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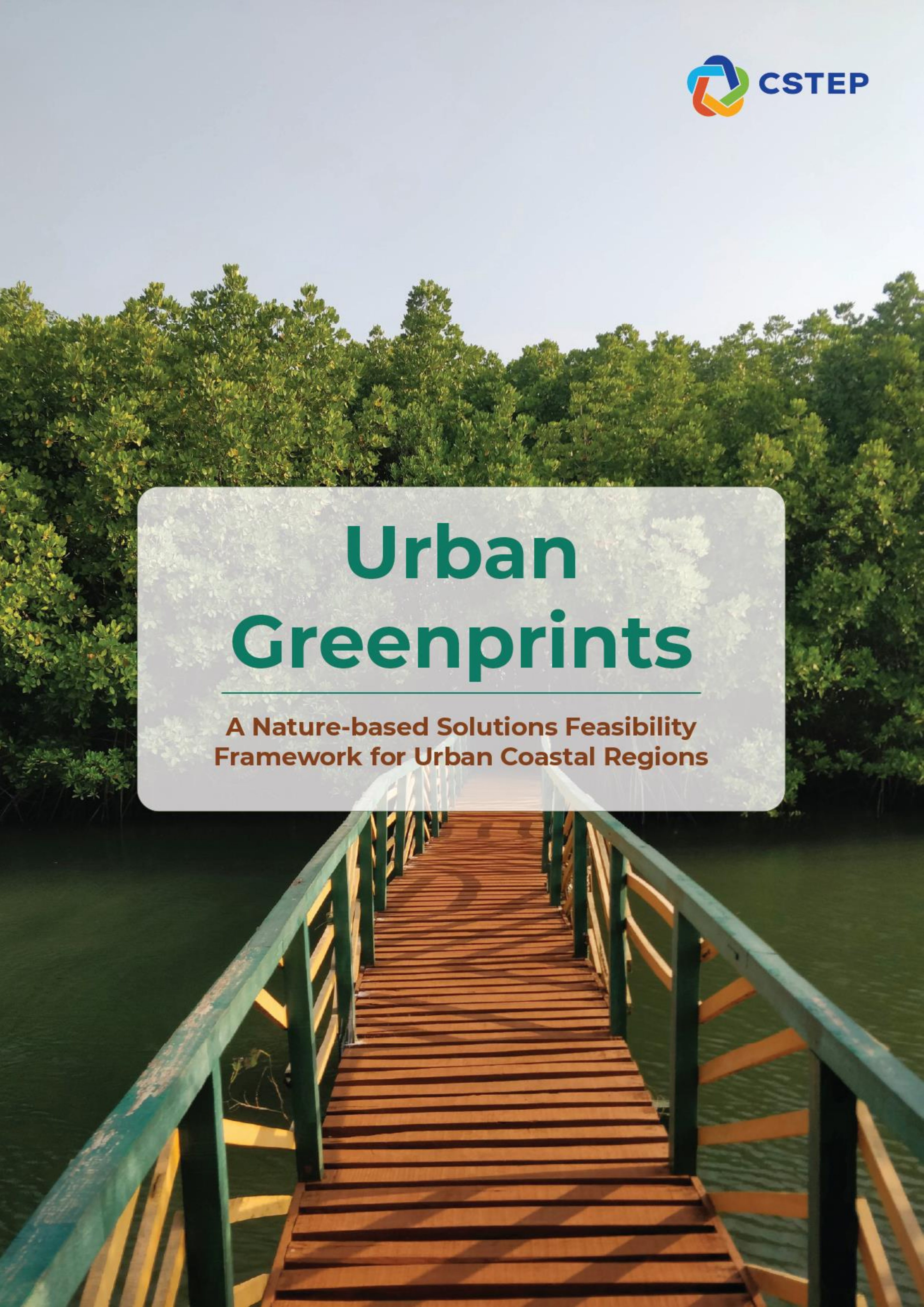

Urban Greenprints

A Nature-based Solutions Feasibility Framework for Urban Coastal Regions

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‘Nature Knows Best’ - Barry Commoner, *The Closing Circle*

In a world being increasingly shaped by climate change, Commoner's words speak to the profound wisdom embedded in natural systems. Nature-based solutions (NbS) offer sustainable and adaptive approaches to urban climate challenges. This report is part of an ongoing effort to build the evidence base for NbS, emphasising the urgent need for a collaborative, all-hands-on-deck approach to embedding nature in urban development. As cities around the world face mounting climate risks, integrating NbS is not just a possibility—it is an imperative for creating sustainable and resilient urban futures.

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Executive Summary

This study proposes a nature-based solutions (NbS) feasibility framework to help Indian cities, particularly urban coastal regions, systematically assess and implement climate resilience strategies. Chennai (Tamil Nadu) and Mangaluru (Karnataka) were selected as case studies because of their exposure to flooding, sea level rise (SLR), and extreme weather events.

Overall, 23 wards covering 64.35 sq km in Chennai and 4 wards spanning 15.75 sq km in Mangaluru were analysed for their NbS potential using land use and land cover (LULC) mapping. Key intervention zones included residential areas, public spaces, transportation corridors, and blue-green infrastructure. Rooftops in residential zones present major opportunities for green infrastructure, with a potential increase in NbS areas of 76% in Chennai and 80% in Mangaluru. Permeable pavements in transport corridors could improve urban drainage, offering a 5% increase in NbS areas in both cities. Additionally, water bodies in select wards can be fully leveraged for wetland restoration and buffer zones.

A decision matrix ranked 13 NbS types based on ecosystem benefits, land requirements, and effectiveness of urban coastal adaptation. High-ranking solutions include mangroves and bioretention areas, while green roofs and permeable pavements offer practical options for space-constrained areas.

A cost–benefit analysis was conducted for two interventions: intensive green rooftops and permeable pavements. The results estimate that investing INR 2,203 crore in NbS for Chennai could yield INR 505.31 crore in annual avoided damages, paying for itself in just over 4 years. Without intervention, Chennai risks INR 10,000 crore in climate-related damages over the next 2 decades. In Mangaluru, an NbS investment of INR 172.97 crore could prevent INR 11.62 crore in damages annually, breaking even in 15 years and turning cost-positive by Year 27 owing to smaller-scale interventions. While Mangaluru's payback period is longer, the long-term benefits in resilience, flood mitigation, and sustainability make NbS a sound investment.

While the findings present a conservative estimate of benefits, they highlight the potential for significant long-term gains. As climate change intensifies, NbS will play a crucial role in mitigating risks and fostering sustainable urban development. Policymakers, urban planners, and stakeholders must prioritise NbS to maximise their ecological and socio-economic benefits, ensuring climate-adaptive urban growth.

Legislative and policy impetus for Nbs In Tamil Nadu and Karnataka

↓

Coastal urban focus: Chennai (Tamil Nadu) and Mangaluru (Karnataka)

↓

Study wards: 23 in Chennai and 4 in Mangaluru

Selected based on exposure to coastal flooding (CSTEP, 2024) and pluvial flooding due to storm surge

↓

13 NbS applicable in study wards

Shortlisted from 45 NbS types (World Bank, 2020) relevant to the context

↓

Calculation of maximum area amenable for Nbs interventions in study wards

Land-use categorisation: approximate green and blue coverage, asphalt areas, and residential rooftop areas

↓

Decision matrix to narrow down 4–6 NbS types in study wards

Based on ecosystem service benefits, land requirement, and effectiveness towards urban coastal adaptation

↓

Design and quantification of flood mitigation potential in study wards

↓

Cost–benefit analysis for two most common NbS types in study wards (green rooftops and permeable pavements)

↓

Roadmap for maximising the uptake of NbS in the two cities

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Abbreviations

AMRUT	Atal Mission for Rejuvenation and Urban Transformation
CBA	Cost–benefit analysis
CMDA	Chennai Metropolitan Development Authority
CSR	Corporate social responsibility
ES	Ecosystem services
GCC	Greater Chennai Corporation
GIS	Geographic Information Systems
INR	Indian Rupee
IUCN	International Union for Conservation of Nature
LULC	Land use land cover
ML	Mega-litres
NDVI	Normalised difference vegetation index
NDWI	Normalised difference water index
NGO	Non-governmental organisation
NPV	Net present value
NSDP	Net state domestic product
PALSAR	Phased Array Type L-band Synthetic Aperture Radar
PES	Payments for ecosystem services
PPP	Public–private partnership
SDG	Sustainable Development Goals
SLR	Sea level rise
WHO	World Health Organisation

1. How to read the report

This report serves as the primary document that offers a structured methodology for decision-making around nature-based solutions (NbS) in Indian urban coastal regions.

Report structure:

- **Main Report:** The core document presents the NbS feasibility framework, case study findings from Chennai (Tamil Nadu) and Mangaluru (Karnataka), and key recommendations for enhancing urban resilience.
- **Addendum 1:** It provides an overview of the policy and governance contexts within which NbS operate. It focuses on Tamil Nadu and Karnataka, covering state legislations, city profiles (Chennai and Mangaluru), and relevant case studies to illustrate NbS uptake and regional momentum.
- **Addendum 2:** It offers a detailed justification for the NbS decision matrix, along with ward-level context assessments for the 27 wards that informed the decision-making framework.

How to navigate this report:

- **For policymakers and urban planners:** Focus on the Main Report for key findings, policy implications, and strategic recommendations
- **For technical experts and researchers:** Refer to the Addenda and Appendices for detailed analyses, methodological insights, and ward-level assessments
- **For practitioners and project implementers:** Use the NbS decision matrix and case studies to inform site-specific interventions and implementation strategies

The Compendium of Nature-based Solutions for Coastal Adaptation (CSTEP, 2024a) complements this report by offering a structured knowledge base for scaling up NbS in urban coastal regions. It aligns NbS strategies with Sustainable Development Goals (SDGs) and existing policy frameworks while providing case studies, implementation insights, and policy recommendations.

Together, this report, addenda, and compendium serve as essential resources for cities aiming to mainstream NbS into climate adaptation and urban resilience planning. Readers are encouraged to engage with these documents holistically to develop science-backed, context-specific NbS interventions that support climate-adaptive and sustainable urban growth.

2. Introduction

Our planet is grappling with complex and unprecedented environmental and climate challenges. Human-induced global warming increases temperature; alters rainfall patterns; and intensifies the frequency and severity of extreme weather events, including heatwaves, droughts, storms, and floods. India's average temperature increased by about 0.7°C between 1901 and 2018 (MoEFCC, 2022). The rise in temperature is primarily because of anthropogenic aerosols and changes in land use and land cover. The rainfall extremes (>150 mm per day) increased by nearly 75% between 1950 and 2015, and the frequency and spatial extent of droughts also significantly increased during this period (MoES, 2021). According to the Indian Meteorological Department (2023), the duration of heatwaves in India has extended by approximately 2.5 days from 1961 to 2021, and climate projections suggest that heatwaves could become 12 times more frequent by the 2040s due to climate change (Pandey & Sengupta, 2023).

Unchecked urban expansion has led to rampant land-use and land-cover change, along with deforestation and reduction in green spaces, exacerbating the impacts of climate change. For instance, the loss of vegetative cover and wetland ecosystems in urban areas has intensified the urban heat island effect and increased the vulnerability of communities to flooding and water scarcity. This disproportionally impacts marginalised groups, particularly those residing in informal settlements that lack adequate infrastructure or access to resources, thereby compounding socio-economic inequities.

Tier 1 coastal cities, such as Mumbai and Chennai, face more complex challenges owing to higher population densities and infrastructure demands, while Tier 2 cities, such as Kochi and Mangaluru, are starting to face similar climate risks but with more opportunities for intervention. With growing populations and economic activity, these cities demand more land and resources, leading to greater stress on ecological capital and natural systems. The associated socio-economic factors, such as migration, housing shortages, and unequal access to resources, further contribute to the systemic vulnerabilities of urban regions. In the face of these interlinked challenges, it is essential to adopt solutions that integrate ecological restoration, urban planning, and social resilience. This study focuses on exploring nature-based solutions (NbS) as adaptive strategies to address urban climate challenges while considering the socio-economic and environmental dimensions that shape urban resilience.

2.1. What are NbS?

NbS is an emerging concept that can help address some of the urban challenges holistically. Indian cities face pressing issues such as urban flooding (Jain & Singh, 2023), air pollution (J. Singh et al., 2020), and biodiversity loss in metropolitan areas (Singhal & Kumar, 2020), making NbS particularly relevant. NbS are strategic approaches defined by the International Union for Conservation of Nature (IUCN) as actions that 'protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously benefiting people and nature' (Cohen-Shacham et al., 2019; IUCN, 2020). In India, NbS approaches including watershed management programmes (Reddy et al., 2017) and coastal wetland restoration (Debnath et al., 2024) exemplify this definition. NbS aim to harness the inherent capabilities of ecosystems to help solve critical issues such as climate change, disaster risk reduction (Ravindranath, 2019), food and water security (Reddy, 2021), biodiversity loss in ecological hotspots (Chaturvedi et al., 2020), and human health, which are pivotal to sustainable development (Tye et al., 2022).

The term 'NbS' encompasses a variety of concepts including nature-based infrastructure, natural climate solutions, and ecosystem-based adaptation, each aligned with specific organisational mandates and focusing on different aspects of environmental and societal benefits. These terminologies, along with others such as Building with Nature and Engineering with Nature, reflect the diverse applications of NbS across global and Indian contexts. Notable examples in India include Chennai's stormwater management system (Palanisamy et al., 2020), the Ganga River restoration project (R. Singh & Singh, 2020), the restoration of mangrove forests to safeguard coastlines from storm surges and erosion, as seen in the Sundarbans (Mukherjee & Siddique, 2024), the creation of urban green spaces in Bhubaneswar to combat heat island effects (Garg, 2024), and the adoption of agroforestry in arid regions of Rajasthan to enhance ecosystem services (ES)[1] (R. Singh et al., 2024). These solutions underscore the importance of healthy ecosystems in providing multiple societal benefits.

For a deeper understanding of NbS concepts, their specific applications, including nature-based coastal adaptation and integrated coastal zone management, refer to CSTEP's Compendium of Nature-based Solutions for Coastal Adaptation (CSTEP, 2024a).

[1] Ecosystem services are the benefits humans gain from ecosystems, including resources such as food, water, and timber; regulating services affecting climate, floods, and water quality; cultural services offering recreation and spiritual value; and supporting services such as soil formation and nutrient cycling. Despite cultural and technological buffers, humans depend on these ecosystem services (MEA, 2005).

2.2. NbS in coastal Indian cities

Indian coastal cities are grappling with the dual challenge of actively devising strategies to address climate hazards, such as heatwaves, flooding, sea level rise, and coastal inundation, while addressing their disproportionate impacts on vulnerable populations, particularly the urban poor and coastal communities. These populations often rely on climate-sensitive sectors for their livelihoods, including fishing, subsistence agriculture, and informal labour markets, which are highly susceptible to disruptions caused by climate variability (Dhiman et al., 2019; Kumar et al., 2024; Malakar et al., 2021) For instance, frequent flooding and storm surges can damage homes, disrupt transportation networks, and destroy fishing boats or crops, directly impacting income and food security. Moreover, prolonged heatwaves can exacerbate health risks for outdoor labourers, reduce productivity, and increase energy costs, further burdening low-income households.

Revised Coastal Regulation Zone norms are in place to limit development near coastlines and promote the conservation of critical ecosystems such as mangroves and wetlands, which not only serve as natural flood defences but also help sustain livelihoods through fisheries and eco-tourism (MoEFCC, 2019). However, the enforcement of these regulations often leads to restrictions on land use and informal settlements, disproportionately affecting the urban poor who reside in these vulnerable areas. Major cities including Mumbai, Chennai, and Kolkata are enhancing resilience through infrastructure improvements including upgraded drainage systems, sea walls, and cyclone-resistant shelters to withstand extreme weather events (Brihanmumbai Municipal Corporation, 2022; Bruhat Bengaluru Mahanagara Palike, 2023; Greater Chennai Corporation, 2022; Kolkata Municipal Corporation, 2022). However, such measures are sometimes misaligned with the socio-economic realities of the most vulnerable, limiting their accessibility and effectiveness in safeguarding livelihoods.

Community-based adaptation approaches, such as mangrove restoration and participatory wetland management, are gaining traction in the Indian context. These initiatives not only bolster natural defences against floods (López-Portillo et al., 2024) but also create employment opportunities and improve ES, directly contributing to the resilience of vulnerable populations. Further, technological advancements such as remote sensing and Geographic Information Systems (GIS) are utilised to map vulnerable areas and implement real-time monitoring systems for early warnings about cyclones and floods, improving the preparedness and response capabilities of communities against disasters.

Despite these efforts, significant challenges persist, including the lack of comprehensive risk assessments that consider livelihood vulnerabilities, suitability and integration of NbS into urban development plans, and inadequate funding mechanisms for adaptation projects. Further, there is often a disconnect between policy development and actual implementation, hindered by complex inter-departmental coordination.

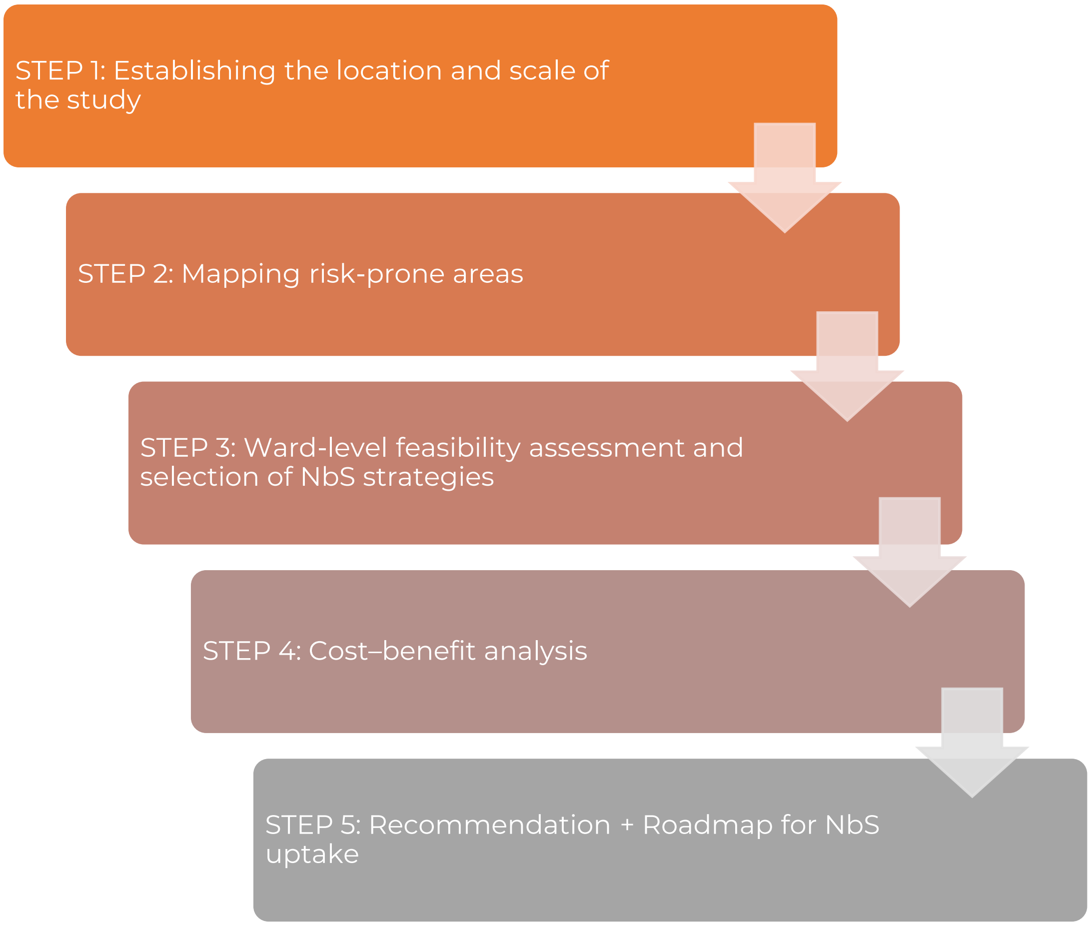
The existing challenges underpin the need for a comprehensive NbS feasibility framework to systematically evaluate the potential and scalability of NbS and to ensure that these strategies are integrated into broader environmental and developmental policies. To address these gaps, this study undertakes the development of an NbS feasibility framework at the ward level in Chennai, Tamil Nadu, and Mangaluru, Karnataka. The framework aims to incrementally evaluate the suitability, scalability, and socio-economic co-benefits of NbS. The specific objectives of the study were as follows:

- Review ongoing NbS efforts in Chennai and Mangaluru
- Identify climate risk-prone areas for NbS application
- Develop an inventory of short-to-long-term NbS typologies based on land requirement, adaptation, and ES benefits
- Perform a cost–benefit analysis (CBA) of select NbS typologies
- Develop actionable recommendations and a roadmap for improved NbS integration to build resilience in coastal urban areas, with a particular focus on safeguarding the livelihoods of vulnerable populations

3. Methodology

The methodology adopted for this study is designed to facilitate a data-driven and evidence-based process, ensuring a scalable and replicable methodology across similar contexts. The key steps are presented in Figure 1.

Figure 1. Overview of the study methodology



3.1. Step 1: Establishing the location and scale of the study

The first step in developing a robust NbS framework is to establish the appropriate location and scale of the study. Cities offer significant potential for NbS and could benefit from enhanced air quality, improved water management, and strengthened climate resilience. Many urban areas also have the necessary governance structures and planning strategies to integrate NbS into their development agendas. According to the 74th Constitutional Amendment Act (1992), municipalities and/or corporations hold the authority to spearhead urban resilience initiatives (National Portal of India, 2012). Furthermore, owing to a concentrated population and infrastructure, urban boundaries represent the optimal scale for addressing both climate and biodiversity challenges (McDonald et al., 2023).

In this framework, spatialising challenges are key to identifying where interventions can have the greatest impact (Rudd, 2022). A site, i.e. a specific geographical area owned or controlled by an individual, organisation, or entity, acts as a unit where NbS interventions can be implemented (Mubeen et al., 2021). However, to ensure scalability, it is important to operate at a scale that balances contextual relevance with replicability. Although more detailed site-specific interventions can be beneficial, NbS are increasingly applied at the landscape scale, as recommended by IUCN and other global frameworks, to ensure ecological and social connectivity across regions. However, for practical implementation and replication in urban contexts, ward level is considered as the primary level of analysis for this framework (Bhan & Jana, 2015). It provides sufficient complexity and detailed data while being manageable for replication across both cities, aligning with broader landscape-scale objectives.

3.2. Step 2: Identifying risk-prone areas

The second step involves mapping climate risks in the select urban regions: Chennai (Tamil Nadu) and Mangaluru (Karnataka). A deeper review of literature within the chosen urban boundaries was performed to identify areas prone to urban flooding risk, which could be exacerbated by coastal inundation. In addition, inputs from CSTEP's recent study on sea level rise (SLR) scenarios and inundation maps for Indian coastal cities were considered (CSTEP, 2024b).

3.3. Step 3: Ward-level feasibility assessment and selection of NbS strategies

The process for assessing ward-level feasibility and selecting NbS begins with land-use land-cover (LULC) mapping, which examines green, blue, and grey areas in the selected wards. This helps in identifying potentials for NbS interventions by assessing current land use (Keerthi Naidu & Chundeli, 2023). In the absence of site visits, a virtual visual assessment using Google Earth can help understand key physical features and any ongoing NbS projects reported in the region (Chrysoulakis et al., 2021). This provides an overview of land parcels, infrastructure, and environment-related aspects in each ward.

This is followed by a detailed analysis, wherein land-use data are examined to understand the NbS potential in each ward. The analysis focuses on residential, commercial, and open spaces to develop NbS strategies such as green rooftops or permeable pavements (Monteiro et al., 2023). Key wards are identified for NbS integration according to their land-use pattern and environmental factors.

Based on these assessments, NbS interventions are prioritised in accordance with the specific characteristics of each ward. A decision-making matrix is developed to assess ecosystem benefits, land requirements, and the effectiveness of NbS for urban coastal adaptation (Albert et al., 2021; Barbarwar et al., 2023; Kooijman et al., 2021). This matrix ranks the suitability of NbS strategies for each ward.

Finally, the study quantifies the water detention capacity of NbS interventions (Penning et al., 2023; Rees et al., 2023; Yadav & Goyal, 2022). Water detention capacity refers to the ability of natural or nature-based systems, such as green roofs, wetlands, or permeable surfaces, to temporarily hold and store rainwater, reducing runoff during storms. By calculating the roof area, rainfall depth, and detention capacity, the flood mitigation potential during storms and annually is estimated. This highlights the direct benefits of implementing NbS for urban flood resilience and its impact on reducing economic losses.

3.4. Step 4: CBA of NbS

Unlike the conventional grey infrastructure, evaluating the financial requirements and benefits of NbS for coastal adaptation is complex. NbS costs vary based on factors such as project scope (protection, rehabilitation, or creation) and variables such as labour, materials, land costs, and stakeholder engagement (Atkinson & Mourato, 2008). NbS also deliver benefits such as ES, socio-economic improvements, and disaster risk reduction.

CBA is a key method to assess the economic viability of NbS by identifying direct and indirect costs alongside benefits such as ES and risk reduction (Van Zanten et al., 2023). It assesses both direct benefits (e.g. avoided flood damages and reduced economic losses) and direct costs (e.g. labour, materials, and land acquisition costs). Although indirect benefits such as ES delivery and community resilience are considered critical, they are not monetised or included in this study owing to methodological and data limitations. Challenges of CBA include monetising non-market benefits, often using techniques such as contingent valuation or hedonic pricing (Bonner, 2022; GIZ, 2013).

In this study, a standard CBA for Chennai and Mangaluru was performed to evaluate the economic viability of two major NbS interventions using net present value (NPV), and benefits were calculated based on avoided flood damages and losses in net state domestic product (NSDP) (Das Neves et al., 2023). The results provide an understanding of the economic feasibility of NbS in urban coastal settings while acknowledging that a more comprehensive valuation of ES would enhance future analyses.

3.5. Step 5: Roadmap for NbS uptake

Developing a roadmap for NbS requires a phased approach, drawing from existing literature on urban resilience and NbS implementation (Dhyani et al., 2021; DOI, 2023). The methodology comprises three key phases, each designed with specific goals, actions, and measurable outcomes. Aspects such as the spatio-temporal scale, short- and long-term targets, and local societal analysis are critical for comprehensive planning; however, these require detailed analysis, including stakeholder feedback, insights from government departments, and assessments of financial mechanisms, to determine feasible steps ahead, and these steps were beyond the scope of this study.

The roadmap proposed in this study focuses on providing a general framework for NbS uptake, leveraging insights from literature review to address urban climate resilience challenges. The interventions will be supported by the integration of capacity building and awareness programmes to ensure stakeholder engagement and institutional adoption. Based on increased visibility, the interventions will need to be institutionalised through public–private partnerships and regional collaboration to ensure long-term sustainability. Future studies could explore additional dimensions, such as incorporating vulnerable population concerns and quantifying specific benefits and co-benefits, to further enhance the applicability and effectiveness of the framework.

4. Developing the NbS Feasibility Framework

4.1. Step 1

Two coastal cities, Chennai and Mangaluru, representing the east and west coasts were selected to study significant characteristic challenges (Table 1, Table 2). Chennai, a Tier 1 metropolis with a high built-up density, contrasts with Mangaluru, a Tier 2 city experiencing rapid peri-urban growth (CSTEP, 2024b). These cities were analysed to provide a comprehensive overview of challenges and relevant NbS, offering a robust framework adaptable to urban coastal contexts.

Addendum 1 features a deep dive into NbS legislations and policies in Tamil Nadu and Karnataka to establish a policy premise in the two cities. It also gives an overview of the propensity for nature-based climate adaptation projects, if any. Further, an in-depth understanding of the key stakeholders based on the literature review helps understand the momentum of NbS in the cities.

4.1.1. Chennai, Tamil Nadu

Map of Tamil Nadu with location of Chennai city

Table 1. Geographic and demographic profile: Chennai

Location	Latitude: 12°59'–13°9' N Longitude: 80°12'–80°19' E
Establishment	1688
Area	Chennai Metropolitan Area: 1,189 sq km Chennai District Area: 426 sq km
Administration	Chennai Metropolitan Development Authority
Number of wards	200
Population density	15,840 pax/sq km
Climate type	Tropical savanna climate (Köppen: Aw)
Elevation	6 m above mean sea level
Per capita green cover	14.9% of the city area (2018); 8.5 sq m per person
Challenges	Population growth, urban agglomeration, drastic land-use changes, reduction in agriculture land, wetland and green cover, urban heat island, increase in temperature, erratic rainfall events, flooding, and sea level rise (Jeganathan et al., 2021)

From the NbS case studies, several themes and challenges emerge for the implementation of NbS:

- Coastal and wetland restoration projects such as the Pallikaranai Marshland Restoration are crucial for improving flood management and biodiversity conservation, acting as natural buffers against extreme weather events.
- River eco-restoration initiatives, such as the Cooum River Restoration, focus on cleaning polluted waterways, reforesting riverbanks, and enhancing urban water management to reduce flooding risks and improve ecosystem health.
- Urban green infrastructure projects emphasise integrating parks and green belts into cityscapes to reduce urban heat islands, manage stormwater, and enhance the quality of life.
- Community engagement and local stewardship are gaining recognition, ensuring that ecosystem restoration projects not only enhance biodiversity but also provide livelihoods and socio-economic benefits to local communities.

However, there are gaps in fully realising the potential of NbS for sustainable urban development:

- Initiatives such as the Chennai Urban Farming Initiative are a step toward urban greening, particularly by building rooftop gardens. However, a gap remains in scaling these efforts across the city, especially in low-income neighbourhoods where urban farming can provide both ecological and socio-economic benefits.
- Although rainwater harvesting is legally mandated in Chennai under the Tamil Nadu District Municipalities Act and the Building Rules, there is a gap in consistent enforcement and monitoring, limiting the potential of rainwater harvesting to significantly reduce stormwater runoff during heavy rains (GoTN, 1978).

- There are strong citizen-driven initiatives to restore lakes, ponds, and wetlands in Chennai, but a gap exists in institutionalising these efforts. Without robust government support and long-term funding, many of these restoration projects struggle with maintenance, leading to a lack of continuity in their positive impact.
- Mangroves, particularly in areas like the Ennore Creek and Pulicat Lake, play a crucial role in mitigating urban flooding in Chennai. While restoration efforts are underway, they remain fragmented, often led by local communities and non-governmental organisations (NGOs) without sustained policy or financial backing.

In summary, although Chennai has made significant strides in advancing NbS, key gaps remain in community participation, long-term policy integration, and equitable outcomes. Addressing these challenges is crucial for effectively scaling up NbS and creating a more resilient and sustainable urban environment for the future.

4.1.2. Mangaluru, Karnataka

Map of the state of Karnataka with location of Mangaluru

Table 2. Geographic and demographic profile: Mangaluru

Location	Latitude: 12°52'–12°55' N Longitude: 74°49'–74°53' E
Establishment	1865
Area	170 sq km
Administration	Mangaluru City Corporation
Number of wards	60
Population density	4,260 pax/sq km
Climate type	Tropical monsoon climate (Köppen: Am)
Elevation	22 m above mean sea level
Per capita green cover	41.9% of the city area (Sanjiv, 2023); 8.4 sq m per person (below WHO standards)
Challenges	Urbanisation, unsustainable urban growth, drastic changes in land use, flood susceptibility, and sea level rise (CSTEP, 2024b; Dhanaraj & Angadi, 2022; Kumari et al., 2024)

In Mangaluru, efforts towards the promotion of NbS include the following:

- Projects such as the coastal bioshield at Tannirbhavi that focus on using mangroves and vegetation as natural defences against erosion and flooding (TOI, 2023)
- Lake and rivulet rejuvenation projects aimed at restoring natural water cycles to enhance flood resilience
- Initiatives such as the INTERACT-Bio project with a focus on integrating green spaces into urban areas, improving biodiversity, and reducing urban heat island effects

Key inferences that can be drawn from the implementation of NbS in Chennai and Mangaluru, with respect to the broader challenges, gaps, and opportunities for achieving sustainable urban development, are as follows:

- While government agencies such as the Forest Department and Mangaluru Smart City Limited are leading large-scale NbS projects including the coastal bioshield at Tannirbhavi and Kavoor Lake Rejuvenation, these efforts often remain top-down with limited community involvement.
- Both Chennai and Mangaluru are making progress in using NbS to tackle issues such as flooding and coastal erosion. However, NbS are often treated as add-ons rather than being central to urban planning.
- Various stakeholders, including NGOs, private companies, and international bodies, are vital for providing funding and expertise. However, local needs must be prioritised over external agendas to ensure that solutions are contextually appropriate.
- Many projects face issues with long-term maintenance and monitoring. Systematic evaluations are needed to maintain momentum and ensure lasting benefits.

- NbS projects can improve biodiversity and water quality and create socio-economic opportunities, but benefits are often unequally distributed, leaving vulnerable communities at risk of exclusion.
- Stronger policy frameworks and coordinated governance mechanisms are needed to fully integrate NbS into urban planning. Projects such as INTERACT-Bio show potential, but long-term success depends on more robust institutional support.

In summary, while promising advancements in NbS have been made, there is a need for inclusive governance, stronger policies, and sustained funding to move from isolated initiatives to a more resilient, sustainable urban development model. Addressing these gaps is critical to effectively and equitably scaling NbS.

4.2. Step 2

In total, 23 wards in Chennai and 4 wards in Mangaluru were selected for this assessment (Table 3). Traditionally, elevation-based assessments have been pivotal in identifying low-lying coastal areas, which are vulnerable to flooding during heavy rainfall events and cyclones. The current study delineates possible coastal inundation areas due to SLR in both Chennai and Mangaluru using the Digital Elevation Model from the Alaska Satellite Facility's Phased Array Type L-Band Synthetic Aperture Radar (PALSAR) with a resolution of 12.5 m (CSTEP, 2024). The spatial information from this model, along with data from other reports on pluvial flooding and storm surges in the cities, was used to identify risk-prone areas in both cities.

4.2.1. Chennai, Tamil Nadu

Overall, 23 wards covering an area of 64.35 sq km in North Chennai were selected (Figure 2) owing to their risk of SLR, coastal inundation, pluvial flooding during monsoons, cyclones, and urban microclimate (CSTEP, 2024b; GoTN, 2022; Jeganathan et al., 2016; Ravikumar et al., 2024; Warrier, 2023).

4.2.2. Mangaluru, Karnataka

Four wards, spanning an area of 15.75 sq km in the south of Mangaluru, were selected for a detailed analysis (Figure 3). These wards, namely Panambur, Port, Hoige Bazaar, and Bengre, represent a critical cross-section of the population that is susceptible to climate-related hazards, featuring diverse land-use types that are pivotal for an in-depth analysis for NbS implementation.

Table 3: Selected wards for NbS intervention in Chennai and Mangaluru

Ward number	Ward name	Area (sq km)
Chennai, Tamil Nadu		
1	Kathivakkam	1.747
2	Ennore	2.939
3	Ernavoor	3.187
4	Ajax	2.096
5	Tiruvottriyur	2.337
6	Kaladipet	1.388
7	Rajakadai	7.739
8	Edyanchavadi	0.729
9	Kadapakkam	0.686
10	Theeyambakkam	0.525
11	Manali	0.638
12	Mathur	0.424
14	Puzhal	0.673
15	Puthagram	8.774
16	Kathirvedu	10.105
18	Assisi Nagar 9th St	8.136
21	Kodungaiyur	1.884
37	Sowcarpet	4.133
38	Central	1.815
39	Choolai	1.05
41	Purasaivakkam	0.899
43	Anna Salai	0.999
46	George Town	1.447
Mangaluru, Karnataka		
11	Panambur	10.913
45	Port	1.857
57	Hoige Bazaar	1.36
60	Bengre	1.575

Figure 2: Land-use land-cover map for the 23 wards in Chennai

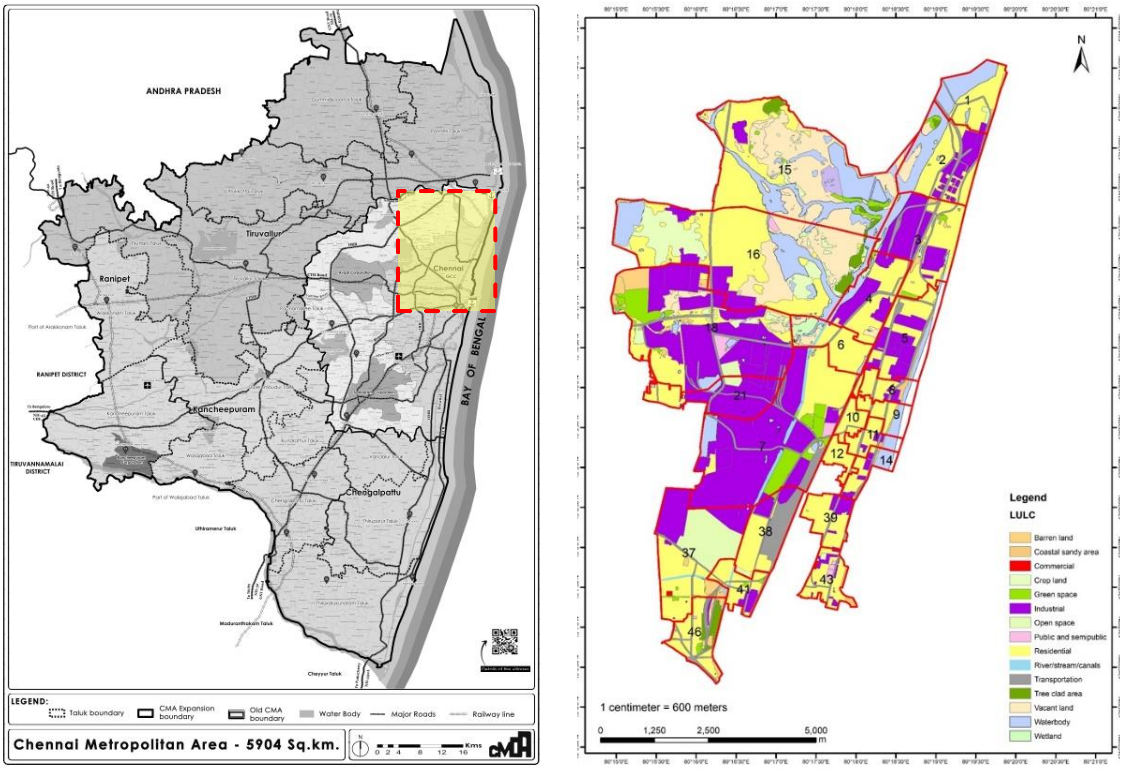
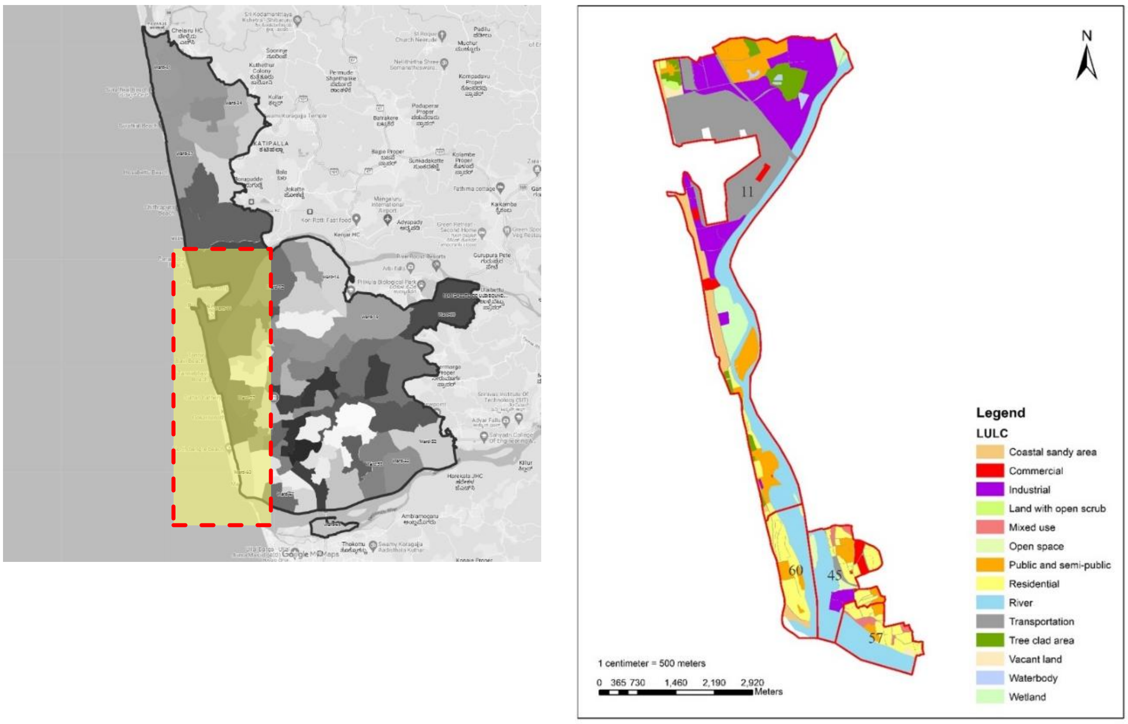


Figure 3: Land-use land-cover map for the 4 wards in Mangaluru



The selected wards are aimed at providing a comprehensive view of the diverse urban and natural environments in the selected cities, enabling targeted interventions to enhance urban resilience.

4.3. Step 3

Using LULC mapping, the study examined green and blue areas, as well as grey infrastructure, to identify opportunities for NbS interventions. By assessing residential footprints, public spaces, and existing infrastructure, the analysis offers insights into how urban wards can integrate NbS to mitigate flood risks.

4.3.1. LULC mapping

In the selected wards, we conducted a visual assessment of the land on Google Earth to understand key physical features of land use. To implement potential NbS, it is critical to understand the permeability of land parcels in the wards. In the absence of field visits, we used a combination of remote sensing, GIS, and Google Earth Engine tools to quantify four distinctive classes of land use:

1) **Normalised difference vegetation index** (NDVI) was used to map green cover regions with the potential to be intensified using NbS (Landsat Missions, 2000). A threshold of NDVI greater than 0.3 helped identify green vegetation areas.

$$NDVI = \frac{(NIR\ -\ RED)}{(NIR\ +\ RED)}$$

2) **Normalised difference water index** (NDWI) was used to map water cover regions with the potential to serve as catchment areas for NbS (B. Gao, 1996). NDWI is effective in distinguishing water from other land covers and uses a threshold greater than 0 to classify water pixels, indicating that areas with more reflected light in the green band than the near-infrared band are likely water.

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)}$$

3) **Open space mapping** was conducted to identify potential permeable areas for NbS interventions. By mapping public parks and open spaces using LULC maps, this approach allowed for the inclusion of non-green cover areas within open spaces, with a likely scope for NbS.

4) **Asphalt mapping** included the approximate calculation of building footprint (rooftop area), road, and pavement areas in the residential land-use class. According to Urban Development Guidelines, circulation area, i.e. pavements and roads occupy 15% of the residential land-use class (IRC, 2018; MoHUA, 2014).

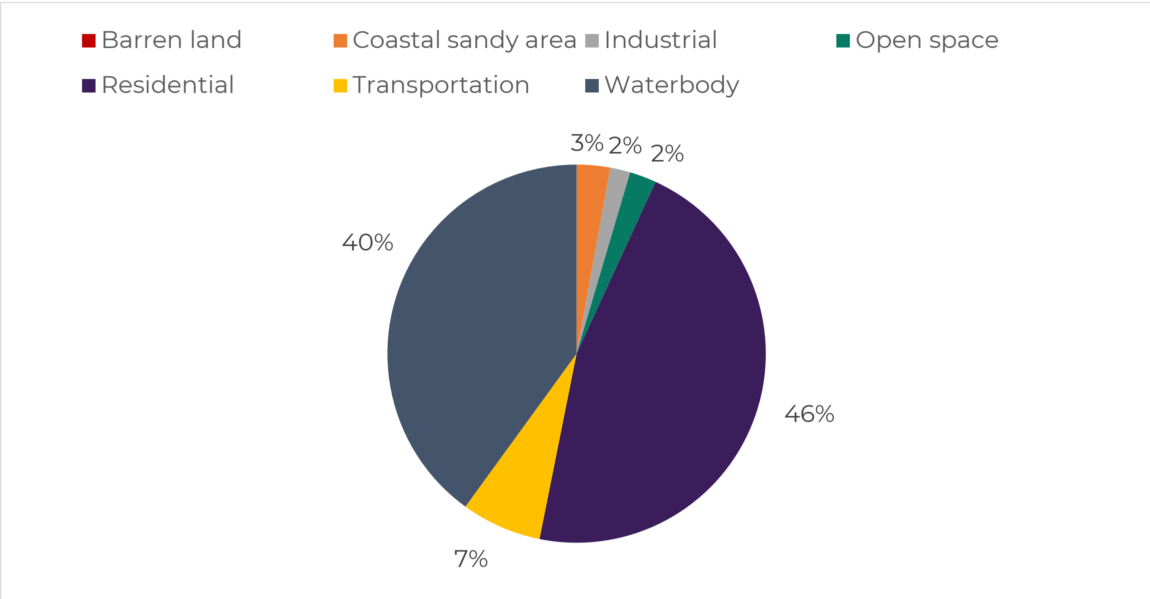
Here an analysis of Ward #01 Kathivakkam in Chennai using the above tools and methods is discussed as an example (Table 4, Figure 4). Areas excluded from the analysis include barren and coastal sandy areas, spanning 3% of the ward area; these areas are either used by fishing communities or already conserved in their natural state, requiring no further interventions. Industrial zones, representing 2% of the ward area, were also excluded owing to verification challenges. Additionally, water bodies, which make up 40.07% of the area and are influenced by Kosasthalaiyar River and Ennore Creek, were excluded from the analysis as they fall under the jurisdiction of the State Government.

Several key insights emerged with respect to land use and the potential for NbS interventions through this analysis. Open spaces, which constitute approximately 2% of the area, were identified as having potential for NbS implementation. The most significant land-use type was residential areas, covering about 46% of the ward, with 39.30% rooftop and 6.93% asphalt areas offering substantial NbS opportunities. Transportation-related land use accounts for 7.11% of the ward, and green areas make up a small portion of around 0.16%.

Table 4. Maximum area suited for NbS interventions in Ward #01 Kathivakkam, Chennai

Land use (sq km)			**Maximum area suitable for NbS interventions (sq km)**			
Net area	Land use	Area	Net rooftop area	Transport area	Blue area	Green area
1.75	Coastal sandy area	0.05	0.69	0.12	0.70	0.04
	Industrial	0.03				
	Open space	0.04				
	Residential	0.81				
	Transportation	0.12				
	Waterbody	0.70				

Figure 4: Breakup of LULC areas in Ward #01 Kathivakkam, Chennai

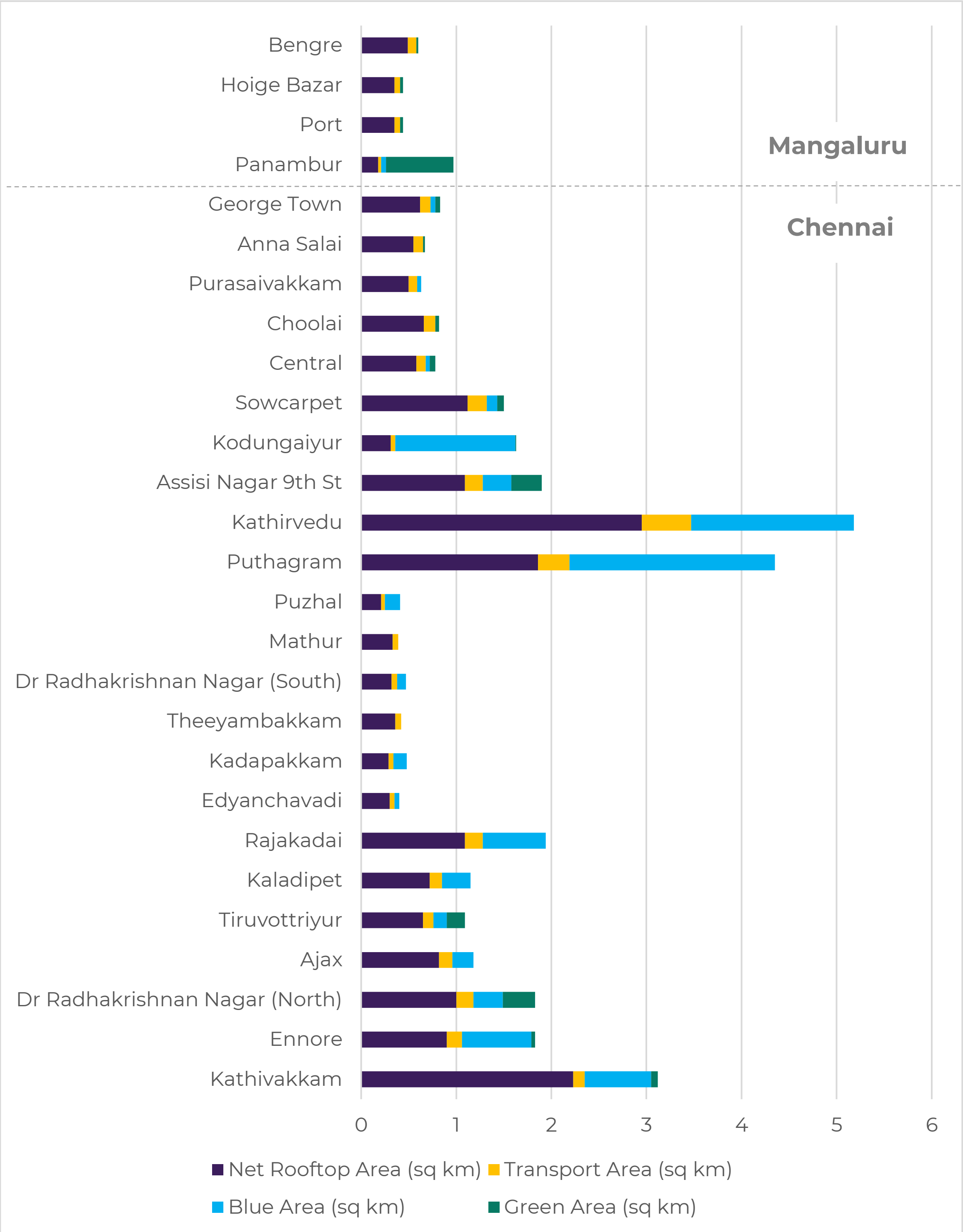


A similar detailed evaluation was conducted for the 27 wards in Chennai and Mangaluru, and the details are provided in Addendum 2. This analysis highlights the potential for integrating NbS interventions, especially in residential and open spaces, to enhance urban resilience against flood risks. An assessment of areas suited for NbS interventions in the identified wards of Chennai and Mangaluru is presented in Figure 5.

It is interesting to note that an analysis of residential areas in the wards reveals rooftop areas as having significant potential for developing rooftop gardens or other green infrastructure such as rain gardens, vertical gardens and urban avenue trees, particularly beneficial in densely built-up areas. The select wards in both cities show potential to scale up NbS on rooftops, with an average improvement in the area ranging from 76% (in Chennai) to 80% (in Mangaluru). The transportation areas, though smaller in proportion, are pivotal for integrating permeable pavements (in alignment with water supply and drainage systems) to enhance water absorption and reduce runoff, crucial for sustainable urban management. In both cities, the increase in NbS in transport areas is more modest, showing an average potential increase of around 5% in area. These interventions, though smaller in scale, are vital for addressing localised urban drainage challenges and leveraging pervasive transport networks for improved water detention. In terms of water bodies, the data show that in both cities, blue areas can be 100% intensified as NbS, wherever applicable offering excellent opportunities for wetland restoration or establishing buffer zones. Further, green areas play a vital role in the urban fabric; in Chennai, where wards have lower ground permeability, shows an average increase in potential NbS area of 48%, whereas in Mangaluru, there is a significant potential to intensify green spaces to develop urban parks or green corridors.

This ward-level analysis pinpoints areas within wards as prime candidates for comprehensive NbS strategies that utilize both the aquatic and terrestrial resources effectively. Conversely, wards with smaller green and blue areas might consider more focused, small-scale projects like green roofs, avenue plantations, or community gardens. Avenue plantations can also help connect scattered parks and gardens across the city, enhancing green connectivity and creating ecological corridors that improve urban biodiversity and resilience.

Figure 5. Comparative assessment of areas suited for NbS interventions in selected wards of Chennai and Mangaluru



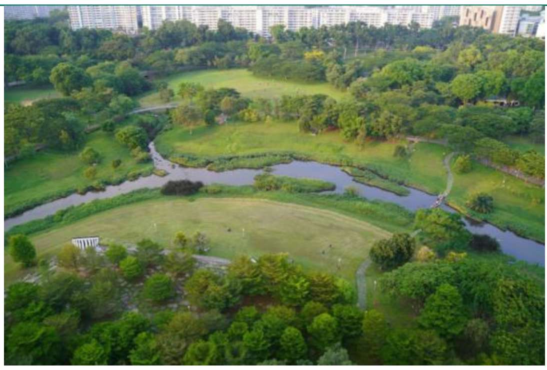
4.3.2. Assessing NbS feasibility

Based on a comprehensive review, 13 NbS for the specific context of this study were chosen, as listed in Table 5.

Table 5: Shortlisted NbS typologies

 *Source: ReefWatch Marine Conservation*	**Artificial reefs:** Constructed from man-made or natural materials, these reefs enhance marine biodiversity and support local economies through recreation and fishing. However, they involve considerable investment and long-term management.
 *Source: Dare County*	**Beach nourishment:** Adding sand or sediment to beaches helps combat erosion and restore beach width, protecting against storm surges and enhancing recreational areas.
 *Source: raleighnc.gov*	**Bioretention areas:** These are essential in regions experiencing heavy monsoonal rains, as features such as bioswales, rain gardens, and permeable pavements effectively help manage stormwater and reduce flood risks.

 Source: *Ashoka Trust for Research in Ecology and the Environment*	**Dune restoration:** Stabilising sand dunes using vegetation and sand fencing protects inland areas from storm surges and wind, acting as natural barriers against environmental impacts.
 Source: *Anna Zakrisson*	**Green roofs:** These systems, installed on building rooftops, help manage building heat and rainwater, offering insulation, reducing heat absorption, and supporting urban biodiversity. Small-scale balcony gardens can also be considered for vertical expansion, providing similar benefits where rooftop space is limited.
 Source: *Sea Grant Florida*	**Living shorelines:** Through the strategic placement of plants, stone, sand, and other materials, these shorelines enhance coastal defences against erosion and provide habitats for marine life, although they require careful design and maintenance.

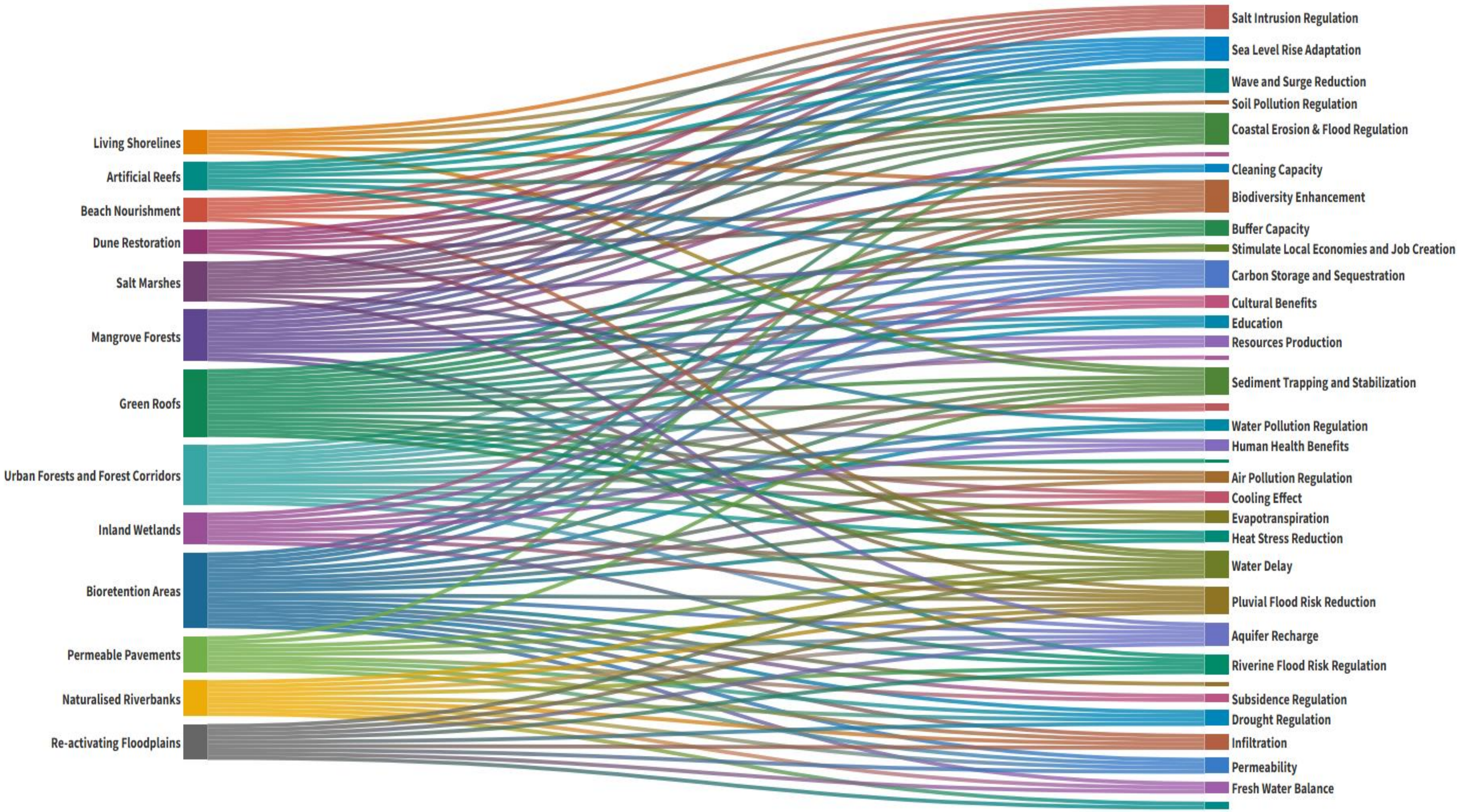
 Source: *Pat Josse / Wikimedia Commons*	**Mangroves:** They are critical for coastal protection, storm surge reduction, and biodiversity enhancement.
 Source: *State of Green*	**Naturalised riverbanks:** River and stream renaturation, including bank and bed stabilisation and stream daylighting, is particularly relevant for enhancing urban water management and supporting biodiversity in estuarine cities.
 Source: *Pavement Network*	**Permeable pavements:** By allowing water to infiltrate surfaces that are traditionally impervious, these pavements reduce runoff and enhance groundwater recharge, which are crucial for managing stormwater in urban settings.
 Source: *South Asia Network on Dams, Rivers and People*	**Re-activating floodplains:** Restoring floodplains to absorb flood waters reduces downstream flood risks and improves water quality but requires significant land and careful management.

 Source: *[Laura Zinke](#)*	**Salt marshes:** These coastal wetlands buffer against storm surges and floods, filter pollutants, and provide breeding grounds for aquatic species, although their restoration can be complex and resource intensive.
 Source: *[U S Fish and Wildlife Service](#)*	**Inland wetlands:** Similar to salt marshes, inland wetlands filter pollutants, store floodwaters, and provide wildlife habitats, essential for maintaining biodiversity and enhancing landscape aesthetics. Small-scale constructed wetlands can also reduce sewage and household waste while recycling water, provided they are integrated with existing ecosystems.
 Source: *[Pasqualino Capobianco / Unsplash](#)*	**Urban forests and forest corridors:** Encompassing urban woodlands, tree-lined streets and avenues, green corridors, parks and gardens, community forests, riparian forest buffers, institutional forests, sacred groves, and playgrounds or recreational areas with green cover, this typology of green spaces enhances urban biodiversity, provides recreational spaces, and helps mitigate urban heat island effects, which are especially important in densely populated cities.

Our study identifies key NbS interventions that provide ES and enhance urban resilience and sustainability. Figure 6 illustrates the interlinkages among the 13 NbS types and ES.

This Sankey diagram illustrates the multifaceted relationships between selected NbS types and the ES they provide. The left side categorises various NbS types, ranging from coastal interventions to urban-focused solutions. The right side lists the broad array of ES, such as climate regulation (e.g. SLR adaptation and carbon sequestration), pollution management (e.g. water and air pollution regulation), biodiversity enhancement, and urban cooling effects. The thickness of the connecting lines indicates the relative strength of each NbS in delivering specific services. This visual underscores the interconnected benefits of implementing NbS, highlighting their multifunctionality across ecological, social, and climate-related domains. It also emphasises the importance of selecting NbS tailored to local challenges and desired outcomes, ensuring maximum ecosystem and societal benefits.

Figure 6. Interlinkages among the select NbS types and ecosystem services



4.3.3. Land requirement for NbS

Although there are no strict universal minimum area requirements for NbS, the necessary area often depends on specific local conditions (Albert et al., 2021; Young et al., 2019), objectives, and the scale of environmental challenges being addressed. It is possible to establish a general range in land area required for specific types of NbS from literature and case studies. This is particularly relevant in urban settings, where land is at a premium, is typically privately owned, and represents the most significant cost for implementation. It is crucial to find a balance between maximising ES, adaptation benefits and optimising land-use efficiency. Table 6 describes the area requirements for the 13 identified NbS.

Table 6. Land area requirements for the 13 identified NbS

Type	Land area requirement
Mangroves	25 hectares upwards (YKAN, 2023)
Living shorelines	Requires moderate space and varies by shoreline stability (NOAA, 2015)
Beach nourishment	Requires 10–30 hectares of beach per km and 30–60-m width (van Rijn, 2011)
Dune restoration	Wider beaches promote dune formation (Nolet & Riksen, 2019)
Salt marshes	Requires 140–280 hectares along India's coastline (Gopi et al., 2019)
Re-activating floodplain	Context-specific area requirements that need careful management owing to conflicts with agriculture and urban development (Serra-Llobet et al., 2022)
Urban forest and forest corridors	Requires 30 sq ft (Miyawaki) up to 10 hectares (Nagar Van) (B.PAC, 2019; MoEFCC, 2017)
Green roofs	Requires a minimum of 10 m^2 (Michalik-Śnieżek et al., 2024)
Bioretention areas	Treats 0.5–1 inch of runoff with 15 ft (W) × 4 ft (H) and 6–8-inch ponding depth (MASSDep, 2011).
Permeable pavements	Replaces existing paved surfaces, requiring ~20 m^2 onwards (Joshi & Dave, 2022)
Inland wetlands	Minimum size: 2.25 hectares and often peri-urban/rural (MOSPI, 2022)
Naturalised riverbanks	Requires 30–300-ft width depending on habitat needs (USDOA, 2020; Wenger, 1999)
Artificial reefs	Minimises spatial conflicts with urban and coastal developments (Reis et al., 2021)

This information helps illustrate the scalability of each solution in terms of the minimum land area required, making it easier to consider implementation in urban settings where space may be limited.

4.3.4. Decision matrix for evaluating NbS feasibility

A decision matrix helps prioritise NbS, considering relevant information on land use, land cover, and other aspects (Albert et al., 2021; Barbarwar et al., 2023; Kooijman et al., 2021). Based on the literature review, three key criteria relevant to the Indian context were identified, namely ES benefits, land requirements, and effectiveness for urban coastal adaptation (IUCN, 2020). Other criteria that require considerable ground truthing prior to being integrated into the decision matrix were not included in this matrix.

ES benefits refer to the ecological contributions provided by a chosen NbS, including biodiversity enhancement, carbon sequestration, water filtration, soil stabilisation, and air purification. The 13 NbS types are ranked as high, medium, or low based on their contribution to biodiversity, carbon storage, and other ecosystem functions. High-ranking NbS (score = 3) support a large number of species (more than 20 per hectare or km), capture at least 3 tons of CO_2 per hectare annually, and provide significant additional benefits such as filtering over 50% of pollutants or absorbing over 50% of stormwater. Medium-ranking NbS (score = 2) support a moderate number of species (10–20 per hectare or km), store 1–3 tons of CO_2 per hectare annually, and offer moderate additional benefits such as filtering 20%–50% of pollutants or absorbing 20%–50% of stormwater. Low-ranking NbS (score = 1) support fewer species (less than 10 per hectare or km), store less than 1 ton of CO_2 per hectare annually, and provide limited additional benefits, filtering less than 20% of pollutants or absorbing less than 20% of stormwater.

Land requirement is ranked based on the amount of space needed for implementing an NbS, considering its suitability for urban and peri-urban areas where land is often limited. The ranking is designed to prioritise solutions that efficiently utilise available land or integrate into existing landscapes. Low land requirement (score = 3) indicates minimal space needs, often integrating into existing infrastructure, such as green roofs or permeable pavements. Medium land requirement (score = 2) applies to solutions needing moderate land, such as bioretention areas or naturalised riverbanks, suitable for semi-urban areas. High land requirement (score = 1) reflects extensive space needs, typically competing with other land uses, such as mangroves or floodplain restoration.

Adaptation effectiveness is ranked based on the capacity of an NbS to mitigate climate risks; enhance resilience; and address challenges such as flooding, heatwaves, erosion, and storm surges. The ranking prioritises solutions that provide scalable, long-term protection against climate impacts. High effectiveness (score = 3) applies to solutions such as mangroves and bioretention areas that address major risks such as flooding or storm surges and offer scalable, long-term resilience. Medium effectiveness (score = 2) includes NbS such as green roofs or living shorelines that manage localised risks such as urban flooding or heat mitigation. Low effectiveness (score = 1) is for solutions such as permeable pavements or beach nourishment, which offer limited or short-term benefits. This ranking prioritises durable and scalable solutions for systemic climate adaptation.

High ES and urban coastal adaptation benefits are more desirable, reflecting a direct, positive impact (Albert et al., 2021; Mallette et al., 2021). Conversely, low land requirement is advantageous, particularly in urban settings where space is scarce and valuable (Prodanovic et al., 2024).

In the matrix (Table 7), each NbS is rated as high, medium, or low across these criteria (refer Appendix 6.1.1). Solutions such as mangroves, which score high in all areas but also require a lot of land, might be less feasible for space-constrained environments (World Bank, 2021). In contrast, interventions such as green roofs offer moderate benefits with minimal land use, making them ideal for dense urban areas. This decision matrix enables a balanced consideration of potential benefits against spatial and logistical constraints, guiding optimal NbS selection for specific local conditions.

Table 7. Decision matrix for evaluating NbS feasibility

Type	Ecosystem service benefits	Land requirement	Adaptation benefits
Mangroves	High	High	High
Living shorelines	Medium	Medium	High
Beach nourishment	Low	High	Medium
Dune restoration	Medium	High	High
Salt marshes	High	High	Medium
Re-activating floodplains	High	High	High
Urban forests	Medium	Low	Medium
Green roofs	Medium	Low	Medium
Bioretention areas	High	Medium	High
Permeable pavements	Medium	Low	Low
Inland wetlands	High	Medium	Low
Naturalised riverbanks	High	Medium	Medium
Artificial reefs	Medium	Low	Medium

4.3.5. Application of the decision matrix in the study wards

A detailed analysis was conducted for 23 wards in Chennai and 4 wards in Mangaluru to assess the suitability of various NbS based on the local urban fabric and diverse land use (Addendum 2). This assessment utilised the decision matrix presented in Table 7. The results are intended to provide a strategic framework for implementing NbS in each ward. Such an approach will ensure the formulation of tailored solutions that reflect each ward's unique conditions, fostering sustainable urban development and climate resilience (Dorst et al., 2021; Narayan et al., 2016; Raymond et al., 2017). This localised focus addresses immediate concerns while contributing to broader environmental and socio-economic goals.

Table 8 presents a sample application of the decision matrix for identifying areas suitable for specific NbS interventions in the Kathivakkam ward in Chennai.

Table 8. Application of the decision matrix in Ward #01 Kathivakkam, Chennai

Net area estimated for NbS interventions			
Usable for green rooftops (sq km)	Usable for permeable pavements (sq km)	Blue area for bioretention spaces (sq km)	Green area for urban forests (sq km)
0.51	0.01	0.70	0.04
Type	ES benefits	Land requirement	Effectiveness for urban coastal adaptation
Urban forests	Medium	Low	Medium
Green roofs	Medium	Low	Medium
Bioretention areas	High	Medium	High
Permeable pavements	Medium	Low	Low

The detailed analysis of NbS across the 27 wards illustrates how local conditions and planning priorities shape the selection and implementation of ecological interventions. Each NbS type—Green Rooftops, Permeable Pavements, Bioretention Spaces, and Urban Forests—serves specific environmental functions and fits into unique urban layouts differently, influencing their adoption in distinct wards.

Based on area estimations and the decision-making matrix, several NbS were identified as particularly feasible for implementation at the ward level:

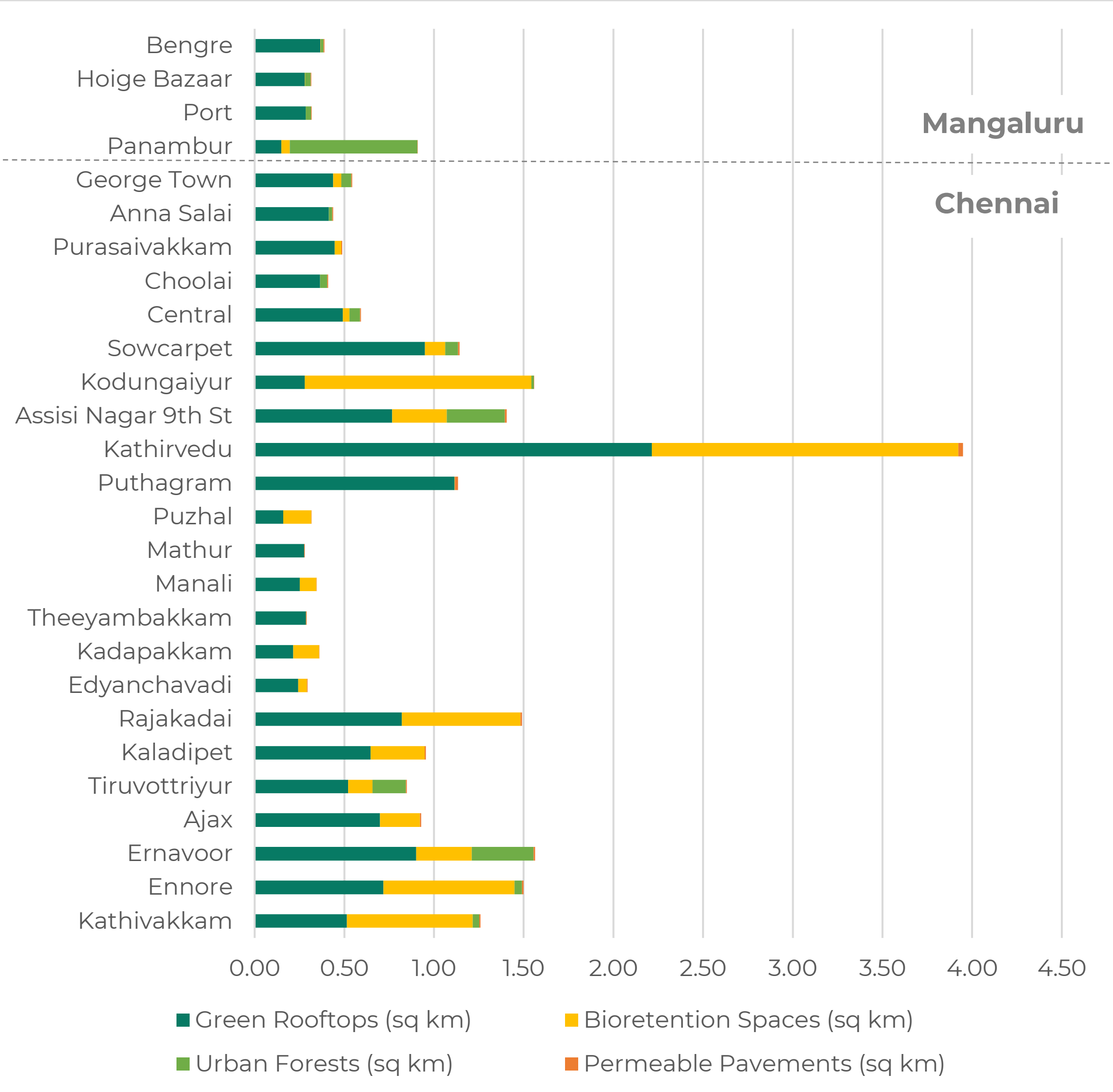
- **Green rooftops:** Predominantly feasible in areas such as Kathirvedu (2.22 sq km), which may have substantial commercial or residential building infrastructure that can support rooftop greening. With medium ecosystem benefits and low land requirements, green roofs have been estimated to be applicable on 25% of the net rooftop area in the ward. This NbS helps in reducing urban heat island effects, managing stormwater (Akther et al., 2018; Paithankar & Taji, 2020), and increasing urban biodiversity. Areas with less dense infrastructure or lower building heights, such as Kumarasamy Nagar, show minimal or no adoption.
- **Permeable pavements:** Generally consistent but low implementation across all wards, with slightly higher implementation in Puthagram and Kathirvedu, indicating minor variations in urban planning that prioritise surface water management and permeability in certain areas more than others. Although these offer low ecosystem benefits, their low land requirement makes them a viable option and have been estimated to cover 5% of the net road area in the residential land use. This intervention helps in managing stormwater and reducing urban heat island effects, although at a smaller scale.
- **Bioretention spaces:** Significantly varied implementation, with the highest implementation in Kathirvedu (1.71 sq km) and a notable presence in Kodungaiyur (1.26 sq km). Positioned in the substantial blue areas in the ward (0.70 sq km), the plan involves utilising all designated water bodies, removing encroachments, and optimising them through detailed, micro-scale designs that improve water quality and reduce runoff. These areas might have specific challenges with water runoff and quality, necessitating larger blue spaces for filtration and groundwater

recharge. Conversely, wards such as Kumarasamy Nagar show no allocation, possibly because of limited space or lower prioritisation of water-related issues.

- **Urban forests:** Showcased prominently in Panambur (0.71 sq km), which may have available land or parks that can be enhanced or converted into urban forests. Institutional green spaces, such as those in universities or research campuses, also offer potential opportunities for intensifying urban forest initiatives, leveraging their relatively stable land use. Anna Salai, George Town, and Central wards host prominent institutional greens. This NbS is crucial for biodiversity, carbon sequestration, and recreational spaces.

Figure 7 presents the net area potentially available across the 27 study wards for specific NbS interventions.

Figure 7. Net area potential (in sq km) for chosen NbS interventions



4.3.6. Quantifying the flood mitigation potential

To effectively quantify the urban flood mitigation (exacerbated due to coastal inundation) potential of NbS in urban settings, it is vital to assess the performance of each solution under specific conditions. For instance, green rooftops can detain about

50%–90% of rainfall, depending on the depth of a substrate and type of vegetation, significantly reducing runoff volume (Alim et al., 2022). Permeable pavements are capable of infiltrating 70%–100% of the rainfall they receive, which varies with the underlying soil and material types (Q. Liu et al., 2021; US EPA, 2015). Bioretention spaces absorb 30%–90% of rainfall through a synergy of soil, plants, and drainage systems (A. I. Shah et al., 2024), while urban forests intercept 10%–15% of rainfall with their canopy, excluding additional absorption by the soil (Kermavnar & Vilhar, 2017; Xiao et al., 1998; Yang et al., 2019).

The formula to calculate the water detention capacity is given below:

$$Water\ detained = \ Roof\ area\ (in\ sq\ m)\ x\ Rainfall\ depth\ (in\ m)\ x\ Detention\ capacity$$

Table 9 presents the water detention capacity (calculated based on standard formulas) resulting from the implementation of different types of NbS in the Kathivakkam ward in Chennai.

During an intense storm scenario with 100 mm of rainfall, the estimated daily water detention for Kathivakkam will be 79.03 mega-litres (ML) per event. Assuming this level of rainfall occurs on 10 days annually, a realistic estimate for Chennai's monsoon season (IMD, 2022), the annual water detention will reach 790.03 ML per year. This substantial volume represents the potential reduction in stormwater that might otherwise contribute to urban flooding. Annually, the Kathivakkam area alone can prevent up to 790.30 ML of stormwater from overloading the city's drainage systems, significantly mitigating the risk of flooding during heavy rainfall.

Table 9. Water detention capacity resulting from NbS implementation in Kathivakkam ward

NbS type	Area (sq km)	Rainfall	Average rain detention	Water detained (ML)
Green rooftops	0.51	100 mm	70%	36.05
Permeable pavements	0.01	100 mm	85%	0.51
Bioretention spaces	0.70	100 mm	60%	42.02
Urban forests	0.04	100 mm	12% (only canopy)	0.44
Total	1.26			79.03

This emphasises the critical need for a wider implementation of diverse NbS across Chennai to enhance the city's resilience against climate-induced extreme weather conditions. By tailoring NbS to local conditions and maximising their ecological and hydrological benefits, cities can not only manage stormwater more effectively but also bolster their overall resilience to climate impacts.

For a much more detailed analysis, green rooftops and permeable pavements were identified as two of the most suited NbS across all wards, and a CBA was conducted for the chosen wards in Chennai and Mangaluru.

4.4. Step 4

The CBA of NbS is based on the NPV of the solutions implemented. NPV measures the difference between the present value of benefits and costs, calculated as follows:

$$NPV = \sum_{t-1}^{T} \frac{B_t - C_t}{(1+r)^t},$$

where

B_t = Benefits in year,

C_t = Costs in year,

r = Discount rate, and

T = Project timeframe (20 years for Chennai and 30 years for Mangaluru).

A positive NPV indicates that net benefits outweigh the costs of implementing NbS, factoring in future benefits (e.g. damages avoided) and initial investments (Das Neves et al., 2023). Although this study focuses on the upfront implementation costs, it is important to note that recurring costs, such as maintenance and operational expenses, can influence the long-term sustainability of NbS. The study used discount rates of 3%, 7%, and 10% to account for variability in time value, risks, and opportunity costs.

For this study, a CBA was conducted for two NbS options identified as the most applicable in both Chennai and Mangaluru: intensive green rooftops and permeable pavements. These solutions mitigate urban flooding, a secondary impact of coastal inundation, while providing co-benefits such as heat reduction and biodiversity enhancement. These NbS are especially relevant for dense urban areas where centralised stormwater systems face space and cost constraints.

4.4.1. Costs

The cost estimates for implementing NbS were derived from LULC maps of residential zones, adhering to Urban and Regional Development Plans Formulation and Implementation guidelines (MoHUA, 2014).

Green rooftops: An average cost of INR 1600/m^2 was used which aligns with market rates of INR 1500–2000/m^2 (Mukherjee, 2014).

Permeable pavements: The cost was averaged at INR 413.34/m^3 within the typical range of INR 400–435/m^3 (Ramkumar & Moorthy, 2019).

The calculated costs for implementing green rooftops and permeable pavements in Chennai and Mangaluru are summarised in Table 10. The total cost for Chennai (23 wards) is INR 2,203 crore, whereas that for Mangaluru (4 wards) is INR 172.97 crore.

Table 10. Cost of implementing NbS in selected wards in Chennai and Mangaluru

	Name	Green rooftops (sq km)	Cost (INR crore)	Permeable pavements (sq km)	Cost (INR crore)
Chennai	Kathivakkam	0.51	82.39	0.01	0.25
	Ennore	0.72	114.98	0.01	0.33
	Dr Radhakrishnan Nagar (North)	0.90	144.06	0.01	0.36
	Ajax	0.70	111.74	0.01	0.30
	Tiruvottriyur	0.52	83.26	0.01	0.24
	Kaladipet	0.65	103.38	0.01	0.26
	Rajakadai	0.82	131.34	0.01	0.40
	Edyanchavadi	0.24	38.73	0.00	0.11
	Kadapakkam	0.22	34.51	0.00	0.10
	Theeyambakkam	0.29	45.71	0.00	0.13
	Dr Radhakrishnan Nagar (South)	0.25	40.36	0.00	0.12
	Mathur	0.28	44.26	0.00	0.12
	Puzhal	0.16	25.43	0.00	0.08
	Puthagram	1.11	178.31	0.02	0.68
	Kathirvedu	2.22	354.40	0.03	1.08
	Assisi Nagar 9th St	0.77	122.54	0.01	0.40
	Kodungaiyur	0.28	44.79	0.00	0.11
	Sowcarpet	0.95	151.83	0.01	0.41
	Central	0.49	78.60	0.01	0.21
	Choolai	0.36	58.34	0.01	0.24
	Purasaivakkam	0.45	71.46	0.00	0.18
	Anna Salai	0.41	66.09	0.00	0.20
	George Town	0.44	69.93	0.01	0.23
	Total		2196.46		6.53
Mangaluru	Panambur	0.15	23.82	0.00	0.06
	Port	0.28	45.41	0.00	0.13
	Hoige Bazaar	0.28	44.57	0.00	0.13
	Bengre	0.37	58.67	0.00	0.18
	Total		172.47		0.50

4.4.2. Benefits

Benefits include avoided damages to assets and economic productivity losses due to reduced flood risks. For estimating avoided damages, asset values (such as buildings, roads, and schools) were calculated using methodologies from Das Neves et al. (2023) and Huizinga et al. (2017). Avoided losses in NSDP per capita were derived based on flood impacts historically recorded in Tamil Nadu and Karnataka (Karthik, 2021; Kumar, 2023).

- Avoided damage to assets: Calculated by identifying assets (e.g. buildings, hospitals, and roads) using OpenStreetMap data and applying damage values (Huizinga et al., 2017).
- Avoided economic losses: Estimated by incorporating historical flood-related damages as a percentage of NSDP:
    - Chennai: Assumes 1% annual loss in NSDP due to floods

Mangaluru: Assumes 0.3% annual loss in NSDP due to floods

Table 11 details avoided damages and economic losses for Chennai and Mangaluru. The total benefits due to NbS implementation amount to INR 505.31 crore annually for Chennai and INR 11.62 crore annually for Mangaluru.

Table 11: Avoided damage to assets and avoided losses in net state domestic product** for selected wards in Chennai and Mangaluru*

	Name	Avoided damage		Avoided loss in NSDP	
		Assets (in sq km)	**Value (in billion INR based on 2019 prices)**	**Inhabitants (as per Census 2011)**	**NSDP per capita per ward (in billion INR based on 2019 prices)**
Chennai	Kathivakkam	0.639	15.14	76,760	11.12
	Ennore	0.992	21.16	66,897	9.69
	Dr Radhakrishnan Nagar (North)	1.256	26.52	52,995	7.68
	Ajax	0.868	20.53	15,186	2.20
	Tiruvottriyur	0.821	15.37	45,204	6.55
	Kaladipet	0.720	18.97	19,523	2.83
	Rajakadai	1.365	24.27	22,161	3.21
	Edyanchavadi	0.305	7.14	33,039	4.79
	Kadapakkam	0.266	6.34	20,306	2.94
	Theeyambakkam	0.384	8.41	44,747	6.48
	Dr Radhakrishnan Nagar (South)	0.319	7.43	33,287	4.82
	Mathur	0.319	8.14	16,254	2.35
	Puzhal	0.246	4.70	35,130	5.09
	Puthagram	1.199	32.70	19,952	2.89

Chennai	Kathirvedu	2.306	64.95	22,947	3.32
	Assisi Nagar 9th St	1.146	22.59	16,424	2.38
	Kodungaiyur	0.432	8.29	16,044	2.32
	Sowcarpet	1.088	27.87	26,491	3.84
	Central	1.270	14.69	35,187	5.10
	Choolai	0.456	10.72	30,573	4.43
	Purasaivakkam	0.584	13.14	21,550	3.12
	Anna Salai	0.500	12.15	15,835	2.29
	George Town	0.437	12.81	12,747	1.85
	Total		404.03		101.28
Mangaluru	Panambur	3.078	5.62	1.55	1.55
	Port	0.571	8.83	1.16	1.16
	Hoige Bazaar	0.334	8.24	1.13	1.13
	Bengre	0.405	10.86	1.33	1.33
	Total		33.55		5.18

*NSDP: Net state domestic product. *Based on Das Neves et al. (2023). **Based on Vicarelli et al. (2022)*

Other assumptions made for the CBA (based on Vicarelli et al., 2022) were as follows:

- The NPV has been estimated for a period of 20 years (Chennai) and 30 years (Mangaluru) from the end of implementation. The rationale is based on the variation in urban planning cycles and the socio-economic contexts of the two cities. For Mangaluru, a longer period was selected to accommodate for slower economic returns and phased implementation in fewer wards than in Chennai.
- The full cost of implementation is paid at Year 0, which is the end of the NbS implementation period.
- A 1% yearly loss in NSDP per capita and assets was considered.
- Until the maturity of the green rooftop in Year 5, there is a progressive increase in benefits (10% in the first year, 20% in the second, 30% in the third, 40% in the fourth and 50% in the fifth).
- The green rooftops reach maturity after 5 years, with full benefits in year six.
- The costs of maintenance, replacements, and lifespan have not been included.
- Additional ES accruing from the implementation of NbS interventions have not been included as benefits.
- Benefits accruing from the implementation of NbS in the identified wards are presented in Table 12.

Table 12: Benefits considered for CBA

	Chennai wards		Mangaluru wards	
Variable	**Total**	**Under NbS scenario**	**Total**	**Under NbS scenario**
Reduction in property damages (annually) in billion INR (based on 2019 prices)	40,402.93	404.03	3,354.36	10.06
Avoided per capita NSDP losses (annually) in billion INR (based on 2019 prices)	10,128.13	101.28	517.66	1.55
	50,531.06	505.31	3,872.02	11.62

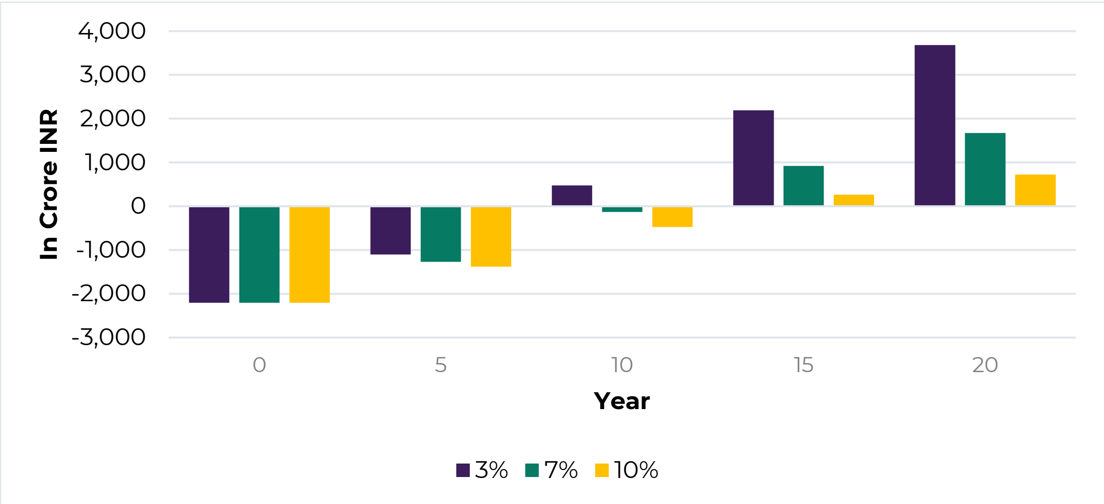
NSDP: Net state domestic product

Discount rates: A discount rate is the rate of return used to discount future cash flows back to the present value. It is used to factor in the time value of money, the riskiness of investment (a lower discount rate implies lower riskiness), and opportunity cost (higher the discount rate, higher the opportunity cost) and to compare different investments. The CBA estimations are performed using three discount rates (3%, 7%, and 10%) to compare outcomes and for robustness check (Greenstone & Stock, 2021). A higher discount rate means that a lower weight is ascribed to the future (Atkinson & Mourato, 2008; Vicarelli et al., 2022).

4.4.3. Results of CBA

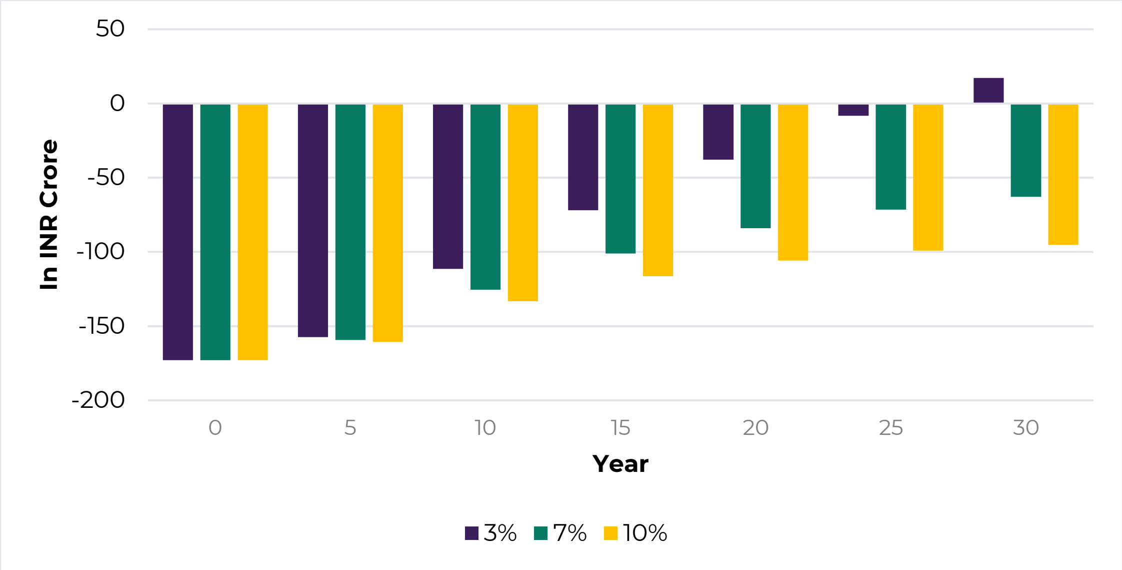
In Chennai, the NPV turns positive by Year 8, at a discount rate of 3%, and by Years 10 and 12 at discount rates of 7% and 10%, respectively (Figure 8). By Year 20, the NPV is estimated at INR 474 crore (3%), INR 108 crore (7%), and INR 9 crore (10%).

Figure 8. Net present value over 20 years for NbS implementation in Chennai.



For Mangaluru, the NPV turns positive later (Year 27), reflecting the lower estimated flood risks (0.3% of NSDP) (Figure 9). At a 3% discount, the net benefit reaches INR 2 crore by Year 30. This delayed payback period highlights the challenges of NbS implementation in smaller scales and regions with lower flood vulnerability.

Figure 9. Net present value over 30 years for NbS implementation in Mangaluru

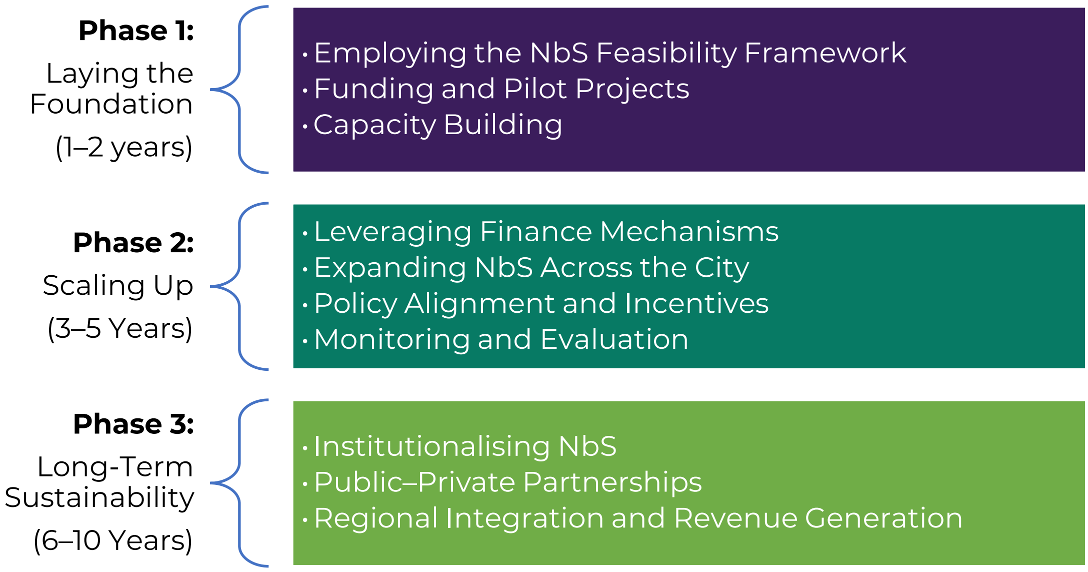


It should be noted that the above estimates are conservative, with benefits expected to be much higher than those considered in this study, and that yearly losses in assets and NSDP per capita are factored in the analysis. In the face of climate change, as the intensity and frequency of floods are expected to increase, the damages are expected to only intensify. Further, in the analysis, only socio-economic benefits in the form of reduced per capita NSDP have been calculated. Owing to data paucity, additional ES benefits have not been incorporated. All of this indicates that the anticipated benefits could considerably exceed the benefits estimated by this analysis.

4.5. Step 5

Figure 10 presents a broad roadmap for the uptake and implementation of NbS in the selected wards in Chennai and Mangaluru. The sections below discuss in detail the process for integrating the three phases of the NbS roadmap in the Chennai and Mangaluru wards.

Figure 10: Roadmap for NbS uptake



4.5.1. Chennai, Tamil Nadu

4.5.1.1. Phase 1: Laying the foundation (1–2 years)

4.5.1.1.1. Employing the NBS feasibility framework

- Apply the NbS feasibility framework to assess vulnerable areas, focusing on zones prone to identified climate impacts. In the case of Chennai, coastal flooding, pluvial flooding caused by cyclones, and heat islands due to dense urbanisation are critical.
- Vulnerable areas such as Ennore, which has high industrial activity and a degraded coastline, should be key focus areas for NbS interventions, particularly for flood risk management. Given its importance for flood mitigation and biodiversity, spatial mapping should identify areas around man-made tanks such as Mylapore and Mambalam and natural reservoirs such as Pallikaranai for restoration and flood mitigation pilot projects (Chella Rajan et al., 2021).
- Spatial mapping will be integral in identifying hotspots where NbS can provide the most significant benefits, ensuring that interventions are data-driven.

4.5.1.1.2. Funding and pilot projects

- In the identified hotspots, pilot projects can begin with high-impact, small-scale interventions such as green rooftops and permeable pavements in densely populated wards such as T Nagar to combat stormwater runoff and mitigate the urban heat island effect. Green corridors connecting parks and open spaces along the Old Mahabalipuram Road and East Coast Road, where urban expansion is intense, will be beneficial.
- These projects will act as proof-of-concept and attract initial funding from government schemes such as the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and Smart Cities Mission; climate funds from the Global Environment Facility and Green Climate Fund; or small grants from environmental NGOs and corporate social responsibility (CSR) initiatives (GEF, 2024; UN News, 2022). Public–private partnerships (PPPs) can also be leveraged at this stage to provide financial support, technical expertise, and stakeholder engagement, particularly to implement pilot projects and co-fund early-stage interventions.

4.5.1.1.3. Capacity building

- Focused capacity-building programmes for local government officials from the Chennai Metropolitan Development Authority (CMDA) and Greater Chennai Corporation (GCC) and residents of flood-prone zones such as Chennai–Kosasthalaiyar basin, Kottivakkam, and Injambakkam to raise awareness about NbS strategies and monitoring practices (ADB, 2021) will be needed.

4.5.1.2. Phase 2: Scaling up (3–5 years)

4.5.1.2.1. Leveraging finance mechanisms

- Leverage CSR budgets from organisations invested in Chennai that can support activities such as mangrove restoration, urban greening, and sustainable water management in high-risk areas including Ennore and Sriperumbudur (Chausson et al., 2023).

- Similar to the Mangrove Bond Initiative by the Hongkong and Shanghai Banking Corporation Limited, Australia, a relevant entity in Chennai could issue bonds specifically for mangrove restoration to protect against coastal flooding (HSBC Australia & Earth Security, 2021).
- Local governments can issue municipal green bonds to fund NbS projects to finance sustainable urban infrastructure and climate adaptation measures (Nykvist & Maltais, 2024).

PPPs can be a pivotal mechanism at this stage, encouraging co-investment from private stakeholders in NbS interventions while providing financial resilience for long-term projects.

4.5.1.2.2. Expanding NbS across the city

- Map ongoing NbS projects at a ward level, and establish an ecosystem approach to integrate and scale up NbS interventions in critical regions.

4.5.1.2.3. Policy alignment and incentives

- Ensure that areas undergoing rapid urbanisation such as Sholinganallur (in the IT corridor) and Perungalathur (in the western peri-urban zone) integrate NbS into all new developments through mandatory green area regulations.

4.5.1.2.4. Monitoring and evaluation

- Implement real-time monitoring systems using GIS, either at a ward level or integrated with the Chennai Disaster Management dashboard in flood-prone and heat-stress areas to track the effectiveness of NbS interventions during the monsoon and summer seasons (GCC, 2024; IUDX, 2021).
- Encourage PPP involvement in deploying advanced monitoring technologies and ensuring that the data is accessible for evidence-based decision-making and adaptive management.

4.5.1.3. Phase 3: Long-term sustainability (6–10 years)

4.5.1.3.1. Institutionalising NbS

- Establish a permanent NbS advisory board within CMDA, and ensure that urbanising zones integrate NbS into long-term urban planning, reducing future risks related to industrial expansion and climate vulnerabilities.

4.5.1.3.2. Building PPPs

- Develop partnerships with real estate developers and industry stakeholders to fund large-scale NbS interventions, particularly in coastal industrial zones.
- Collaborations among government bodies such as the Park Department at the GCC, Tamil Nadu Forest Department, and Tamil Nadu Wetlands Authority and private entities such as Chennai Smart City Limited and Tamil Nadu Green Climate Company can help pool resources for larger-scale NbS projects.

4.5.1.3.3. Regional integration and revenue generation

- Coordinate with neighbouring cities such as Kanchipuram and Chengalpattu to create a regional NbS network, which can help pool resources for larger ecosystem resilience projects and share best practices.
- Eco-tourism should be promoted around green spaces serving as public parks or restored wetlands like Pallikaranai, where guided tours can attract moderated visitors and generate income for its upkeep and maintenance.
- Payments for ES (PES) can incentivise businesses to invest in NbS by paying for benefits such as improved water quality or flood risk reduction (Sangha et al., 2024). In Chennai's coastal industrial corridor, PES schemes could be operationalised by encouraging industries to fund mangrove restoration and wetland conservation projects. These contributions could be linked to tax benefits or compliance with CSR mandates. A localised PES framework (Pagiola, 2008) with oversight from the Tamil Nadu Pollution Control Board and GCC could ensure equitable and effective implementation.
- Generate carbon credits by strategically selecting areas such as degraded lands and urban parks for tree planting using native species. These projects can be certified under standards like the Verified Carbon Standard to ensure credibility. To address implementation challenges, such as the limited uptake in Delhi despite good carbon stocks, a phased approach with baseline assessments, pilot projects, and stakeholder collaboration is recommended to enhance feasibility and uptake.

4.5.2. Mangaluru, Karnataka

4.5.2.1. Phase 1: Laying the foundation (1–2 years)

4.5.2.1.1. Employing the NbS feasibility framework

- Apply the NbS feasibility framework to assess vulnerable areas in Mangaluru, particularly focusing on regions prone to coastal erosion, flooding from storm surges, and increased landslide risks due to the city's hilly topography.
- Vulnerable areas such as Surathkal and Ullal, which experience high coastal erosion, should be key focus areas for NbS interventions aimed at coastal resilience. Spatial mapping should also target areas around Pilikula Lake and Gurupura River for restoration and flood mitigation.
- Use spatial mapping to identify hotspots where NbS can provide significant benefits, particularly in low-lying and densely populated areas such as Pandeshwar and Kottara.

4.5.2.1.2. Pilot projects

- In identified hotspots, pilot projects can focus on high-impact interventions such as building permeable pavements and green rooftops in residential neighbourhoods, e.g. Bendoorwell, to reduce stormwater runoff. Additionally, green corridors can be established along the Netravati River to manage flooding and enhance biodiversity.

- Pilot projects can be funded by government schemes and international climate funding organisations, including the GEF and World Bank, while leveraging small grants from local NGOs and CSR initiatives.

4.5.2.1.3. Capacity building

- Capacity-building programmes should target local government officials from the Mangaluru City Corporation and residents in vulnerable zones such as Hoige Bazaar and Panambur to raise awareness about NbS strategies and monitoring. Involving local communities in the maintenance of projects such as wetland restoration along the Gurupura River will be key to long-term success.

4.5.2.2. Phase 2: Scaling up (3–5 years)

4.5.2.2.1. Leveraging finance mechanisms

- Leverage CSR budgets of organisations invested in Mangaluru's coastal and industrial zones to support activities such as coastal dune restoration and urban greening. For instance, companies in the New Mangalore Port area can contribute to mangrove restoration to protect against coastal flooding.
- Mangaluru could explore issuing green bonds to raise capital for large-scale NbS projects aimed at flood protection and coastal resilience, following examples from global initiatives.

4.5.2.2.2. Expanding the NbS footprint in Mangaluru

- Map ongoing NbS projects at the ward level, and adopt an ecosystem approach to integrate and scale up these interventions in critical regions such as Derebail, Kadri, and Kankanady.

4.5.2.2.3. Policy alignment and incentives

- Ensure that areas undergoing rapid urbanisation, such as Kulur and Baikampady, incorporate NbS into all new developments by enforcing mandatory green area regulations. NbS should also be a central component in Mangaluru's urban master planning process.
- Collaborate with Karnataka's Forest Department to protect and expand forest corridors and mangrove belts along the coast.

4.5.2.2.4. Monitoring and evaluation

- Implement real-time monitoring systems using GIS in areas prone to landslides and coastal erosion, such as Kudupu and Thokottu, to track the effectiveness of NbS interventions and adjust strategies during monsoon seasons.

4.5.2.3. Phase 3: Long-term sustainability (6–10 years)

4.5.2.3.1. Institutionalising NbS

- Establish a permanent NbS advisory board within the Mangaluru Urban Development Authority to ensure that NbS are integrated into long-term urban planning, reducing future risks related to coastal erosion and rapid urbanisation.

4.5.2.3.2. PPPs

- Foster collaborations with local industries, especially the port authority and shipping companies, to fund coastal NbS projects such as dune restoration and living shorelines.
- Develop partnerships with industries located along Bajpe and Surathkal, as well as real estate developers, to fund large-scale NbS interventions that address coastal flooding and urban heat islands.
- Collaborations between government bodies and private entities such as Mangaluru Smart City Limited and regional climate organisations can help pool resources for large-scale projects.
- Explore sustainable tourism opportunities linked to restored mangroves and urban forests to generate revenue for NbS maintenance.

4.5.2.3.3. Regional integration and revenue generation

- Coordinate with neighbouring cities, including Udupi and Kundapura, to create a regional NbS network, sharing best practices and pooling resources for larger ecosystem resilience projects, particularly along the coast.
- Promote eco-tourism around restored green spaces and wetlands such as Pilikula Biological Park, generating income through guided tours that can be used for park maintenance.

5. Policy Implications

This study underscores the economic feasibility and scalability of NbS, such as green rooftops and permeable pavements, for mitigating urban flooding. Key takeaways are given below:

- **Strategic investment in NbS:** With positive economic outcomes, especially in Chennai, integrating NbS into urban planning offers long-term benefits. Policymakers should incentivise NbS adoption in flood-prone and densely urbanised areas.
- **Urban zoning and NbS mandates:** Targeting residential zones for rooftop greening and permeable pavements aligns with national urban planning guidelines. Policies mandating green rooftops in new buildings or incentivising retrofitting can significantly reduce flood risks.
- **Co-benefits:** Beyond flood mitigation, NbS offer urban cooling, biodiversity enhancement, and improved air quality. Recognising these co-benefits strengthens the case for mainstreaming NbS in policy frameworks.
- **Data-driven planning:** Granular data, such as asset-level flood risk maps, are critical for refining benefit estimations and guiding NbS implementation. Policymakers should invest in developing such datasets.

To effectively address climate challenges, India needs to advocate for a robust national policy framework that promotes the preservation of blue infrastructure and ES. This framework should align with the international sustainability goal of SDG 13, which focuses on climate action leading to enhanced resilience to climate hazards. A strong legislative base, similar to the Coastal Regulation Zone notification and Supreme Court judgments on buffer zones, is essential for safeguarding blue-green infrastructure from urbanisation impacts.

Further, integrating stringent environmental regulations into local and national planning processes, such as the AMRUT and Smart Cities Mission, is crucial. Urban models should evolve to incorporate climate-resilient features, ensuring that land-use planning actively prevents environmental degradation and fosters restoration. This approach includes leveraging scientific and hydrological insights to guide urban infrastructure developments towards resilience, such as identifying optimal locations for recharge wells and stormwater management systems.

A shift in perspective among policymakers and urban administrators is essential to prioritise climate resilience, fostered through collaborations between various government departments and NGOs. Engaging local communities from the outset of projects can help ensure that urban resilience projects align with cultural values and address the needs of vulnerable populations, thereby promoting inclusivity and equity in urban planning. By integrating NbS into the urban landscape, cities can exemplify how sustainable liveable environments can be achieved through collaborative, integrated, and community-centric planning.

India's approach to urban development must pivot to include NbS, addressing not just the immediate but also long-term climate risks. This will ensure cities are better prepared for future challenges, making urban environments more liveable, resilient, and sustainable.

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7. Appendices

7.1.1. References for the NbS decision matrix

Type	ES benefits	Land requirement	Adaptation benefits
Mangroves	**High:** 46 crab species and ~60 fish species (Murugan & Anandhi, 2016); carbon: 6–8 tons CO_2/hectare/year (Harishma et al., 2020); 13%–66% wave reduction of over 100 m (McIvor et al., 2012)	**High:** 25 hectares upwards (YKAN, 2023)	**High:** trap carbon-rich particles; foster sediment accretion; and mitigate saline intrusion (Cuenca-Ocay, 2019)
Living shorelines	**Medium:** 10–15 marine and coastal species per hectare; carbon: 1–2 tons CO_2/hectare/year; reduce sediment loss and mitigate erosion; improve water quality by filtering pollutants (Smyth et al., 2022); enhance wave attenuation and sediment deposition (Sekoni et al., 2023)	**Medium:** require moderate space, varies by shoreline stability (NOAA, 2015)	**High:** long-term storm resilience and flood protection (Hernandez et al., 2022)
Beach nourishment	**Low:** limited biodiversity support for shorebirds and intertidal organisms (Kindeberg et al., 2023); temporary erosion control with 10–30 m³ of sand per linear metre (Dean, 2005); habitat creation hindered by sand disturbances (Hart et al., 2023)	**High:** requires 10–30 hectares of beach per km and 30–60-m width (van Rijn, 2011) and sand replenishment needed every 2–5 years (Finkl, 1981)	**Medium:** 10%–20% wave energy reduction during mild storms (Hart et al., 2023); protection reduced by 50% without regular replenishment (de Schipper et al., 2021)
Dune restoration	**Medium:** vegetated dunes reduce erosion by up to 37% (Root biomass) (Figlus et al., 2022); carbon sequestration through ecosystem-specific sequestration (J. Liu et al., 2023)	**High:** wider beaches promote dune formation (Nolet & Riksen, 2019); competes with urban development (Nordstrom, 2021)	**High:** flood mitigation reduced urban flooding by 42% in Sicily (Marino et al., 2023); resilience improves with minimal restoration after 6 years (Johnston et al., 2023); storm protection stabilises coasts; no wave energy data (Linares, 2012).
Salt marshes	**High:** 20–40 species per hectare, supporting fish, shellfish, crabs, and waterfowl (Giuliani & Bellucci, 2019); carbon: 4–8 tons CO_2/hectare/year (Doolan & Hynes, 2023); remove 22% nitrogen and 60% phosphorus, improving water quality (Greene, 2005); reduce wave energy by 30%–50% over 100 m (Vuik, 2019)	**High:** require 140–280 hectares along Tamil Nadu's coastline (Gopi et al., 2019)	**Medium:** flood restoration valued at USD 21 million, increasing with sea level rise (Taylor-Burns et al., 2024); moderately effective but vulnerable to climate change (Eden & Thorenz, 2024)
Re-activating floodplain	**High:** detains 1,500–3,000 m³ of floodwater per hectare (Ibe et al., 2014); supports 10–20 species/hectare, including birds, amphibians, and aquatic species (Schindler et al., 2016); carbon: 1–2 tons CO_2/hectare/year (Dufour & Piégay, 2005)	**High:** requires careful management due to conflicts with agriculture and urban development (Serra-Llobet et al., 2022)	**High:** reduces peak flood discharge by 30%–70% (Opperman et al., 2024); traps 20%–40% sediments and pollutants (Kiedrzyńska et al., 2015); low maintenance, long-term flood mitigation (Serra-Llobet et al., 2022)
Urban forest and forest corridors	**Medium:** host 15–30 species/hectare, including birds and pollinators (Solomou et al., 2019); carbon: 2.12 tons CO_2/hectare/year (Steenberg et al., 2023); reduce temperatures by 1–2°C (Russo & Cirella, 2024); filter 20–50 kg particulate matter/hectare annually (Elderbrock et al., 2023)	**Low:** require 30 sq ft (Miyawaki) up to 10 hectares (Nagar Van) (B.PAC, 2019; MoEFCC, 2017) and reduce rainfall intensity by 42%–50% (Alivio & Bezak, 2023)	**Medium:** mitigate heat islands, stronger in coastal cities (Xu et al., 2024); effective for urban cooling and flooding, limited against large-scale coastal risks (Xing et al., 2024)
Green roofs	**Medium:** reduce rooftop temperatures by 2–4°C (Vourdoubas, 2024); filter 10–30 kg particulate matter/hectare annually (Kostadinović et al., 2023); support 5–10 species per rooftop (Ramesh et al., 2015); carbon: 0.2–0.5 tons CO_2/hectare/year (Rowe, 2011)	**Low:** require a minimum area of 10 m² (Michalik-Śnieżek et al., 2024)	**Medium:** reduce flood volume by up to 62% and runoff by 24% (Bose et al., 2024); decrease peak flow rates by 22%–93% (Y. Li & Babcock Jr, 2014); effective for localised flood management but limited against large-scale coastal risks (Bose et al., 2024)
Bioretention areas	**High:** remove 82% particulates and 83% particulate-bound metals (Croft et al., 2024); carbon: 0.5–1 ton CO_2/hectare/year (Kavehei et al., 2019); and reduce localised temperatures by 1–2°C (Ayutthaya et al., 2023)	**Medium:** treat 0.5–1 inch of runoff with 15 ft (W) × 4 ft (H) and 6–8-inch ponding depth (MASSDep, 2011)	**High:** reduce peak flow by over 80% (Laub et al., 2024); effective for stormwater management in urban coastal areas (G. Li et al., 2021)
Permeable pavements	**Medium:** reduce surface runoff by 30–50% (Zhou et al., 2024); infiltrate 10–20 litres of water/m² during rainfall (Madrazo-Uribeetxebarria et al., 2023); and support soil-dwelling insects such as wild bees and wasps (Weber et al., 2024)	**Low:** replace existing paved surfaces, requiring ~20 m² onwards (Joshi & Dave, 2022)	**Low:** improve drainage efficiency, mitigating localised flooding (Mohamad, 2024); limited to small-scale flood management, not large-scale coastal strategies (Zhou et al., 2024)

Type	ES benefits	Land requirement	Adaptation benefits
Inland wetlands	**High:** support 20–30 species/hectare, including birds and amphibians; detain 500–1,000 m^3 of water/hectare for flood mitigation (Zelnik & Germ, 2023); carbon: 2–4 tons CO_2/hectare/year (Mandishona & Knight, 2022); and reduce nitrogen by 18%–28% and phosphorus by 4%–11% (Peng et al., 2024)	**Medium:** minimum size: 2.25 hectares, often peri-urban/rural (MOSPI, 2022)	**Low:** effective for inland flooding, limited against coastal challenges such as storm surges (Middleton & Boudell, 2023)
Naturalised riverbanks	**High:** reduce bank erosion by 50%–70% (Tisserant et al., 2021); support 20–40 species/km, including riparian flora and fauna; filter 30%–60% of sediments and pollutants (Zawadzka et al., 2019); and carbon: 2–5 tons CO_2/km/year (Yin et al., 2023)	**Medium:** require 30–300-ft width depending on habitat needs (USDOA, 2020; Wenger, 1999)	**Medium:** reduce flood peaks and stormwater runoff (Esraz-Ul-Zannat et al., 2024); effective for riverine systems, limited for coastal flooding (Zagare, 2022)
Artificial reefs	**Medium:** host 10–20 species per structure, including fish and coral colonies (S. Gao et al., 2024; Komyakova et al., 2021); enhance marine habitats and fisheries (Madiedo et al., 2024); and limited carbon sink potential (Shu et al., 2022)	**Low:** minimise spatial conflicts with urban and coastal developments (Reis et al., 2021)	**Medium:** reduce wave energy by 10%–20% (van Gent et al., 2023); buffer mild storm surges, less effective against high-intensity events; require regular maintenance for long-term benefits (Vivier et al., 2021)

7.1.2. Calculation of water detention potential due to NbS

	Ward	Name	Land-use land-cover assessment (sq km)					Area allocated towards NbS (sq km)									Water detention potential (ML)				
			Net area	Rooftop area	Transport area	Blue area	Green area	Green rooftops	Average % increase in potential rooftop area	Permeable pavements	Average % increase in potential transport area	Bioretention spaces	Average % increase in potential blue area	Urban forests	Average % increase in potential green area		Green rooftops	Permeable pavements	Bioretention spaces	Urban forests	Total
Chennai	#1	Kathivakkam	1.75	2.23	0.12	0.70	0.07	0.5150	76%	0.0061	5%	0.7004	78%	0.0368	48%	**An intense storm scenario with 100 mm of rainfall**	36.0475	0.5150	42.0220	0.4414	79.0259
	#2	Ennore	2.94	0.90	0.16	0.73	0.04	0.7186		0.0079		0.7306		0.0414			50.3040	0.6737	43.8333	0.4971	95.3081
	#3	Dr Radhakrishnan Nagar (North)	3.16	1.00	0.18	0.31	0.34	0.9004		0.0088		0.3093		0.3447			63.0260	0.7503	18.5550	4.1368	86.4681
	#4	Ajax	2.10	0.82	0.14	0.22	0.00	0.6984		0.0072		0.2234		0.0000			48.8879	0.6162	13.4014	0.0000	62.9055
	#5	Tiruvottriyur	2.10	0.65	0.11	0.14	0.19	0.5204		0.0057		0.1358		0.1870			36.4276	0.4879	8.1454	2.2441	47.3050
	#6	Kaladipet	1.39	0.72	0.13	0.30	0.00	0.6461		0.0063		0.3020		0.0000			45.2293	0.5384	18.1219	0.0000	63.8896
	#7	Rajakadai	7.77	1.09	0.19	0.66	0.00	0.8209		0.0097		0.6603		0.0000			57.4634	0.8209	39.6173	0.0000	97.9016
	#8	Edyanchavadi	0.63	0.30	0.05	0.05	0.00	0.2421		0.0027		0.0500		0.0000			16.9442	0.2269	2.9986	0.0000	20.1697
	#9	Kadapakkam	0.56	0.29	0.05	0.14	0.00	0.2157		0.0025		0.1436		0.0000			15.0968	0.2157	8.6175	0.0000	23.9300
	#10	Theeyambakkam	0.53	0.36	0.06	0.00	0.00	0.2857		0.0032		0.0003		0.0000			19.9962	0.2678	0.0164	0.0000	20.2804
	#11	Dr Radhakrishnan Nagar (South)	0.60	0.32	0.06	0.09	0.00	0.2523		0.0028		0.0912		0.0000			17.6586	0.2365	5.4729	0.0000	23.3681
	#12	Mathur	0.42	0.33	0.06	0.00	0.00	0.2767		0.0029		0.0000		0.0000			19.3656	0.2441	0.0000	0.0000	19.6097
	#14	Puzhal	0.63	0.21	0.04	0.16	0.00	0.1589		0.0019		0.1575		0.0000			11.1260	0.1589	9.4488	0.0000	20.7338
	#15	Puthagram	8.77	1.86	0.33	2.16	0.00	1.1144		0.0164		0.0023		0.0000			78.0109	1.3931	0.1366	0.0000	79.5405
	#16	Kathirvedu	10.11	2.95	0.52	1.71	0.00	2.2150		0.0261		1.7085		0.0000			155.0514	2.2150	102.5105	0.0000	259.7769
	#18	Assisi Nagar 9th St	8.70	1.09	0.19	0.30	0.32	0.7659		0.0097		0.3049		0.3241			53.6106	0.8206	18.2947	3.8895	76.6154
	#21	Kodungaiyur	3.12	0.31	0.05	1.26	0.01	0.2799		0.0027		1.2628		0.0132			19.5947	0.2333	75.7672	0.1587	95.7539
	#37	Sowcarpet	4.13	1.12	0.20	0.11	0.07	0.9489		0.0099		0.1138		0.0703			66.4254	0.8373	6.8298	0.8438	74.9364
	#38	Central	1.82	0.58	0.10	0.04	0.06	0.4912		0.0051		0.0373		0.0580			34.3867	0.4334	2.2399	0.6965	37.7566
	#39	Choolai	1.05	0.66	0.12	0.00	0.04	0.3646		0.0058		0.0000		0.0396			25.5231	0.4972	0.0000	0.4755	26.4957
	#41	Purasaivakkam	0.90	0.50	0.09	0.04	0.00	0.4466		0.0044		0.0371		0.0000			31.2646	0.3722	2.2275	0.0000	33.8643
	#43	Anna Salai	1.00	0.55	0.10	0.00	0.02	0.4131		0.0049		0.0000		0.0200			28.9145	0.4131	0.0000	0.2401	29.5676
	#46	George Town	1.45	0.62	0.11	0.05	0.05	0.4371		0.0055		0.0459		0.0547			30.5959	0.4683	2.7568	0.6570	34.4780
Mangaluru	#11	Panambur	10.82	0.18	0.03	0.05	0.71	0.1489	80%	0.0015	5%	0.0474	24%	0.7112	99%		10.4222	0.1314	2.8449	8.5349	21.9334
	#45	Port	1.97	0.35	0.06	0.00	0.03	0.2838		0.0031		0.0000		0.0309			19.8658	0.2661	0.0000	0.3703	20.5022
	#57	Hoige Bazaar	1.36	0.35	0.06	0.00	0.03	0.2786		0.0031		0.0019		0.0319			19.5002	0.2612	0.1142	0.3830	20.2585
	#60	Bengre	1.51	0.49	0.09	0.00	0.02	0.3667		0.0043		0.0006		0.0173			25.6695	0.3667	0.0389	0.2072	26.2823

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