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A social-ecological-technological vulnerability approach for assessing urban hydrological risks

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ABSTRACT

In the context of urban population growth and climate change, and ever greater number of people are anticipated to face severe risks associated with extreme climate events; major ones are due to stormwater-related hazards. This study offers novel understanding of the complex nature of water-related risks in urban geographies by employing a Social-Ecological-Technological Systems (SETS) framework to assess vulnerabilities. Hydrology-informed urban risk index was developed, quantifying seventeen indicators from historical and modeled data on sewer overflow and flood events. The spatially explicit SETS-based approach identifies high-risk communities and hotspots where multiple vulnerabilities intersect and can serve as a valuable tool for guiding policy and decision-making to support more resilient urban futures. Our findings reveal that social vulnerability plays a critical role in determining the overall risk (R = 0.4), with the greatest impacts imposed on socially vulnerable communities. However, insights from the ecological (R = 0.2) and technological (R = 0.1) domains provide essential guidance for future risk reduction strategies—such as upgrading outdated sewer infrastructure and exploring green space potential for run-off mitigation. The framework proposed is generalizable to other cities facing similar environmental challenges, highlighting its potential as a foundational tool for policymaking to reduce risks associated with extreme climate events.

1. Introduction

Climate change adaptation has become one of the most pressing challenges of our times. Urban areas, where most of the global population resides (UN DESA, 2022), are particularly affected by climate change, and the vulnerability of urban systems to climate change related issues poses novel challenges to residents, ecosystems, and infrastructures (Hamdi et al., 2020; Chang et al., 2021). Water lies at the heart of climate change adaptation challenges in cities (Yang et al., 2021). Globally to locally, the urban water systems are undergoing rapid transformations amid global climate change. These systems encompass the infrastructure and processes used to manage water within cities, including water sources, treatment plants, distribution networks, sewage systems, and stormwater management (Loucks and van Beek, 2017). In many regions, more frequent extreme precipitation events, declining groundwater levels, and water shortages are expected or have already been observed (US EPA, 2023; IPCC, 2022). Urban regions with critical infrastructure and sensitive ecosystems are particularly vulnerable to extreme events (Chester et al., 2023; Lund et al., 2020a,b; Rockström et al., 2023).

Abbreviations: CSO, Combined Sewer Overflow; GIS, Geographic Information System; NBS, Nature-Based Solutions; SETS, Social-Ecological-Technological Systems; IPCC, Intergovernmental Panel on Climate Change; WWTP, Wastewater Treatment Plants; CSSs, Combined Sewer Systems; RCP, Representative Concentration Pathway; AMB, Metropolitan Area of Barcelona (catalan: Àrea Metropolitana de Barcelona).

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Intense stormwater runoff, inadequate drainage infrastructure, and high population densities exacerbate hydrological risks in cities, such as flooding and combined-sewer overflows (CSOs). A recent evaluation of the European Urban Wastewater Treatment Directive underscores poor stormwater management as a significant contributor to pollution and pressure on surface water bodies (EC, 2000). Point source pollution from CSO events, in combination with diffuse pollution from urban runoff, introduces a diverse list of contaminants into water bodies (Miller et al., 2022; Sojobi & Zayed, 2022).

There is increasing recognition that climate risk cannot be understood purely as a physical system and should be examined as integrated Social-Ecological-Technological Systems (SETS); however, the literature on CSOs is typically segmented across single SETS domains. For instance, from a social perspective, studies have evaluated the threat posed by CSOs to public health, considering pathways such as contaminated water consumption, aerosolization of pathogens, and direct contact with polluted environments (Brokamp et al., 2018; Sojobi & Zayed, 2022). Within the ecological domain, studies focused on the environmental impact of CSOs, delving into aspects such as the mal-/functioning of aquatic ecosystems and the decrease/improvement of overall river water quality (Wang et al., 2013; Angerville et al., 2013). The technical domain, which is more prominent in the field of urban hydrology, takes a highly engineering-oriented approach and concentrates on understanding CSO and pluvial flood dynamics through the modeling of street-drainage system water distribution (Sriwastava, 2018). Additionally, it focuses on the maintenance of combined sewer systems (Montserrat, 2015), and the prediction of water levels in CSO chambers (Rosin et al., 2021).

There is a growing recognition of the need for integrated, transdisciplinary, and distributed urban water management to effectively address cities' challenges (Gibelli, 2015). Merz et al. (2010) point out the persistent imbalance in water-related risk analysis, with disproportionate emphasis on the hazard itself rather than its resulting impacts. When dealing with water-related hazards, such as floods, it is crucial to consider vulnerability, as some populations are disproportionately affected by hazards. For example, during Hurricane Sandy in the US, residents in low-income areas were disproportionally impacted by flooding (Lieberman-Cribbin et al., 2021), highlighting that socioeconomically vulnerable individuals are excessively at risk of water-related hazards (IPCC, 2012). An integrated SETS approach can represent the dynamics of the complex water hazards as the wicked problems they are.

Drawing from the IPCC's 2012 risk framework and SETS vision (McPhearson et al., 2016; Chang et al., 2021), this article investigates the hazard, SETS vulnerability, and exposure associated with pluvial flooding and CSOs in urban environments. Building on previous work (Chang et al., 2021), it is hypothesized that social and ecological indicators are the primary drivers of urban stormwater related risks. The main objective of this article is to develop and test a framework to evaluate urban risks associated with stormwater-related hazards.

2. Literature Review

2.1. The Social-Ecological-Technological systems approach

The SETS framework (McPhearson et al., 2016) conceptualizes social, ecological, and technological domains as interconnected components of a unified system, rather than as distinct and independent subsystems (Chester et al., 2023). The interactions within and between SETS domains represent a critical aspect of this framework, essential for fostering sustainable urban transformations that enhance synergies while minimizing trade-offs across domains (McPhearson et al., 2022). The various perspectives on the application of SETS highlight its versatility and significance in framing and tackling urban challenges. Some perspectives place a higher emphasis on resilience aspects, aiming to enhance the ability of urban systems to withstand and recover from disturbances. Chang et al. (2021) emphasize the integration of SETS in resilience planning, advocating for a comprehensive framework that captures the transition trajectory of flood vulnerability management systems, moving away from the current reliance primarily on technological components. Other research focuses on maximizing the benefits derived from urban nature. Keeler et al. (2019) highlight the importance of considering SETS in maximizing the benefits of urban nature and emphasizing the need for targeted research to address equity and governance in ecosystem service assessments. McPhearson et al. (2022) emphasize that the effectiveness of nature-based solutions in delivering ecosystem services for climate adaptation is significantly influenced by social, ecological, and technological factors. Pineda-Pinto et al., (2021) propose the use of environmental justice as a lens for understanding urban injustices by operationalizing the SETS framework to identify ecological justice hotspots. Kim et al. (2022) focus on leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change, emphasizing the need for transformative approaches that incorporate SETS capabilities to address climate uncertainties. Branny et al. (2022) demonstrate how SETS can bridge gaps between smart, green, and social agendas in urban development, promoting holistic approaches that enhance multi-actor engagement and management of urban infrastructure. Building on the insights of Kim et al. (2022) and Branny et al. (2022), the current research applies the SETS framework to the complex water-related risks in urban environment of Barcelona.

2.2. Hazard, Exposure, vulnerability and risk

Numerous efforts have been made to establish widely accepted definitions of key terms central to the field of risk, as highlighted by Thompson et al. (2005). For scientific discipline to be effective, it must be based on clearly defined and universally understood terms and concepts, ensuring both consistency and clarity in communication (Aven, 2016). Established methodologies, such as the IPCC's risk framework (IPCC, 2012), provide valuable tools for understanding the interplay of various risk components (Fig. 1). In this context, *Risk* can be defined as the result of the interaction between natural or human-induced hazards, the exposure, and the ecological, social, and technological vulnerabilities of urban communities.

Hazard is defined as the potential occurrence of physical events, whether natural or human-induced, capable of causing adverse effects

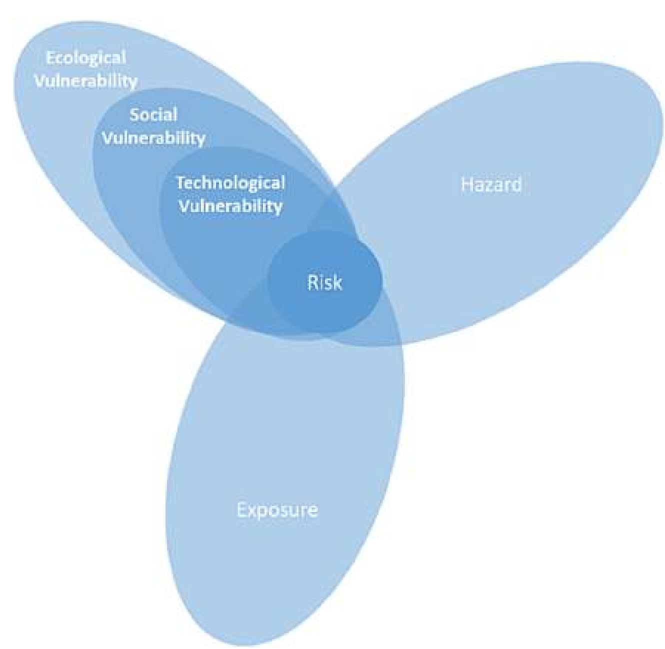

Fig. 1. Risk-based approach analytical framework with SETS dimensions of vulnerability (own elaboration inspired by IPCC, 2012; Chang et al., 2021).

such as loss of life, injury, or other impacts on health or the environment (IPCC, 2012). Within these primary hazards, sub-criteria are delineated based on their impact on urban communities. *Exposure* is defined as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by hazards (IPCC, 2012). Note that this updated understanding and definition of exposure represents a critical shift from the IPCC 2007 to IPCC 2012 paradigm, the former still widely employed elsewhere (Camacho-Caballero et al., 2024; Aznarez et al., 2024). *Vulnerability* can be understood as the propensity or predisposition to experience adverse hazards, encompassing a spectrum of concepts and elements. It is important to highlight that the approach used in this study differs from the vulnerability-based framework of the IPCC 2007, used in the studies like Chang et al. (2021), which defines vulnerability as a function of exposure, sensitivity or susceptibility to harm, and a lack of capacity to cope with and adapt. Instead, this work adopts a risk-based approach, where vulnerability is considered a component of risk. Although, the vulnerability of human, technological and natural systems when exposed to hazards is a critical aspect in the literature, independently and as a component of risk assessment (IPCC, 2012).

2.3. A SETS vulnerability approach as a component of risk

Many different examples of vulnerability-based approaches are found in the literature. These range from the conceptual origins and models of vulnerability (Giupponi and Biscaro 2015; Estoque et al. 2023) to the relationships and integration of vulnerability with resilience and adaptation (Gallopín 2006), as well as its connection to risk (Sharma and Ravindranath 2019; Chang et al. 2021). Furthermore, some reviews have emphasized indicators of vulnerability and geographical applications of vulnerability assessments, such as societal (Cutter 2012) and urban contexts (Leal Filho et al. 2018). However, we diverge from Cutter et al. and Gallopín perspective by breaking down vulnerability into the three SETS components, which addresses vulnerability comprehensively, including considerations of social equity, ecological resilience and infrastructure development. Risk frameworks may benefit from an expanded interpretation of vulnerability that integrates different SET domains. In our perspective, vulnerability-based approaches often fall short in capturing the variability of hazard events, particularly their intensity and frequency, and may not adequately address how exposure is influenced by the specific characteristics of hazards. In this study, we expand vulnerability assessment in risk evaluations by integrating the SETS perspective, specifically examining ecological and technological vulnerabilities in relation to stormwater-related hazards. Despite the importance of these factors, they remain underexplored, limiting our understanding of the full scope of urban rainwater-related issues.".

This work presents a risk assessment using SETS to gain a more complete perspective of the underlying vulnerabilities. We understand *social vulnerability* as characteristics of local communities that might make them vulnerable to hazards. A socially vulnerable population is more likely to be adversely affected during a hazard and may take longer to recover. The social domains determining social vulnerability include age, income, ethnicity, and health conditions. *Ecological vulnerability* is understood as characteristics of the ecosystem that determine their capacity to provide ecosystem services. It is presented with indicators such as ecological connectivity, sensitivity, biodiversity, and the percentage of green areas. Ecological components involve organisms, their populations, and the physical environment, such as soil, air, water, and climate. *Technological vulnerability* is defined as engineering and landscape characteristics that influence the ability of technological systems to function without failure. Technological components comprise infrastructure, including roads, buildings, water collection and distribution systems.

3. Methodology

The objective of this study's integrated SETS-based risk assessment is to systematically understand and quantify the potential risk associated with CSOs and flooding, aiding in more informed decision-making regarding urban water management strategies. Utilizing a holistic approach that considers the multiplication of risk components—hazard, exposure, and SETS vulnerability—and employing an indicator-based approach (Fig. 2). We address the City of Barcelona as a case study.

3.1. Case study: The city of Barcelona

Cities worldwide contribute to the intensification of hydrological hazards, such as flooding and combined sewer overflows (CSOs), due to factors including intense stormwater runoff, inadequate drainage infrastructure, reliance on combined sewer systems, and high population densities. Coastal urban areas, in particular, face heightened risks due to their exposure to extreme weather events, rising sea levels, and the complex interactions between natural and built environments (Azevedo de Almeida & Mostafavi, 2016). Barcelona serves as a representative case study of these challenges. In this study, we apply a Social-Ecological-Technological Systems (SETS)-based vulnerability approach to assess urban water-related risks in the city.

Barcelona (Fig. 3), the capital of Catalonia, covers an area of approximately 101 km^2 and is inhabited by around 1.6 million people (2021). Positioned between the Besòs and Llobregat Rivers, it is bordered by the Littoral Range and the Mediterranean Sea. The region receives around 600 mm/year of rainfall annually, characterized by heavy storms typical of the Mediterranean climate, leading to frequent flooding and CSO events. Sewer systems follow the topography of catchments from mountains to the sea or the River Besòs. Coastal sewers intercept stormwater runoff to prevent discharge into the sea or river, but excess rainwater leads to CSOs (Jose et al., 2012). Along severe flood events with return periods exceeding 100 years, the region witnesses frequent minor flood events each year, primarily due to convective and local precipitation in late summer and autumn (Llasat et al., 2022; Cortès et al., 2018).

Coastal cities and their infrastructure are vulnerable to water-related issues, affecting energy, transportation, water, and wastewater systems (Azevedo de Almeida & Mostafavi 2016). This vulnerability is exacerbated in coastal zones like Barcelona, which experiences the highest number of heavy rain episodes, primarily due to localized convective rainfall events, as seen in many other Mediterranean cities (Llasat et al., 2022). This issue is compounded by the projection that by 2050, 70 % of the global population will be concentrated in coastal cities (Benoit and Comeau, 2012).

Barcelona serves as a typical example of a Mediterranean coastal region, characterized by significant urbanization of flood-prone areas and high population density intersected by numerous streams. Despite this, there remains a limited understanding of flood dynamics in Mediterranean urban areas, including both drivers and consequences (Cortès et al., 2018). The findings of a recent UN-Habitat report indicate that approximately 20 percent of urban residents globally be affected by a 100-year flood event, with over 600 cities at risk of complete inundation from such a flood (UN DESA, 2022). Storm Daniel caused widespread devastation in the Mediterranean in September 2023, impacting Greece, Bulgaria, and Türkiye with record-breaking extreme rainfall and flooding. Between the 4th and 6th of September of 2023, certain areas in Greece received an amount of rain equivalent to the average rainfall for an entire year in just one day, well above the 100-year return period (He et al., 2023; CIMAfoundation, 2024). In October 2024, extreme rainfall, caused by a high-altitude low-pressure weather system isolated from the jet stream (locally known as DANA), led to deadly flash floods that severely impacted southern and eastern Spain. Regions such as the Costa del Sol, including the city of Malaga, and Valencia in the east were hit particularly hard, leaving communities struggling to cope with the

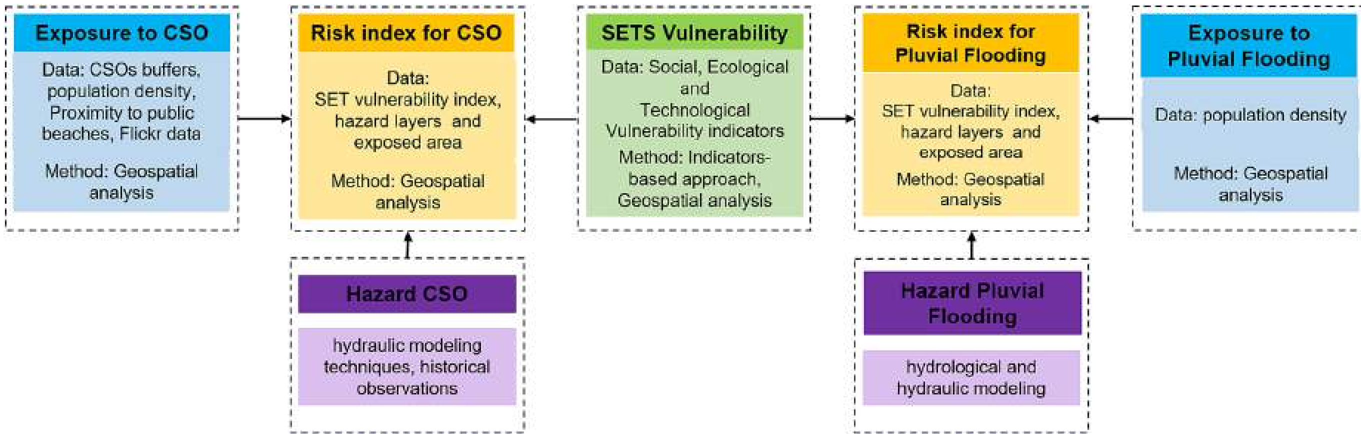

Fig. 2. Methodological Framework (own elaboration).

aftermath (ESA, 2024). Consequently, analyzing flood risk requires a holistic approach that considers all relevant factors, including the nature of the hazard, vulnerability, and exposure (Cortès et al., 2018; Llasat et al., 2022).

Barcelona utilizes a Combined Sewer System (CSS), managing both sanitary sewage and stormwater runoff in a single pipeline that is vulnerable to CSOs during times of high stormwater flows. Combined systems are prevalent not only in Europe but also in numerous urban locales worldwide (Karamouz and Zahmatkesh, 2017; US EPA, 2023). CSOs can distribute pollutants over wide areas and incur high ecological damage and costs for repair and pollutant collection, making them a global environmental issue of concern for various environmental organizations (Abbasi et al., 2021). In addition to ecological impacts on freshwater and marine organisms, CSO spills in urban areas pose a threat to the safety of public bathing. Barcelona, being a renowned tourist destination, highlights the crucial significance of the city's public beaches. With a scenic 4.5 km Mediterranean coastline, these beaches serve as essential tourism hubs. During the bathing season, from May to September, they attract approximately 5 million visitors (AMB, 2022). The Barcelona City Council's impact assessment framework considers the health repercussions stemming from insufficient bathing water quality, primarily attributed to elevated *E. coli* concentrations resulting from CSOs. Economic losses were quantified at €39 million in 2009 (BCASA, 2020). Surveys conducted by Martínez-Gomariz et al. in 2021 reveal a notable lack of awareness among residents concerning CSO hazards, which underscores the need for additional reporting and raising awareness regarding issues related to CSOs in coastal cities.

3.2. Selection of hazard, exposure, and vulnerability indicators

To implement a risk assessment following the SETS approach, three common urban water hazards were considered: (a) urban flooding, (b) the influence of CSOs near the outflow points, and (c) the effect of CSOs on the bathing water quality at public beaches located nearby. Since these three studied hazards have slightly different characteristics and can be applied in various settings, the developed risk methodologies vary in exposure indicators but utilize the same SETS vulnerability approach (Fig. 2). Potential indicators were evaluated using an inductive methodology to select the most appropriate ones based on the conceptual framework, geographical specificity, and data availability (Table 1). The indicators have been analyzed, calculated and mapped in QGIS version 3.32.

The data for this work was collected from publicly available sources. Municipal data for social vulnerability and exposure indicators, meticulously organized in census groups, were extracted from the *Instituto Nacional de Estadística (INE),* and *Institut d'Estadística de Catalunya*. Ecological indicators, vital for understanding environmental aspects, were sourced from La *Generalitat de Catalunya' Hypermap*. Technological indicators together with hazard indicators were taken from the reports *Pla Estratègic del cicle integral de l'aigua, PECIA,* 2023 *(Strategic Plan of the integral water cycle of the AMB;* AMB, 2023) and *Pla Director Integral de Sanejament de Barcelona, PDISBA, 2019* (*Comprehensive Barcelona Sanitation Master Plan;* BCASA, 2020) (Additional information on data sources is provided in Appendix A; further description and justification for hazard, exposure and hazard indicators are provided in Appendix B).

3.3. Normalization and aggregation to SETS vulnerabilities

3.3.1. Social domain vulnerability indicators

To account for population variation across census blocks, we calculated rates as percentages of each block's total population. Indicator values were then normalized to a 0–1 range using min–max rescaling. Next, a vulnerability score was calculated by summing the weighted normalized values of each indicator. This score was subsequently rescaled to a 0–1 range using the geometric mean, where 0 indicates minimal vulnerability and 1 indicates maximum vulnerability. Finally, the spatial data were converted to raster format with a 40 m spatial resolution to facilitate integration with ecological and technological vulnerability domains. (Additional modeling and mathematical details are provided in Appendix C).

3.3.2. Ecological and technological domains vulnerability indicators

The data, initially in vector format, was converted to raster format with a 40 m resolution to facilitate integration. All indicators were normalized to a 0–1 range to ensure consistency across scales and units. Next, we calculated the mean value for each dimension group, applying equal weight to each indicator and using the raster calculator to determine the vulnerability score for each pixel. Finally, the vulnerability score was rescaled to a 0–1 range, where 0 represents minimal vulnerability and 1 represents maximum vulnerability. (Additional modeling and mathematical details are provided in Appendix C).

3.3.3. Data aggregation

The next step involved creating an aggregated SETS vulnerability index by calculating the geometric mean for each pixel, consolidating the SETS vulnerabilities into a single index using the cell statistic function in QGIS, with equal weighting for social, environmental, and technological domains. To assess risk from CSO and pluvial flooding, we integrated hazard, vulnerability, and exposure by combining SETS vulnerability, hazard, and exposure maps to generate a unified risk score, calculated with the Raster Calculator as follows: (1).

$$Risk\ index = hazard\ index * exposure\ index * vulnerability\ index \qquad (1)$$

This approach ensures a balanced consideration of hazard,

Table 1
Indicators selection.

Indicators	Resolution	Justification	Indicator +/-	References
Hazard				
CSOs location based on historic observation and hydrological and hydraulic modelling				AMB, 2023, BCASA, 2020
Flood layers based on hydrological and hydraulic modelling				BCASA, 2020 RESCCUE project
Exposure				
Proximity to public beaches	20 *m*	Losing colling effect of public beaches		Martínez-Gomariz et al. 2021
Population density	20 *m*	More densely populated areas more affected		Cutter et al. (2003)
Demand for public beaches	20 *m*	Higher demand on the beach could affect more people during CSO		
Proximity to CSO discharge points	20 *m*	The proximity to CSO discharge points increases the likelihood of exposure to contaminated water aerosols.		Brokamp et al. (2018)
Social Vulnerability				
% senior population	Census tract	Older people more sensitive health conditions	+	Martínez-Gomariz et al. 2021
% 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	+	Ashbolt et al. 2010, McBride et al. 2013
% of the population who may have problems with language skills and unfamiliarity with the local system	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 et al., 2019, Creese and Wiebe 2012
% of population with income above of the median	Census tract	Higher income people have more means to cope	–	Angerville et al. 2013; Montserrat, 2015;
% 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 cars. Limited financial resources could hinder their ability to address health issues arising from water, have fewer resources to cope	+	Passerat et al., 2011; Miller, Ebelt, and Levy 2022
% of the 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 cars. Limited financial resources could hinder their ability to address health issues arising from water, have fewer resources to cope, rely on government support	+	
Ecological Vulnerability				
Ecological connectivity	20 *m*	A measure of the quality of ecosystems, influencing their ability to retain water and mitigate runoff.	–	Passerat et al. 2011
Functional biodiversity	30 *m*	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 CSO	–	Passerat et al. 2011
% of green area	30 *m*	Higher ability to retain rainwater and reduces peak flow	–	Fahy and Chang 2019
Technological Vulnerability				
Impervious surface	20 *m*	Impervious surface area increases direct runoff	+	Palla et al., 2015
Deficit of sewer capacity	20 *m*	Deficit leads to higher chances of the overflow and reaching capacity of the sewer system	+	
Slope greater than 20 %	20 *m*	Influences its collection efficiency	+	Pratt and Chang 2012

vulnerability and exposure factors in the final risk assessment. The resulting risk score maps provide a spatially explicit representation of the CSO and pluvial flood risk, offering valuable insights into the overall risk landscape associated with water-related hazards domains (All detailed explanation and formulas used could be found in Appendix C).

3.4. Geospatial analysis

QGIS 3.32 was utilized to integrate each indicator layer, generating maps for SETS vulnerabilities. The vulnerability scores were categorized and displayed using quartiles. To determine which census block groups exhibited vulnerability in one or more of the SETS domains, we overlaid all possible combinations of the top quartile vulnerability maps for each domain (S, E, and T). This approach allowed us to classify the vulnerable areas into seven distinct categories (i.e., S, E, T, S-E, S-T, E-T, and S-E-T), which we then mapped accordingly.

3.5. Statistical analysis

Spatial correlation was conducted to explore the relationship between SETS vulnerabilities, exposure, and hazard indicators using the normalized values of each index in ArcGIS Pro 3.2, employing the Multiscale Geographically Weighted Regression (MGWR) tool. The MGWR tool constructed a local linear regression model by applying weighted regression to each spatial feature and its neighbors. The hazard indices were used as dependent variables. Statistical tools like MGWR can identify significant patterns and spatial dependencies that may not be apparent through simple observation of geospatial analysis.

4. Results

4.1. SETS vulnerability

The *social vulnerability* within Barcelona is woven into the fabric of its diverse neighborhoods, each representing a distinct story of economic and demographic disparities. When examining the socio-economic landscape, the results show that vulnerable populations are concentrated in specific areas. Areas characterized by lower income levels, such as Torre Baró (39,40, Fig. 3), el Raval (8, Fig. 3), Zona Franca (19, Fig. 3), el Besòs, el Maresme i Provençals (6, Fig. 3), and Sant Martí (7, Fig. 3) exhibit heightened social vulnerability. The primary focus of *Ecological Vulnerability* reveals characteristics that may influence the retention/detention capacity of ecosystems. This distinct pattern is most pronounced in the highly urbanized areas encompassing almost all of Barcelona city, except for the northern green areas. High population density and imperviousness co-occur in the central areas of the case study area — an indication of the profound impact of urban development on the local ecology. Even green areas such as Park De La Ciutadella (4, Fig. 3), Park Diagonal Mar (5, Fig. 3), and Park Montjuïc (18, Fig. 3), which serve as main green hubs within the area, exhibit low scores in indicators representing the quality of ecosystems as they remain somewhat isolated within highly urbanized areas. For *Technological vulnerability*, a key aspect of our analysis, a notable pattern emerging higher vulnerability is often associated with a combination of

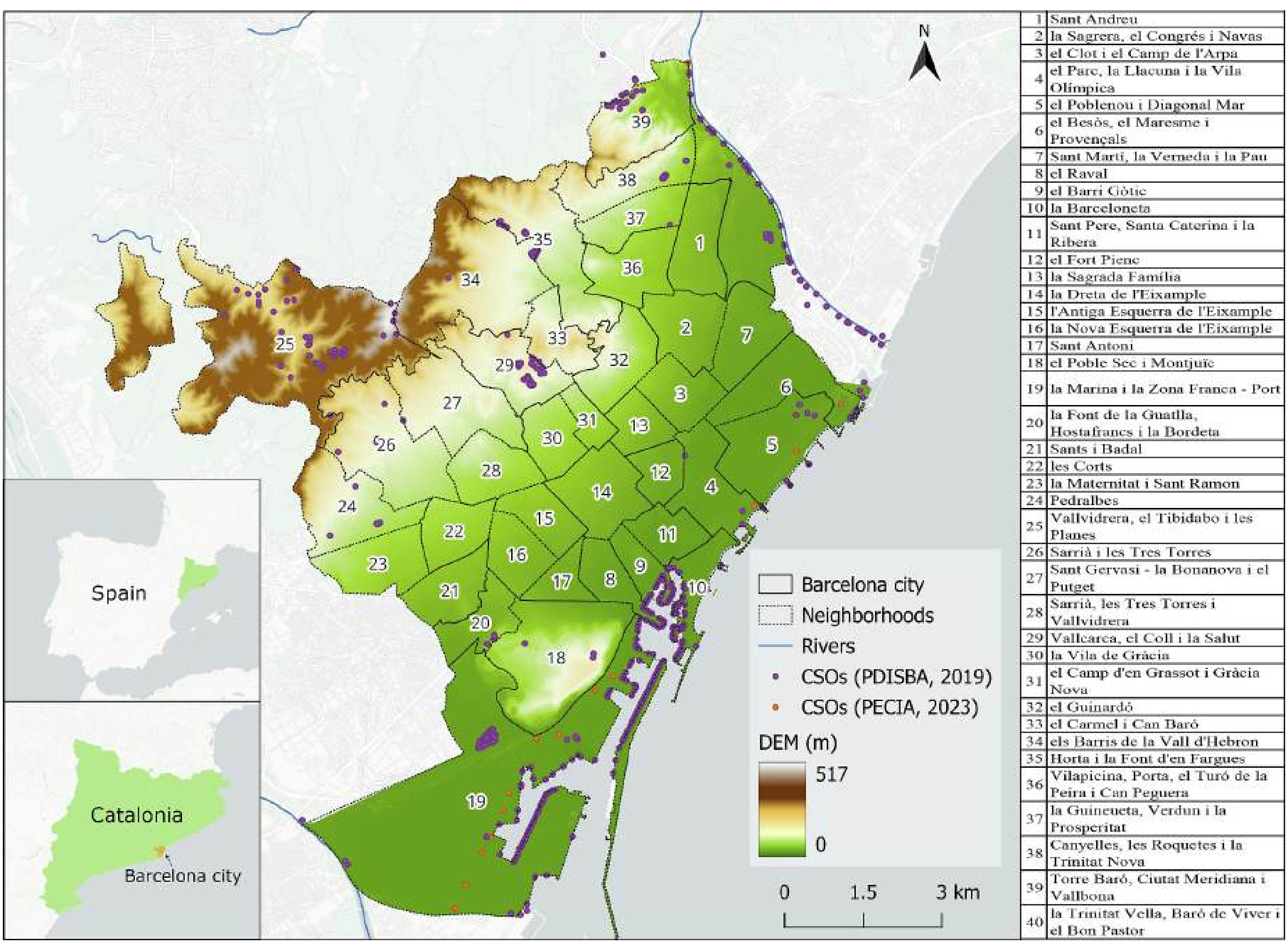

Fig. 3. Topographical and Neighborhood Map of Barcelona City (own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

steeper slopes and extensive impervious urbanized areas. This can be observed for instance in Vallvidrera (25, Fig. 3), Vall d'Hebron (34, Fig. 3) and Horta (35, Fig. 3) situated in the northern region of Barcelona city, as well as in the distinctive landscape of Distrito de Sants-Montjuïc (18, Fig. 3) within Barcelona city. The area of L'Eixample (12, 13, 14, 15, 16, Fig. 3) also received a relatively high score due to the deficit of sewer capacity in the district.

The combination of the SETS Vulnerability Index (Fig. 4) and the top-quartile social, ecological, and technological vulnerability maps (Fig. 5) highlighted unique patterns of vulnerability from a social-ecological-technological perspective. The integration of spatial analysis of SETS vulnerability with the top-quartile SETS vulnerability helps to identify drivers of vulnerability. There are areas with high SETS vulnerability driven by high social vulnerability, such as La Trinitat Vella (40, Fig. 3), characterized by low income, a high percentage of people receiving unemployment benefits, and a significant population over 65 years. Areas dominated by social-technological vulnerability include Torre Baró (39, Fig. 3), which is characterized by low income, a high percentage of people receiving unemployment benefits, and steep slopes. Areas with higher final SETS scores of vulnerabilities driven by social and ecological components include El Besòs and El Maresme i Provençals (6, Fig. 3), Sant Martí (7, Fig. 3), and El Raval (8, Fig. 3). These areas are characterized by a high presence of industrial lands, low income, and little vegetation. Additionally, areas that received higher scores by coupling all three domains—social, ecological, and technological—such as Zona Franca (19, Fig. 3), are characterized by a high presence of impervious industrial lands, low income, a high percentage of people receiving unemployment benefits, little vegetation and deficits in the sewer capacity.

4.2. Integrated risk assessment

In terms of pluvial floods (Fig. 6), the areas receiving the highest risk scores are located in central Barcelona, the southwest area of Eixample (6, 7, Fig. 3), and adjacent areas of El Raval (8, Fig. 3). L'Eixample (12, 13, 14, 15, 16, 17, Fig. 3) exhibits high technological vulnerability due to extensive impervious surfaces and a significant deficit in sewer capacity. L'Eixample has a history of pluvial flood events and high population density. El Raval (8, Fig. 3) is identified as a risk area based on a combination of exposure, hazard, and social-ecological vulnerability. Furthermore, La Bordeta (20, Fig. 3) and Sants (21, Fig. 3) show high risk scores, characterized by high exposure-technological vulnerability and dense population. Examining the statistical analysis (Fig. 7), a significant correlation was observed between the hazard layer and

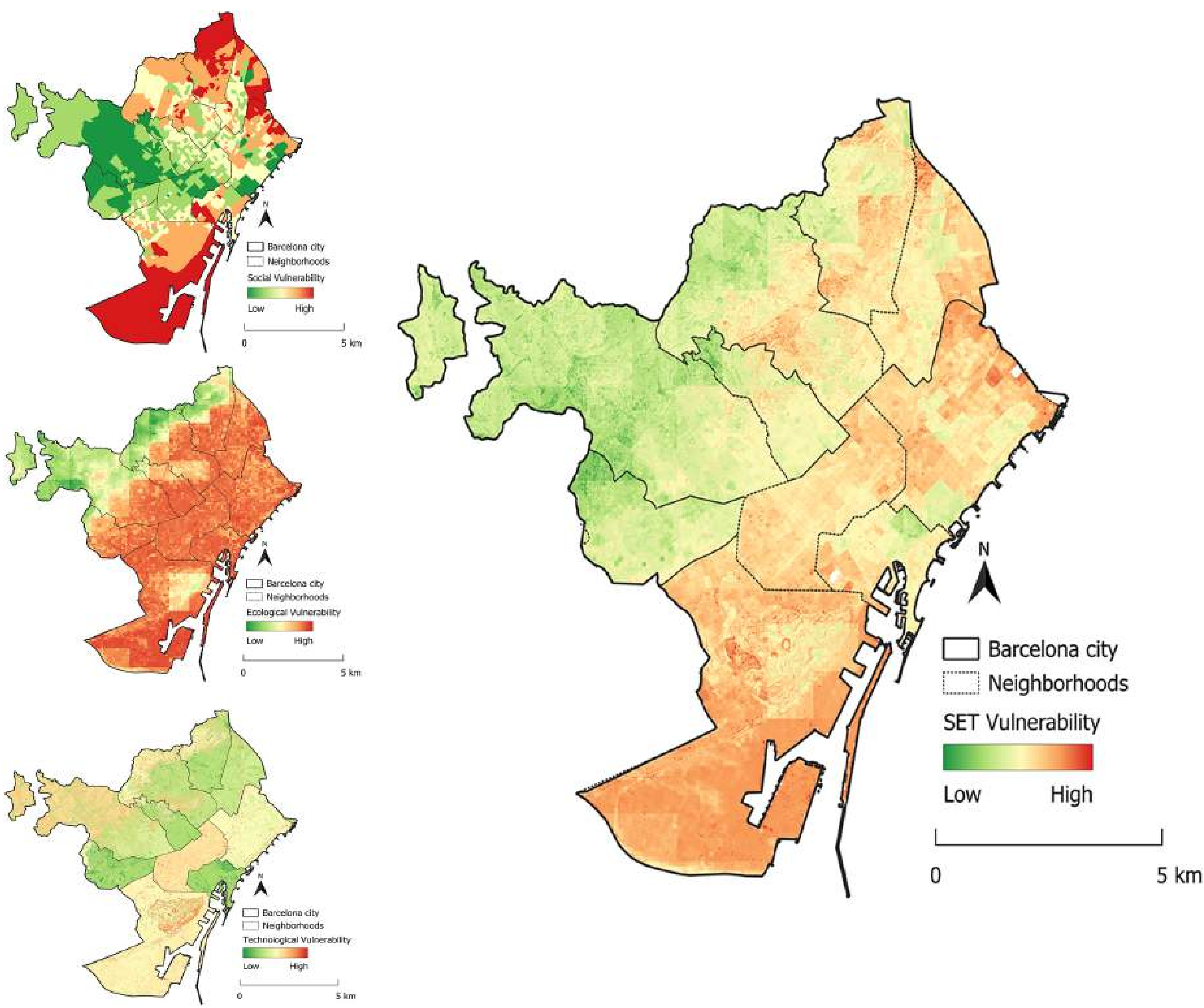

Fig. 4. SETS Vulnerability Index (own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

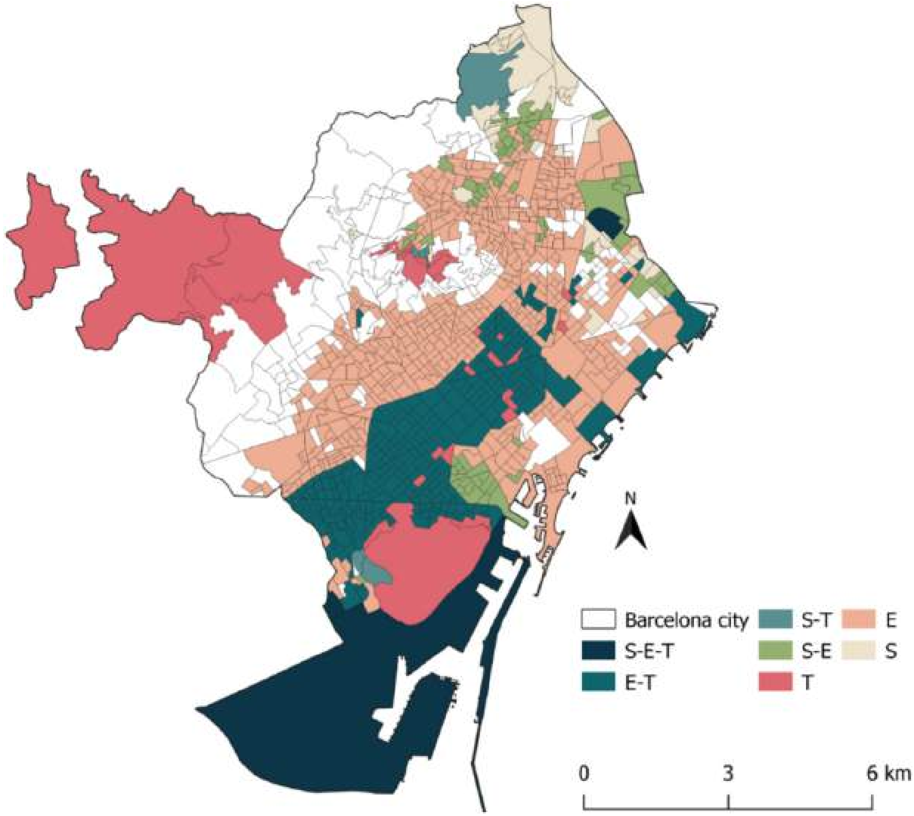

Fig. 5. Combined top-quartile social (S), ecological (E), and technological (T) vulnerability (own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

technological and ecological vulnerabilities. This underscores the importance of factors such as impervious surfaces, limited green spaces, and sewer deficits as potential drivers of pluvial flood events. Additionally, there was a noteworthy correlation between exposure and hazard, indicating a higher incidence of pluvial floods in densely populated areas.

In terms of geospatial analysis, the pattern of combined SETS vulnerability, exposure, and sewer discharge hazard is clustered along the Besòs River (40, Fig. 3) in the northeast part of Barcelona (Fig. 8). This area is characterized by high S-T vulnerability and high exposure. Additionally, the coastal area of Barcelona, including Barceloneta (10, Fig. 3) and some areas of Sant Marti (7, Fig. 3), are affected by CSOs and exhibit relatively high levels of S-E vulnerability. Regarding statistical analysis (Fig. 9), there is a positive correlation between hazard and social vulnerability and a negative correlation between hazard and exposure, ecological and technological vulnerability.

In terms of geospatial analysis, the Risk Index for public beach users highlights populated areas near the coastline (Fig. 10), such as Sant Marti (7, Fig. 2), Barceloneta (10, Fig. 3) and Ciutat Vella (8, 9, 11, Fig. 3). Specifically, within Ciutat Vella, El Raval (8, Fig. 3) exhibits high S-E vulnerability. The northwest area of Sants-Montjuïc (18, Fig. 3) also indicates a concentration of risk hotspots, where there is an overlap between high S-E-T vulnerability, exposure, and relative proximity to public beaches. Regarding statistical analysis (Fig. 11), noticeable positive correlations were identified between exposure and hazard, as well as between hazard and ecological and technological vulnerability. This highlights the presence of hazards in highly populated areas, as well as in areas affected by the dominance of impervious surfaces and limited green spaces.

5. Discussion

5.1. Understanding SETS for urban climate change adaptation

Despite advancements in modeling and assessing climate change impacts on cities, persistent challenges in urban water management research persist. Notably, there is a gap in assessing the impact of climate change on urban water systems using a SETS-based, risk-centric approach (Cortès et al., 2018; Llasat et al., 2022). The application of the SETS-based vulnerability approach for assessing urban water-related risks yields several crucial insights with implications for the local context. Our study reveals that certain areas face heightened risks from water-related hazards and require climate change adaptation measures more urgently, primarily due to the social structure of their population, which enhances their vulnerability. All three hazards under study show a positive linear relationship with social vulnerability in the statistical analysis (Figs. 7, 9, and 11), indicating that disadvantaged groups in Barcelona are more likely to be affected by water-related hazards.

Analyzing the distribution of social vulnerability (Fig. 4), our findings align with recent research on the spatial dynamics of urban inequalities (Checa, 2021; Piasek et al., 2022) as well as assessments conducted by the Institute of Regional and Metropolitan Studies of Barcelona (IERMB). These studies identify Torre Baró (39, 40, Fig. 3), El Raval (8, Fig. 3), Zona Franca (19, Fig. 3), El Besòs and El Maresme i Provençals (6, Fig. 3), and Sant Martí (7, Fig. 3) as among the most socially vulnerable neighborhoods. Social vulnerability in these areas has been linked to factors such as education levels, income, and housing prices. From the perspective of the 'social and employment' dimension of vulnerability—which encompasses both sociodemographic and labor-related variables—Piasek et al. (2022) highlight the neighborhoods of the Sant Martí district (7, Fig. 3), particularly those near the River Besòs (6, Fig. 3), as well as the Gòtic and Raval neighborhoods (8, Fig. 3), as

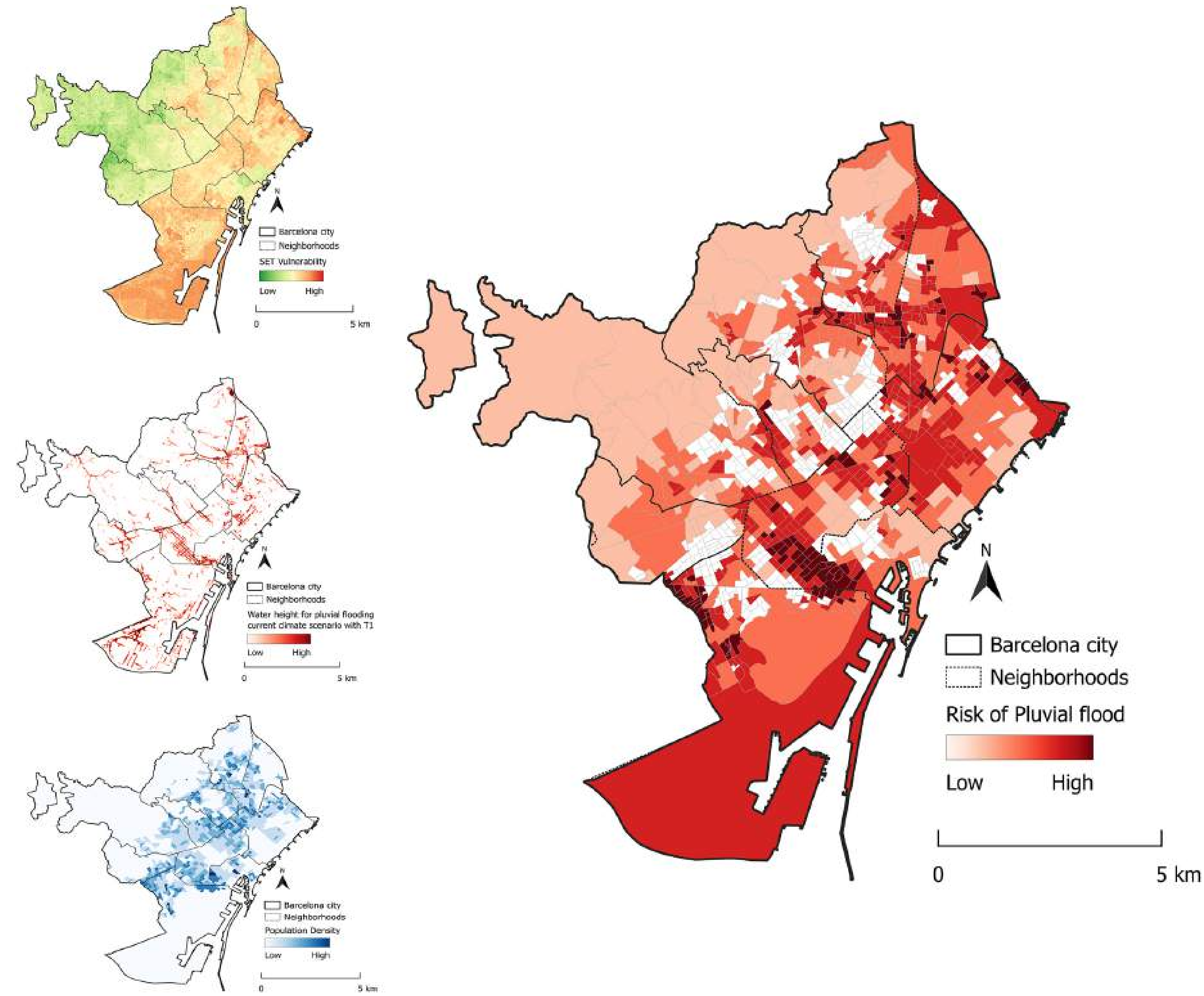

Fig. 6. Risk Index for Pluvial flood at the census block group level (own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

areas of heightened social vulnerability. Social vulnerability in these areas has been linked to the extent of residents' integration into the workforce and civic life, reflecting varying levels of social capital.

While our study showcases that understanding social vulnerability is a necessary condition for more equitable urban climate change adaptation (Cutter, 2016; Pineda-Pinto et al., 2021), it also indicates this social dimension alone is not sufficient to properly understand the underlying factors to mitigate water-related urban risks. Only a limited number of studies have assessed the role of ecological indicators in mitigating flood impacts (Fahy & Chang, 2019). Similarly, most technological vulnerability studies tend to overlook ecological factors (Kim et al., 2017). Urban systems are strongly determined by interwoven and interacting ecological and technological systems components, such as the urban sewer system, and their spatial distribution that mediate the localized risk of climate change related hazards. For example, in some areas of Barcelona, water-related risks are higher due to the influence of various environmental indicators, such as sparse vegetation resulting from compact urban development, which affects water detention and infiltration capacity, leading to higher amounts of runoff. Additionally, technological factors, such as historical patterns of sewer development and the challenges associated with the natural gradient of rainwater movement from topographically higher areas, also contribute to these risks. For instance, concerning pluvial flooding risk, the most significant correlations are observed with technological and ecological vulnerability (Fig. 7).

Additionally, many previous flood vulnerability-based studies have focused on individual SETS domains (Cho & Chang, 2017), which often lack a systematic approach that captures the complex interactions and the influence of various indicators on rainwater-related hazards. Our study especially underscores the importance of the urban drainage system's capacity to efficiently collect rainwater and the utilization of nature-based solutions (NBS) or green infrastructure to mitigate runoff and related risks of flooding and CSO. The existing urban drainage system in Barcelona is characterized by very low renovation rates, averaging 7.2 km or 0.5 % per year (Ortiz et al., 2020). The system is already at its capacity limit, and replacing existing collectors or making splits to expand the network's capacity only moves the problem further downstream (BCASA, 2020). The primary tactic currently used in water management to counter CSOs is to store runoff volume during rain events until both the interceptor and the sewage treatment plant can handle it. However, this option has many disadvantages, such as large capital costs, embodied carbon of the largely concrete structures, and required pumping and upkeep (BCASA, 2020). What was once cutting-edge technology at the emergence of modern cities has now become

Fig. 7. Output of MGMR for Pluvial flood (PopDens-Population density, SV- social vulnerability, EV-ecological vulnerability, TV- technological vulnerability, PluvFlood- pluvial flood with T10 hazard layer, own elaboration using ArcGIS Pro 3.2).

outdated, constituting a major technological lock-in and a barrier to climate change adaptation. Focus should be placed on smart technologies, such as rainwater and stormwater harvesting, decentralized green infrastructure, and real-time monitoring of rainfall events to optimize the performance of the existing infrastructure.

Planning for climate change (CC) adaptation must aim to create more flexible solutions for the future. Insights from this study can inform nature-based solutions (NBS) (E), as well as financial and social support programs (S), hybrid approaches, such as green-gray infrastructures (T-E) and digital alert systems (S-T). Our study suggests prioritizing the integration of NBS (e.g., rain gardens, green roofs, urban wetlands) can enhance the system's capacity to manage stormwater. This will reduce the need for expensive, space-consuming infrastructure expansion and mitigate the risk of CSOs by absorbing and managing runoff more effectively. As shown in many previous studies, green spaces and well-designed and managed NBS demonstrate strong capacities to prevent flooding by runoff mitigation (Hatt et al., 2009; Ortiz et al., 2020; Salata et al., 2022; Alves et al., 2024). Future research should explicitly evaluate the efficacy and feasibility of green spaces and NBS, assessing a comprehensive array of variables such as institutional capacities, existing regulatory frameworks, social accessibility, functional capacity, local climate conditions, and characteristics of the built urban environment. Moreover, to promote the widespread implementation of NBS across both private and public spaces, it is essential to establish supportive policies and incentives. This can be achieved through a combination of regulatory mandates, such as requiring new developments to incorporate green infrastructure, and financial incentives, like subsidies for retrofitting properties with rainwater management systems. These measures will facilitate the integration of NBS into urban planning, ensuring long-term sustainability and resilience against climate-related challenges.

5.2. SETS-based knowledge integration

This study extends earlier endeavors by Chang et al. (2021), who emphasize integrating SETS in resilience planning by advocating for a comprehensive framework that captures the transition trajectory of flood vulnerability management systems and moves away from the current reliance primarily on technological components. The exploration of risk in water management has yet to fully embrace the SETS systems perspective (Chang et al., 2021), hindering our understanding of the extent to which climate change will influence water management and its implications for urban communities. Compared to previous SET flood vulnerability work, our study demonstrates how SETS can bridge gaps in understanding water hazards associated with CSOs, where there is significant fragmentation across different disciplines, particularly regarding the threats posed by CSOs to public health (Brokamp et al., 2018; McBride et al., 2013; Miller et al., 2022; Sojobi & Zayed, 2022), mal-/functioning of aquatic ecosystems (Wang et al., 2013; Angerville et al., 2013), and the modeling of street-drainage system water distribution (Sriwastava, 2018). The novel understanding of wicked urban problems through a SETS perspective has been exemplified through the urban water-system in Barcelona. Barcelona's CSS further emphasizes the need for innovative solutions. Like many other European and American cities, this infrastructure is reaching its capacity, increasing the risks of CSOs, which pose significant ecological and economic consequences.

The water-related risk assessment in Barcelona underscores the importance of recognizing a broader range of factors that shape vulnerability and reinforce the relevance and applicability of the SETS approach. Barcelona, a Mediterranean coastal city with significant urbanization in flood-prone areas and high population density, is increasingly exposed to flood risks due to climate change. These developments underscore the urgent need for a comprehensive, integrated approach to flood risk management, which reduces hazards in one domain while mitigating vulnerabilities in another. For instance, cities can strategically develop green spaces to improve social capital in economically disadvantaged areas, thereby promoting equity and mitigating displacement risks during ecological improvements. We assume that the additional lessons that can be learned from a SETS approach are not unique to urban water related risks but could be scaled towards understanding other climate change-related risks and adaptation needs in cities, making it a valuable tool for urban adaptation planning and management in the face of increasingly complex environmental

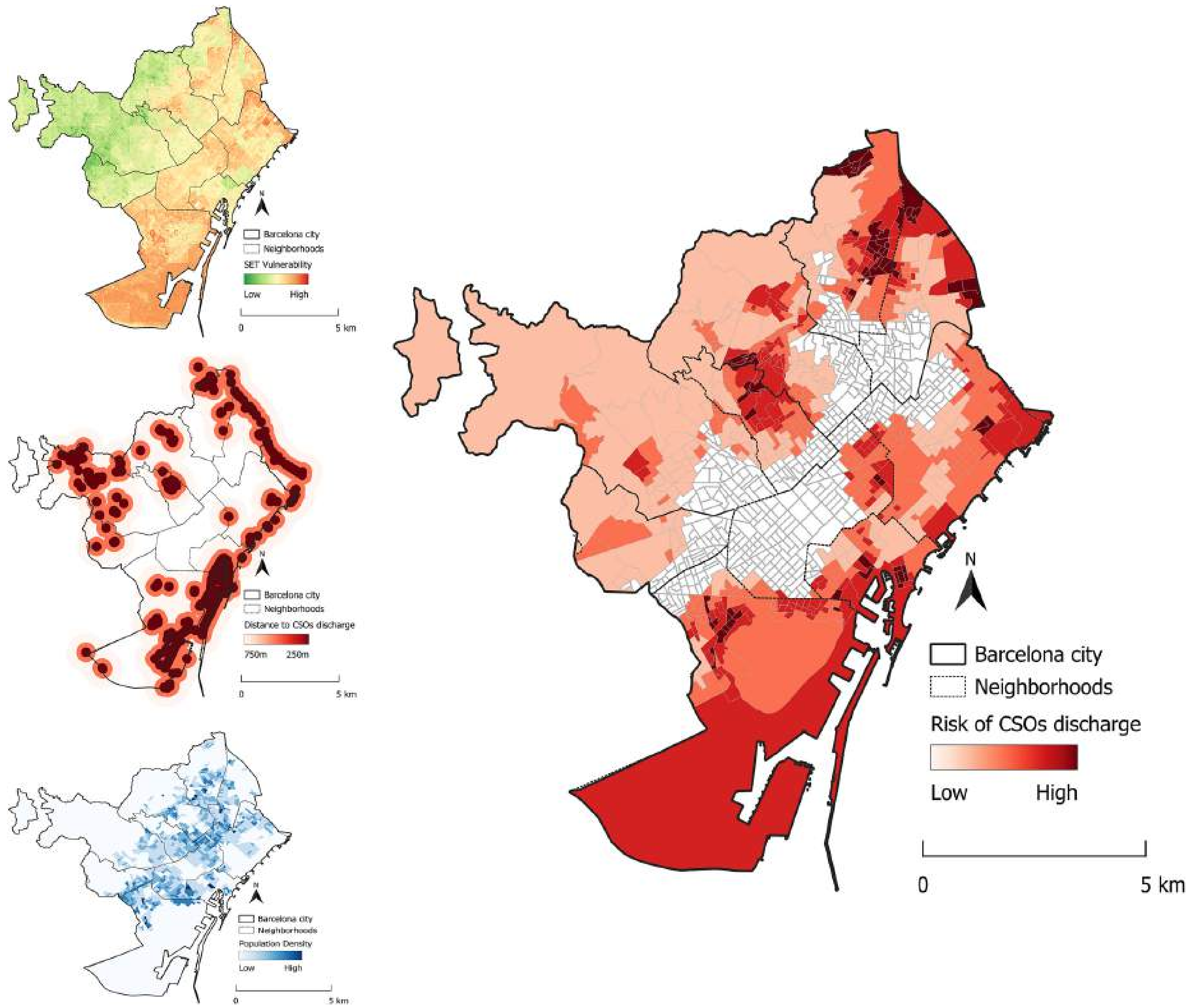

Fig. 8. Risk Index for CSOs discharge at the census block group level (own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

challenges (McPhearson et al., 2016; Chang et al., 2021). A valuable next step for future research in risk assessment would be to expand the SETS framework to incorporate exposure, as well as to account for varying frequencies and magnitudes of hazard events. Additionally, extending the study beyond a single-city approach and testing the conceptual framework and methodology in different climatic and urban contexts would contribute to improving its universality and applicability.

5.3. Need for future SETS collaborations

The SETS approach to modeling urban water-related risks is useful in identifying communities most at risk, but it has also highlighted future collaboration needs to include additional knowledge across multiple domains. Expanding social indicators to identify the drivers of social vulnerability and assessing how different socially disadvantaged groups will face hazards presents a significant avenue for further work. The lack of stakeholder perspectives in assessing vulnerability indicators and their relative importance is crucial to emphasize. While our approach contributes to this understanding by including social indicators into analysis, it falls short of fully aligning with ambitious goals for social justice aimed at ensuring equitable benefits. A stronger emphasis on distributive aspects and participatory processes in collaboration with local stakeholders is strongly recommended for future research. It is imperative to seek and heed the voices of different stakeholders and integrate these varied viewpoints into resilience planning initiatives. The urban SETS water-related risk framework provides a platform for engaging diverse stakeholders in the co-production of knowledge aimed at enhancing water-related hazard resilience amidst changing social and climatic conditions. A more collaborative effort would help ensure the sustainability of equitable economic investments in infrastructure and technological systems, which are pivotal for reducing risk of water-related hazards and enhancing resilience in both ecosystems and communities.

Furthermore, where social and ecological data were generally accessible in our study, access to technological data, especially concerning urban water systems, represented a significant barrier to the integrated SETS assessment. One notable technical limitation arises from the difficulty in accurately mapping the distribution of contaminated water, which complicates precise risk assessments. This complexity is further compounded when attempting to model spatial dynamics, underscoring the urgency for improved methodologies to

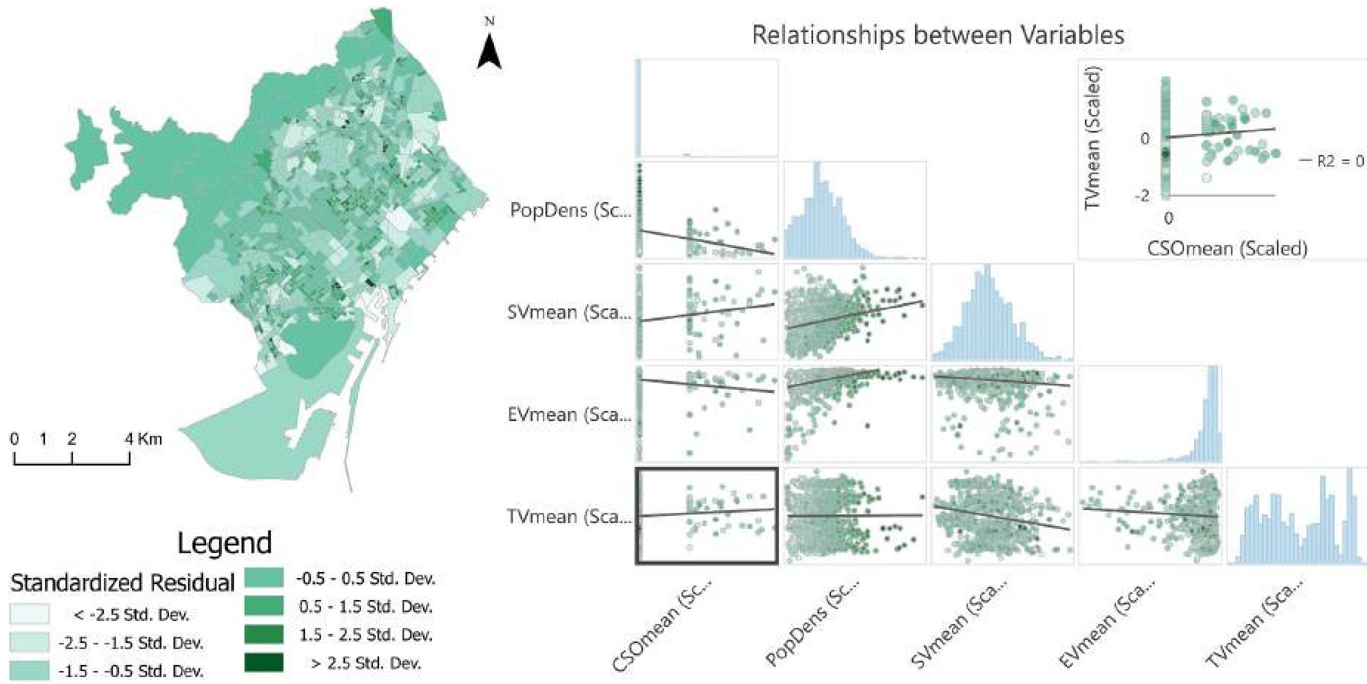

Fig. 9. Output of MGMR for CSOs discharge (PopDens-Population density, SV- social vulnerability, EV-ecological vulnerability, TV- technological vulnerability, CsoBuf- CSOs hazard layer; own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

manage rainwater movement in intricate terrains and interactions within sewer systems on municipal level. The issue of limited accessibility to technological indicators, particularly information concerning sewer and drainage systems, poses a significant challenge, necessitating time-intensive and costly collaborations with public or private institutions. The lack of publicly available data on the technological domain of urban water systems is not limited to the Barcelona case study but constitutes a critical issue observed globally (Rosenzweig et al., 2021). New collaborative data pooling initiatives and open data policies – already widely established in the social and ecological domain – would enable independent analysis of urban water risks and the timely development of necessary climate change adaptation measures.

An additional approach to overcoming technical limitations and data accessibility challenges lies in the emergence of high-resolution datasets, which present new opportunities for enhancing risk assessments in the broader context of climate change. For instance, high-resolution soil moisture data (e.g., Lal et al., 2023) can improve flood forecasting through data assimilation techniques (Wanders et al., 2014). Similarly, high-resolution global gridded population data (e.g., Lloyd, Sorichetta, and Tatem, 2017) and global urban change datasets (e.g., Liu et al., 2020) could contribute to more comprehensive risk assessments. Integrating these datasets into climate risk models can improve predictive accuracy and support evidence-based decision-making for urban resilience planning.

5.4. Risk index validation

The assessment of urban flood resilience conducted by Russo et al. (2020) projected that the highest risk scores for a 10-year storm event were concentrated in central Barcelona, particularly in the southwest area of L'Eixample (12, 13, 14, 15, 16, 17, Fig. 3), as well as adjacent areas of El Raval (8, Fig. 3), La Bordeta (20, Fig. 3), and El Turó de la Peira (36, Fig. 3). These areas were identified as having significant risks for both pedestrians and vehicles. Furthermore, the study by Russo et al. (2015) validated a calibrated 1D/2D coupled model using output from the rain event of July 30, 2011. The model results were compared with post-event emergency reports from police and firefighters, as well as amateur videos and photographs recorded during the storm. Notable flooding was documented along Diagonal Avenue, Casanova Street in L'Eixample (12, 13, 14, 15, 16, 17, Fig. 3), and Sant Pau Street in El Raval (8, Fig. 3). Additionally, news reports and videos from September and October 2018, published on Betevé and RTVE webpages, confirmed flooding incidents in El Raval (8, Fig. 3) and L'Eixample (12, 13, 14, 15, 16, 17, Fig. 3). The alignment between these previously documented flood-prone areas and the risk index obtained in this study (Fig. 6) further reinforces the reliability of findings.

6. Conclusion

The risk assessment presented in this paper combines the vital components of risk into one framework at the metropolitan area level, confirming that risk can be analyzed as a function of SETS vulnerability, exposure, and hazard experienced by the urban system. Analyzing the composition of SETS vulnerability in the urban water system of Barcelona allowed us to uncover the principal factors determining water-related risks caused by pluvial flooding and CSOs under different exposure factors.

The first major insight is that social vulnerability is the primary driver of water-related risks in Barcelona, underscoring the disproportionate impacts of water hazards on vulnerable communities. However, the ecological and technological domains also play crucial roles in shaping future risk reduction strategies. Specifically, overcoming technological lock-ins in the sewer system and leveraging the potential of green infrastructure to mitigate runoff are essential for reducing future flood risks and enhancing resilience.

Second, by carefully assessing the local contexts that shape water-related risks, our findings contribute to the development of effective risk management strategies. This highlights the need for approaches that not only address the technical aspects of water management but also tackle socio-economic disparities in vulnerability. Our findings underscore the disproportionate impact of water-related hazards on socially vulnerable communities. This aligns with broader discussions on environmental justice, emphasizing the unequal distribution of risks and vulnerabilities across different socio-economic groups. Moving forward,

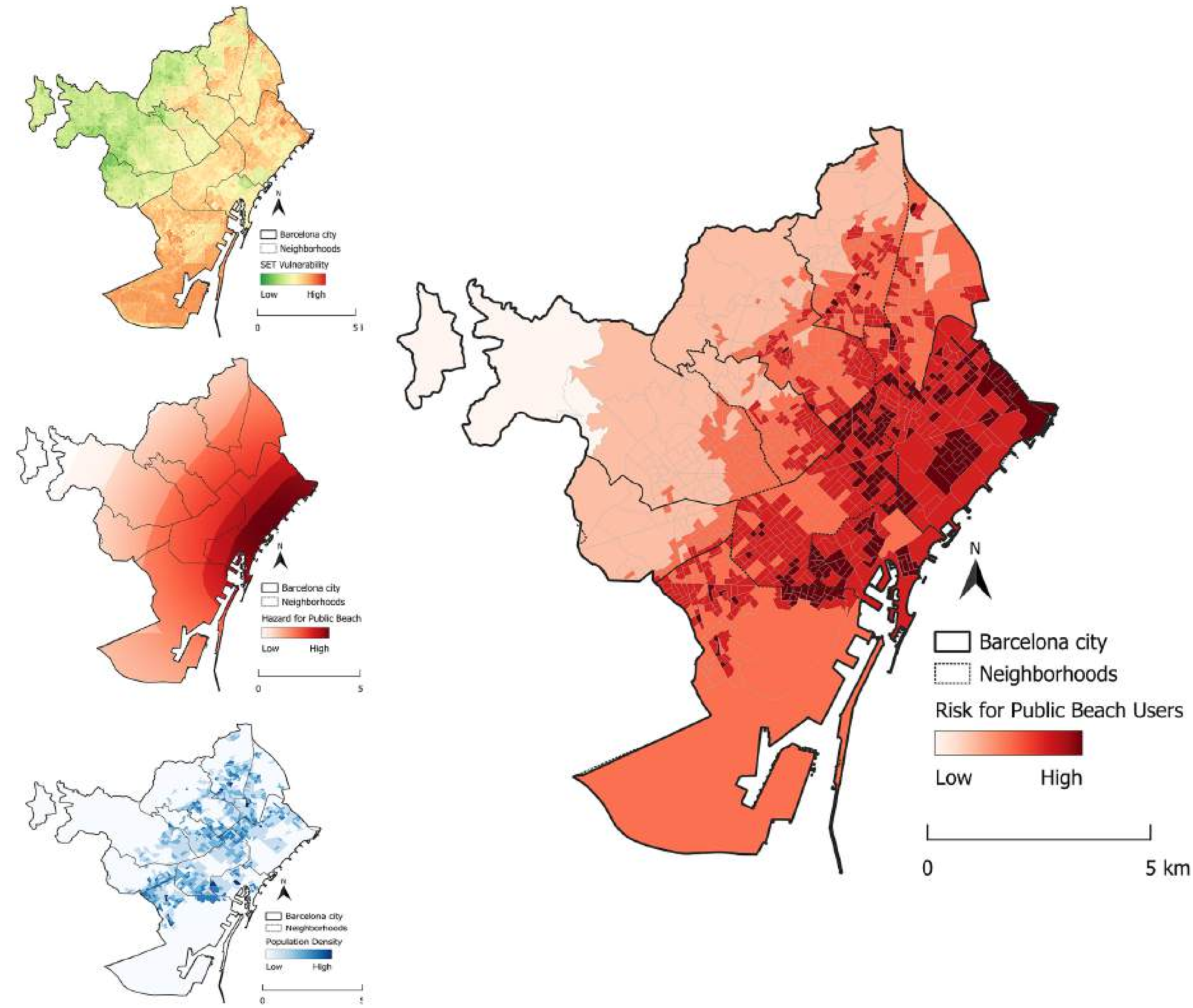

Fig. 10. Risk Index for Public Beaches Users at the census block group level (own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

addressing these disparities requires integrated approaches that not only enhance resilience but also promote equity in urban climate adaptation strategies. To strive towards this, a suitable risk analysis is needed, an example of which is presented in this article.

Finally, our research reinforces the importance of collaborative efforts in shaping future urban resilience. On the one hand side, this should involve explicit engagement with local stakeholders, including community members, for instance in the assignment of weights to evaluation criteria, ensuring that diverse perspectives are incorporated into future resilience planning endeavors. On the other hand, the study highlights significant barriers, particularly the limited public accessibility to technological data on urban water systems, which impedes comprehensive risk assessments and adaptation planning, necessitating stronger inclusion of data holders and efforts to dismantle technology-data monopolies.

7. Policy recommendations

Based on the findings of this study, we recommend that urban climate adaptation strategies in Barcelona and similar cities address risk posed by stormwater related hazards like pluvial flood and CSO. Key policy measures should include:

Improving Social Equity in Climate Adaptation: Policies should specifically target vulnerable communities, ensuring that adaptation measures address social disparities. This includes enhancing social capital in economically disadvantaged areas by developing green spaces and providing financial support for climate-resilient infrastructure.

Modernizing Urban Water Systems: Urban water infrastructure, particularly the sewer systems, should be renovated to overcome technological lock-ins that hinder effective climate change adaptation. Investment in smart technologies like decentralized rainwater harvesting systems and real-time monitoring of rainfall events is essential for optimizing the existing infrastructure and reducing future risks.

Strengthening Data Availability and Collaboration: Efforts should be made to improve access to technological data, particularly concerning urban water systems, to facilitate comprehensive risk assessments and the development of climate adaptation strategies. Collaborative data pooling and open data policies, similar to those in the social and ecological domains, can enhance independent analysis and the timely development of adaptation measures.

Investing in Green Infrastructure: Prioritize the integration of NBS such as rain gardens, green roofs, and urban wetlands to enhance the

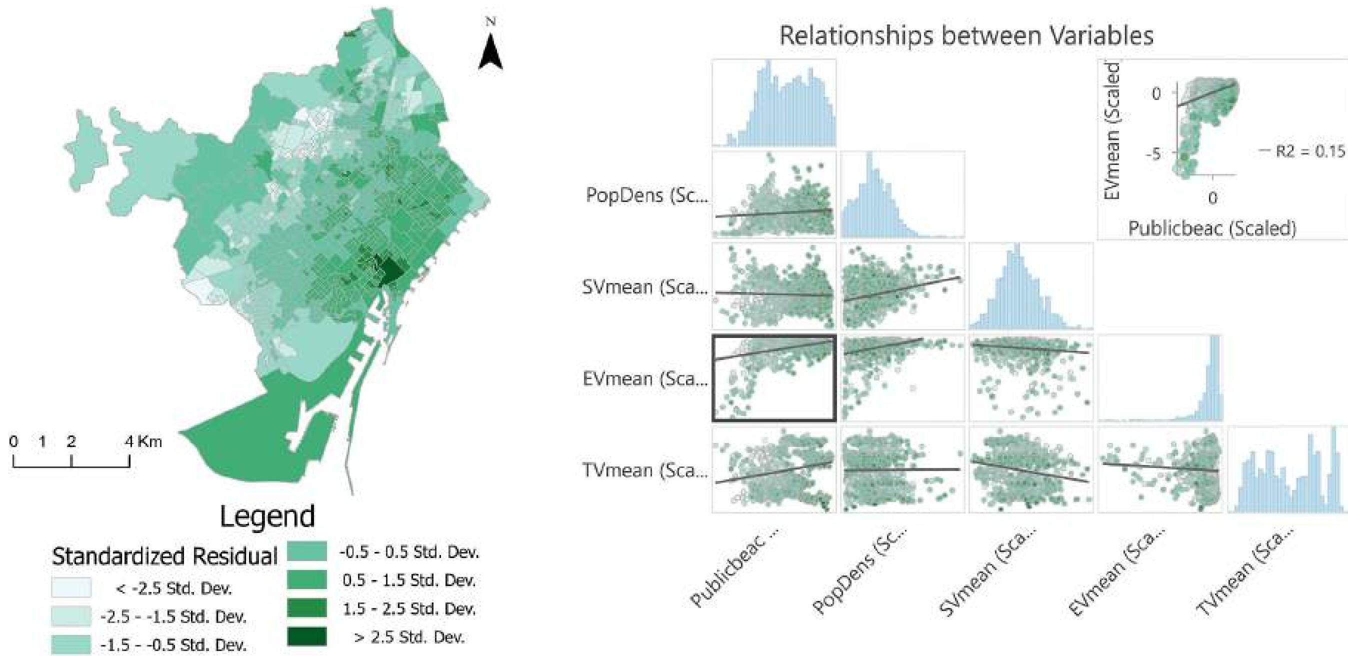

Fig. 11. Output of MGMR for Public Beaches Users (PopDens-Population density, SV- social vulnerability, EV-ecological vulnerability, TV- technological vulnerability, ExPuBea- public beach users hazard layer; own elaboration using ArcGIS Pro 3.2 and open-source data explained in Appendix A).

urban drainage system's capacity, reduce flood risks, and mitigate Combined Sewer Overflow (CSO) occurrences. These solutions can reduce the need for expensive, space-consuming infrastructure expansions and provide long-term resilience against stormwater management challenges.

8. Glossary

- Nature-based solutions – solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. (European Commission)
- Pluvial Flooding – inundation of land by rainfall runoff that exceeds the capacity of natural or engineered drainage systems to manage it effectively. Unlike river or coastal flooding, which involves water bodies exceeding their banks, pluvial flooding occurs when intense rainfall overwhelms urban drainage systems, leading to water pooling or flowing overland. This type of flooding is common in urban areas with impermeable surfaces like roads and buildings, where rainfall cannot infiltrate into the ground quickly enough (Falconer et al., 2009).
- Combined Sewer Overflow (CSO) – discharge of untreated or partially treated sewage and stormwater from a combined sewer system into nearby water bodies during periods of heavy rainfall or snowmelt. Combined sewer systems collect both sanitary sewage (from toilets, sinks, etc.) and stormwater runoff in the same pipe network. During heavy precipitation, the volume of water entering these combined sewers can exceed their capacity, leading to a release of untreated sewage and stormwater mixture, often to prevent backups into buildings or streets. CSOs can introduce pollutants, pathogens, and other contaminants into water bodies, posing environmental and public health risks (US EPA, 2023).
- Hazard – potential occurrence of physical events, whether natural or human-induced, capable of causing adverse effects such as loss of life, injury, or other impacts on health or the environment (IPCC, 2012).
- Exposure – presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by hazards (IPCC, 2012).
- Vulnerability – propensity or predisposition to experience adverse hazards, encompassing a spectrum of concepts and elements. These include sensitivity or susceptibility to harm, alongside a lack in capacity to effectively cope with and adapt. The vulnerability of human, technological and natural systems when exposed to hazards is a critical aspect in literature, independently and as a component of risk assessment (IPCC, 2012).

CRediT authorship contribution statement

S. Khromova: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **G. Villalba Méndez:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **M.J. Eckelman:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **P. Herreros-Cantis:** Writing – review & editing, Methodology, Conceptualization. **J. Langemeyer:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113334.

Data availability

Data will be made available on request.

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