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# Nature-Based Solutions for Flood Mitigation: The Case Study of Kochi

**Arun Antony Aloscious , Mario Artuso and Sara Torabi Moghadam ***

Interuniversity Department of Territorial Sciences, Projects and Policies, Polytechnic of Turin, 10125 Turin, Italy; s301993@studenti.polito.it (A.A.A.); mario.artuso@polito.it (M.A.)
* Correspondence: sara.torabi@polito.it

**Abstract:** Flood risks are escalating globally due to unplanned urban expansion and the impacts of climate change, posing significant challenges for urban areas and necessitating effective mitigation strategies. Nature-based solutions (NBSs) have emerged as innovative and sustainable approaches for managing flood risks. The International Union for Conservation of Nature (IUCN) defines NBSs as actions that conserve, manage, and restore natural and modified ecosystems to address societal concerns while benefiting both people and the environment. This research focuses on developing NBS strategies for the most flood-prone area within Kochi, a city highly vulnerable to flooding. The study begins with a comprehensive site examination to identify flood sources and causes in Kochi, aiding in selecting flood vulnerability indicators. An analytical framework incorporating flood risk assessment and exposure studies using physical and social indicators, alongside GIS mapping techniques, revealed that approximately half of Kochi is affected. The study identified key vulnerability hotspots, particularly within the Central Business District (CBD), where high population density and inadequate infrastructure exacerbate flood risks. Proposed NBS interventions include restoring natural floodplains, enhancing canal capacities, creating urban forests, and establishing green infrastructure like permeable pavements and rainwater harvesting systems. Key findings emphasize the effectiveness of integrating NBSs with traditional flood management strategies, forming a mixed flood control system. These interventions mitigate flood risks, improve biodiversity, reduce the urban heat island effect, and enhance community well-being. Importantly, the research underscores the role of public participation and community-driven maintenance plans in ensuring the sustainability of NBS interventions. Aligning these strategies with Kochi's Master Plan 2040 ensures coherence with broader urban planning and climate resilience goals. The research anticipates changes in climate, land use patterns, and urban dynamics to inform NBS suitability in Kochi. Ultimately, the research demonstrates how implementing NBSs can deliver a range of socio-environmental benefits, significantly influencing urban development in vulnerable zones. By advocating for the integration of NBSs into urban infrastructure planning, this study offers a blueprint for resilient and sustainable flood management strategies that are applicable to other coastal cities facing similar challenges.

**Keywords:** flood resilience; nature-based solutions (NBS); urban infrastructure management; climate change adaptation; sustainable development; urbanization; climate resilience; SWOT analysis

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Academic Editor: Andrzej Walega

Received: 25 November 2024
Revised: 7 February 2025
Accepted: 19 February 2025
Published: 25 February 2025

**Citation:** Aloscious, A.A.; Artuso, M.; Torabi Moghadam, S. Nature-Based Solutions for Flood Mitigation: The Case Study of Kochi. *Sustainability* **2025**, *17*, 1983. https://doi.org/10.3390/su17051983



## 1. Introduction

Over the past few decades, the issue of climate change and extreme weather events has been a matter of great concern globally [1]. In 2024, natural disasters and severe weather events caused $417 billion in global economic losses, with $154 billion covered by insurers, marking the hottest year on record since 1850 and highlighting the escalating impact of climate change on extreme weather events [2]. Urban flooding has emerged as a major global concern, causing economic damages totalling $451 billion over the past two years alone [3]. The United Nations Office for Disaster Risk Reduction reported that >2 billion people were affected by floods between 1998 and 2017, constituting 45% of the global population affected by meteorological disasters [4]. South Asia, especially India, with its diverse geography, dense population, and intricate socio-economic fabric, is highly susceptible to the changing climate [5]. With India's extensive coastline spanning between 8° N and 37° N latitudes, it experiences significant impacts of climate change [6]. The aftermath of these changes has brought about a profound transformation in India's environmental, socio-economic, and urban landscapes [5]. According to the Intergovernmental Panel on Climate Change (IPCC), global sea levels have risen at an average rate of about 3.3 mm per year since 1993 with contributions from melting ice sheets and glaciers [7]. This surge severely threatens India's coastal regions, including large cities that house millions of people. Extreme precipitation events have increased considerably recently [8,9] and extreme one-day rainfall events in parts of India have increased by four times over the last four decades due to the effects of climate change [10]. The Indian Meteorological Department (IMD) has documented a growing trend in heavy rainfall incidents and extreme precipitation [11]. These intense rainfall events have direct consequences, including flash floods, riverine flooding, and landslides, leading to extensive destruction of residential areas, agricultural lands, and critical infrastructure throughout the nation [12]. Each year, flooding in India from extreme rains results in a loss of around $3 billion, which constitutes about 10% of global economic losses [13]. Twenty-three out of thirty-two states/union territories in the country are subject to floods, and 40 m ha of land, roughly one-eighth of the country's geographical area, is prone to flooding [14]. The research focuses on the city of Kochi, in Kerala State, India, which is challenged by continuous urban flooding intensifying each year coupled with climate change [15]. The 2018 and 2019 floods caused the maximum destruction and stood out as the most significant natural disasters in the region's recent history. The state faced the worst floods in the century due to above-normal rainfall from June to August 2018 [16]. Floods frequently inundate farmlands, pour into households [17], and cause direct quantifiable losses, including affected human resources and damage to buildings, infrastructure, and natural resources [16].

With Kochi's intricate network of 44 rivers, their tributaries and distributaries, around 48 backwaters, and countless numbers of ponds, streams, and rivulets [18], the city is now more vulnerable to the hazards and impacts brought on by climate change [19] and experiencing cloud bursts, cyclone-caused urban floods, and tidal water intrusion [20,21]. The city of Kochi lies barely 5 m above sea level and has a coastline of 48 km [22]. Over the past decade, the rise in sea level has, among others, led to growing concerns about climate change's impact on Kochi [23]. Consequently, the local self-governing (LSG) bodies are exploring options to transform Kochi into a sponge city model to overcome flooding and the relative challenges caused by climate change [24]. "At the recently concluded National Urban Conclave, the Greater Cochin Development Authority (GCDA) presented a master plan for the future expansion of Kochi. As per the new plans, a sponge city has been envisioned for Kochi's city center for better water conservation and to improve the city's ecological balance" [25]. The concept of a sponge city means constructing a new urban area model for flood management and strengthening ecological infrastructure and drain networks [26]. It is discussed in the proposed Master Plan of Kochi Municipal Corporation 2040 that the implementation of nature-based solutions (NBSs) could provide useful insights for utilizing natural elements to improve resilience against flooding [24].

Based on the above observations, the primary goal of the research is to identify and discuss the potential of nature-based solutions for flood mitigation in Kochi's urban ecosystem.

The research started with the question, "How can the strategic implementation of nature-based solutions mitigate flooding risks in the vulnerability peaks of Kochi, and what are the key socio-environmental factors influencing the effectiveness and adoption of these solutions?" The question points to a direct challenge that the city is facing and, to answer the question (results), three objectives were developed; (i) analyze the impact of climate change and the necessity of implementing nature-based solutions, (ii) identify critically vulnerable regions in the study area based on intrinsic vulnerability characteristics, and (iii) assess and identify suitable approaches for incorporating nature-based solutions and recommend planning interventions for flood-resilient spatial growth development.

## 2. Materials and Methods

### *2.1. Methodology Framework*

The methodology framework is divided into three distinct phases, each designed to guide the research from inception to completion: (i) preliminary study, (ii) assessment, and (iii) recommendations. Phase 1 (preliminary study) began with a detailed survey of the background conditions and challenges within Kochi's urban ecosystem to determine the optimal scenarios for implementing nature-based solutions (NBSs). Various global definitions and guidelines of NBSs from organizations such as the International Union for Conservation of Nature (IUCN) [27], the European Union [28], and the Organization for Economic Co-operation and Development (OECD) [29] were examined, along with different classification approaches used worldwide. The preliminary study concluded with a municipality-led investigation into flooding and climate change, framing the need for NBS assessment in Kochi. Flood scenarios in the study area were analyzed in detail, employing SWOT analysis to identify strengths, weaknesses, opportunities, and threats regarding NBS usage for flood mitigation. This hierarchical study approach encompassed two delineated site levels: the macro level (Kochi Municipal Corporation) and the micro level (functional zones within Kochi Municipal Corporation). The analysis, studies, and evaluations were based on scientific sources, including monographic and documentary references, and direct investigations facilitated by the authors in Kochi, conducted through interviews with local public officials. These investigations built upon the preliminary study, providing diverse perspectives and frameworks that supported the next steps of the research. Secondly, Phase 2 (assessment) was the flood vulnerability assessment derived from an analytical overview method of flood risk analysis and a flood exposure study. This assessment utilized multiple geospatial datasets, including LANDSAT 8 imagery, Shuttle Radar Topography Mission (SRTM) data, Climate Research Unit (CRU) precipitation data, and Corporation maps. These datasets were processed to extract critical parameters such as land use, elevation, stream density, and precipitation distribution. Flood risk analysis maps were developed using the software "ArcMap 10.8.2" and the flood exposure study maps were collected from the Master Plan of Kochi Municipal Corporation 2040 [24]. The risk map development involved vectorization and raster data conversion, followed by the selection of key risk indicators such as land use land cover, elevation, stream density, distance from water bodies, slope, and rainfall. A weighted raster overlay method was applied to perform the flood risk analysis, and the results were further reclassified into risk categories using natural break (Jenks) intervals. The final risk analysis included four reclassification categories, low, moderate, high, and very high, based on reclassified indicator values. Next, in line with our hierarchical order selection, the most impacted functional zone was selected using the analytical overview method of the generated risk analysis map and collected exposure study maps. Finally, Phase 3 (recommendations) was the final part and was the continuation of the assessment. To recommend different IUCN NBS approaches [27], the local environment and existing municipal urban policies were considered for the city of Kochi. This outline focused on determining the affected area's vulnerability to flooding and outlining viable flood resilience solutions. Identifying various projects to support implementations in the most affected zones with the help of the proposed master plan and land use plan automatically add sustainability and feasibility to the findings. Figure 1 shows the detailed research methodological framework and the scale of which the phases were performed.

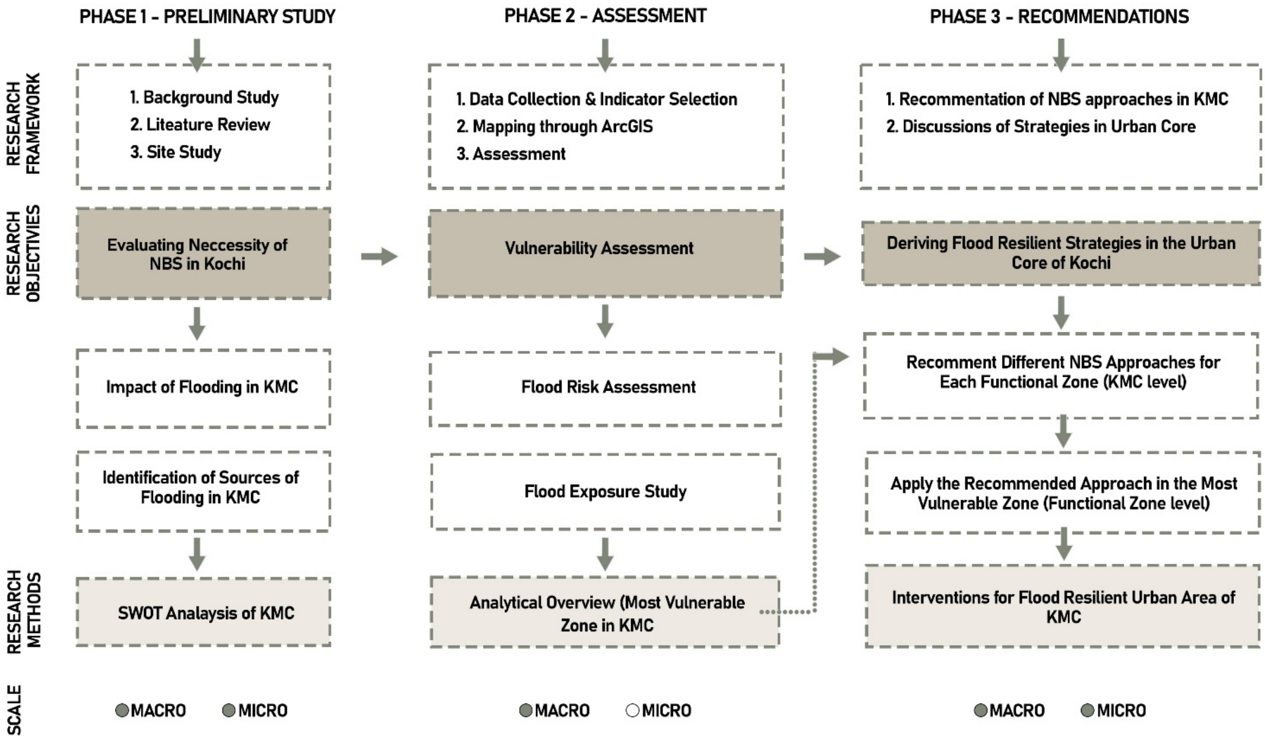



**Figure 1.** Methodological framework of the research; Abbreviation: KMC—Kochi Municipal Corporation (Source: Author).

### 2.2. Case Study

Geographically, Kochi lies on the southwest coast [30] and is the third largest city after Mumbai and Surat on the western coast of India [31]. Kochi (Cochin) is a versatile city, an emerging bustling cosmopolitan, and the commercial capital of Kerala [32]. It is bounded by the Arabian Sea on the west, and its eastern regions are largely urbanized [33]. The average altitude toward the eastern side is 7.5 m above mean sea level (MSL) and less than one meter to the west [33]. It is one of India's most prominent coastal cities, featuring a major port and harbor [34]. Additionally, Kochi's proximity to various natural water bodies and the presence of Willingdon Island [35] at its heart further defines its geographic identity. It is situated in the estuary formed at the mouth of Vembanad Lagoon in the south of Kerala [32]. Figure 2 shows Kochi's location relative to India, Kerala, and Ernakulam.

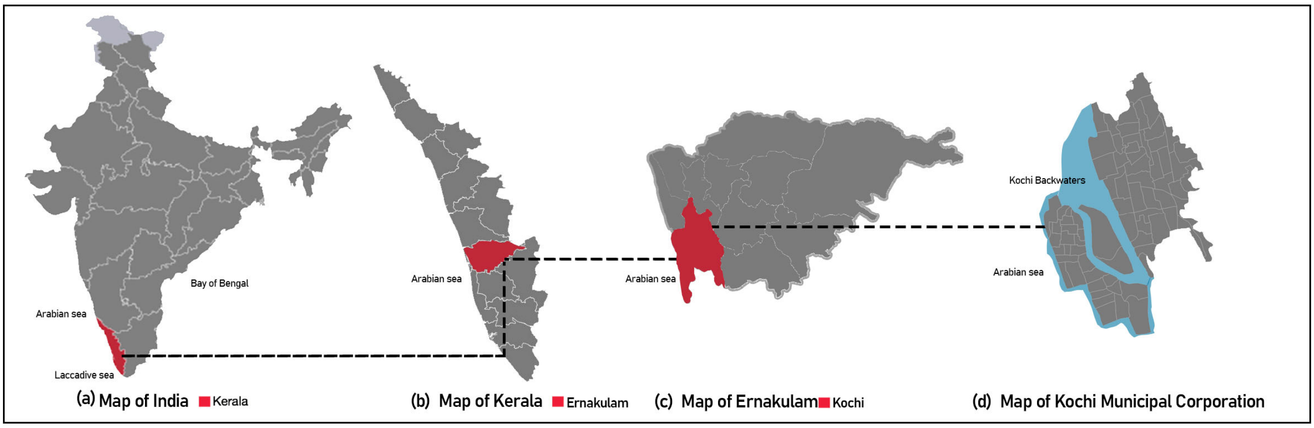



**Figure 2.** Location map of Kochi Municipal Corporation: (**a**) map of country of India, (**b**) map of state of Kerala, (**c**) map of district of Ernakulam, and (**d**) map of study area—Kochi Municipal Corporation (Source: Author).

The city of Kochi is also part of the Greater Cochin Development Region [36] and is classified as a tier-II city by the Government of India [37]. Kochi's 2024 population is now estimated at 3,507,050. In 1950, the population of Kochi was 230,173. Kochi has grown by 100,990 in the last year, which represents a 2.97% annual change [38]. It is one of the few cities in India that has all major modes of transport connecting the city with the rest of the state. The city serves its daily commuters through three dominant modes of transport: firstly, road-based transportation; secondly, rail-based transportation; and thirdly, a limited network of water transport services mainly from the islands to the mainland [39]. The civic body that governs the city is the Kochi Municipal Corporation, which was constituted in the year 1967, and the statutory bodies that oversee its development are the Greater Cochin Development Authority (GCDA) and the Goshree Islands Development Authority (GIDA) [40]. Kochi is highly susceptible to multiple climate vulnerabilities, including coastal erosions, urban flooding, and the heat island effect [41]. The local governments find it difficult to cope with infrastructure problems caused by unplanned urban sprawl and the occurrence of natural hazards. The government of Kerala is developing and allotting several funds for different programs aimed at mitigating the various impacts of climate change in Kochi [42]. Operation Breakthrough is a program that was devised in response to the city's constant struggle with waterlogging, which often brought life to a halt [43]. But, due to weak enforcement and lack of priority, there have been no city-level plans or policies on climate change in Kochi itself [44]. In response to the challenges, a significant amount of analysis and project implementation is required, with the research exploring various alternative approaches by incorporating nature-based solutions into state-level and local-level policies. For research purposes, the study area is divided into two scales: macro level and micro level.

### 2.2.1. Macro Level—Kochi Municipal Corporation

The Kochi Municipal Corporation (KMC) area is spread over 98 sq. km., with a population of 0.6 million [45]. Metropolitically, KMC is divided into 74 wards [46], and while some aspects of the urban environment are controllable, others are influenced by cultural, historical, and regional factors. One of the main issues faced by the Kochi Municipal Corporation is that much of the modern city has developed outside the official city limits that were last defined in 1967. Notable initiatives like the Kochi Smart City [47] project and the development of IT parks and business districts highlight Kochi's ambition to become a global city.

2.2.2. Micro Level—Functional Zones of Kochi Municipal Corporation

As per the research methodology, Kochi Municipal Corporation was further split into functional zones depending on its development philosophy. We considered this segmentation of functional zones and suggested treatments on a micro-level scale. The functional zones in Kochi were defined as zones that were segregated based on the functioning and character of a certain section of the city. To propose and execute alternative solutions and strategies, it was best to categorize wards with similar characteristics, development patterns, land use, and other variables. According to the existing urban situation and the studies specified in the Master Plan of Kochi Municipal Corporation Area 2040, Kochi was split into four zones, and their current state is shown in the Figure 3 and Table 1 below.

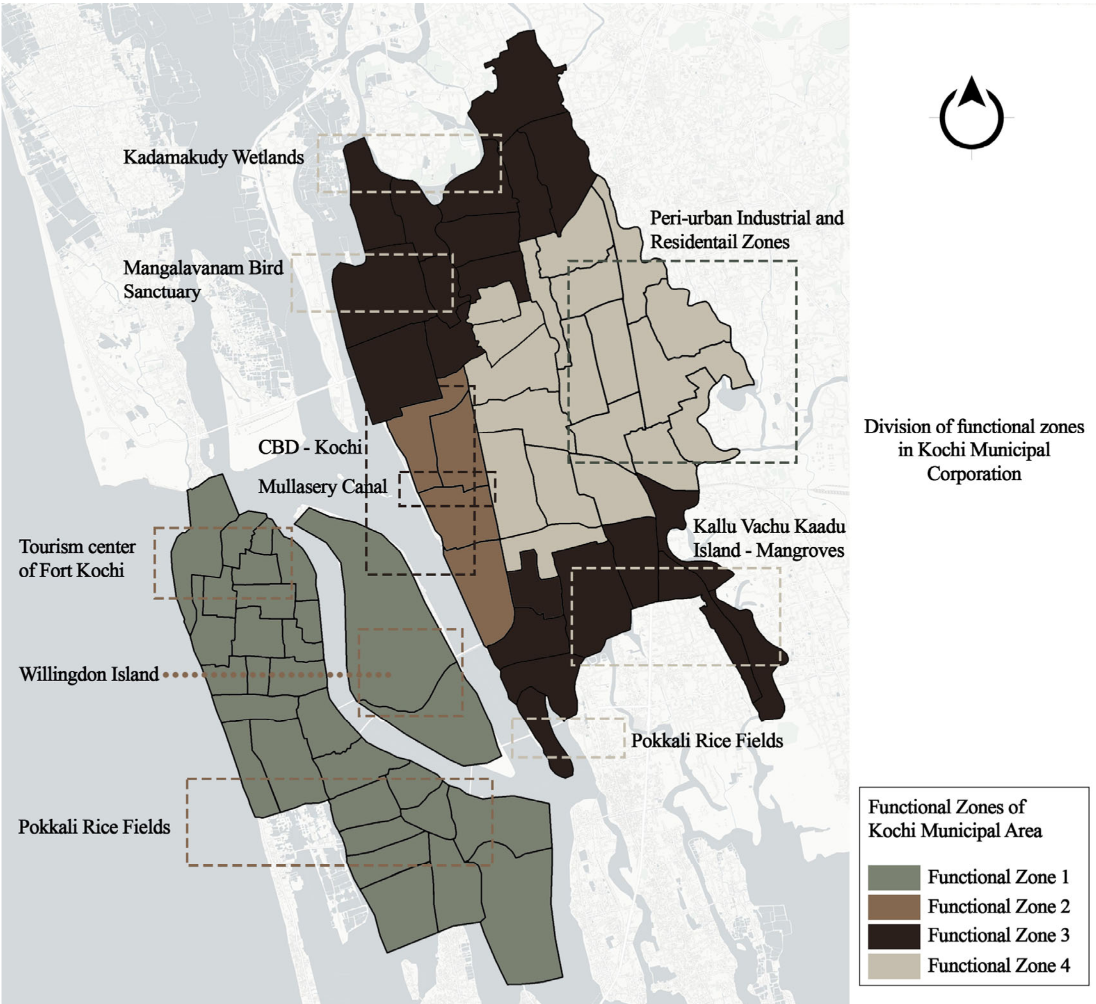



**Figure 3.** Kochi Municipal Corporation and its functional zones (Source: Master Plan of Kochi Municipal Corporation).

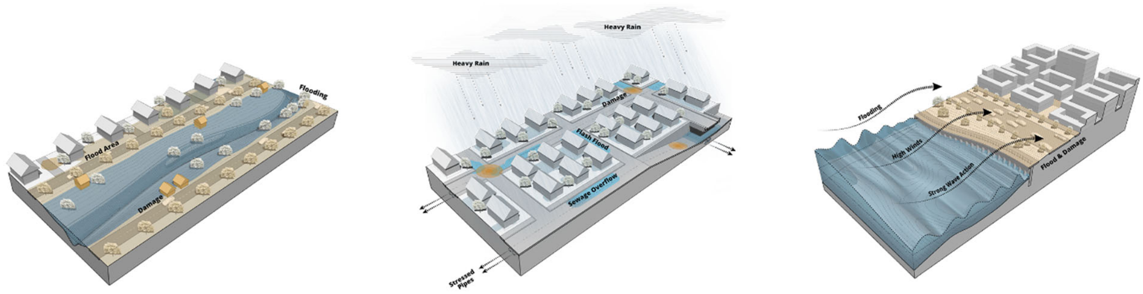
**Table 1.** Functional zones and zone conditions.

| Functional Zones Identified | Zone Conditions |
|---|---|
| Functional Zone 1 | Ecological hotspot, tourist destination, and heritage zone |
| Functional Zone 2 | The area along the metro corridor, CBD of Kochi |
| Functional Zone 3 | Areas of the city that are influenced by bodies of water |
| Functional Zone 4 | Outer city area in the path of urbanisation |

### 2.2.3. Recent Major Floods and Types of Floods in Kochi Municipal Corporation

Studies have shown that structures built on wetlands, pollution leading to choking of canals, and improper construction causing siltation in backwaters stem the natural flow of water, leading to flood-like situations in the city [33]. In 2018, the city faced severe flooding caused by 47% excess rainfall, resulting in the overflowing rivers and canals, compounded by poor drainage systems [24]. The following year, 2019, brought another extreme rainfall event, with flooding exacerbated by siltation in urban drainage channels [24]. In 2020, extreme rainfall continued to be a major issue, but poor maintenance and insufficient capacity of the urban drainage system worsened the situation [24]. Additionally, tidal effects and sea storms contributed to the flooding. These recurrent floods highlight the urgent need for improved urban planning and infrastructure maintenance to manage the city's water systems better.

Flooding occurs mostly from June to September due to the Southwest monsoon in most parts of India and from October to December in the Southern peninsula due to the Northeast monsoon. Almost all of the cities in Kerala were flooded during the severe state-wide floods in Kerala in 2018, but the worst affected was Cochin [48]. Even before the severe flooding in Kerala, many studies in Kochi had been carried out to find out the sources and different types of flooding scenarios in the KMC [49,50]. Based on the location and the existing conditions, the city experiences three types of flooding: (i) riverine flooding [51], (ii) stormwater flooding [52], and (iii) coastal flooding [53], illustrated in Figure 4.




(**a**) (**b**) (**c**)

**Figure 4.** Illustration of different types of flooding in Kochi: (**a**) riverine flooding, (**b**) stormwater flooding, and (**c**) coastal flooding (Source: [54]).

In the face of the aforementioned risks, climate change adaptation needs to play a more important role in the future of urban planning and development [44]. In terms of mainstreaming climate change, high-level strategies in general exist at the national and state levels (National Action Plan on Climate Change and Kerala State Action Plan on Climate Change) [55,56]. Also, as solutions to the problems faced by the city of Kochi, the proposed Master Plan of Kochi Municipal Corporation holds a vision of Kochi for its development to become a global city [24]. Creating world-class infrastructure and facilities with a focus on the sustainable and efficient use of both natural and artificial resources is the best method to prioritize the development of a mitigation strategy. This may be achieved by integrating national- and state-level action plans into the KMC vision. The ultimate objective is to improve the quality of life for Kochi's residents and, by promoting inclusion and resilience, the vision aims to build a city that not only adapts to current difficulties but also actively engages its varied communities. Furthermore, a thorough understanding of the local flooding scenario makes it easier to conduct risk assessments, which aid in identifying and prioritizing the areas most vulnerable to flooding. This knowledge makes it possible to choose NBSs that are in line with the particular difficulties that each type presents. Furthermore, long-term planning and the most efficient use of resources are made possible by projecting future changes in land use and climate, which are guided by a thorough comprehension of the flooding context.

# 3. Results

## 3.1. Phase 1—Preliminary Study

The preliminary study encompassed a background study, literature review, and case study conducted to evaluate the necessity of nature-based solutions (NBSs) and the results, presented in the form of SWOT analysis, cover both macro and micro levels and incorporate the findings from the identification of the impacts and sources of flooding within the Kochi Municipal Corporation. The levels of conducting the SWOT analysis is shown in Figure 5. This SWOT analysis aids in identifying the potential strengths of the present scenarios of Kochi and understanding different opportunities for the Corporation to implement NBSs, thereby addressing the identified weaknesses and threats.

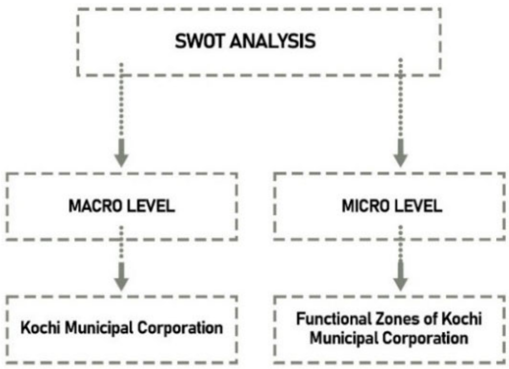



**Figure 5.** SWOT analysis framework (Source: Author).

### 3.1.1. Macro Level—Kochi Municipal Corporation

The Table 2 highlights the key factors influencing Kochi's environmental resilience, outlining both internal and external dynamics. Kochi benefits from a natural drainage system, aided by its network of canals and the Periyar River, which helps to manage water runoff and provides some protection against sea level changes. However, rapid urbanization has encroached on floodplains, leading to the loss of vital wetlands and marshlands and also the destruction of many existing canal systems in the city. This has heightened the city's vulnerability, particularly in dense coastal areas where siltation and pollution are common in canals. A key strategy for these regions is the regeneration of these canal systems. To ensure socio-economic sustainability and optimize drainage and flood resilience, it would be most effective to implement nature-based solutions in their redevelopment. Kochi has promising opportunities to enhance its flood resilience through nature-based solutions (NBSs), integrating grey and green infrastructure to manage water more effectively. Initiatives such as seeding of local tree species, rainwater harvesting, and hazard mapping could also help the city to prepare for future floods. By adopting concepts like the sponge city model [57] and updating the District Disaster Management Plan [58], Kochi could significantly strengthen its defenses against environmental threats.

**Table 2.** SWOT analysis of Kochi Municipal Corporation.

| | |
|---|---|
| **Internal** | **Strengths**<br>Kochi benefits from a robust natural drainage system, supported by its 18 canals and the Periyar River, which facilitate effective runoff management. The Bay Area offers a natural shield for the mainland against sea changes, contributing to the city's resilience. |
| | **Weakness**<br>Urbanization encroaches on floodplains, leading to the loss of essential wetlands and marshlands. Dense coastal areas are particularly vulnerable, and the city's canals suffer from siltation and pollution. Variability in rainfall patterns and rising sea levels exacerbate the sinking of low-lying areas, adversely affecting the city's physical, environmental, economic, and social integrity. Furthermore, inadequate drainage exacerbates these challenges. |
| **External** | **Opportunities**<br>To address these issues, Kochi can explore nature-based solutions (NBSs) and integrate grey and green infrastructure to enhance rainwater percolation. Enforcing rainwater harvesting as mandated by the water policy of 2015 can significantly improve water management. Hazard and vulnerability mapping, coupled with public dissemination and technical support, can prepare the city for future floods. Embracing concepts like room for water and the sponge city model, along with updating the District Disaster Management Plan, can bolster Kochi's resilience against environmental threats. |
| | **Threats**<br>The city faces considerable threats, including the urban heat island effect and reduced groundwater recharge due to increased impermeable surfaces from urbanization. Changes in temperature and precipitation patterns could alter local ecosystems. Recurrent floods pose a severe risk to numerous neighborhoods, particularly those near canals. Rising sea levels and the sinking of low-lying areas present ongoing threats to the coastal communities' physical, environmental, economic, and social stability. |

### 3.1.2. Micro Level—Functional Zones of Kochi Municipal Corporation

This SWOT analysis presents a comprehensive analysis of four functional zones, each exhibiting distinct internal strengths and weaknesses, while also confronting a range of external opportunities and threats. Functional Zone 1 demonstrates significant internal strengths, particularly its historical and cultural value, strong tourism potential, economic activity, and strategic location. However, the zone is constrained by infrastructural challenges, environmental degradation, and traffic congestion. Externally, it holds promise for heritage conservation, waterfront development, and tourism expansion but faces external threats, including the impacts of climate change, over-tourism, and competing development pressures. Functional Zone 2 is characterized by its robust economic activity, bolstered by its solid infrastructure, commercial diversity, and connectivity. Despite these internal strengths, it struggles with traffic congestion, aging infrastructure, and a scarcity of green spaces. Externally, it presents opportunities for mixed-use development, urban infrastructure upgrades, smart city initiatives, and advancements in technology. However, the zone is vulnerable to external threats such as economic downturns, climate change, and shifts in land use patterns. In Functional Zone 3, the strengths lie in its rich biodiversity, water regulation capacity, and ecosystem services. Nonetheless, it faces significant internal challenges, including encroachment, pollution, invasive species, and a lack of public awareness. This zone offers opportunities for restoration, conservation, ecotourism, and enhanced community engagement. However, it is simultaneously threatened by urban expansion, climate change, over-extraction of resources, and land use changes. Functional Zone 4 is noted for its agricultural potential, green spaces, and cultural heritage, yet it contends with land use conflicts, infrastructure deficits, water management issues, and limited public services. Opportunities arise in the form of agroecology initiatives, biodiversity conservation, green belt development, and community-based planning. The zone, however, faces external risks such as unplanned urbanization, pollution, climate change impacts, and land fragmentation. While each zone exhibits unique internal and external dynamics, common challenges persist across all zones, particularly the looming threats of climate change, urbanization, and unsustainable resource use. These shared vulnerabilities highlight the critical need for integrated, targeted interventions. To promote sustainable development across these zones, infrastructure upgrades, strategic conservation efforts, and active community engagement are essential. The findings underscore the importance of proactive management to ensure long-term resilience, optimize economic and ecological benefits, and address the growing pressures from external forces.

This SWOT analysis, conducted at both macro and micro levels, offers a comprehensive framework for developing tailored strategies and implementations that align with the unique characteristics of the Corporation and its functional zones. By integrating broad, systemic insights with detailed, site-specific factors, the analysis enables the formulation of strategies that are not only effective but also highly sustainable and adaptable. This approach ensures that the implementations are responsive to both current conditions and future challenges, fostering long-term resilience and success.

### *3.2. Phase 2—Assessment*

Identifying areas in the city that are more exposed to varied climate change-induced natural disasters and slow-onset events is an essential step in identifying climate risks and assessing vulnerability [59]. Vulnerability has been defined as the degree to which a system, or part of it, may react adversely during the occurrence of a hazardous event. This concept of vulnerability implies a measure of risk associated with physical, social, and economic aspects and implications resulting from the system's ability to cope with the resulting event [60]. It applies to people, groups, institutions, ecosystems, and systems. There are many different causes of vulnerability and it can also take many different forms. Although this definition is commonly acknowledged, it is still unclear how to implement it to measure vulnerability. In the research, we wanted to assess Kochi's vulnerability to flooding, as well as its susceptibility to other geophysical and socio-economic factors. Evaluating all of these social and geophysical vulnerabilities is essential for disaster preparedness, efficient flood risk management, and advancing the safety and well-being of city dwellers. For an effective assessment, the research examined three strategies:

1. The first strategy concentrates on the risk of flooding. Research on this theme sought to evaluate the risk of flooding and the extent to which this specific event affected the land cover of Kochi Municipal Corporation.
2. The second strategy tries to explain the extent of flooding's impact on the study area's social conditions as social indicators. This can be explained as an exposure study of the region to the hazard of flooding, which was defined as those conditions that make people more likely to suffer effects as individuals, families, or communities.
3. The third strategy identifies the vulnerability to flooding through an analytical overview (by overlapping the risk analysis mapping to the exposure details that were generated) and tries to identify the most vulnerable zones of the Kochi Municipal Corporation and find our area of interest.

#### 3.2.1. Vulnerability Assessment Framework

The research involved constructing several fundamental thematic layers using data from diverse sources, including Corporation maps, satellite photos, reference maps of Kerala and Kochi, and climate data from the Climate Research Unit (CRU) [61]. The basic layers comprised corporate divisions (administrative units), land use/land cover, streams, annual rainfall, slope, distance from waterbodies, drainage block sites, elevation (SRTM DEM), public and semi-public spaces, hospitals, and schools. Remote sensing images of the current land cover and land use were visually interpreted using LANDSAT 8 satellite imagery obtained on November 11, 2023, from the USGS Earth Explorer [62]. Additionally, the SRTM DEM data were downloaded from the same source. Annual rainfall data for 2020, with a resolution of 0.5 degrees, were sourced from the CRU. For flood risk analysis and all GIS operations, including database creation and spatial analysis, the standard software package ArcMap 10.8.2 was employed. The framework for the vulnerability assessment is shown in Figure 6.

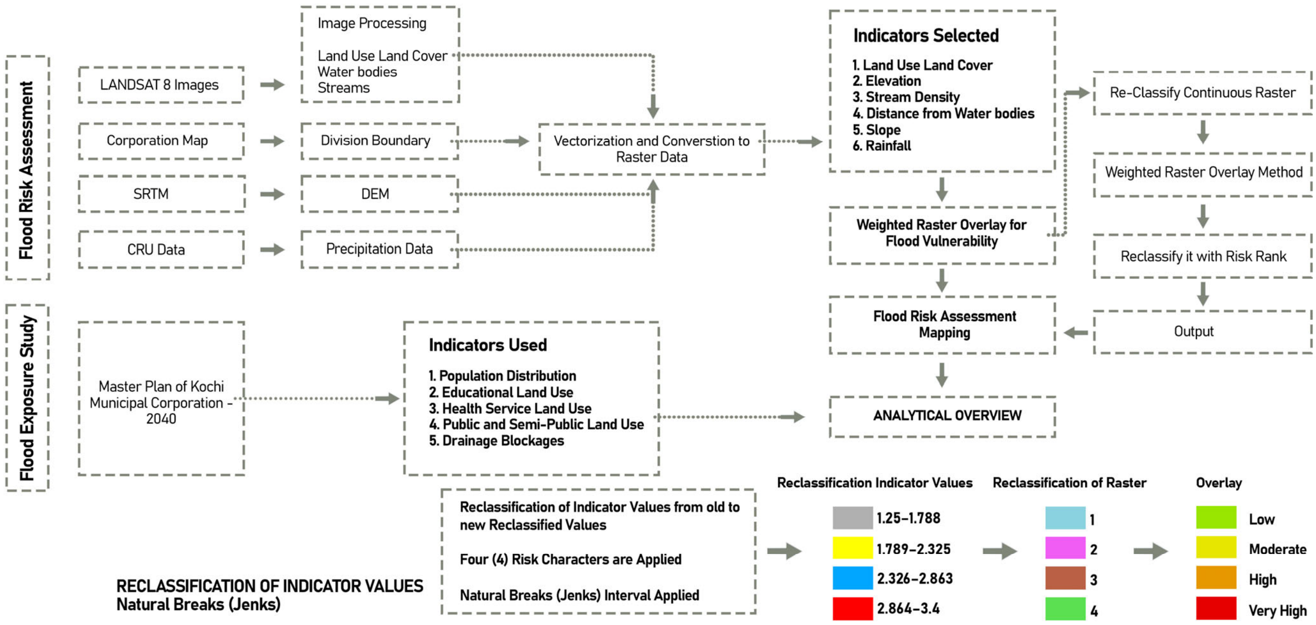



**Figure 6.** Methodological framework of the vulnerability assessment. (Source: Author).

### 3.2.2. Flood Risk Assessment of Kochi Municipal Corporation

For the indicator selection, multiple research papers were studied within the context of Kochi for the flood risk assessment [49,50]. This provided multiple insights about different indicators of flood risk assessment and their importance in understanding the impact of flooding in an urban context. Along with these indicators, different scenarios mentioned in the Master Plan of Kochi Municipal Corporation 2040 [24] were also considered in the indicator selection process. The selected indicators for the research of the flood risk analysis in Kochi included: (1) land use land cover, (2) stream density, (3) distance from waterbodies, (4) slope, (5) rainfall, and (6) elevation and shown in Figures 7 and 8.

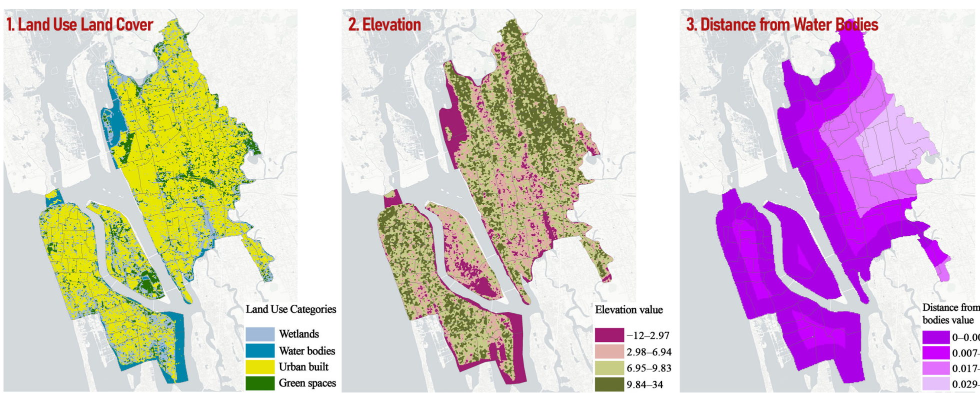



**Figure 7.** Selected indicators: (**1**) land use land cover, (**2**) elevation, and (**3**) distance from water bodies (Source: Author).

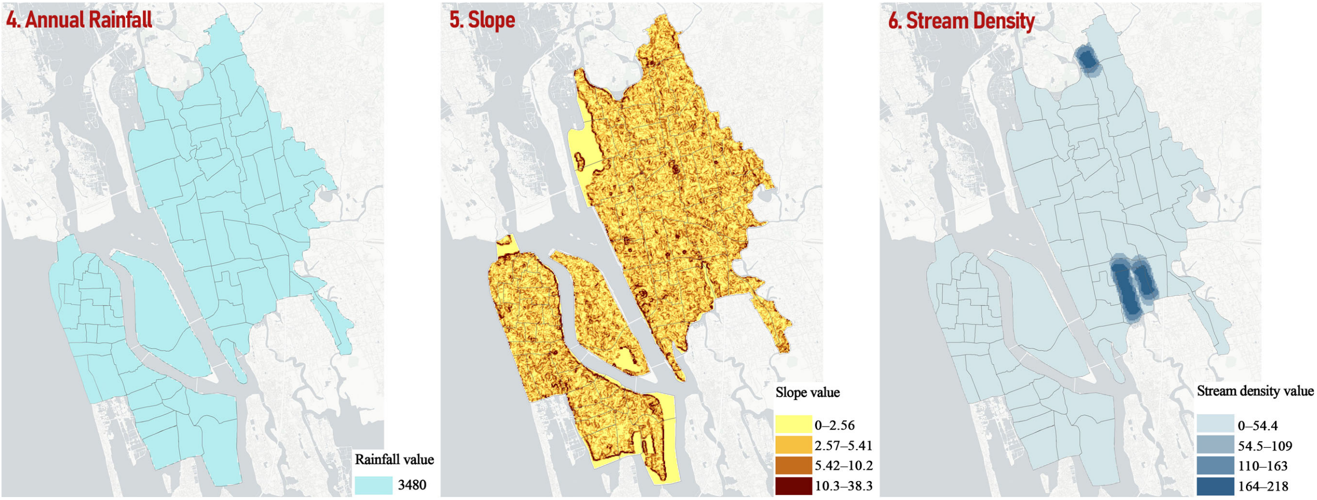



**Figure 8.** Selected indicators: (**4**) annual rainfall, (**5**) slope, and (**6**) stream density (Source: Author).

After generating all of the required indicator mapping for the flood risk analysis, it was required to identify the weight percentage for each indicator, which were assigned as follows: (1) land use land cover—10%, (2) elevation—15%, (3) stream density—15%, (4) distance from water bodies—25%, (5) slope—10%, and (6) rainfall—25% [24]. Based on each indicator's potential to impact urban flooding, these fixed percentages of weight were assigned to each layer by hierarchical order. Greater influence and susceptibility to urban flooding are indicated by heavier weight. Factors with more direct, widespread, and consistent impact came under primary factors, such as rainfall and distance from water bodies, which were given higher weight percentages (25%). These two factors are key drivers of flooding, as overflow, backflow, and excessive runoff overwhelm surrounding areas and drainage systems. By contrast, localized factors were categorized as secondary and tertiary, with 15% and 10%, respectively. Elevation and stream density were given secondary weights, as they contribute significantly but not independently. Tertiary weights (lower weights—10%) were given to land use land cover and slope, as their influences are indirect. This weighting scheme appropriately prioritized the indicators based on their relative contribution to urban flood susceptibility. All of the indicator output layers were categorized using the natural breaks method (Jenks). A multi-criteria evaluation (MCE) method was used to integrate the reclassified influencing thematic layers. The identification and zoning of urban flood risk areas were determined using the weighted overlay analysis technique of the developed indicator maps. Weighted overlay analysis is a type of overlay analysis that allows for the calculation of a multiple-criteria analysis between serval rasters [63]. It involves defining the problem, breaking the model into sub-models, and identifying the input layers [64]. Each input layer is assigned a weight according to its importance, and the output is a weighted raster that shows the suitability of each location based on the criteria [63]. Using this approach, the weights allocated to the various thematic contributory layers according to their relative contributions to the vulnerability to urban flooding were added up to determine the final integrated map's total weights.

The map in Figure 9 is the flood risk assessment map generated with the selected indicators through the weighted overlay analysis technique. It displays the area that is affected by flooding danger according to its risk level. All of the indicators work together to illustrate the impact on the city regions. The Kochi Municipal Corporation's two island structures and the mainland, both of which are close to the sea, are very prone to flooding events. The results of the risk assessment can help to reduce the effect of disasters by using safe and ecologically responsible land use management techniques. The authorities should act quickly to improve the strategies, taking into account the zonation and the locations identified in the results. This action could involve maintaining current infrastructure, implementing green solutions, upgrading local ecosystems, and taking other pertinent measures to combat flooding and related hazards.

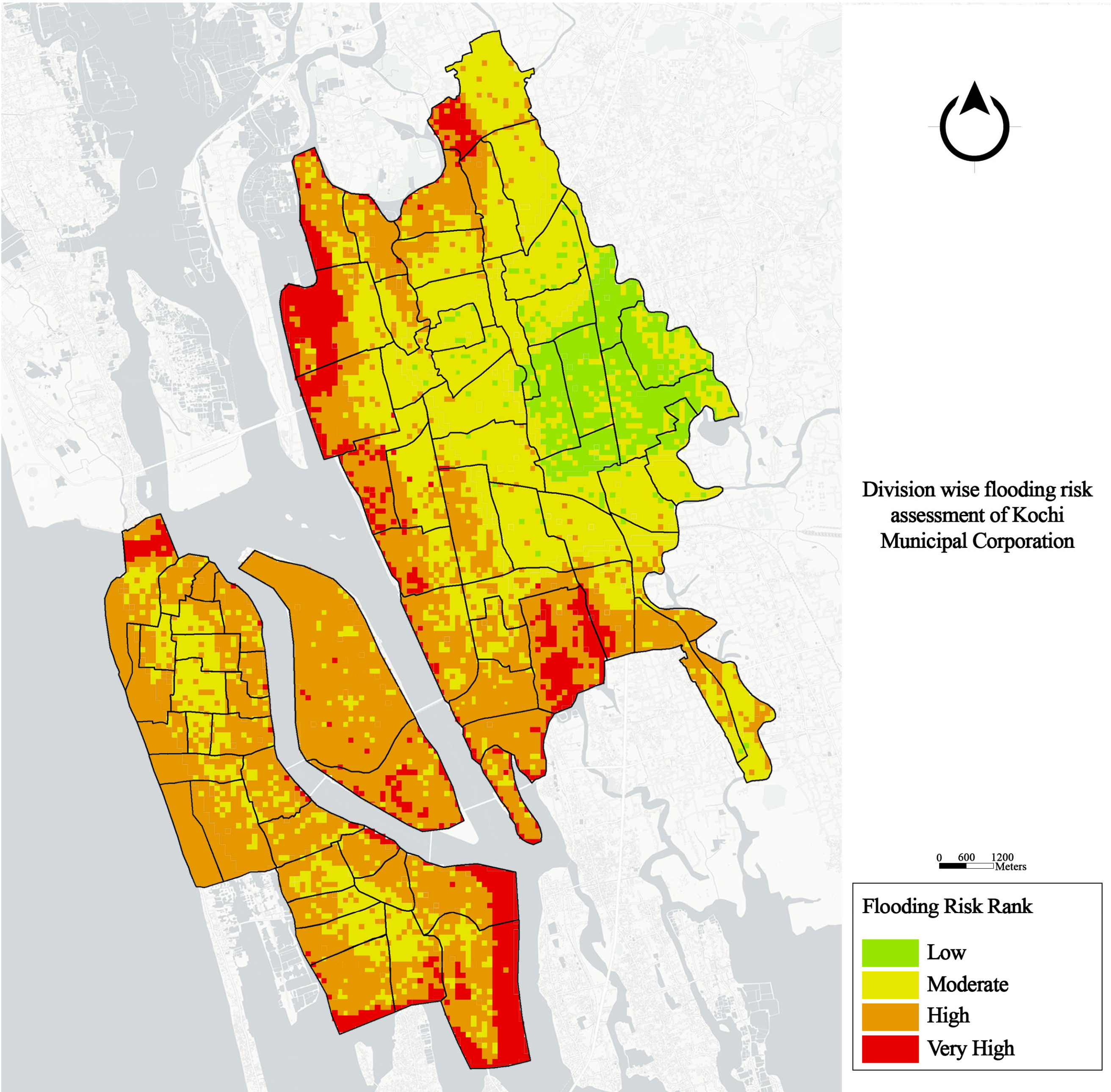



**Figure 9.** Mapping showing the generated flood risk assessment of Kochi Municipal Corporation. (Source: Author).

### 3.2.3. Flood Exposure Study of Kochi Municipal Corporation

The Master Plan of Kochi Municipal Corporation 2040 [24] was the main reference for selecting the indicators for the exposure study. The research focused on the social conditions and factors that would be impacted by flooding, and the indicators chosen based on relevance and conditions were: (1) population distribution, (2) educational land use, (3) health service land use, (4) public and semi-public land use, (5) drainage blockages, and (6) functional zone divisions and shown in the maps of Figures 10 and 11.

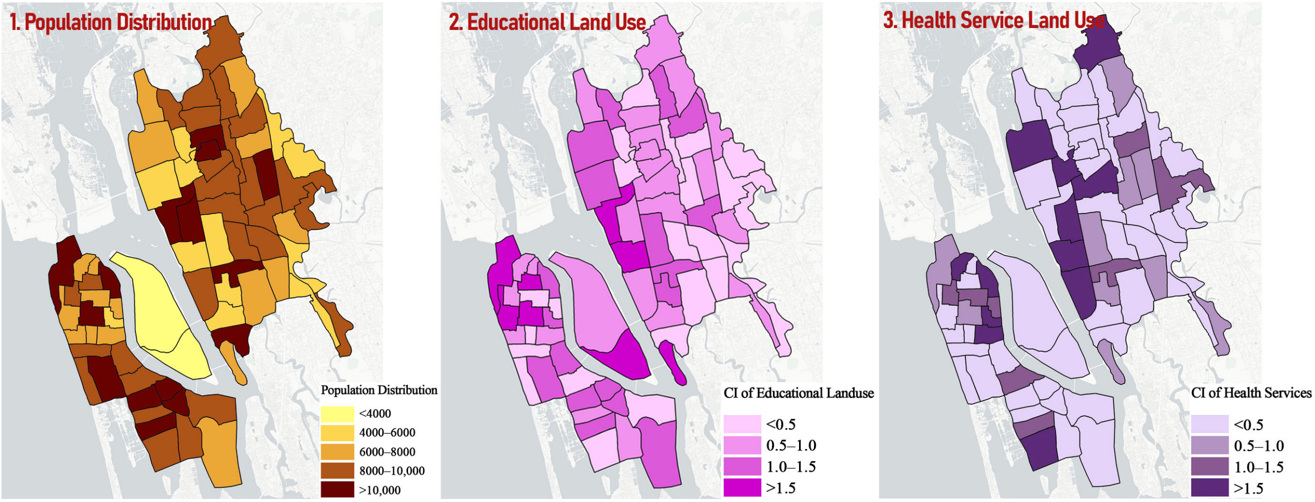



**Figure 10.** Selected indicators: (**1**) population distribution, (**2**) educational land use, and (**3**) health service land use (Source: Author).

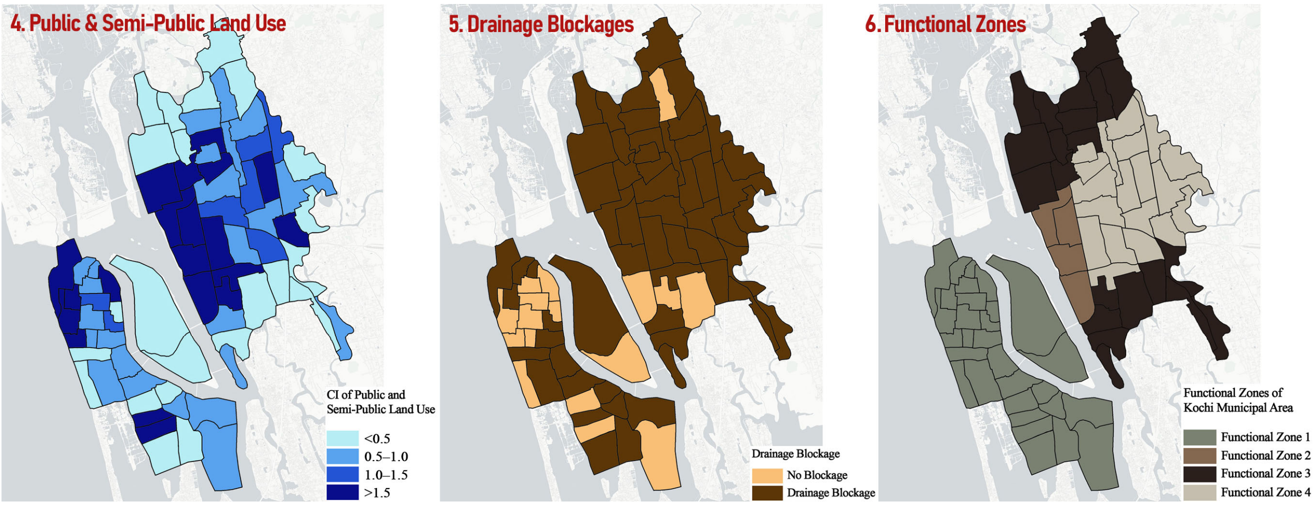



**Figure 11.** Selected indicators: (**4**) public and semi-public land use, (**5**) drainage blockages, and (**6**) functional zone divisions (Source: Author).

The presence of these indicators illustrates the significant influence of the human population on the functioning of the Kochi Municipal Corporation, while also highlighting the prevalence of specific social conditions across different zones within the Corporation. Detailed ward-level data for each of these social indicators were systematically collected from relevant and authoritative sources. A thorough analysis of this ward-level data facilitated the identification of areas where the impact of human activities is more concentrated within the smaller municipal divisions of the Corporation, providing critical insights for targeted urban planning and policy interventions.

#### 3.2.4. Analytical Overview for Identifying the Most Vulnerable Functional Zone of Kochi Municipal Corporation

The analytical hierarchy process (AHP) is an effective method for multiple decision-making processes used in many fields, such as finance, business, education, politics, and engineering [65]. The analytical overview approach employed in this research served as a critical decision-making tool for identifying and comparing the most flood-vulnerable areas within the Kochi Municipal Corporation. This method involved overlaying the final flood risk assessment map with five exposure indicator maps, alongside the functional zone division map, to determine which zones face the highest concentration of risk factors and social exposure. In addition to identifying the most exposed functional zone, this overlapping technique allowed for a qualitative assessment of the intrinsic characteristics of the neighborhoods and functional areas, providing a clearer understanding of their specific risks. This, in turn, supported the development of customized mitigation strategies aimed at reducing vulnerability and enhancing resilience.

Figure 12 shows the overview results and the comparison of their indicator values. Through the analytical overview, the zone with maximum risk and exposure is Functional Zone Two; includes wards 61, 66, and 67, which is the Central Business District (CBD) of Kochi Municipal Corporation. It is recognized as Kochi's development and economic center and is heavily populated with a variety of amenities [24]. The CBD's flood risk will ultimately decrease if it is redeveloped by utilizing the proper nature-based solution approach and the strategies and techniques should be detailly planned. From the SWOT analysis, it is evident that Functional Zone Two shows various opportunities for tackling its flood occurrence through mixed-use development, urban infrastructure upgrades, smart city initiatives, and advancements in technology. With these opportunities, the city's center may be developed for better operations and amenities across the corporation.

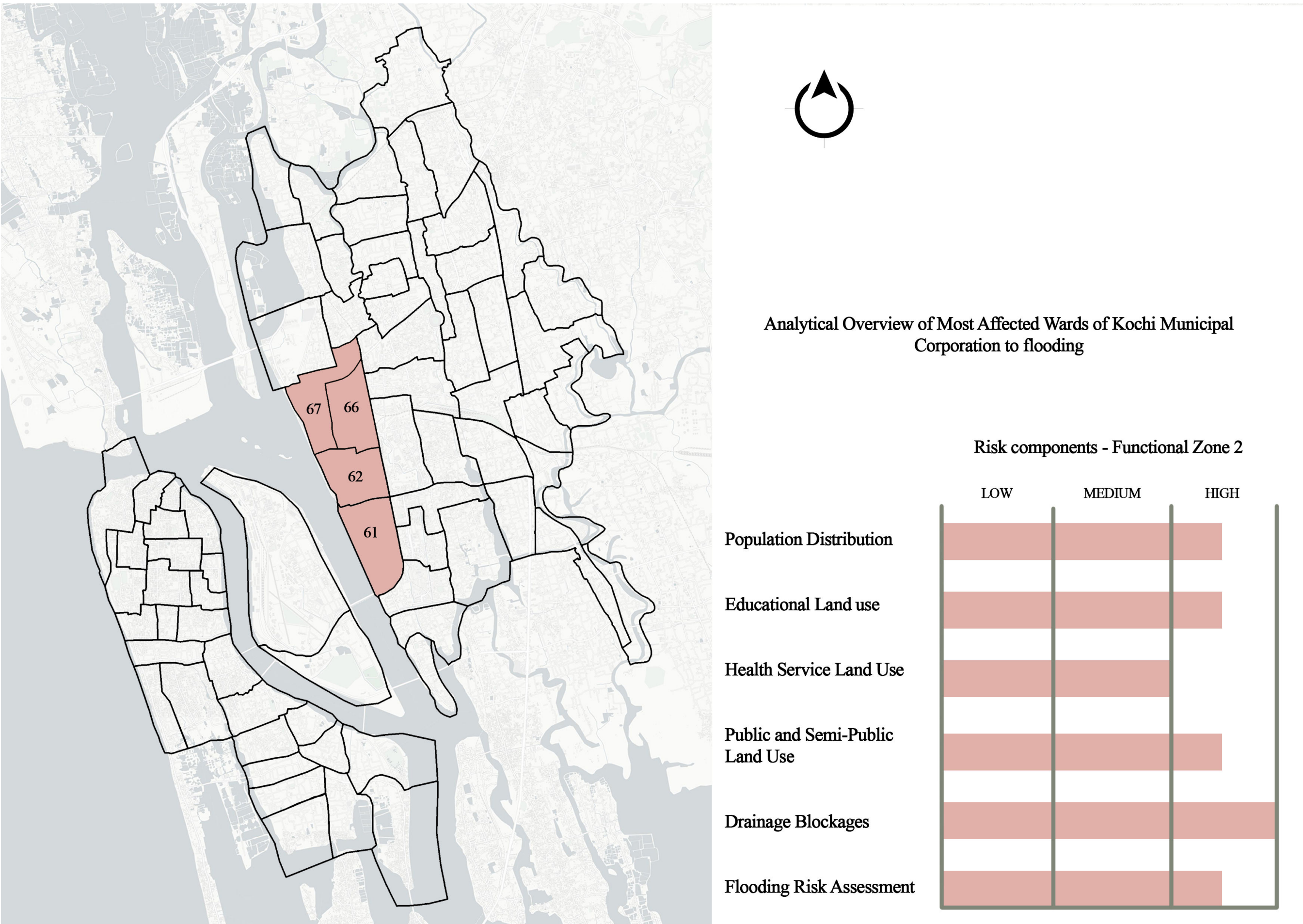



**Figure 12.** Analytical overview mapping (Source: Author).

Given that Kochi is being developed under a structural planning framework, it is essential to address various urban difficulties using a variety of guidelines that both promote and encourage positive structural plan adaptations. To effectively address the challenges, it is crucial to conduct specialized studies at the city level that assess climate-related hazards and associated risks. This approach should prioritize identifying specific sections of the

Kochi Municipal Corporation that exhibit the highest potential for implementing methods, particularly in alignment with the sponge city concept. Additionally, it is essential to outline the fundamental elements and framework necessary for conducting vulnerability and risk assessments, which will serve as vital components in the development planning tools for the Kochi City Region Development Plan (2011–2031). Engaging stakeholders, including local ruling bodies, government agencies, and environmental organizations, in the planning process is critical to ensuring diverse perspectives and thereby enhancing the effectiveness and acceptance of different local plans, including the Kochi City Region Development Plan. Furthermore, establishing a reliable monitoring and assessment mechanism will allow for continuous evaluation of the effectiveness of various methods over time, ensuring regular assessments of their impact on economic, social, and environmental outcomes and facilitating informed structural plan adjustments as needed. These overall guidelines will be developed to plan different recommendations for the corporation and functional zones, and the research developed it on two scales: (i) general recommendations applicable to all functional zones, and (ii) detailed strategies specifically designed to address flooding and urban hydrology issues in the most vulnerable functional zone (Functional Zone 2). Acknowledging the urgent need for effective adaptation strategies, the emphasis was on nature-based solutions and, by incorporating green infrastructure such as wetlands, green roofs, and permeable surfaces, the aim was to mitigate vulnerability to flooding while enhancing ecological health. Furthermore, these nature-based strategies not only tackle immediate flood risks but also strengthen community resilience, promoting sustainable development that aligns with environmental conservation objectives. Ultimately, the implementation of these recommendations will be vital in protecting functional areas from future flood threats and ensuring the well-being of their residents.

### *3.3. Phase 3—Recommendations*

#### 3.3.1. Recommendations of Nature-Based Solution Applications in Functional Zones

The third phase dealt with the recommendations of different nature-based solution approaches by the IUCN [27] in four functional zones, requiring integration into urban planning rules for environmental resilience and peaceful coexistence. The identification of each NBS approach for the respective functional zone was based on the results of Phase 1—the SWOT analysis. The suggested recommendations prioritized this synergy, aiming to alleviate the inherent hazards associated with flooding and promote sustainable development within these functional zones. This comprehensive strategy underscored the importance of aligning natural solutions with established urban design guidelines to enhance adaptation and resilience in the face of environmental challenges. Figure 13 presents an overview of the recommended NBS approaches, followed by Table 3, which details the corresponding recommended actions. These actions are based solely on the characteristics of the functional zones and their spatial profiles. Figures 14–17 illustrate sections of the functional zones, aiding in identifying their profiles.

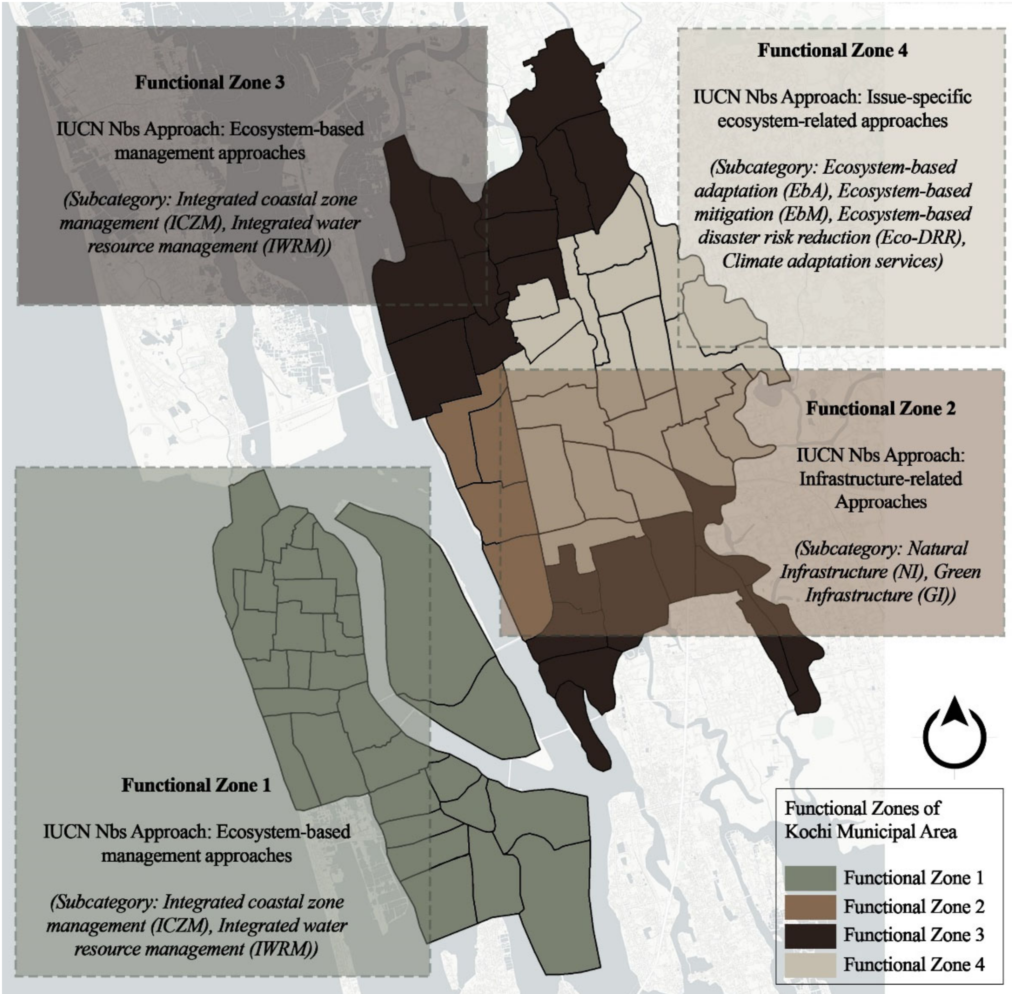



**Figure 13.** Functional zones and the recommended NBS approaches (Source: Author).

**Table 3.** Recommendations for NBS approaches in the functional zones of Kochi Municipal Corporation.

| Functional Zone | Characteristics of Functional Zone | NBS Approach | Recommendations |
|---|---|---|---|
| Functional Zone 1 | • Historic center<br>• Ecological hotspot<br>• High-density urban consolidation<br>• Compact residential<br>• High-potential tourism center | Ecosystem-based management approaches | • Green corridors and urban forests<br>• Sustainable water management<br>• Cultural heritage conservation<br>• Community-based conservation<br>• Climate-resilient infrastructure |
| Figure 14 | | | |
| Functional Zone 2 | • High-density urban consolidation<br>• Compact residential and commercial hub<br>• Administrative buildings and development | Infrastructure-related approaches | • Green roofs and walls<br>• Urban parks and green spaces<br>• Tree planting<br>• Sustainable transportation<br>• Climate-resilient infrastructure |
| Figure 15 | | | |
| Functional Zone 3 | • Urban consolidation<br>• Residential<br>• Wetlands<br>• Mangrove garden environment | Ecosystem-based management approaches | • Wetland restoration<br>• Green corridors<br>• Community-based conservation<br>• Sustainable agriculture practices<br>• Climate-resilient design<br>• Ecotourism initiatives |
| Figure 16 | | | |
| Functional Zone 4 | • Peri-urban facilities<br>• Residential<br>• Infrastructure | Issue-specific ecosystem-related approaches | • Agroforestry<br>• Urban agriculture<br>• Watershed management<br>• Green infrastructure planning<br>• Community-led conservation<br>• Low-impact development |
| Figure 17 | | | |

**Figure 14.** Section through Functional Zone 1 (Source: Author).

**Figure 15.** Section through Functional Zone 2 (Source: Author).

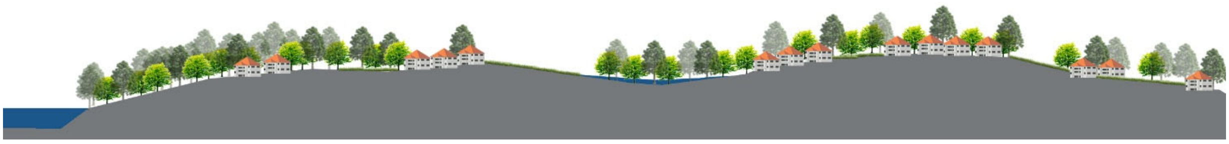


**Figure 16.** Section through Functional Zone 3 (Source: Author).

**Figure 17.** Section through Functional Zone 4 (Source: Author).

With the backing of the City Development Plan (CDP) of Kochi [66], incorporating these suggestions into the Corporation's present plans and policies will improve the city's effectiveness, economy, and alignment with the Corporation's objectives, supporting an all-encompassing and sustainable framework. The recommendations emphasize the allocation of spaces for recreation, sustainable development, and conservation within designated zones. By meticulously designing zoning plans that reflect environmental considerations, the Corporation can contribute to long-term ecological health and community well-being. As the city of Kochi is surrounded by numerous water bodies, the incorporation of sustainable water management practices is essential to address the potential impact of development on water quantity and quality. This involves adopting measures to responsibly manage water resources, minimizing pollution, and ensuring the conservation of water ecosystems. The recommendations also underscore the significance of prioritizing habitat restoration and conservation in specific regions, aiming to bolster ecosystem resilience and biodiversity. This strategic focus aligns with contemporary environmental priorities, fostering a harmonious relationship between development and nature. Furthermore, incorporating our recommendations into Kochi's water policy of 2015 [67] guarantees the establishment of a water distribution network, effective groundwater management, rainwater harvesting, and the conservation of wetlands. Optimal results in the functional zones can be achieved by infusing these water resource management approaches with our suggested measures, all of which can be implemented through sustainable practices, landscape enhancements, and community involvement.

#### 3.3.2. Strategies for Implementing Nature-Based Solutions in the Most Vulnerable Zone (Functional Zone 2—Central Business District)

From Section 3.3.1, it was identified that for the Central Business District (Functional Zone 2), infrastructure-related approaches [27] are useful to prevent flooding and different hydro-ecological issues. This NBS approach reflects a comprehensive and sustainable approach to infrastructure construction and management that is consistent with environmental conservation and climate adaptation concepts. The core idea behind formulating strategies to implement nature-based solutions in the Central Business District (CBD) is to transform the zone into a water-absorbing sponge to mitigate fast flooding. To achieve this, integrating both structural and non-structural flood control systems is advisable. Structural and non-structural amplification approaches are predicted to help the process of flood prevention and achieve more optimal control [68]. Structural measures are physical modifications designed to reduce the frequency of damaging levels of flood inundation and they include dams and reservoirs, canal modifications, levees or floodwalls [69], etc., and non-structural measures are measures such as zoning ordinances and codes, flood forecasting, floodproofing, evacuation and canal clearing, flood fight activities, and upstream land treatment or management to control flood damage without physically restraining flood waters [70]. While structural measures give immediate protection and control, non-structural measures provide long-term solutions that are compatible with natural processes. The integrated mixed method of structural and non-structural flood control approaches enhances flood resilience, promotes environmental sustainability, and promotes community well-being, aligning with the ideals of nature-based solutions. It emphasizes building infrastructure that harmoniously extends the environment, acknowledging the interdependence of natural systems and human well-being. This concept encompasses all of the individual concepts of low-impact development (LID), blue-green infrastructure (BGI), water-sensitive urban design (WSDS), and sustainable urban drainage systems (SUDs) under one umbrella concept. Figure 18 shows the approach of applying mixed methods of flood control systems.

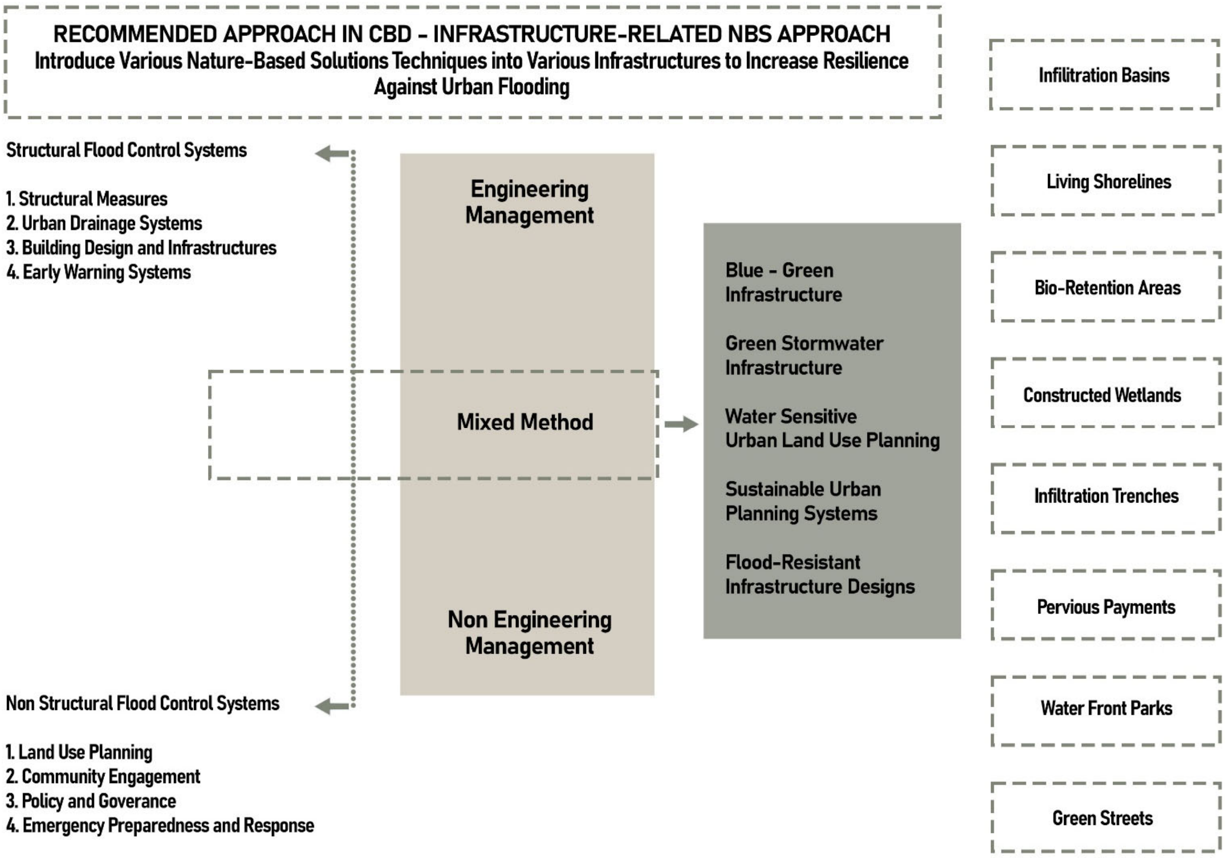



**Figure 18.** Planning interventions of NBSs as an approach to flood resilience in the CBD area of Kochi (Source: Author).

This developed strategy entails the selection and implementation of various low-impact development (LID) controls, such as bio-retention cells, rain gardens, and artificial wetlands, which are chosen based on a thorough assessment of the current land use plan. By carefully considering these factors, effective combinations of LID controls can be proposed that address immediate flood prevention with resilience and sustainability of urban environments over the long term. This integrated approach holds significant potential for enhancing existing urban infrastructure, thereby achieving optimal long-term outcomes in flood management.

#### 3.3.3. Development of Current Infrastructure and Resilient Network Mapping in the Central Business District of Kochi

The mixed method approach has been particularly beneficial in the Central Business District (CBD) of Kochi, where urban infrastructure can be significantly improved through this ideology. The development and sustainability of a neighborhood are profoundly influenced by its sense of community, which can be strengthened through various interventions and programs aimed at upgrading neighborhood elements. Local bodies such as the Kochi Municipal Corporation (KMC) and the Greater Cochin Development Authority (GCDA) advocate for the CBD's recovery from flooding and subsequent thriving by implementing nature-based solutions through diverse projects and initiatives to upgrade the current urban infrastructure [24].

The Central Business District (CBD) of Kochi Municipal Corporation has seen high urbanization in the past few decades, thus turning it into an economic hub of the city [71]. With its wide network of canals and rich foliage, the CBD provides a plethora of resources and strong infrastructure. As the city's economic hub, this neighborhood not only promotes local trade but also encourages inclusive public spaces. The CBD, supplemented by its natural surroundings, has the potential to become an inclusive and community-friendly space. However, there is a pressing need for activities that promote community growth and identity. Strengthening these components can help to create a more resilient urban landscape. An overview of the different infrastructures present in the CBD is shown in Figure 19.

Figure 19 illustrates the infrastructure of Kochi's CBD, highlighting the Mullassery Canal as a significant feature. The canal-based drainage system in Kochi has been used for transportation, fishing, and flood control for generations. Over time, these canals have severely degraded, polluting waters and increasing flood risks, primarily due to inadequate maintenance [72]. Effective management of the drainage system requires coordinated efforts among various agencies, necessitating proposals for interagency cooperation and comprehensive system evaluations. The adoption of flood forecasting and monitoring systems, as well as steps to prevent solid waste from being dumped into drainage channels, provides an effective framework for this management. Kochi's CBD, as the economic hub, accommodates a diverse range of land uses and essential facilities, including parks, hospitals, educational institutions, and commercial buildings. The vulnerability of the CBD arises from the rapid expansion of infrastructure that has not been matched by adequate resilience planning. Addressing these vulnerabilities through strategic planning and interagency collaboration is crucial to ensuring the long-term sustainability and resilience of Kochi's Central Business District.

After conducting interviews and discussions with local self-government bodies, it would be prudent to initiate several significant projects that align with diverse infrastructure development initiatives within the municipality. The objective is to tailor these activities to Kochi's unique demographic environment by proposing solutions that directly address current urban challenges and leverage different infrastructural advancements. This approach ensures that the initiatives not only meet the city's present needs but also enhance its capacities and promote development according to modern urban planning principles.

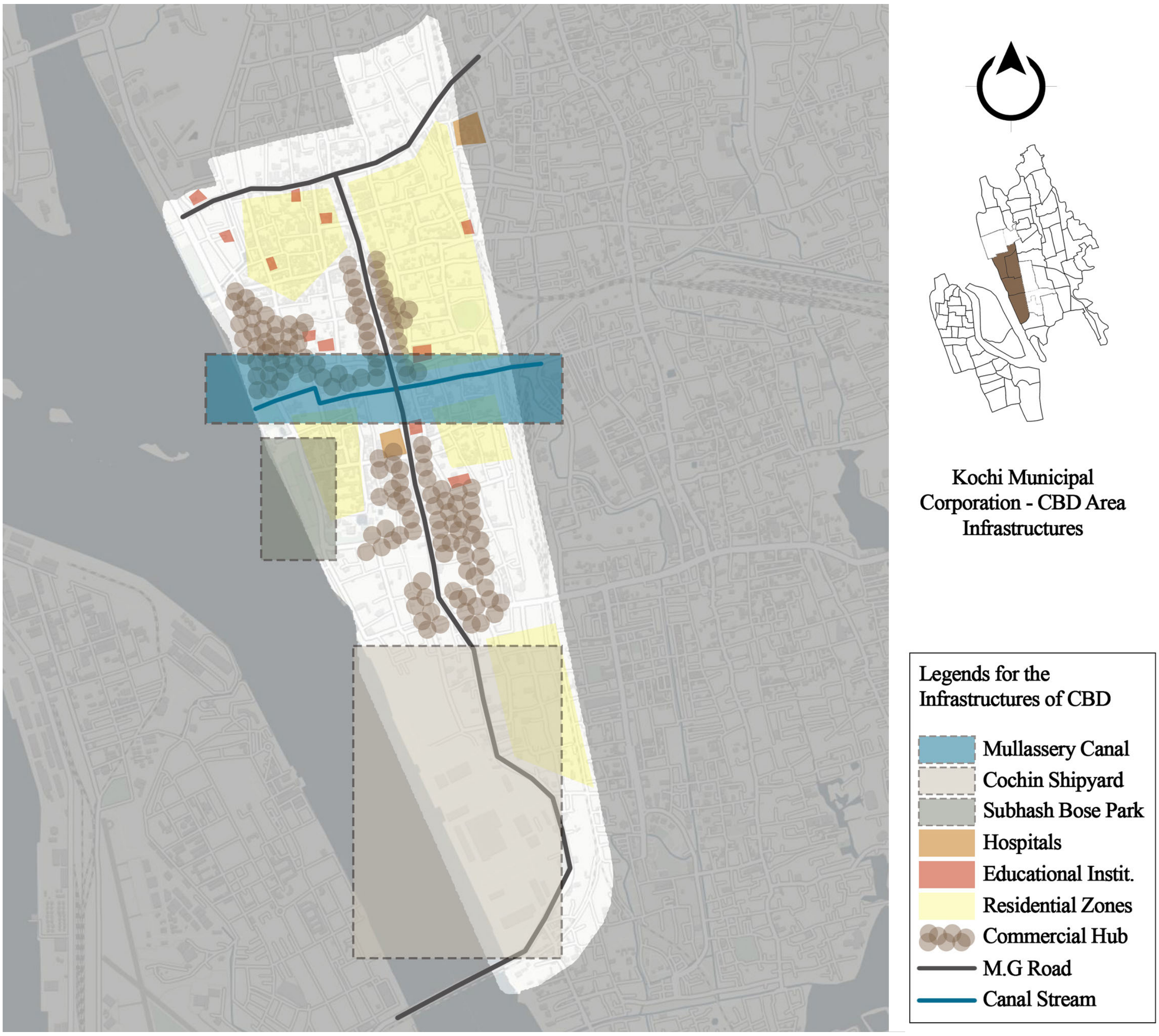



**Figure 19.** Existing urban infrastructure in the Central Business District of Kochi (Source: Land Use Land Cover Map, Kochi Municipal Corporation).

To generate well-informed recommendations, a comprehensive understanding of the existing conditions within the Central Business District (CBD) is essential. This requires extensive research utilizing a variety of credible sources, including government websites, media reports, official documents, and land use planning materials. By analyzing the data collected from these diverse sources, patterns and conceptual frameworks that guide development at both the CBD and municipal levels can be identified. This analytical process provides a foundation for formulating project proposals that are not only responsive to specific infrastructure requirements but also align with Kochi's broader vision and strategic direction for urban growth. The proposed projects based on the existing proposals and the conducted studies, which could be a potential regeneration strategy in the CBD area through the application of nature-based solutions, are listed below.

1. Development of Mullassery Canal and the surrounding area through nature-based Solutions.
2. Extension of Kawaki Project (community-led tree-based intervention for climate resilience) to the Central Business District of Kochi Municipal Corporation.

3. Implementation of urban green spaces through pocket parks in the densely compacted commercial zones of the Central Business District of Kochi Municipal Corporation.
4. Smart green infrastructure development through the implementation of rainwater harvesting systems in the residential zones and the renovation of streets with the green streets concept.

The four projects mentioned above were developed based on the results from Phase 1 and fully align with the proposed master plan. Various existing infrastructures, such as canals, buildings, and parks, were selected for this project, and their conditions were improved using nature-based solutions to maximize resilience against urban flooding. The regeneration of the Mullassery Canal [73] and its surroundings with nature-based solution practices is the initial implementation. In line with the existing municipality's proposal [74] of introducing mixed flood control systems with nature-based solutions at selected subsites in the 1.4 km canal stretch, through this strategy the canal can be integrated into the city's planning framework, re-establishing connections between urban greenery and water bodies. This approach offers effective drainage solutions while creating potential community parks and gathering spaces, serving as a model for reimagining the city's relationship with water and enhancing its resilience to flooding and other hazards. Additionally, the Kawaki Project [75], a community-led tree-based intervention for climate resilience developed by the WRI in various locations across Kochi, could be beckoned in the Central Business District (CBD). The program uses geospatial technology and community knowledge to map tree coverage and recommend planting areas. It brings together stakeholders from several sectors, including the Kochi Municipal Corporation (KMC), World Resources Institute India, and the Cities4Forests program, as well as educational institutions and health service buildings. The project proposed to implement the planting of diverse local tree species in the CBD to improve water infiltration and promote ecological enhancement. Simultaneously over the past three years, the Kawaki Project has planted over 1200 trees and employed over 100 women. The town has actively promoted community participation by partnering with local organizations and funding tree planting and maintenance efforts. Expanding the project to the Central Business District (CBD) is expected to yield similar outcomes, contributing to the development of sustainable ecosystems and improving the community's financial sustainability. Furthermore, this proposal aligns with stakeholder commitments to extend the project to new areas. Thirdly, the proposal of pocket parks in the densely compacted commercial cones of the central business district is very context-related, as the CBD is tightly packed with various commercial markets. Pocket parks are unique because they can be created from underutilized areas, vacant lots, or neglected spaces in urban settings. They offer a resilient solution to address flooding and other environmental hazards in areas with limited land and infrastructure. By effectively managing stormwater, pocket parks help to absorb rainwater runoff and promote sustainable, eco-friendly water management. While their ecological footprints are modest, these parks still act as small refuges for biodiversity and contribute to increasing the city's permeable surface area. The trees and plants within pocket parks create a microclimate, acting as "green lungs" that mitigate the effects of flash flooding and other climate change impacts. The fourth proposal encourages the design of green roofing systems for buildings, the construction of green streets, and the widespread installation of rainwater collecting systems on the rooftops of Kochi's business and residential buildings [67,76]. This proposal's primary idea is to modify smart technology for this use. To address the complex issues of environmental sustainability and urbanization in Kochi, a well-thought-out plan for the development of intelligent green infrastructure has to be proposed. The goal of incorporating well-placed green areas and avenues lined with trees into the urban fabric is to improve air quality, promote biodiversity, and improve the city's overall aesthetics.

Beyond flood resilience, the four proposals emphasize a dedication to awareness-raising and community engagement. The success of these projects will depend heavily on public involvement and educational initiatives that will instill in Kochi's citizens a sense of environmental stewardship and ownership. Essentially, these extensive proposals embody an all-encompassing strategy for sustainable urban growth in Kochi. The city hopes to establish a standard for smart and sustainable cities worldwide by skillfully fusing technology and infrastructure with environmentally friendly solutions and creating an urban environment that is both resilient to climate change and improves the general quality of life for its citizens.

Table 4 presents a comprehensive overview of the above-mentioned proposals within Kochi's Central Business District (CBD) region. It also features key stakeholders involved in these initiatives, including institutions and organizations, fostering a collaborative approach to shaping the future of Kochi's CBD and also different nature-based solution methods installed in these proposals.

**Table 4.** Proposed pilot projects in the CBD area and the type of infrastructure developments in the area.

| Project | Type of Infrastructures Developed | Stakeholders Participating throughout the Project | NBS Applications Installed in the Project |
|---|---|---|---|
| Rejuvenation of Canal and Surroundings | Redevelopment of Mullassery Canal and its surroundings through the installation of nature-based solutions | • Kochi Municipal Corporation (KMC)<br>• Greater Cochin Development Authority (GCDA)<br>• Ministry of Housing and Urban Affairs, Government of India<br>• Educational Institutions<br>• Kudumbashree<br>• Local residents<br>• Commercial owners<br>• NGO—Foundation for Restoration of National Values | • Constructed wetlands<br>• Raingardens<br>• Permeable pedestrian streets<br>• Tree pits and upgraded stormwater pits<br>• Green buffers<br>• Bio-retention areas<br>• Living shorelines |
| Kawaki Project | Community-led tree-based intervention for climate resilience | • Kochi Municipal Corporation (KMC)<br>• World Resource Institute (WRI)<br>• Center for Heritage, Environment & Development (c-hed)<br>• Kerala Forest Research Institute (KFRI)<br>• Kudumbashree<br>• Educational institutions<br>• Local residents | • Raingardens<br>• Tree pits and upgraded stormwater pits<br>• Green buffers<br>• Local vegetation<br>• Infiltration trenches |
| Implementation of Urban Greens through Pocket Parks | Development of densely compacted urban commercial zones through the instalment of pocket parks | • Kochi Municipal Corporation (KMC)<br>• Commercial owners<br>• Greater Cochin Development Authority (GCDA)<br>• Local residents<br>• Center for Heritage, Environment & Development (c-hed)<br>• Kudumbashree | • Bio-retention areas<br>• Raingardens<br>• Permeable pedestrian surfaces<br>• Stormwater pits<br>• Green buffers |
| Smart Green Infrastructure Development | Implementation of rainwater harvesting system as per the instructions from KMBR and the renovation of the streets with the green streets concept | • Local residents<br>• Kochi Municipal Corporation (KMC)<br>• Commercial owners<br>• NGOs—promoting sustainability development | • Rainwater harvesting<br>• Rooftop farming<br>• Permeable pedestrian streets<br>• Tree pits and upgraded stormwater pits<br>• Green spaces, including butterfly parks and similar infrastructure |

A resilient network map was systematically developed using the detailed information from the proposal and research results, as shown in Figure 20. This map integrates various nature-based solutions implemented through the proposals, offering a comprehensive strategy to address environmental challenges. It illustrates how these new developments are integrated into Kochi's Central Business District (CBD), encompassing both the ecosystem and existing infrastructure while providing a physical representation of their implementation and impact. As these initiatives take shape in the city center, the transformative effects of nature-based solutions become more evident, reshaping the urban landscape and fostering sustainability. The highlighted projects not only enhance environmental resilience but also demonstrate the potential to integrate nature-based solutions into urban planning, improving both the quality of life and the aesthetic and functional values of the city core. Streets are being developed using green infrastructure, and low-impact development (LID) has been strategically constructed in suitable areas. In addition, the canal mouth located in the CBD has been treated with living shorelines to reduce wave energy, thereby mitigating unexpected flooding and coastal erosion [77]. Green buffers have been introduced along the coastal perimeter, and various ecological regeneration strategies have been implemented in the city's urban parks. These parks have been redesigned with rain gardens, infiltration trenches, and butterfly parks, which not only promote water absorption and flood control but also enhance the aesthetic appeal, attracting local gatherings and fostering community interaction. Public and private buildings in the CBD are encouraged to implement various rainwater harvesting methods to address related environmental challenges. Pavements are being upgraded with permeable materials, while stormwater pits and tree pits have been installed to enhance water management efficiency. Together, these measures aim to develop the CBD in response to Kochi's current challenges, particularly flooding. Additionally, proper management and monitoring systems, supported by digital technologies, should be implemented to ensure ongoing effectiveness. Aligning these strategies with existing municipal and district policies, as these proposals are part of the city's corporation plans, will help Kochi to evolve into a flood- and climate-resilient city, with improved infrastructure management systems.

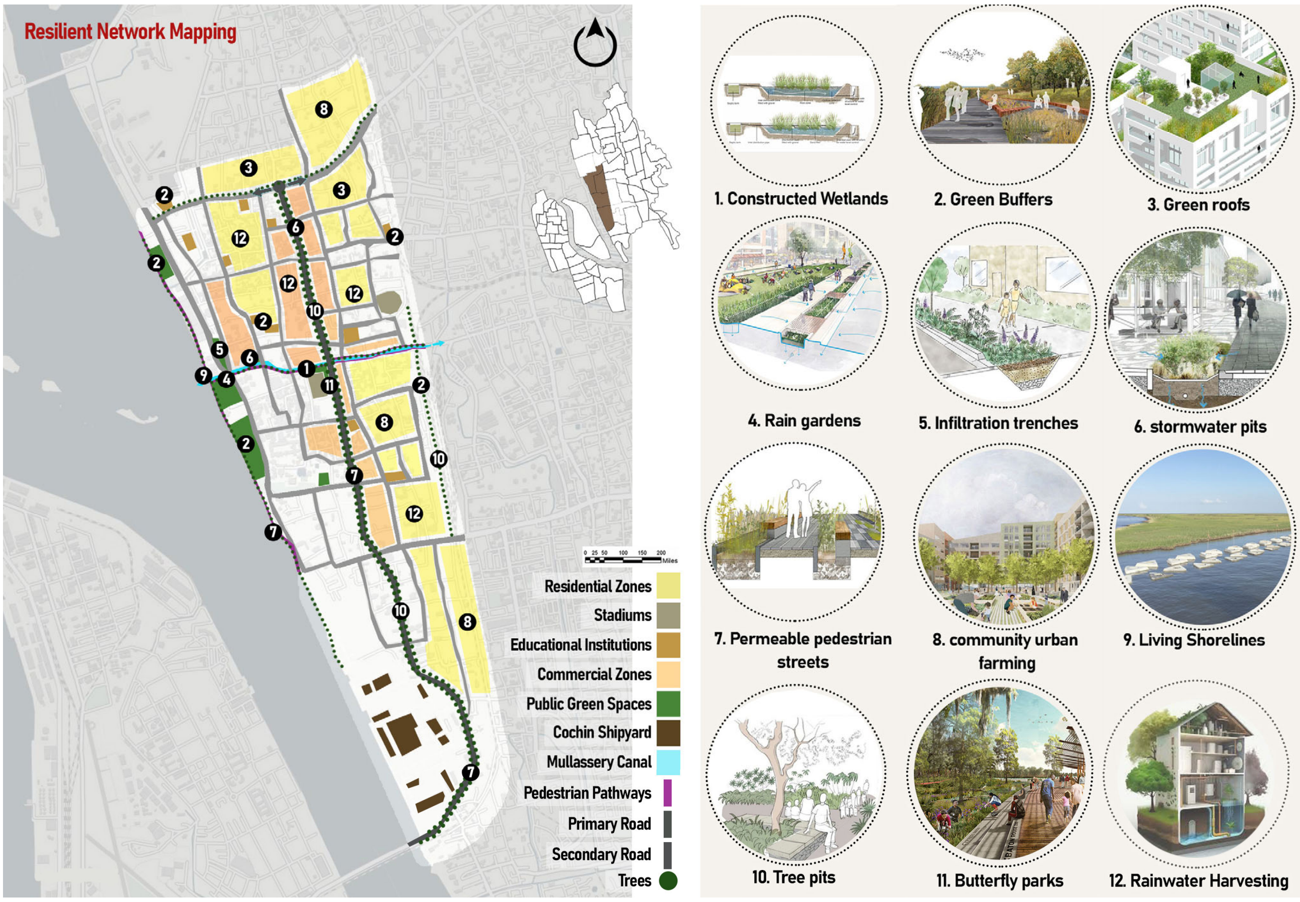



**Figure 20.** Resilient network for the CBD area of Kochi (Source: Author).

## 4. Discussion

This research explored the potential of nature-based solutions (NBSs) as an effective flood mitigation strategy within Kochi's urban center, with a particular focus on the Central Business District (CBD). The study demonstrates that NBSs can significantly enhance urban flood resilience, especially in flood-prone areas. By integrating natural processes into urban infrastructure management, NBSs offer a sustainable alternative to traditional flood control measures, balancing the restoration of ecological systems with the mitigation of flood risks. The findings reveal that Kochi's current infrastructure struggles to cope with the increasing frequency and intensity of floods, highlighting the need for long-term, sustainable solutions that strengthen the city's flood resilience. Nature-based interventions, such as the restoration of natural floodplains, the creation of green infrastructure, and the preservation of wetlands, are essential in reducing flood risks by absorbing and regulating stormwater runoff. These interventions are not only effective for flood mitigation but also enhance biodiversity and the overall quality of urban life, contributing to long-term environmental sustainability and aligning with global examples of successful NBS applications, such as New York's Bluebelt program [78] and Rotterdam's urban floodplain restoration [79] efforts, which have demonstrated measurable improvements in flood risk reduction and ecological restoration.

A key contribution of this research is the identification of vulnerability hotspots within the Kochi Municipal Corporation, achieved through flood risk and exposure assessments. Using a weighted overlay method in ArcMap, the research produced a flood risk map that serves as a valuable tool for decision making and resource allocation. This map identifies high-risk areas, enabling targeted interventions such as preserving critical infrastructure, implementing green solutions, and enhancing nearby ecosystems. The flood risk map goes beyond being a mere document; it is a critical tool for guiding urban planning decisions aimed at reducing hydrogeological hazards. Importantly, its findings align with the sectoral proposals in the Master Plan of Kochi Municipal Corporation 2040, especially within the disaster management section, which emphasizes adopting NBSs to manage runoff, enhance water detention capacities in canals, and improve water retention in green spaces. This integration underscores the importance of incorporating socio-environmental assessments into urban planning, making the flood risk map an essential instrument for fostering sustainable and resilient city design.

The study highlights that Kochi's CBD, as the economic core of the city, is particularly vulnerable to flooding. Given its high population density and concentration of services, implementing NBSs in this zone can significantly reduce flood risks while also enhancing resilience to climate change. The research proposes a mixed flood control system for the CBD that combines structural and non-structural flood control measures, offering flexibility and long-term sustainability. By integrating NBSs with traditional infrastructure, this approach provides a comprehensive solution to flood management. Furthermore, the introduction of low-impact development (LID) and blue-green infrastructure strategies into Kochi's planning framework can improve urban water management and contribute to the city's overall resilience. All of these strategies are incorporated in the CBD through various proposals. The development of the Mullassery Canal through an NBS, for instance, restores the canal's capacity to manage rainwater and prevent flooding, while also boosting ecological health and addressing the challenges posed by improper canal management and repeatedly occurring canal blockage issues. Extending the Kawaki Project, a community-led tree-based climate resilience initiative, into the CBD brings urban forestry that mitigates the urban heat island effect, absorbs excess rainwater, and reduces flood risks. Additionally, pocket parks in densely populated commercial areas not only enhance flood resilience by improving water absorption but also provide green spaces that lower temperatures and boost biodiversity. The development of smart green infrastructure, such as rainwater harvesting systems and permeable pavements in residential zones, addresses stormwater management and flood avoidance. These NBS interventions directly address Kochi's vulnerability to climate change, such as increased rainfall and rising temperatures, by incorporating natural systems into urban development. Together, these initiatives present a comprehensive strategy for mitigating flood risks, improving environmental sustainability, and enhancing urban livability, positioning Kochi as a model for climate-resilient urban development.

The study's findings align closely with the Master Plan of Kochi Municipal Corporation 2040, particularly with its objectives to enhance climate resilience and promote sustainable urban ecosystems. The lack of understanding of governance in implementing novel solutions for ecosystem restoration is a key knowledge gap in achieving the UN Sustainable Development Goals (SDGs) [80], but integrating these solutions into the city planning framework aligns urban development with climate resilience. By addressing the research's key objectives of analyzing climate change impacts, identifying vulnerable regions, and recommending planning interventions, this study provides a clear path forward for Kochi to become a leader in flood-resilient urban development. While the ecological and technical aspects of NBSs are critical, the research also underscores the importance of socio-environmental factors in ensuring the long-term success and sustainability of these interventions. Public support, community engagement, and local understanding of the benefits of NBSs are essential to their effective implementation. The research emphasizes that community involvement, particularly in the planning and implementation phases, directly influences the adoption and success of NBS solutions. In Kochi, incorporating robust maintenance plans into the urban development process is essential for sustaining the effectiveness of NBSs and green infrastructure. Maintenance goes beyond being a technical challenge; it involves economic and social dimensions that require active participation from local communities.

From an economic standpoint, ensuring that local resources are available for the maintenance of these solutions is crucial to their long-term viability. But equally important is the social aspect: engaging local populations in the maintenance of these projects fosters a sense of ownership, strengthens social ties, and builds community resilience. The research highlights that these maintenance plans must be integrated into the project's design and implementation phases to ensure the sustainability of the interventions. This approach contributes to a broader notion of a "sustainable urban ecosystem," where resilience is not solely based on infrastructure but is also supported by active community involvement. Community engagement is crucial for sustainable development, as it ensures projects align with local needs while promoting environmental conservation, social equity, and active participation in maintaining a sustainable urban ecosystem [81]. This research also connects the importance of maintenance to the broader urban planning strategies outlined in the Master Plan of Kochi Municipal Corporation 2040. By linking community involvement in the maintenance phase with the city's overarching goals of sustainability and resilience, the study suggests that the success of NBS interventions hinges on incorporating community input throughout the planning and execution processes. Interviews with government officials underscore the need for collaborative governance and public participation in NBS projects, demonstrating that education and engagement are key to ensuring the long-term viability of these interventions. Policies that promote community participation in maintenance, such as local employment programs like the Ayyankali Urban Employment Guarantee Scheme [82], can foster economic empowerment, enhance community pride, and further support the sustainability of these projects.

The research offers a crucial foundation for future studies on urban flood risk management in Kochi, particularly regarding the integration of NBSs into urban planning. Mapping vulnerability hotspots and implementing targeted NBS interventions will serve as practical guidance for urban planners, policymakers, and municipal authorities, even though, apart from these findings, the proposed framework also faces serval limitations. Limited land availability in Kochi due to rapid urbanization and encroachment, combined with the city's low-lying geography, restricts the feasibility of certain proposed interventions [32]. As all of the proposals are supported by the proposed Master Plan of Kochi Municipal Corporation 2040, governance issues, including fragmented coordination and insufficient policy integration, further complicate implementation. Furthermore, the framework's reliance on community participation for maintenance, while promising, depends on sustained public engagement and adequate institutional support, as also noted in studies about nature-based solutions to address global societal challenges by the IUCN [27], which can be difficult to achieve in practice. Furthermore, continued monitoring and assessment of NBS projects will be essential to evaluate their long-term effectiveness and adaptability in addressing evolving climate challenges. Addressing these limitations requires a multi-stakeholder approach, robust funding mechanisms, and enhanced policy integration to ensure the long-term sustainability of the proposed framework.

## 5. Conclusions

This study underscores the need for a comprehensive, evidence-based approach to flood mitigation in Kochi, emphasizing the importance of vulnerability assessments to ensure targeted interventions. The findings highlight several key points that are crucial for ensuring the sustainability and long-term success of NBS interventions. The success of NBSs relies not only on the strategic application of these solutions but also on active community involvement and public awareness. Therefore, fostering local support and aligning NBS projects with existing municipal policies and development goals is essential for long-term sustainability. The following key points summarize the main findings and highlight essential aspects for the future success of nature-based solutions (NBS) in flood mitigation for Kochi.

- Nature-based solutions (NBSs) can significantly reduce flood risks in Kochi's CBD.
- Flood risk maps identify flood-prone areas, aiding in targeted interventions and prioritizing flood mitigation.
- IUCN-based NBS recommendations are tailored to the specific characteristics of Kochi's functional zones.
- A mixed flood control approach combining NBSs with traditional flood management techniques is necessary for long-term resilience.
- The proposed projects align with NBS themes, incorporating the proposed master plan and local urban policy initiatives.
- NBSs promote ecological health, reduce the urban heat island effect, and enhance biodiversity.
- Community involvement is crucial for the successful implementation and maintenance of NBSs, fostering ownership and strengthening social cohesion.
- The master plan of Kochi Municipal Corporation 2040 prioritizes active community engagement in maintaining these systems.

Looking ahead, the research also emphasizes the importance of expanding NBS applications to all functional zones of Kochi, creating a city-wide strategy that can effectively address flood risks across diverse urban landscapes. Future research should delve into the socio-environmental dynamics of NBSs, particularly how community participation, social acceptance, and governance structures influence the effectiveness of these solutions. To assess the viability and sustainability of these projects, comprehensive cost–benefit analyses, incorporating social return on investment (SROI) [83], should be conducted. This approach will provide decision makers with a clear understanding of the economic and social impacts of each project, including potential savings in healthcare costs, enhanced community well-being, and long-term resilience to climate change. Moreover, engaging stakeholders in these assessments ensures that NBS interventions are aligned with local needs and conditions. As part of this process, developing community-based maintenance plans is essential for ensuring the longevity of NBS projects. These plans not only guarantee the continued ecological benefits of the interventions but also foster local employment opportunities, contributing to both social and economic resilience. Ultimately, by incorporating NBSs into the urban development framework and ensuring comprehensive stakeholder engagement, Kochi can position itself as a model for climate-resilient cities, where ecological preservation, infrastructure development, and community participation are harmoniously integrated for long-term sustainability.

**Author Contributions:** Conceptualization, A.A.A. and S.T.M.; methodology, A.A.A.; validation, S.T.M. and M.A.; formal analysis, A.A.A.; investigation, A.A.A.; resources, S.T.M., and M.A.; data curation, A.A.A.; writing—original draft preparation, A.A.A.; writing, review and editing, all authors; visualisation, A.A.A.; supervision, S.T.M. and M.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Ethical review and approval were waived for this study because it utilized data that did not involve direct or sensitive personal information.

**Informed Consent Statement:** Patient consent was waived as this study relied solely on publicly available demographic and statistical data.

**Data Availability Statement:** The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

**Acknowledgments:** The author would like especially to thank the co-authors, Sara Torabi Moghadam and Mario Artuso, for their valuable guidance throughout the research and the invaluable counsel received from the officials of the Greater Cochin Development Authority (GCDA), and Kochi Municipal Corporation (KMC), Government of Kerala, for their guidance and assistance in accessing essential official data for this research. Finally, thanks to the Polytechnic University of Turin and the Interuniversity Department of Territorial Sciences, Projects and Policies for the opportunity to conduct the research as part of the author's master's degree thesis.

**Conflicts of Interest:** The authors declare no conflicts of interest. Anyone other than the authors had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## Abbreviations

| | |
|---|---|
| CBD | Central Business District |
| CDP | City Development Plan |
| CRU | Climate Research Unit |
| DEM | Digital Elevation Model |
| IPCC | Intergovernmental Panel on Climate Change |
| IUCN | International Union of Conservation of Nature |
| GCDA | Greater Cochin Development Authority |
| GIDA | Goshree Islands Development Authority |
| GIS | Geographic Information System |
| KMC | Kochi Municipal Corporation |
| LID | Low Impact Development |
| LSG | Local Self-Governing |
| NBS | Nature-Based Solutions |
| SROI | Social Return on Investment |

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