS approach to vulnerability assessment offers a compelling and nuanced perspective on comprehending vulnerabilities within a specific area. The examination of distribution dynamics within SET dimensions unravels unique drivers that exhibit limited overlap. While the assessment of social vulnerability to CSO and floods aligns with prior evaluations of vulnerable groups in metropolitan areas, the integration of the Ecological (E) and Technological (T) dimensions introduces a fresh and comprehensive viewpoint.

In line with the findings of Chang et al. (2021), who underscore the significance of ecological indicators such as productivity and wetlands, our research underscores a noticeable impact on the final vulnerability assessment results due to the inclusion of ecological indicators. The recognition of this influence emphasizes the interconnectedness of social, ecological, and technological aspects in shaping vulnerabilities. This integrative approach sheds light on the multifaceted nature of vulnerability, transcending conventional assessments focused solely on social factors.

Furthermore, our study highlights the need for a holistic understanding of vulnerabilities by incorporating ecological and technological dimensions. By doing so, we contribute to a more comprehensive and robust framework for vulnerability assessment that considers the interplay of various factors. This expanded perspective facilitates a more accurate identification of vulnerabilities and the development of targeted mitigation strategies that address the diverse and interconnected challenges faced by communities in the studied area.

6.1 Limitations

It is essential to acknowledge the challenge posed by the limited accessibility of technological indicators, such as information pertaining to sewer and drainage systems. This data is not publicly available and often necessitates a time-consuming collaboration with public or private institutions. This underscores the intricate nature of comprehensive vulnerability assessments that encompass diverse dimensions. Each dimension contributes valuable insights, but the process requires careful navigation through various data access challenges.

From a framework perspective, there is an open question regarding the integration of the SETS framework into understanding vulnerability.It necessitates more interdisciplinary communication to comprehensively incorporate components like sensitivity and adaptive capacity from ecological and technological perspectives. Bridging this gap is imperative for a more holistic understanding of vulnerability, as it allows for a nuanced examination of how social, ecological, and technological factors intersect and influence the overall vulnerability landscape. This interdisciplinary approach is crucial for refining vulnerability assessments and developing effective strategies for resilience and mitigation.

Another of these limitations is the difficult task of determining the distribution of contaminated water, an intractable puzzle that makes accurate risk assessment difficult. The complexity increases when trying to understand spatial dynamics, which emphasizes the need to develop better modelling methodologies to effectively manage the movement of rainwater in such complex terrain and sewer system interactions. Furthermore, it is important to emphasize the lack of stakeholder perspectives in assessing vulnerability indicators and their relative importance. The multifaceted nature of these viewpoints requires a more nuanced approach, and further research will be proposed to address gaps in understanding and provide a more comprehensive framework for addressing vulnerability and risk to CSOs.

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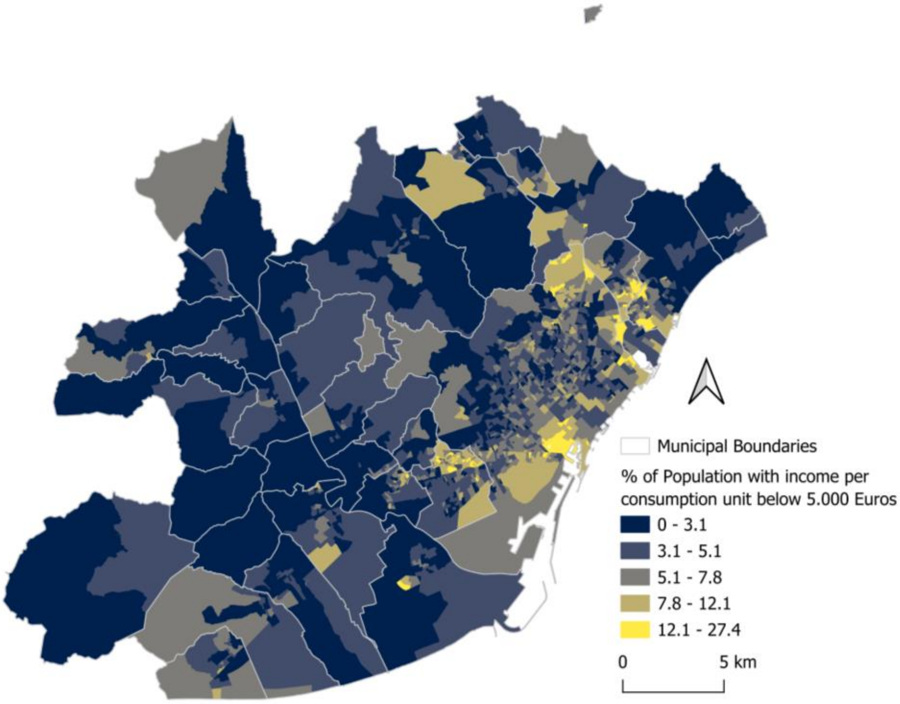
8 Annex 1 (Barcelona)

8.1 Social vulnerability

Population with income below average (minimum income)



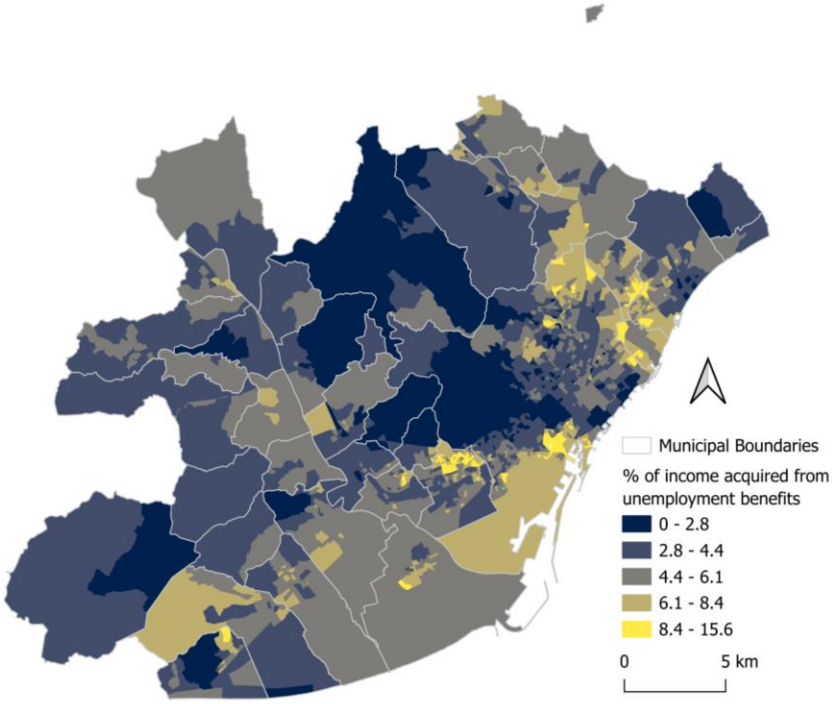
The significance of this demographic lies in the unique challenges faced by individuals in low-income areas, where economic constraints can amplify the risks associated with environmental hazards.

One critical aspect is the potential lack of access to safe bathing water in low-income areas. Individuals residing in these communities may find themselves relying on local water sources that are contaminated due to insufficient infrastructure or limited resources for water treatment. The inability to access cleaner alternatives, such as public beaches or recreational areas with better water quality, is often compounded by the absence of personal transportation, making it challenging for residents to travel to safer environments.

Moreover, limited financial resources can hinder the ability of individuals in low-income areas to address health issues arising from exposure to contaminated water. Medical expenses, including treatment for waterborne illnesses, can strain already tight budgets. The economic burden of healthcare further exacerbates the vulnerability of this population, creating a cycle where financial constraints impede the capacity to address and recover from health-related challenges.

In times of flooding or sewer overflow, individuals with lower incomes also face additional hurdles in coping with the aftermath. The lack of financial resources limits their ability to secure temporary accommodations, replace damaged belongings, or rebuild homes and infrastructure. This economic vulnerability prolongs the recovery process and increases the long-term impact on the well-being of those in low-income areas.

Income in census group acquired from unemployment benefits



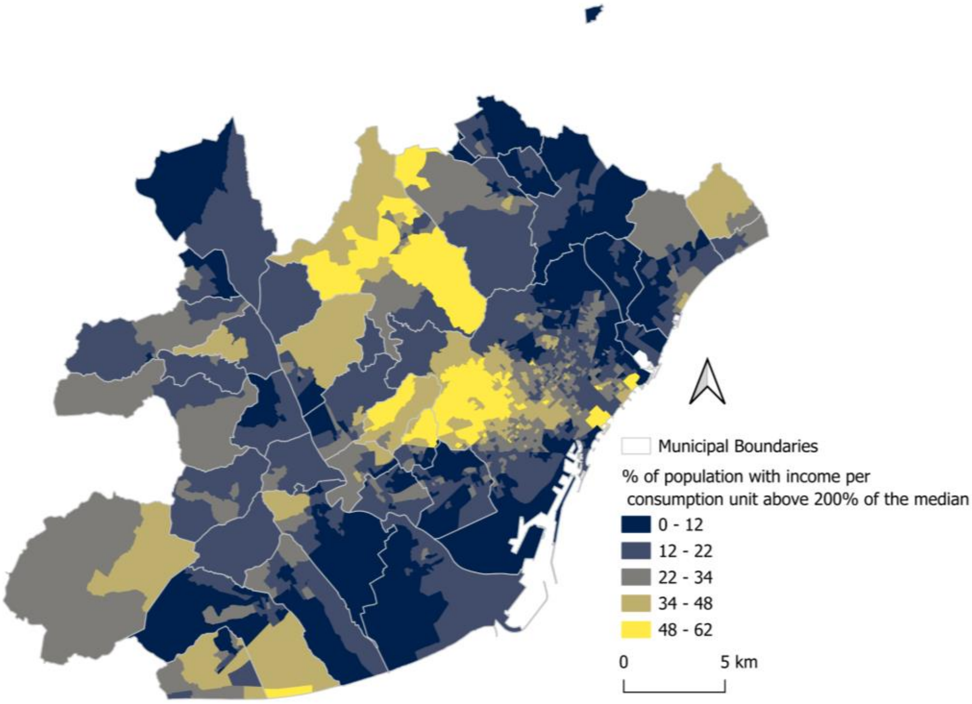
This demographic holds significant importance due to the unique challenges faced by individuals who, dependent on public assistance, may confront heightened risks associated with environmental hazards.

A critical aspect involves the potential lack of access to safe bathing water among those relying on government support. Residents in this category may find themselves compelled to depend on local water sources that are contaminated, driven by inadequate infrastructure or insufficient resources for water treatment. The inability to access cleaner alternatives, such as public beaches or recreational areas with better water quality, is compounded by the lack of personal transportation, making it challenging for these individuals to travel to safer environments.

Furthermore, the constrained financial resources of those relying on unemployment benefits can impede their ability to address health issues arising from exposure to contaminated water. The economic limitations may restrict access to medical care, including treatment for waterborne illnesses, adding an extra layer of vulnerability. The financial constraints create a scenario where individuals have fewer resources to cope with health challenges and the aftermath of environmental hazards.

During flood or sewer overflow events, individuals dependent on unemployment benefits may face additional hurdles in coping with the aftermath. Limited financial resources may restrict their ability to secure temporary accommodations, replace damaged belongings, or rebuild homes and infrastructure. This economic vulnerability prolongs the recovery process and intensifies the long-term impact on the well-being of those relying on government support.

Population with income per consumption unit above the median

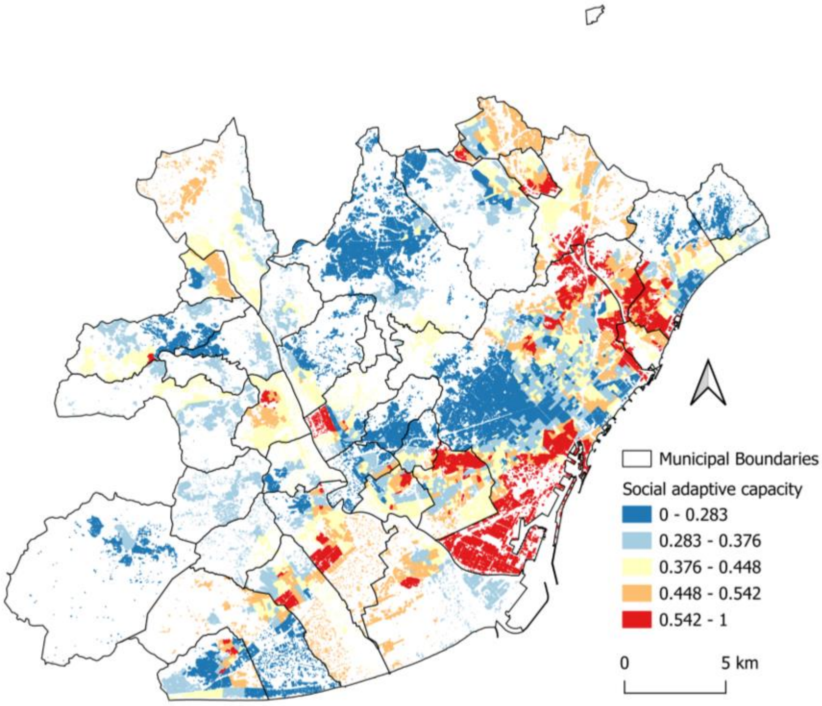


The importance lies in the inherent capacity of individuals with higher incomes to navigate and cope with the challenges posed by environmental hazards.

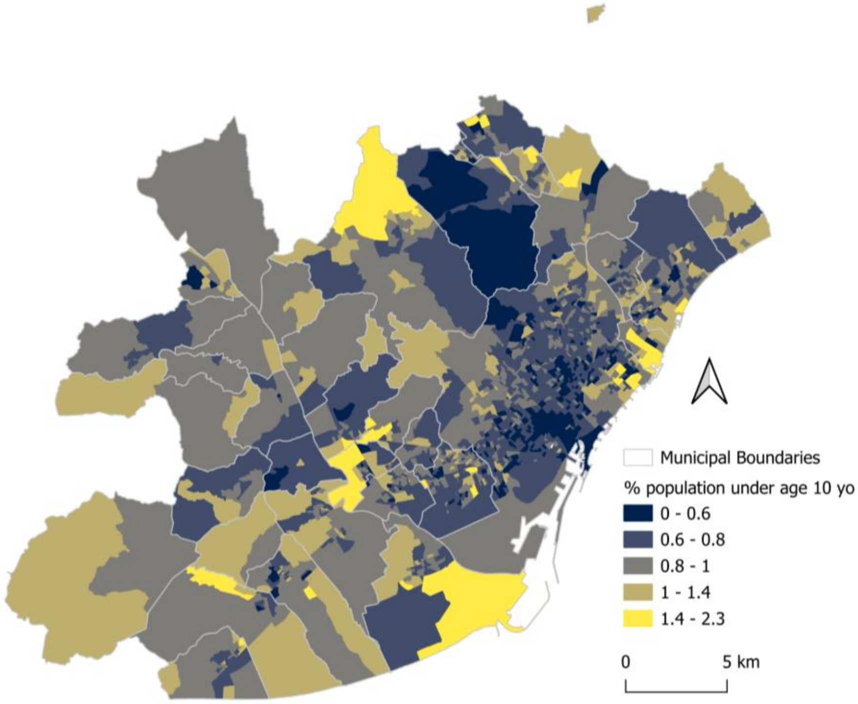
One fundamental aspect is that higher-income individuals possess greater means to adapt and respond effectively in the face of flood-related adversities. Financial resources translate into the ability to implement protective measures, such as investing in resilient infrastructure, securing insurance coverage, and accessing alternative accommodations during emergencies. This economic advantage equips them with a robust defense against the disruptions caused by floods and sewer overflows.

Additionally, higher-income individuals are often better positioned to access timely information and resources that can aid in preparedness and response efforts. Whether it's through advanced warning systems, private infrastructure solutions, or participation in community resilience initiatives, their financial capabilities enable them to proactively engage in measures that reduce their vulnerability to environmental risks.

Map of adaptive capacity

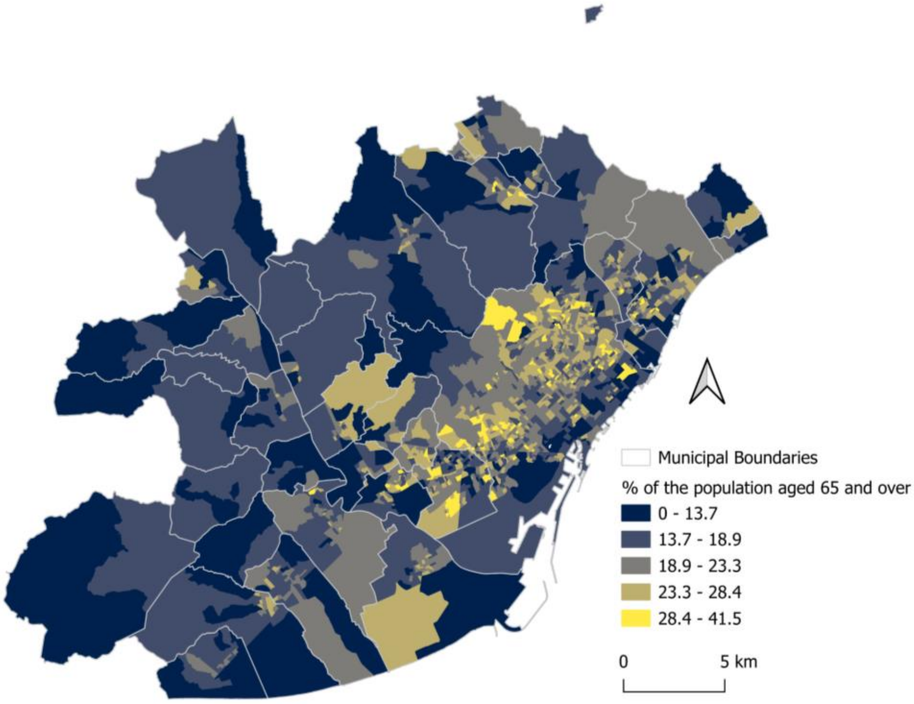


Minor population



Children, in their formative years, possess developing physiological systems that render them more susceptible to the adverse effects of environmental hazards.
Firstly, their physiological systems, from respiratory to immune, are still in the process of maturation, making them less resilient to the impact of pollutants associated with floods and sewer overflows. Their organs and defenses are not as robust as those of adults, rendering them more vulnerable to the health risks posed by contaminated water and air. (Ashbolt et al. 2010)
Secondly, children exhibit higher rates of ingestion relative to their body weight compared to adults. Whether it's through drinking water, playing in flooded areas, or simply putting hands in their mouths after exposure, their increased contact with contaminated substances heightens the risk of pollutant intake. This heightened exposure, coupled with their developing systems, amplifies the potential health consequences.

Senior population

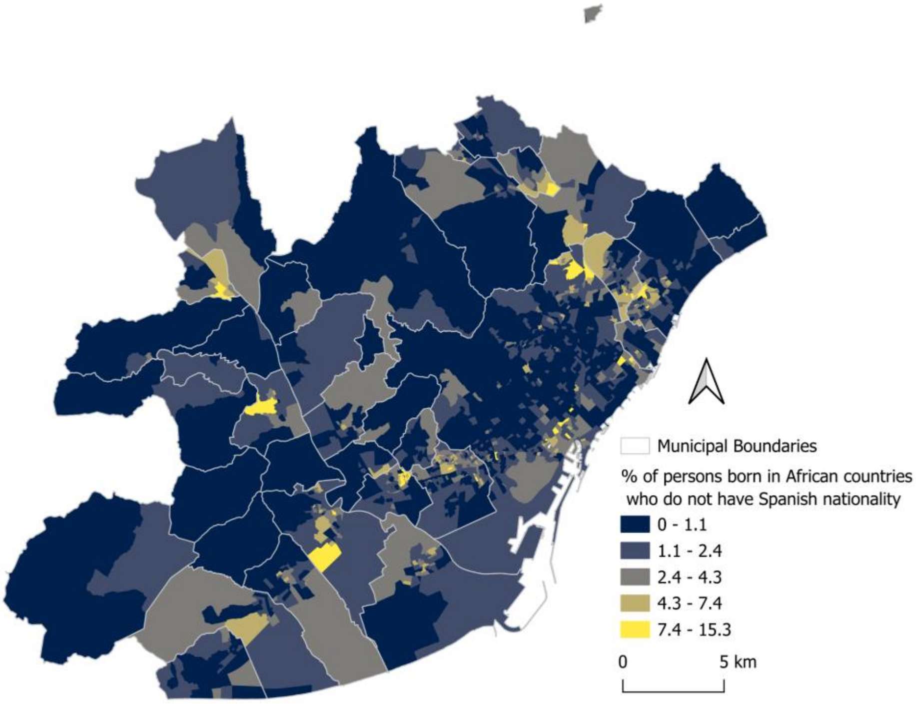


The demographic composition of a community, particularly the proportion of individuals aged 65 and above, serves as a crucial barometer when assessing vulnerability to flood and combined sewer overflow. The aging population brings with it unique challenges that significantly influence their ability to cope with environmental hazards.

Older individuals, by nature, tend to be less mobile than their younger counterparts. This reduced mobility can pose a substantial obstacle when swift evacuation or relocation is necessary in the face of flooding or sewer overflow. The need for assistance becomes more pronounced, as many elderly individuals may require additional support in navigating evacuation routes, accessing shelters, or meeting basic needs during emergency situations.

Furthermore, the aging population is often characterized by a higher prevalence of sensitive health conditions. Chronic illnesses limited physiological resilience, and a heightened susceptibility to stressors make older adults more susceptible to the adverse health effects associated with floods and sewage overflows. The exacerbation of existing health issues and the increased risk of acquiring new ailments underline the importance of tailored emergency response strategies for this demographic.

Communities that may have difficulty with language skills and unfamiliarity with local system



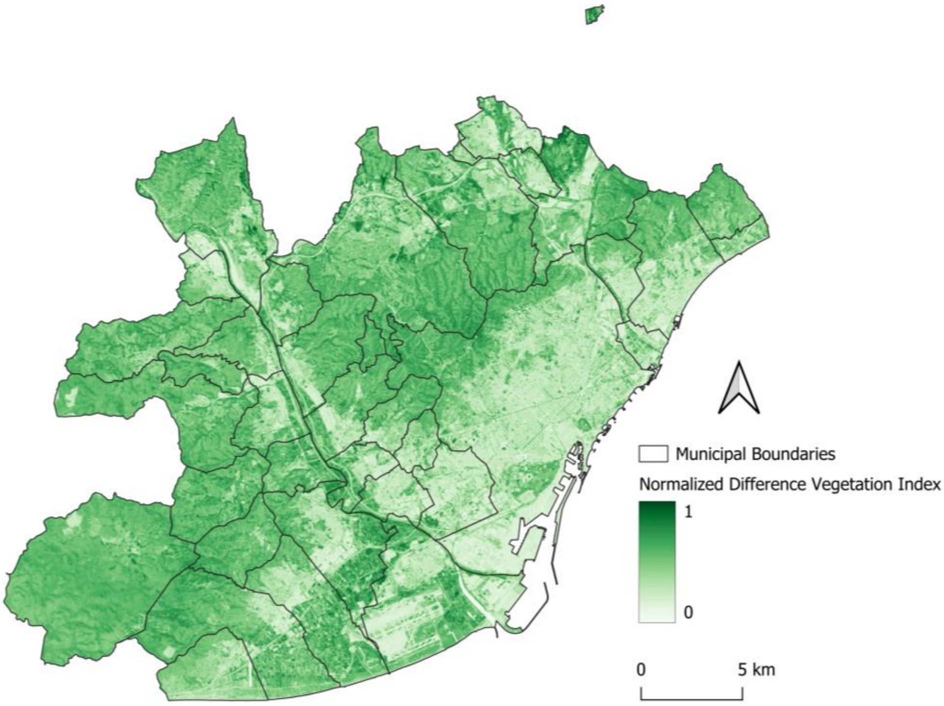
Among the various indicators, the significance of this demographic group lies in the presence of language barriers and unfamiliarity with local water sources, factors that can impede their comprehension of water quality and safety measures, consequently leaving them at heightened risk of exposure to contaminated water.

Language barriers pose a substantial obstacle for immigrant and refugee communities when it comes to accessing vital information about water safety. Communication gaps may lead to a lack of awareness regarding the risks associated with floods and sewer overflows. Without clear, accessible information in their native languages, these communities may struggle to grasp the severity of the situation and the precautions necessary to protect themselves and their families.

Moreover, the unfamiliarity with local water sources exacerbates the vulnerability of immigrant and refugee communities. Many may not be accustomed to the specific water dynamics of their new environment, including potential contaminants or the risks associated with floods. This lack of familiarity can result in inadvertent exposure, as individuals might unknowingly use or come into contact with water that poses health risks.

8.2 Ecological vulnerability

Green area

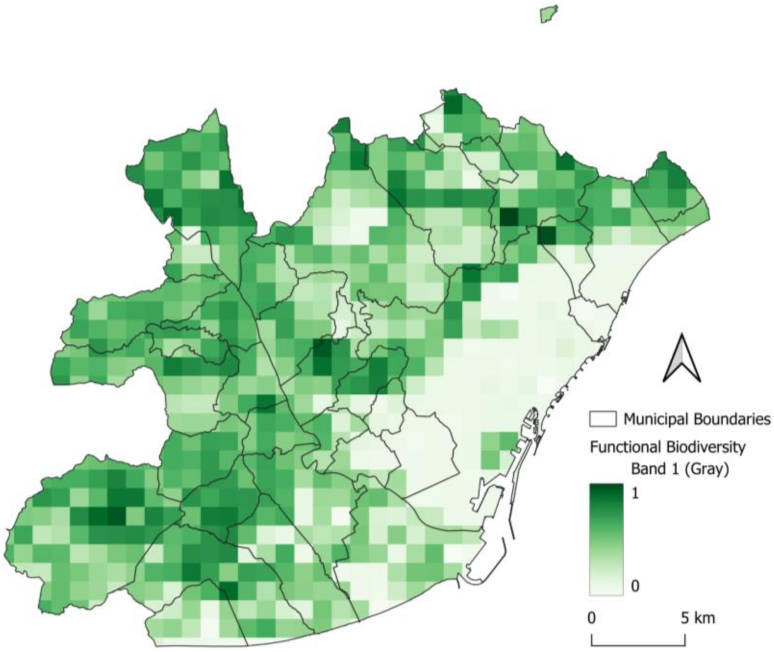


The presence of green spaces, characterized by vegetation and permeable surfaces, holds significant importance in mitigating the impact of environmental hazards, notably by enhancing the landscape's ability to retain rainwater and reducing peak flow.

Green areas, such as parks, gardens, and natural landscapes, play a pivotal role in rainwater retention. The vegetation in these areas acts as a natural sponge, absorbing and holding rainwater. The permeable surfaces, such as soil and vegetation, allow water to infiltrate into the ground rather than contributing to surface runoff. This inherent quality of green spaces helps regulate water levels, preventing rapid runoff and reducing the risk of flooding during heavy rainfall events.

Furthermore, the presence of green areas contributes to a reduction in peak flow. When rainwater is absorbed by soil and vegetation, it is released gradually, easing the pressure on stormwater drainage systems. This gradual release of water helps prevent sudden and intense surges in water flow, minimizing the risk of combined sewer overflow. By acting as a buffer against peak flows, green areas contribute to the overall resilience of urban environments, protecting infrastructure and reducing the likelihood of flooding.

Functional biodiversity



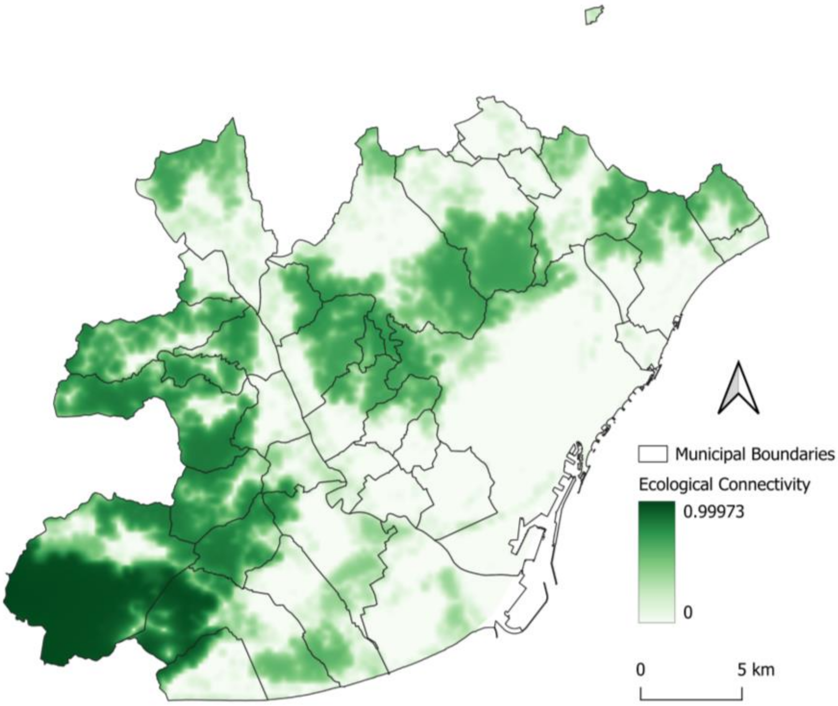
This metric serves as a measure of the quality of ecosystems, influencing their ability to retain water and mitigate runoff. The interplay between functional biodiversity and the challenges posed by combined sewer overflow (CSO) events highlights the intricate relationship between urban flooding and the health of terrestrial ecosystems.

Functional biodiversity represents the diversity of species within an ecosystem and the specific roles they play in maintaining ecological balance. This indicator becomes crucial in assessing vulnerability because the richness and functionality of a biodiverse system directly impact its capacity to manage water dynamics effectively. Ecosystems with high functional biodiversity are better equipped to retain water, slowing down runoff and reducing the risk of flooding.

Combined sewer overflow events have the potential to exacerbate urban flooding, particularly in areas where the combined sewer systems become overwhelmed. This overflow can introduce pollutants and excess water into terrestrial ecosystems, altering ecological thresholds and parameters. The presence of functional biodiversity becomes a determining factor in the system's ability to absorb, filter, and recover from the impacts of combined sewer overflow.

Healthy and diverse ecosystems provide a range of services, including water retention and purification, which are crucial in mitigating the consequences of CSO events. The roots of various plant species, for instance, help bind soil, preventing erosion and enhancing water infiltration. Biodiverse habitats also contribute to the overall resilience of the landscape, acting as natural buffers against the disruptions caused by excessive water flow.

Ecological connectivity



This metric serves as a reflection of the quality of an ecosystem and holds significant importance in influencing the system's ability to retain water and diminish runoff. The intricate connections within an ecosystem, denoted by ecological connectivity, play a critical role in shaping the landscape's resilience to the challenges posed by urban flooding and combined sewer overflow events.

Ecological connectivity refers to the network of interactions and linkages between different components of an ecosystem, including various habitats, species, and ecological processes. The presence of robust ecological connectivity indicates a landscape that functions as an integrated and harmonious system. This interconnectedness is essential in influencing the landscape's capacity to manage water dynamics efficiently, particularly in the face of excessive runoff and flood events.

The ability of an ecosystem to retain water and reduce runoff is closely tied to its ecological connectivity. Well-connected habitats facilitate the flow and absorption of water, preventing rapid runoff and minimizing the risk of flooding. In contrast, fragmented or degraded ecosystems may struggle to retain water effectively, leading to increased runoff and heightened vulnerability to the impacts of combined sewer overflow.

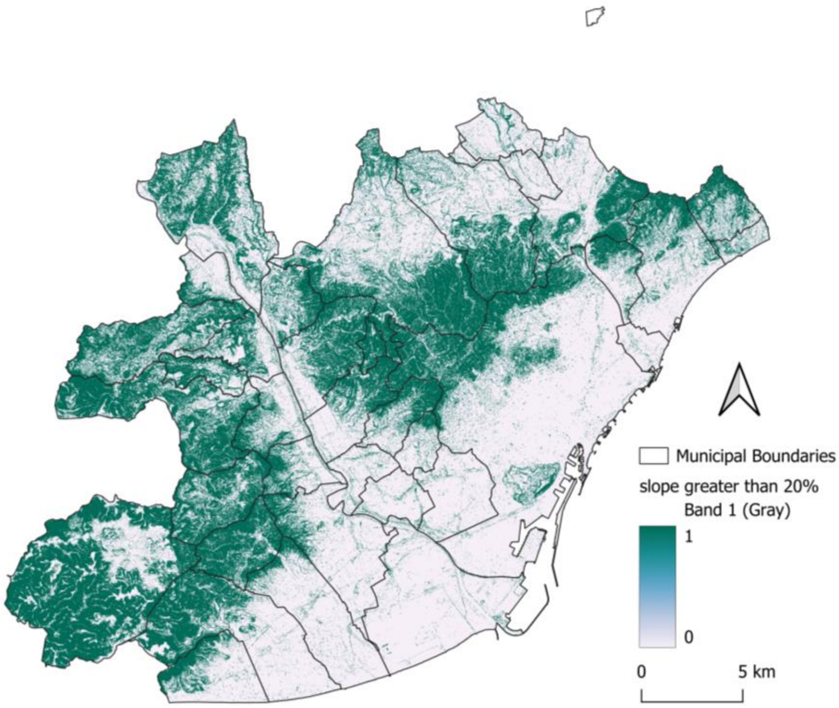
Urban areas, in particular, benefit from strong ecological connectivity as it enhances the landscape's natural capacity to absorb, filter, and manage water. Intact ecosystems act as permeable buffers, slowing down the movement of water and reducing the pressure on stormwater drainage systems.

Presents of wetlands

Wetlands, characterized by their unique ecological functions, play a pivotal role in mitigating the impacts of environmental hazards, serving as natural sponges that absorb excess floodwater and offering essential water filtration and habitat preservation benefits.
Wetlands act as natural sponges during periods of flooding, effectively absorbing and storing excess water. Their capacity to hold significant volumes of water helps regulate water levels, preventing widespread flooding in adjacent areas. This natural retention of floodwater is instrumental in safeguarding communities from the destructive consequences of inundation, providing a buffer against the potentially devastating effects of extreme weather events (Chan et al. 2018).
Moreover, Taylor et al.2022 studied the water filtration capabilities of wetlands contribute significantly to maintaining water quality. As floodwaters pass through these ecosystems, various natural processes, such as sedimentation and nutrient absorption, work to filter and purify the water. This not only improves the quality of water resources but also reduces the risk of contamination associated with combined sewer overflow events. Wetlands, in this regard, act as nature's water treatment systems, enhancing the resilience of ecosystems and protecting the health of surrounding communities.
Beyond flood mitigation and water filtration, wetlands serve as vital habitats for diverse plant and animal species. The preservation of these ecosystems is crucial for biodiversity and ecological balance. The presence of wetlands contributes to the overall resilience of natural environments, fostering habitats that support various species and promoting ecological diversity.

8.3 Technological vulnerability

Slope greater than 20%

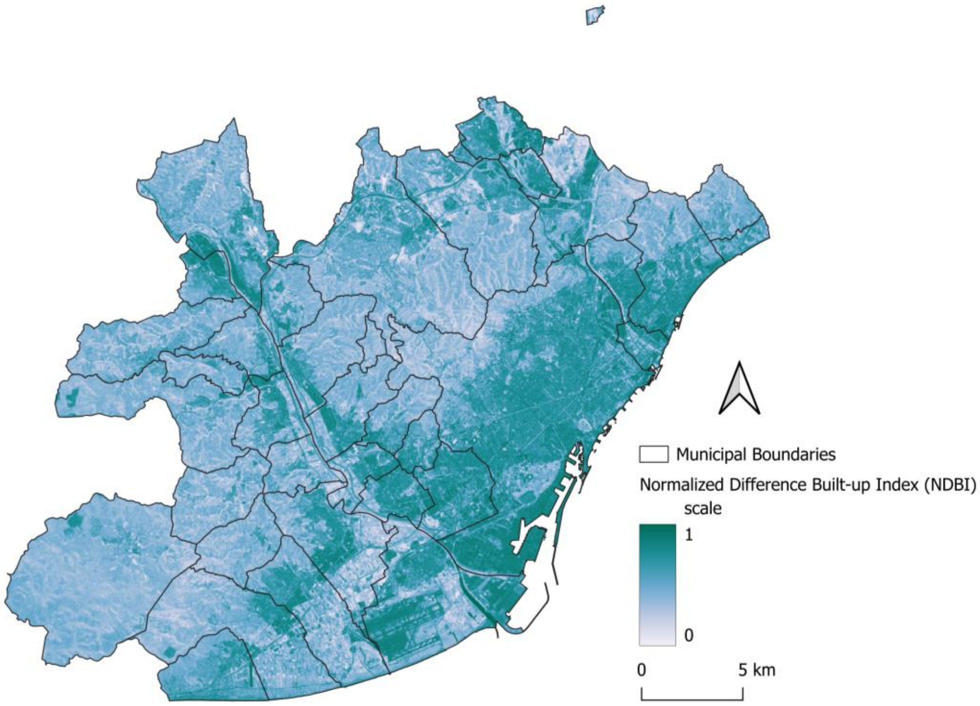


Steep slopes, characterized by gradients exceeding 20%, significantly impact the velocity of water flow, influencing its collection efficiency and intensifying the risks associated with environmental hazards.

Slopes greater than 20% amplify the velocity of water runoff during heavy rainfall or flooding events. The accelerated flow, driven by the force of gravity on steep inclines, poses challenges to the effective collection and drainage of water. This increased speed can overwhelm existing sewer systems, leading to reduced efficiency in managing the volume of water, and subsequently contributing to combined sewer overflow.

In the context of flood vulnerability, steep slopes create conditions where water can rapidly accumulate and descend, increasing the likelihood of surface runoff. This runoff, when unchecked, can result in flooding in lower-lying areas, affecting both urban and natural landscapes. Additionally, the elevated speed of water flow on steep slopes raises the risk of erosion and sediment transport, further impacting the quality of water and contributing to the challenges associated with combined sewer overflow.

Impervious surfaces



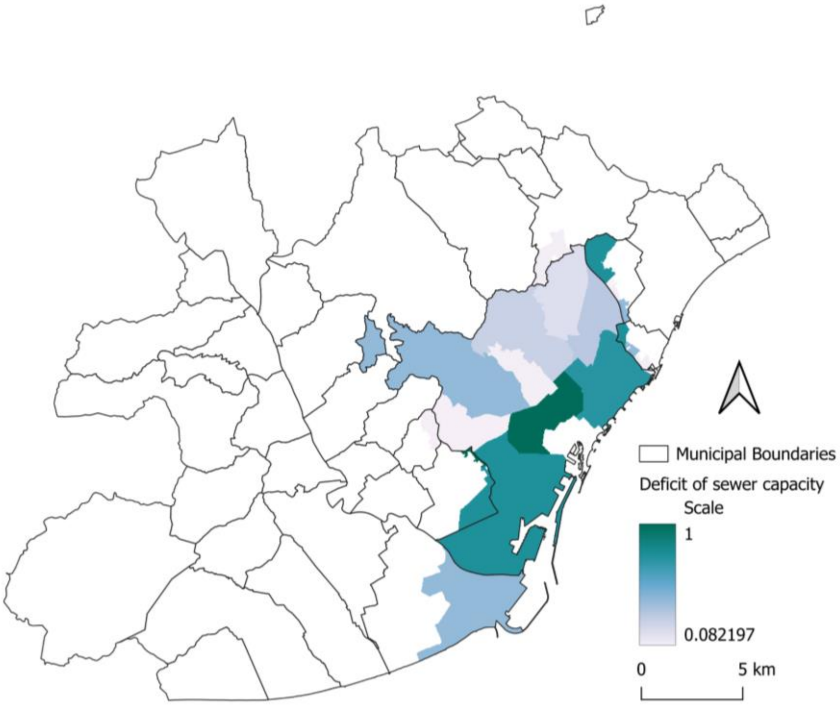
The presence of impervious surfaces plays a key role in increasing direct runoff, exacerbating the challenges associated with flood events and combined sewer overflow.

Impervious surfaces, characterized by their inability to absorb water, create conditions that elevate the direct runoff of rainfall. Unlike natural surfaces with permeable qualities, such as soil or vegetation, impervious surfaces prevent water from infiltrating into the ground. Instead, rainwater quickly flows over these surfaces, accumulating in larger volumes and intensifying the potential for flooding.

In urban landscapes with high percentages of impervious surfaces, the impact is particularly pronounced. The rapid runoff from roads, parking lots, and other impermeable structures increases the risk of localized flooding, overwhelming drainage systems and leading to surface water accumulation. This heightened vulnerability is exacerbated during intense rainfall or storm events, where the impermeability of surfaces prevents the natural absorption of water.

The importance of impervious surfaces as an indicator lies in their role as drivers of direct runoff. As urbanization and development contribute to the proliferation of impermeable surfaces, understanding the implications for flood vulnerability becomes crucial. High percentages of impervious surfaces not only increase the risk of flooding but also play a significant role in the challenges associated with combined sewer overflow, as overwhelmed drainage systems struggle to manage the excess water.

Deficit of sewer capacity



The inadequacy of sewer capacity becomes pivotal in influencing the vulnerability of an area to environmental hazards, particularly by increasing the likelihood of overflow events and pushing the sewer system to its limits.

A deficit in sewer capacity significantly raises the risk of overflow during periods of intense rainfall or flooding. When the volume of water exceeds the capacity of the sewer system, it leads to the spillover of untreated or partially treated wastewater into surrounding areas. This overflow poses not only environmental risks but also jeopardizes public health by exposing communities to contaminants and pollutants present in the wastewater.

The importance of identifying a deficit in sewer capacity lies in its direct correlation with the increased likelihood of combined sewer overflow events. In urban areas with aging or insufficient sewer infrastructure, the system may struggle to cope with the influx of water during heavy rainfall, leading to backups and overflow. This vulnerability is further compounded in situations where the capacity of the sewer system is insufficient to handle the demands of a growing population or changing climate patterns.

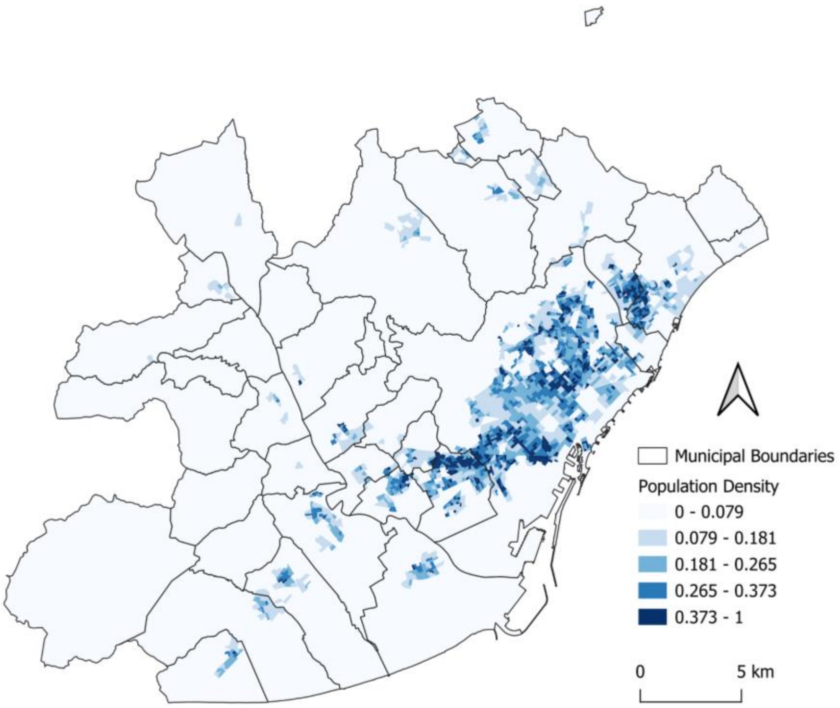
The consequences of a deficit in sewer capacity extend beyond immediate overflow events. They also contribute to the long-term challenges associated with maintaining water quality, protecting ecosystems, and ensuring the resilience of urban infrastructure. Addressing and mitigating the deficit in sewer capacity is essential for building sustainable and resilient sewer systems that can effectively manage the complexities of stormwater and wastewater during extreme weather events.

8.4 Exposure

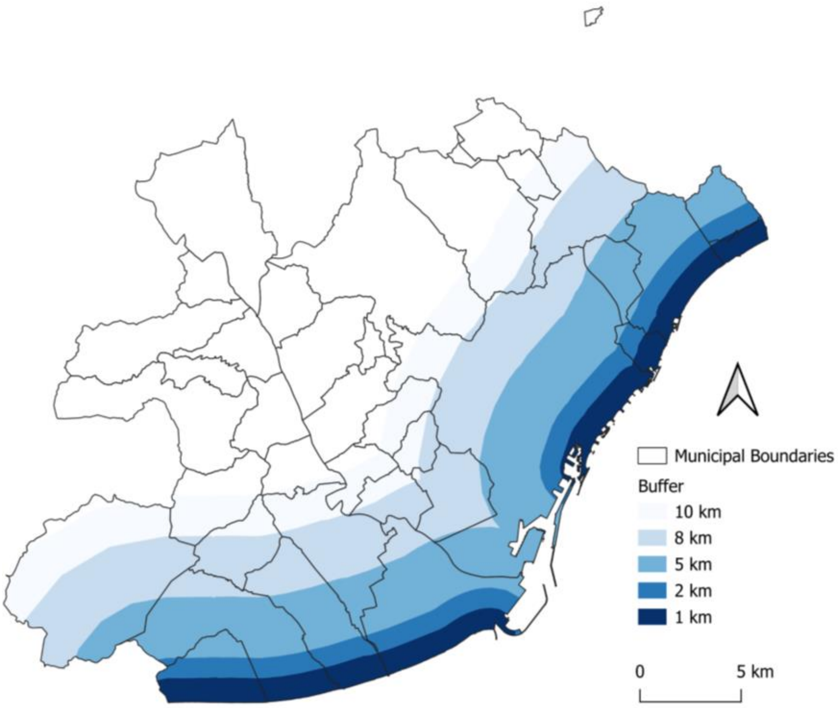
8.4.1 CSO

The evaluation of exposure to sewer overflows is based on official data regarding population density in the area, along with authoritative information on public beaches. This analysis includes a buffer distance from these beaches, ranging from 1 km to 8 km. The underlying hypothesis suggests that individuals living closer to the beach are more inclined to choose nearby areas, while those residing farther away have a broader range of options. This data is subsequently correlated with the distribution of CSO (Combined Sewer Overflow) points within the specified area. It is noteworthy that areas in proximity to hazard sites may have a higher probability of being affected by contaminant releases.

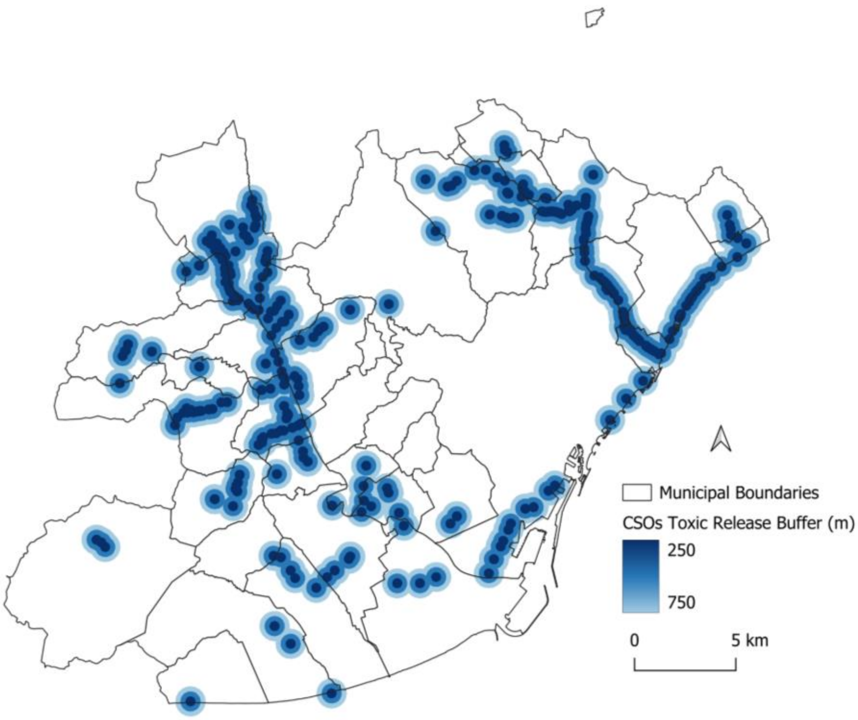
Population density



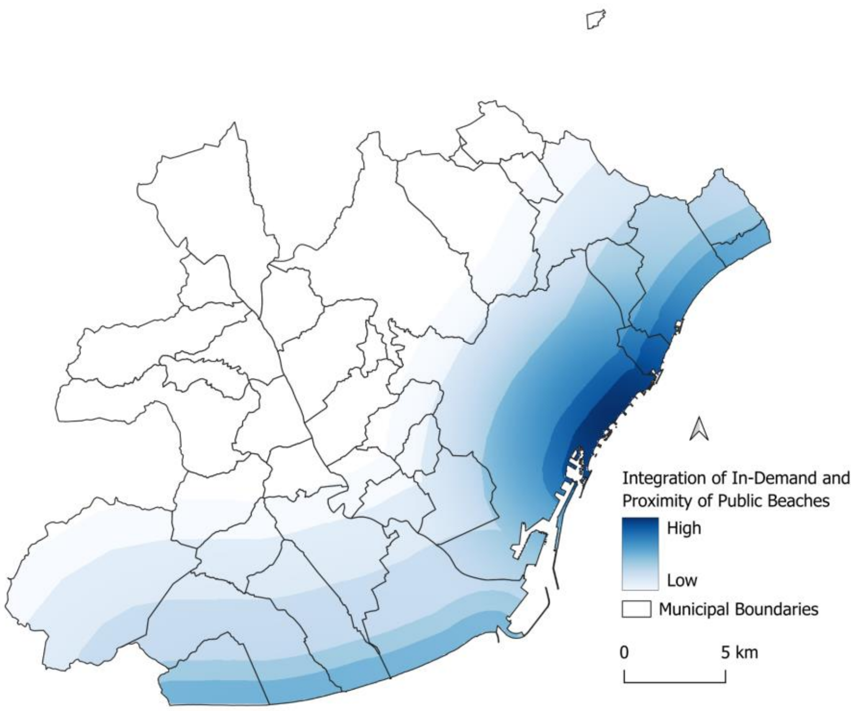
Proximity to public beaches



Proximity to CSOs toxic release



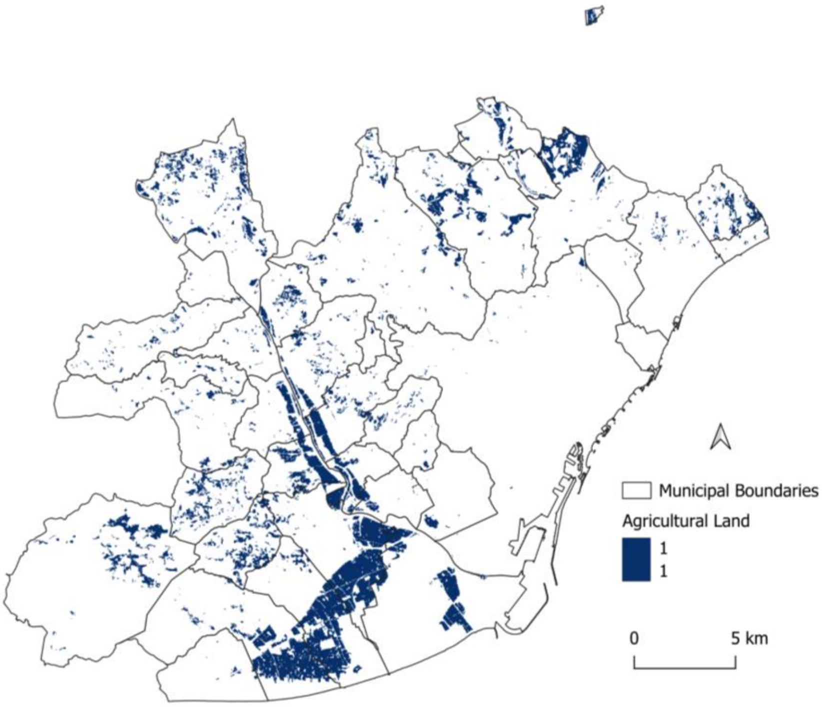
Social media data and proximity to public beaches (different value associate with each public beaches, depends on the number of social media posts)



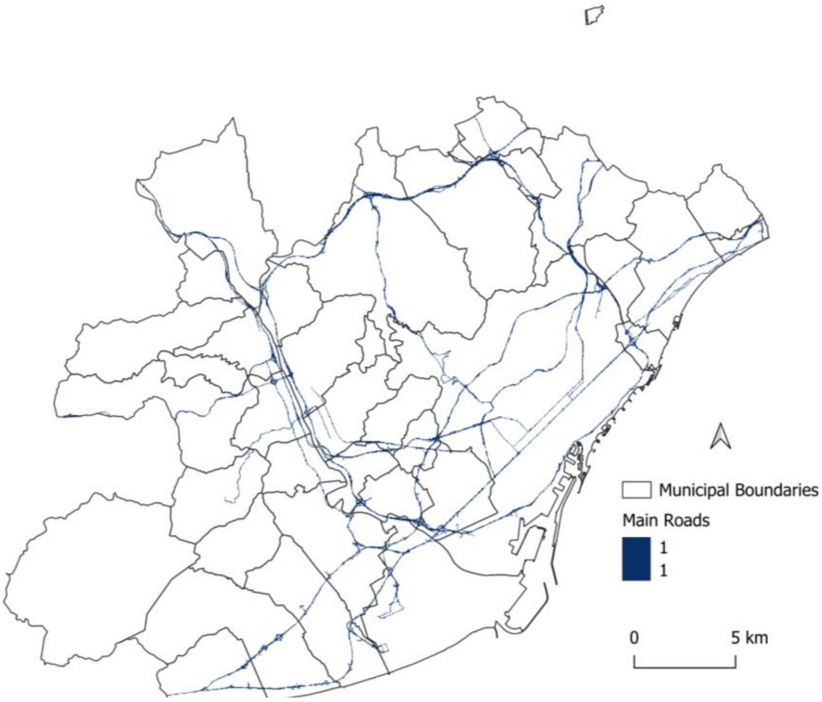
8.4.2 Flood

The assessment of flood exposure involves scrutinizing official data on population density and critical infrastructure, encompassing roads and power stations. Flood-induced damages to critical infrastructure (CI) have the potential to trigger disruptions in society, creating a ripple effect that extends across different spatial and temporal scales (Pant et al. 2018, Wilbanks and Fernandez (2014); Guidotti et al. (2016)). Additionally, the analysis considers the impact on agricultural areas critical for sustaining the food supply (Pathak et al. 2018). This data is subsequently integrated with flood risk information, specifically 500 years.

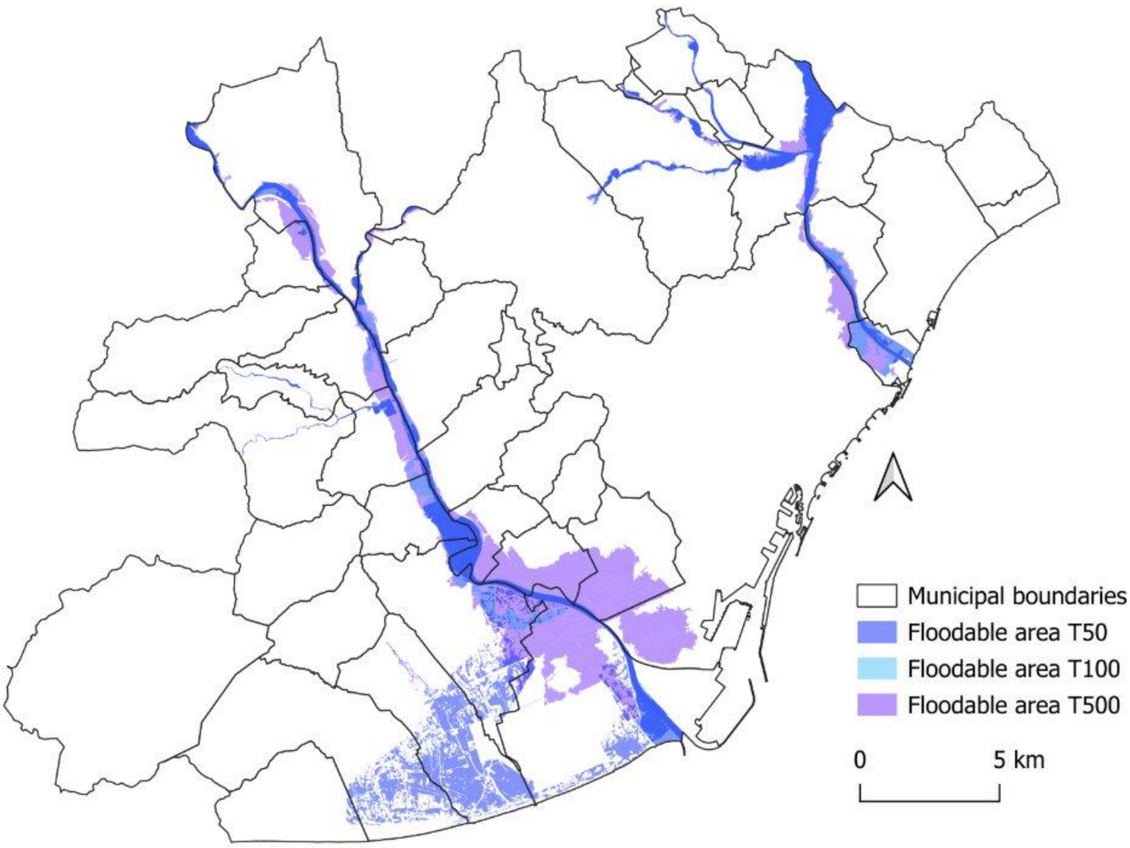
Agricultural land



Main Roads

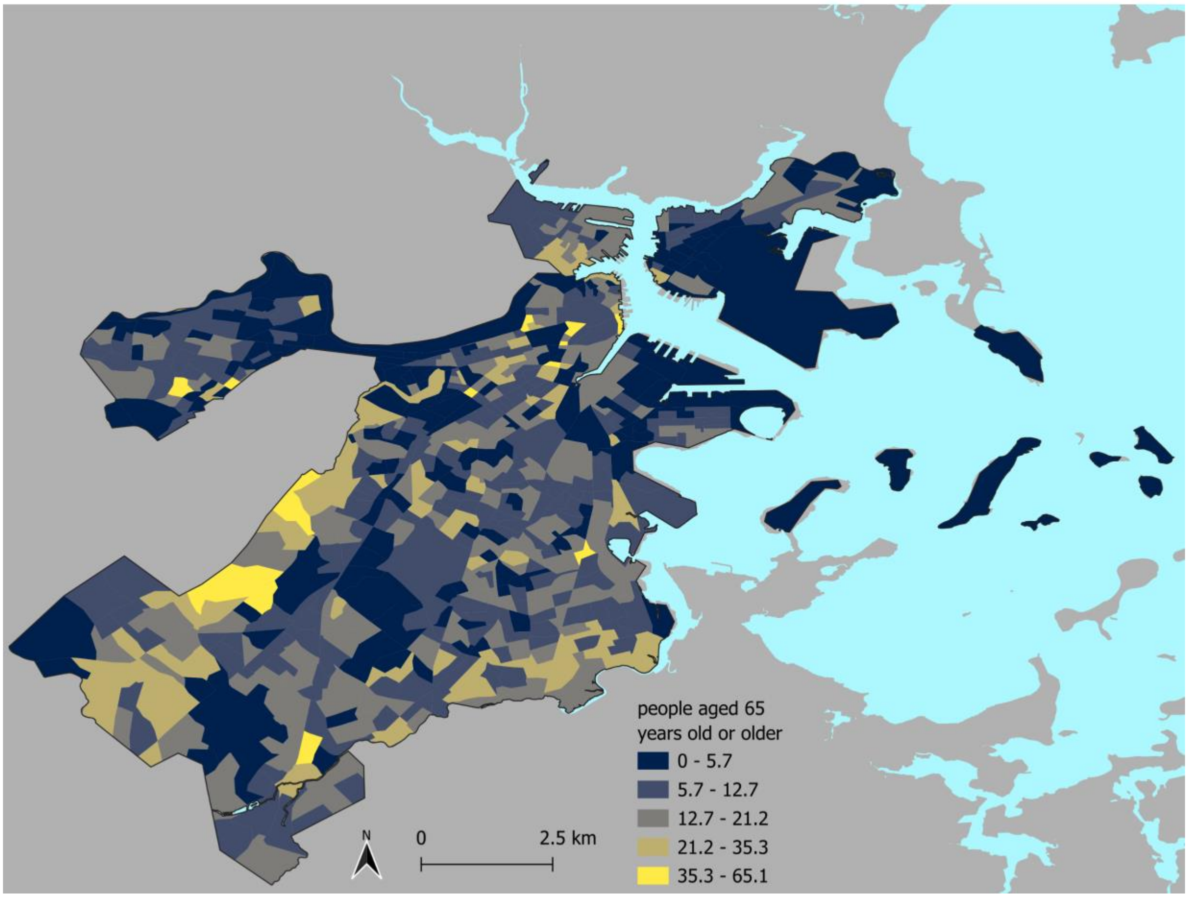


Floodable areas with T50, T100, T500

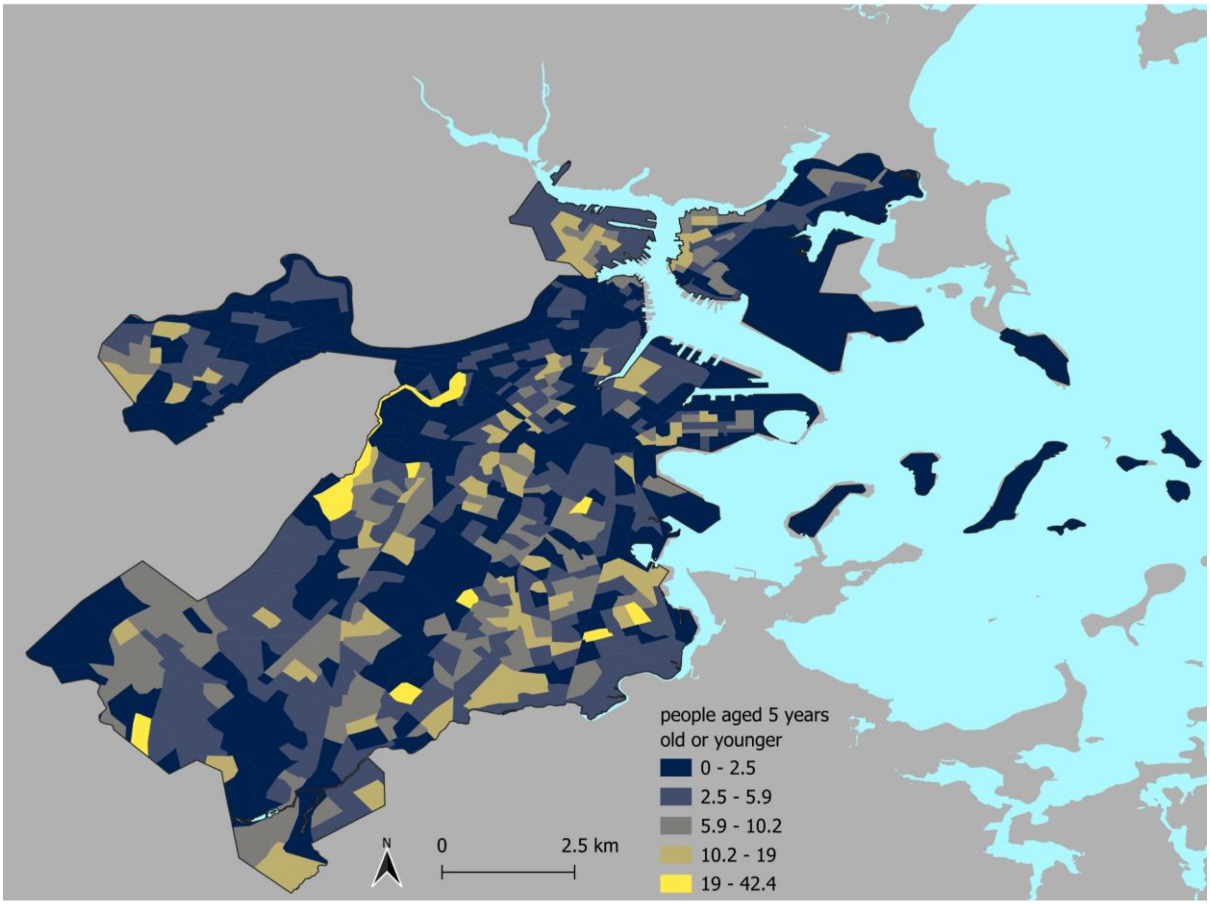


9 Annex 2 (Boston)

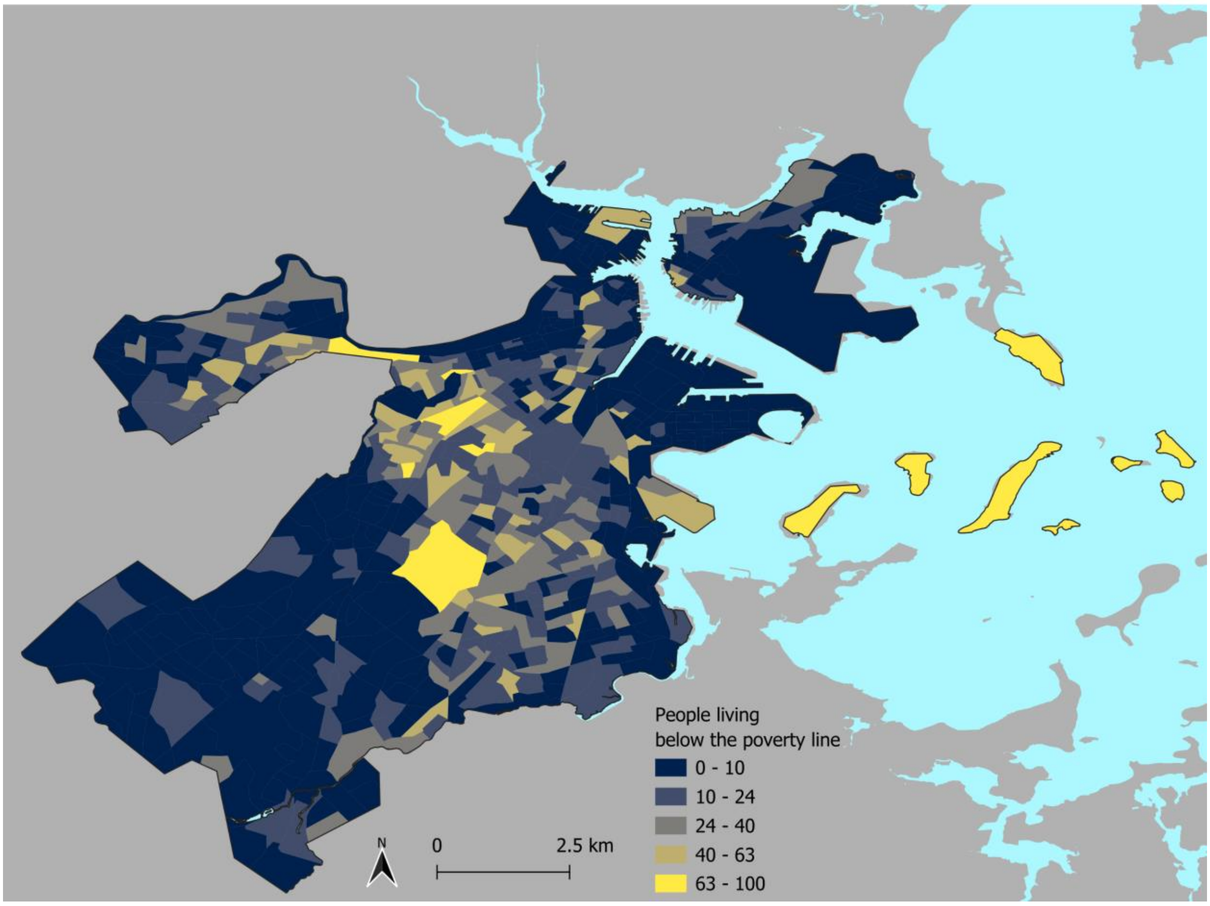
Senior population



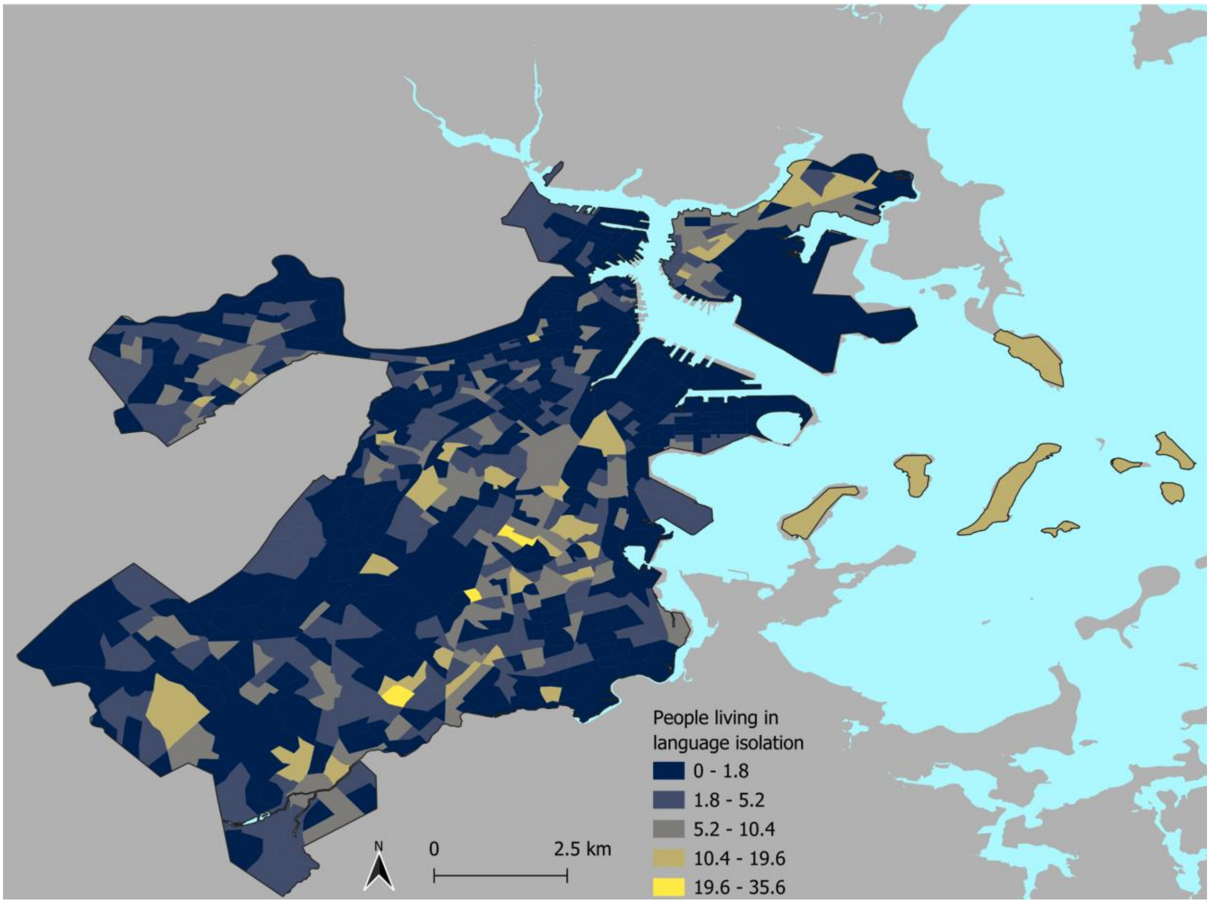
Minor population



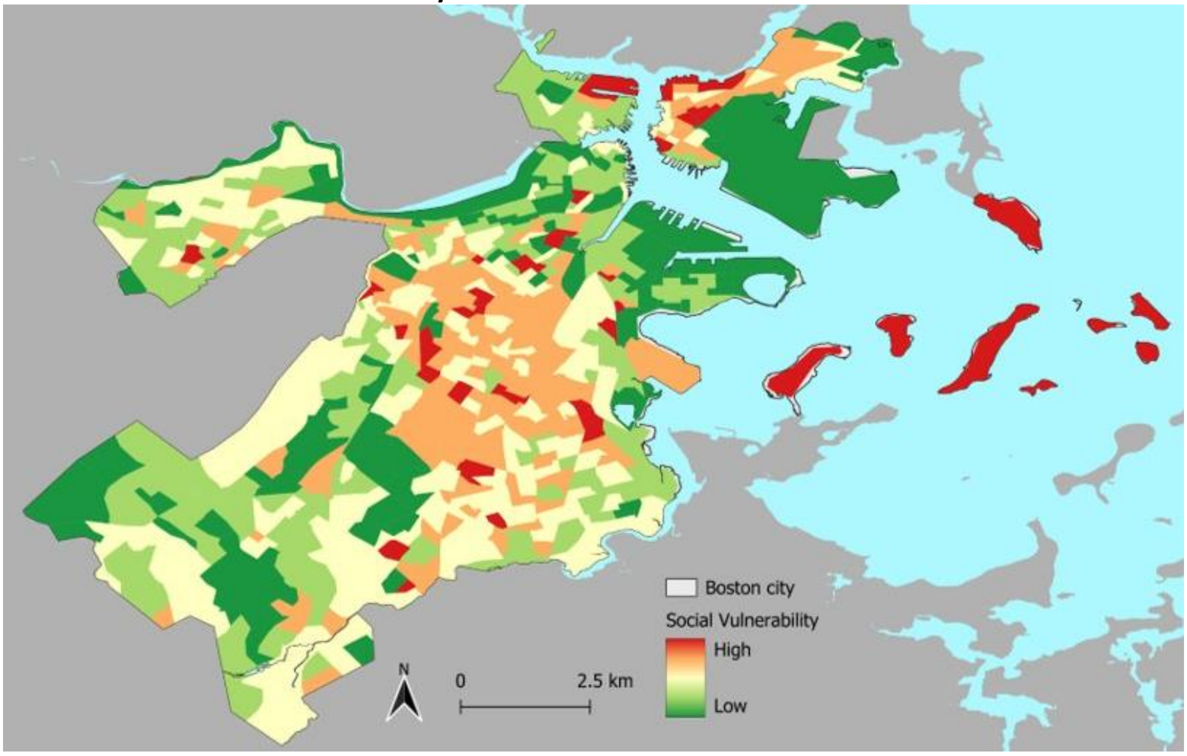
People living below the poverty line



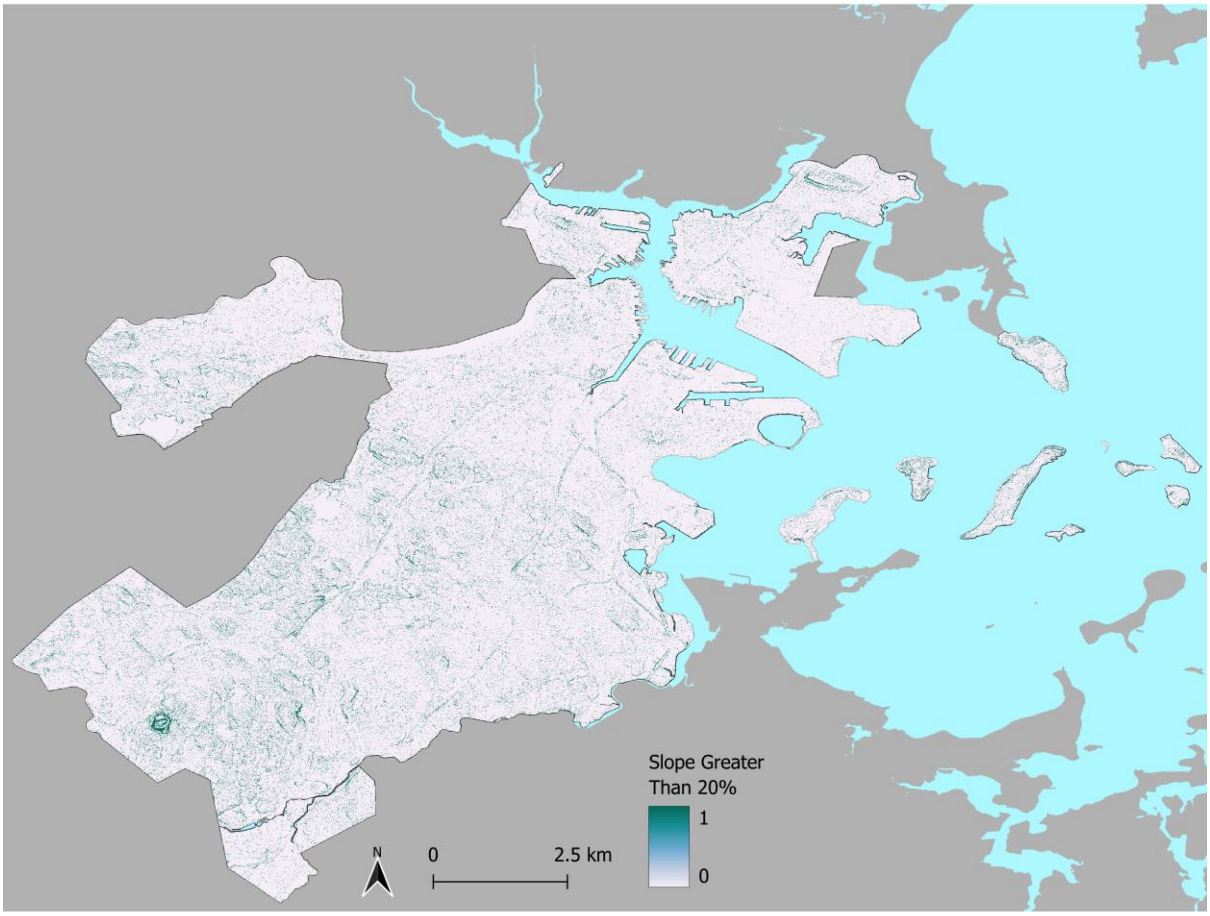
People living in language isolation (speaks English less than "well")



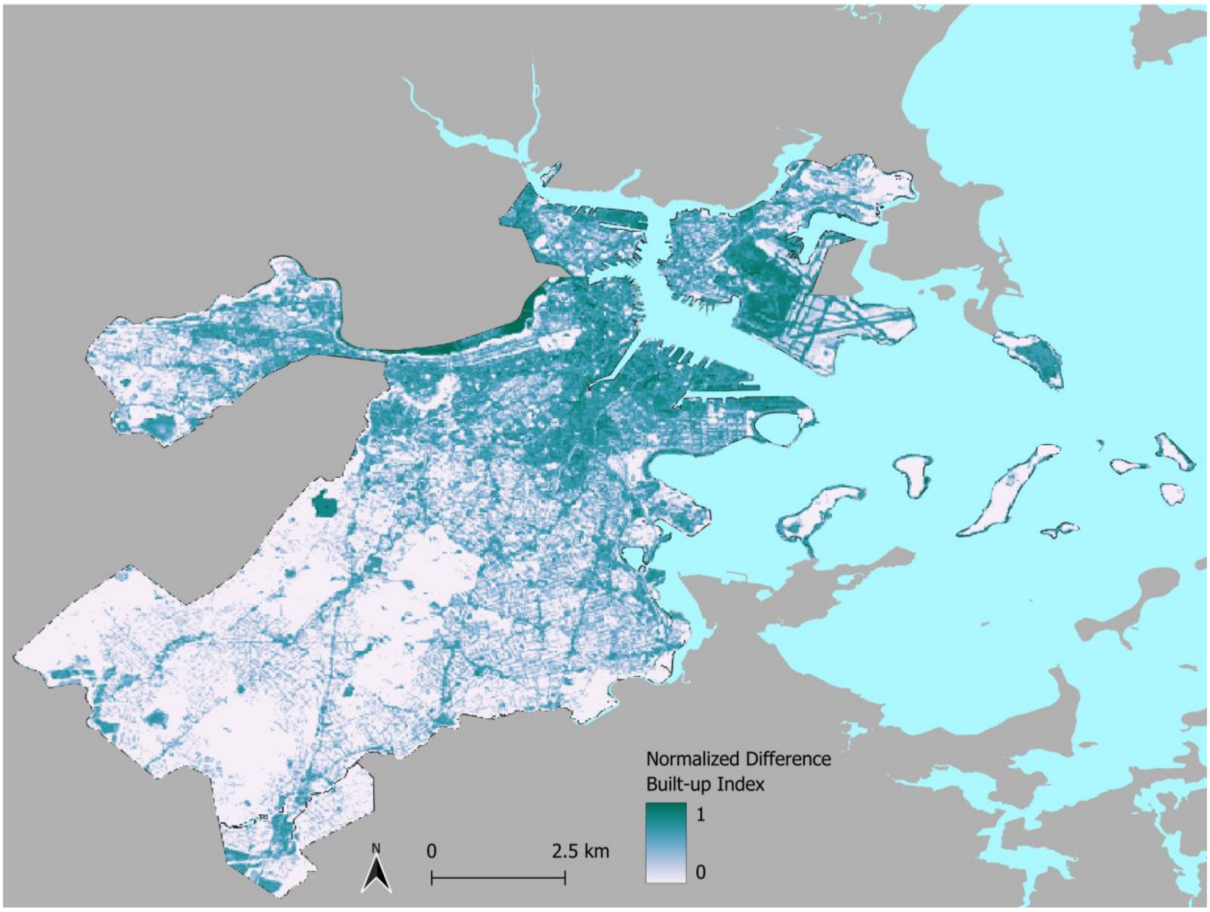
Social Domain on Social Vulnerability



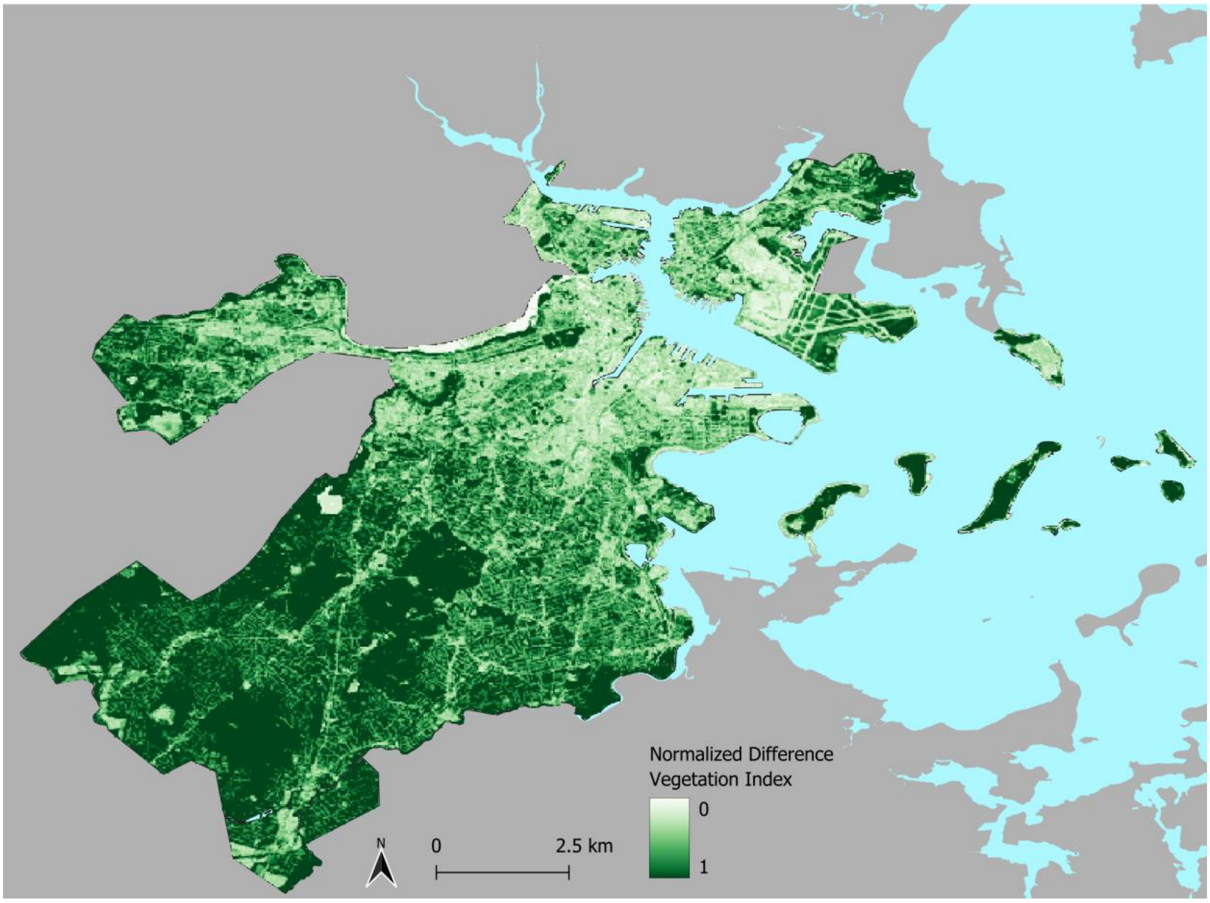
Slope greater than 20%



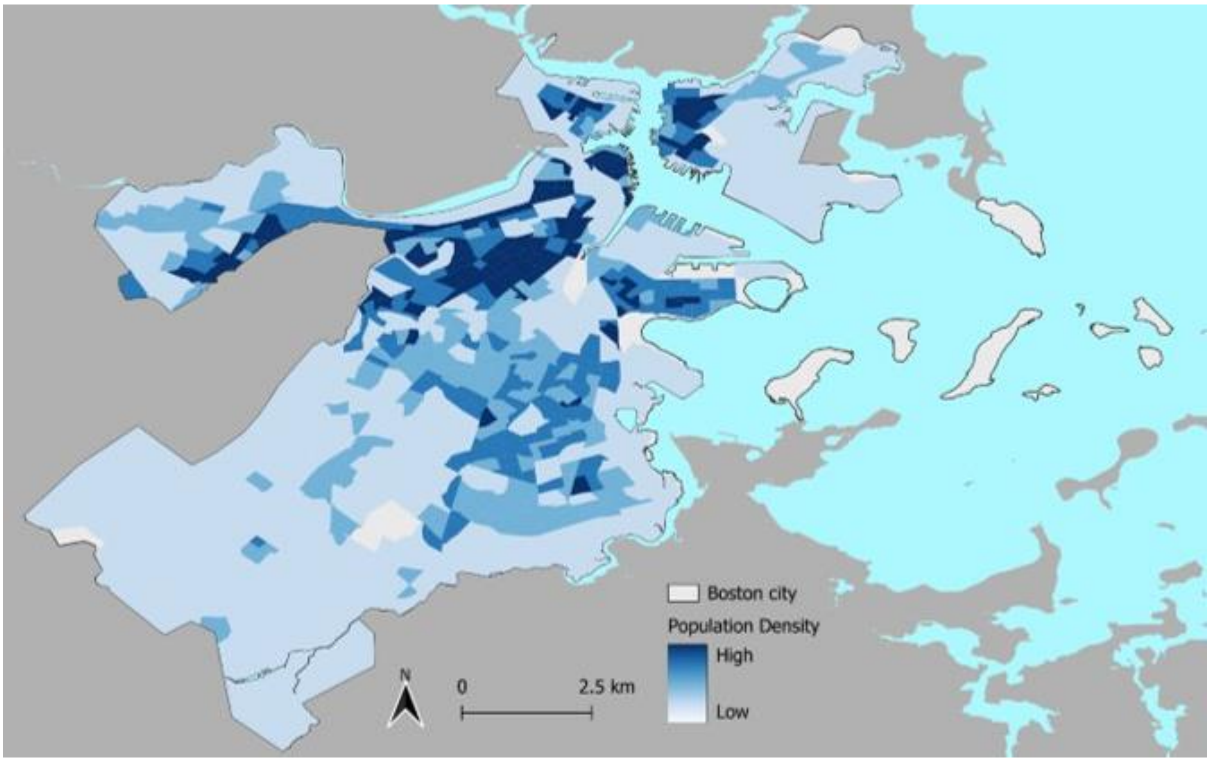
Impervious area



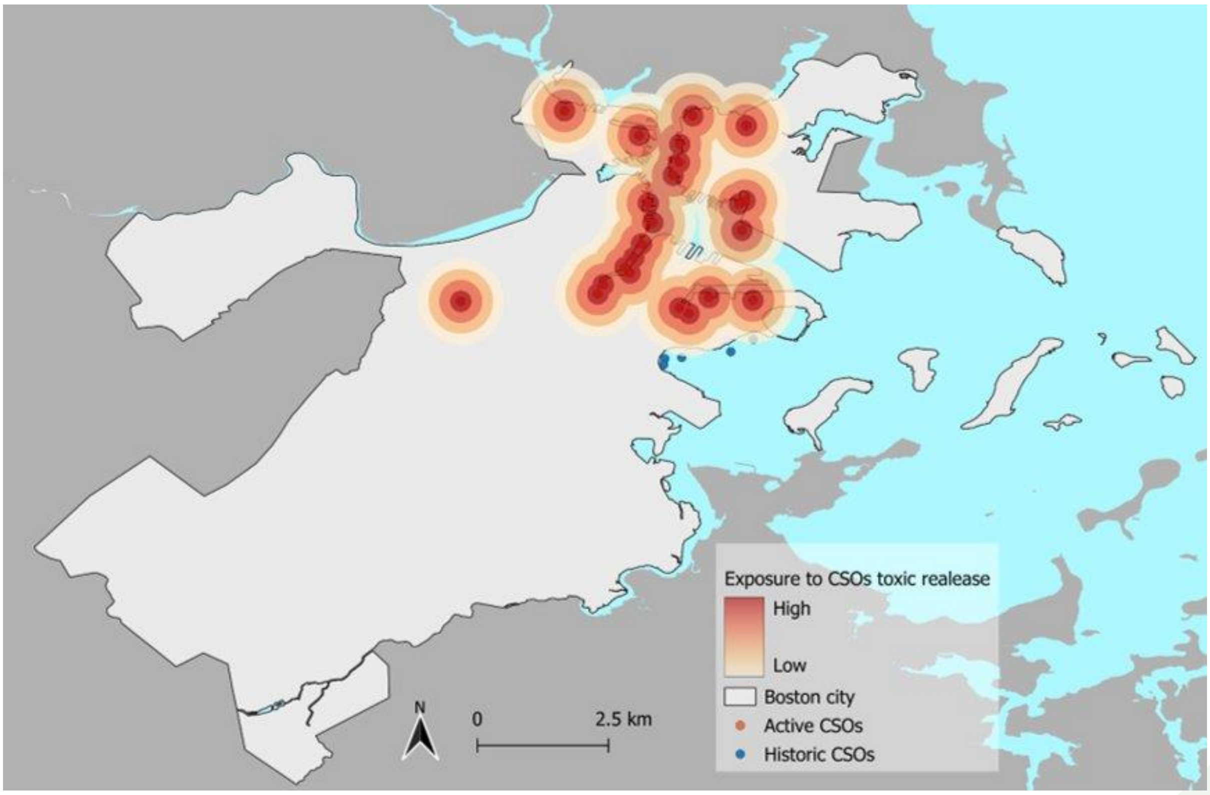
Green area



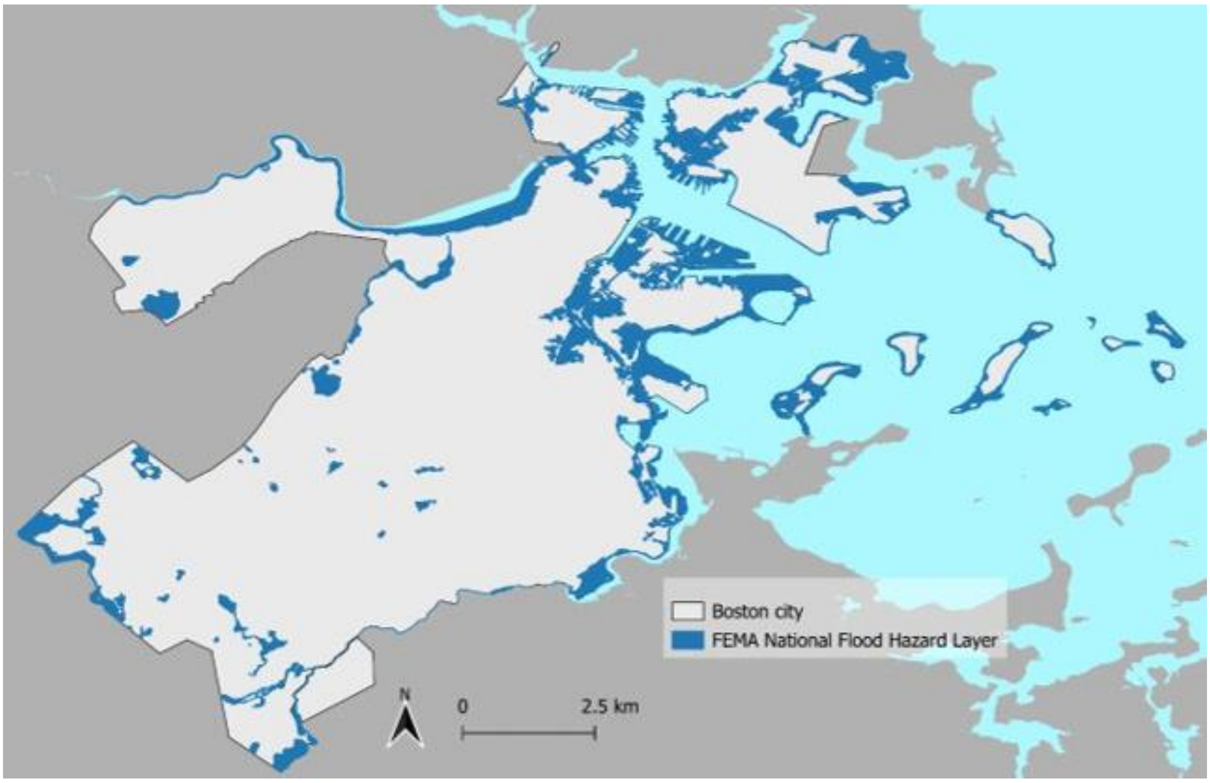
Population density



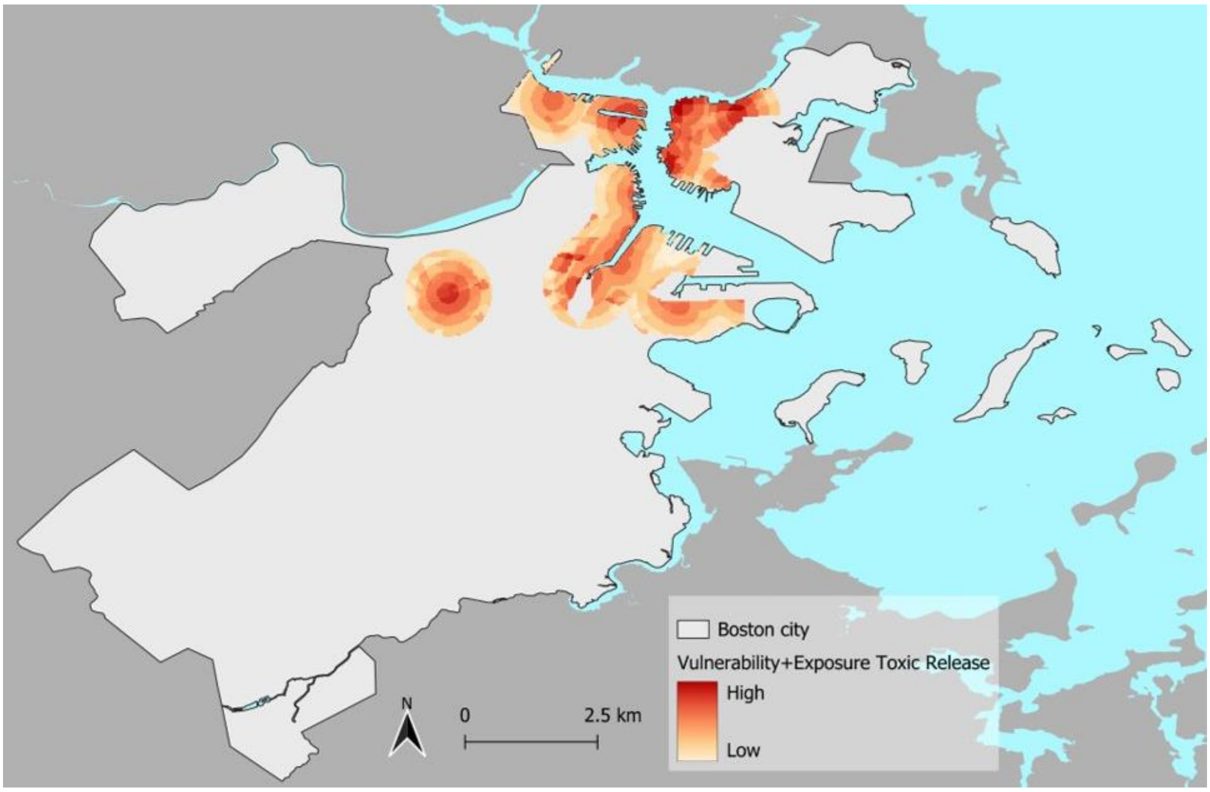
Proximity to toxic release



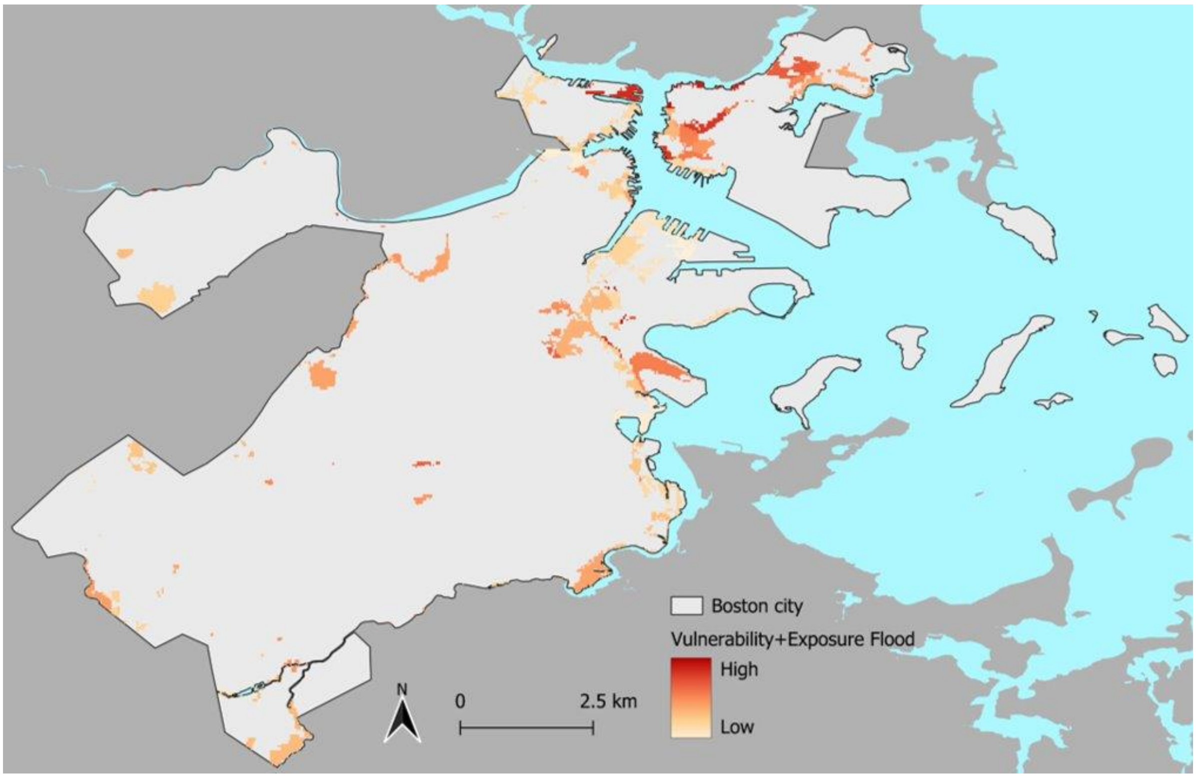
Flood hazard map



Vulnerability + exposure to CSOs toxic release

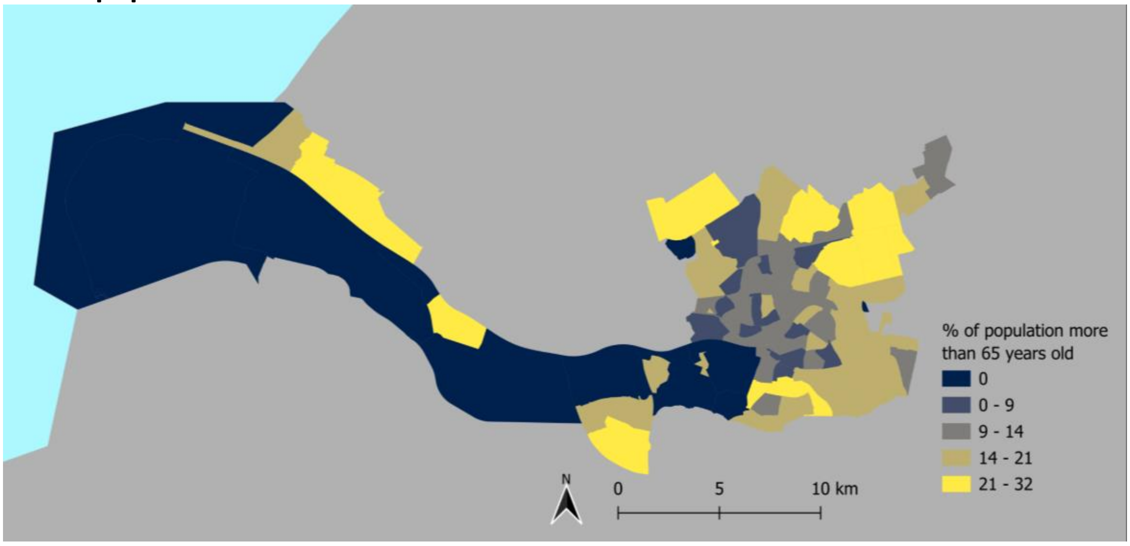


Vulnerability + exposure to flood



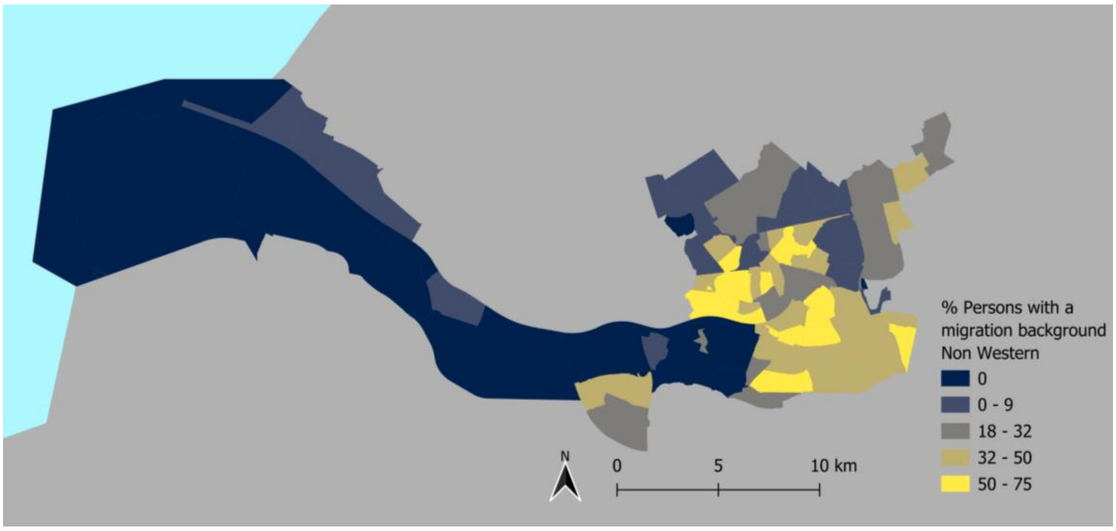
10 Annex 3 (Rotterdam)

Senior population

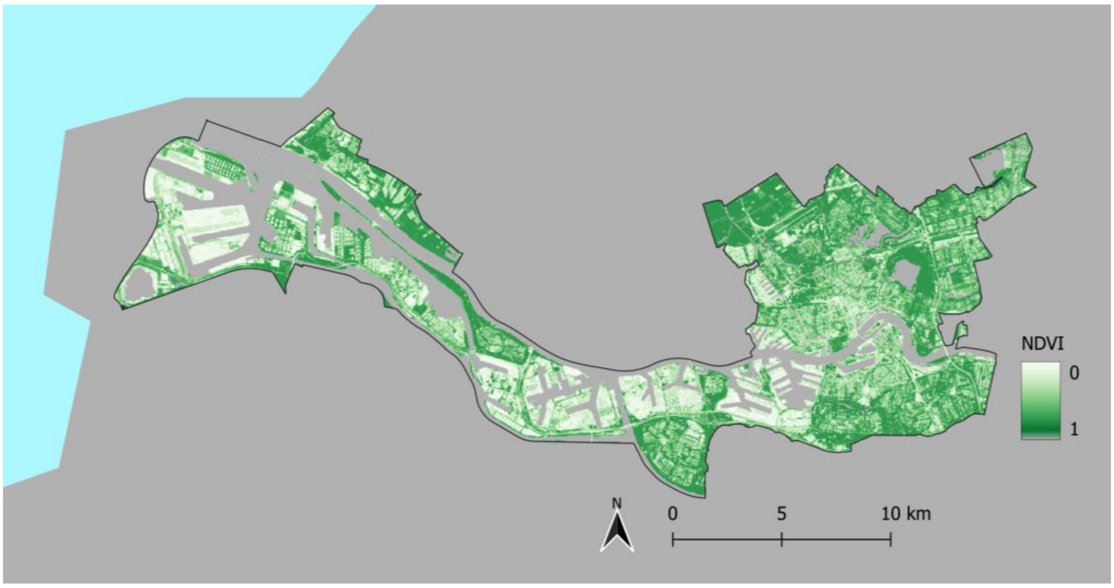


Minor population

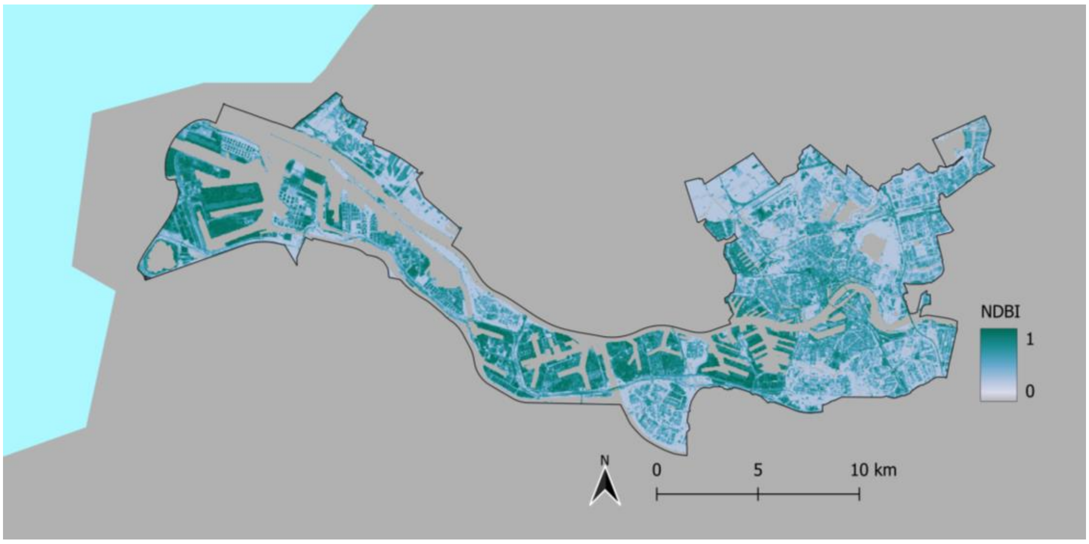
Person with a migration background whose origin group is one of the countries in the continents of Africa, Latin America and Asia (excluding Indonesia and Japan) or Turkey.



Green area



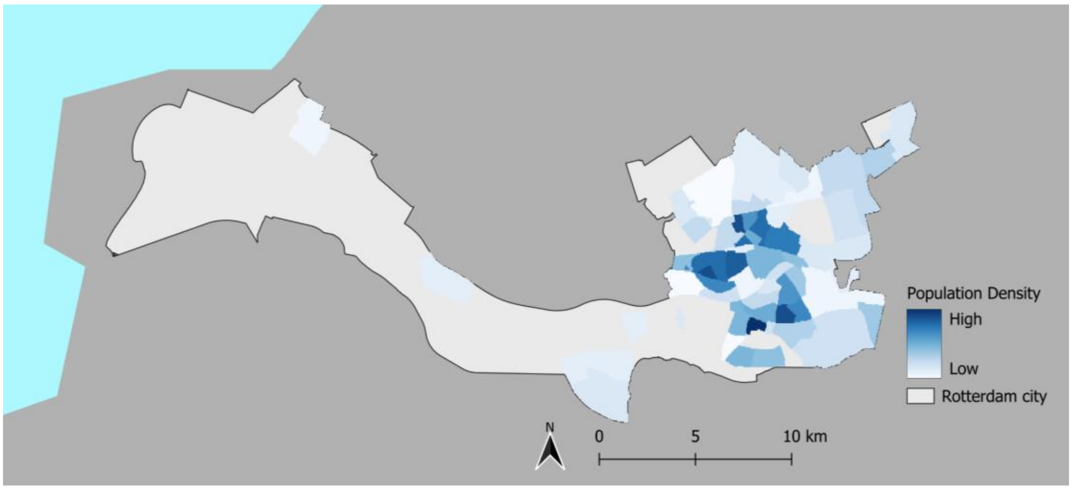
Build-up area



SET Vulnerability

Exposure to CSOs toxic release while swimming (Based on PC Lake model made in D2.1)

Population Density



Vulnerability + exposure to CSOs toxic release while swimming