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

2.3 Baseline and themed NBS scenarios and site potential maps

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Executive Summary

This report, Deliverable 2.3 titled ‘Baseline and Themed NBS Scenarios and Site Potential Maps’ outlines a systematic and replicable methodology for delineating potential NBS implementation areas for urban water management, considering socio-ecological-technological constraints within cities. It also presents NICHES scenarios as feasibility maps illustrating feasibility levels for different NBS types. These scenarios consider social, ecological, and technological indicators that influence NBS feasibility, categorising areas from entirely feasible to not feasible. Detailed NBS-specific feasibility maps are presented for two of the case study cities, Barcelona and Boston, to exemplify this approach. The presented methodology can be used to assist urban administrations in prioritising and planning NBS implementation to enhance water infiltration and reduce flood risks.

1 Introduction: Scenario development within the NICHES Project

The NICHES (Nature-based Innovation for Climate-resilient Urban Hydrological Solutions) project endeavours to explore and identify innovative solutions in urban water management. Many cities face a growing problem of Combined Sewer Overflow (CSO) due to the increase in heavy rainfall, coupled with drainage infrastructure that mixes stormwater and sewage urban water. During heavy rainfall, which is exacerbated by climate change (Hosseinzadehtalaei et al. 2020, Lana et al. 2020), the combined sewage system reaches its maximum capacity and toxic water flows directly into natural water bodies, resulting in negative health impact, beach closures, impacts on biodiversity, algal overgrowth, hypoxia and aesthetic impacts from floating debris or oil slicks.

To alleviate the social, economic and environmental burden caused by CSO events, NICHES seeks to establish a comprehensive framework for the implementation of nature-based solutions (NBS), using a Social-Ecological-Technological Systems (SETS) approach. NICHES scenarios will help in comprehending the impacts of various NBS implementations in urban stormwater management. These scenarios serve as inputs for modelling changes in runoff volume and variations in water quality in receiving water bodies. Additionally, the project assesses other advantages and trade-offs associated with NBS implementations. The results of hydrological modelling are coupled with supplementary analyses, including a spatial vulnerability assessment, ecological modelling, and evaluations of people's preferences for ecosystem services offered by NBS. These components collectively contribute to the development of an integrated assessment framework and transition pathways for urban stormwater management.

In this context, the NICHES scenarios represent potential future scenarios for implementing diverse NBS solutions. To enhance the practicality of these results, the scenarios are constrained within feasibility boundaries, acknowledging the challenges and limitations within the prevailing SETS (McPhearson et al., 2022).
The urban stormwater SETS encompasses a range of governance structures, social dynamics, actors, hydrological and topographical features, and historically established technological arrangements with existing infrastructures (Chang et al., 2021). Understanding and considering these different SETS components is crucial for effective management.

While scenarios for assessing NBS effectiveness often concentrate on ecological and technological feasibility, we assert that explicitly incorporating social factors that promote or restrict specific developments can yield more comprehensive outcomes. In doing so, we aim to address Anguelovski and Corbera’s (2023) call for a rigorous assessment of NBS's capacity to deliver benefits. At the same time, by assigning different feasibility levels to certain options, we understand current social and governance arrangements as not set in stone. While they make certain developments less likely, societal transformation and changes in political climate might question current governance schemes in the future.
The NICHES project includes three main case studies: the Barcelona Metropolitan Area, Boston, and Rotterdam. Due to time and data availability constraints, this report will focus on presenting the work based on the examples of the Barcelona Metropolitan Area and Boston.

2 Case studies

2.1. Barcelona Metropolitan Area (AMB)

The Barcelona Metropolitan Area comprises the city of Barcelona and 35 adjacent municipalities, spanning over an urban and peri-urban area of 636 km2. The population of this region is 3,239,337 people (2016), with half of the population concentrated in the municipality of Barcelona, which houses 1,608,746 people (2016). The city is situated between the rivers Besós and Llobregat, flanked by the Littoral Range and the Mediterranean Sea. This region is characterised by its intricate urban environment and Mediterranean climate, characterised by mild, wet winters and hot, dry summers. This climatic variability often results in intense, sporadic rainfall events, making the region susceptible to urban flooding and CSO. At the same time, the urbanisation of the Barcelona Metropolitan Area has led to a dense network of impermeable surfaces, such as roads and buildings. The existing drainage infrastructure in many parts of the city combines stormwater and sewage, leading to frequent CSO events during heavy rainfall. These overflows result in environmental pollution, public health concerns, and damage to the urban ecosystem.

The Barcelona Metropolitan Area has been proactive in implementing NBS to reduce the pressure on the combined sewage system and increase the city's resilience to flooding, including green roofs and walls on buildings (Smith et al., 2019), urban parks and green spaces (López-Batlló et al., 2020), restoration and rehabilitation of urban rivers and watercourses (Martínez et al., 2018), or permeable pavements for roads and sidewalks (Sanchez et al., 2017). These NBS initiatives in the Barcelona Metropolitan Area have brought several benefits, including a reduction in the frequency and severity of urban flooding (Jiménez et al., 2016), improvements in water quality in the region's rivers and coastal waters (Gómez et al., 2019) and enhanced urban aesthetics, making the city more liveable and attractive (González et al., 2021). On the other hands, NBS implementation has also encountered challenges, such as space constraints (Pérez et al., 2020), economic costs (Torres et al., 2018), or difficulties in encouraging citizens and businesses to change their behaviour as to adopt and maintain NBS (Rodriguez et al., 2019).

The Barcelona Metropolitan Area's experience underscores the importance of a holistic, integrated approach that involves policy support, public engagement, and continued investment in sustainable solutions (Martínez-Beltrán et al., 2022).

2.2. City of Boston

Boston, the capital city of Massachusetts in the United States, has a population of 650,706 (2022) and spans approximately 125 km2. Located in the northeastern United States, Boston's urban environment is characterised by coastal proximity and variable weather patterns.
Boston is situated along the Eastern Seaboard, experiencing a temperate maritime climate with cold, snowy winters and warm, humid summers. The city is prone to occasional heavy rainfall, leading to urban flooding and CSO concerns, particularly in older areas with combined sewer systems. The city's extensive urbanisation has resulted in the proliferation of

impervious surfaces, including roads, buildings, and infrastructure. A significant part of Boston's urban core still relies on combined sewers, which pose a challenge during intense rainfall events, causing overflows and pollution of local water bodies, including Boston Harbor. Historically, Boston has grappled with harbour pollution, earning the reputation for having one of the most polluted harbours in the US (The Boston Harbor Association, 2014).
Furthermore, about 21 km2 of Boston's shoreline is reclaimed land which is notably low-lying, compounded by the broader issue of coastal Massachusetts sinking at a rate of approximately 1.5 mm per year.

Boston has made considerable efforts to implement NBS to address urban flooding and CSO problems, including an ambitious green infrastructure program that incorporates permeable pavements, green streets, and urban tree canopies (Grossi et al., 2019), restoration of urban rivers and waterways, such as the Muddy River and the Neponset River (Beatty et al., 2018), and implementing living shorelines along the city's coastline (Davis et al., 2020). These NBS initiatives have contributed to a reduction in urban flooding events and their associated impacts (Goldman et al., 2017), improvements in water quality in local water bodies (Peters et al., 2021) and enhancing the city's resilience to climate change (Hoekstra et al., 2018). Nevertheless, some of the challenges encountered in implementing NBS include space constraints (Katz et al., 2019), difficulties to obtain funding (Benjamin et al., 2020) and difficulties to engage the communities to support NBS (Zimmerman et al., 2017).

Boston's experience underscores the importance of long-term planning, policy support, and community involvement in the successful adoption of NBS and is another example of a city aiming to incorporate NBS as part of their comprehensive strategies for sustainability and resilience.

3 Methodology

The NICHES scenarios amalgamate indicators representing social, ecological, and technological characteristics that influence the feasibility of NBS solutions' implementation in specific locations. Individual maps are generated to illustrate the feasibility of implementing different types of NBS.

3.1. Selection of Nature-Based Solutions

Nine NBS were selected for consideration in this study, based on the available Low Impact Development Technologies in the MIKE+ modelling tool. This is the model which will be used in Task 2.4., “Modelling mitigation potential”, with the data resulting from the scenarios produced in this deliverable.

The NBS considered were:

1. Rain Garden

Rain gardens are shallow, landscaped depressions designed to capture, filter, and infiltrate stormwater runoff from impervious surfaces such as roofs, streets, and sidewalks. (Dussaillant et al. 2003; Feldman et al., 2019; Majidi et al.,2019).

2. Bioswale
Bioswales are vegetated, linear channels designed to slow, filter, and direct stormwater runoff. They often line roads or parking lots and serve as an alternative to traditional stormwater drainage systems by transporting rainwater away from critical infrastructure and improving water quality (Florida 2008; Ghadim and Hin 2017; Dinic Brankovic et al. 2019).

3. Vegetative swale
Vegetative swales are planted channels designed to manage stormwater runoff by slowing, filtering, and absorbing rainwater. Often placed along roadsides or in urban areas, they reduce the flow of pollutants into water bodies, improve water quality, and provide additional benefits such as enhancing biodiversity and reducing the urban heat island effect.

4. Porous Pavement
Porous pavement is a permeable surface that allows stormwater to percolate through it into the ground rather than running off into drains. It is used in place of traditional impervious surfaces like asphalt or concrete (Sample et al. 2014; Majidi et al. 2019).

5. Urban Parks
Urban parks are multipurpose green spaces in cities that offer ecological, recreational, and social benefits. Urban parks can also additionally contribute to stormwater management through integrated other NBS types like rain gardens, bioswales, and permeable paths

6. Agricultural land
Agricultural land, as a nature-based solution, refers to areas used for farming that can play a significant role in managing stormwater and enhancing ecosystem services. When managed with sustainable practices, agricultural land can help absorb and filter rainwater, reducing runoff.

3.2. Selection of indicators

We then decided which social, ecological and technological aspects need to be considered, that might impact the feasibility of the implementation of the NBS to come up with a set of indicators. The selected indicators and their suitability for specific NBS applications are summarised in Table 1.

Table 1: Suitability of Indicators for Different NBS

	Social		Ecological			Technological	
INDICATORS	Existing Zoning Policies	Current Land Use	Ground Slope	Soil Permeability	Polluted water for land use	Distance Buildings	Underground Structures

	NBS							
1	Rain garden	✓	✓	✓	✓	✓	✓	✓
2	Vegetative swale	✓	✓	✓	✓	✓	✓	✓
3	Bioretention cell (with underdrain)	✓	✓	✓	x	x	x	x
4	Infiltration trench (with underdrain)	✓	✓	✓	x	x	x	x
5	Porous pavement (with underdrain)	✓	✓	✓	x	x	x	x
6	Urban parcs	✓	✓	✓	✓	✓	✓	✓
7	Agricultural land	✓	✓	✓	✓	✓	✓	✓

In both case study cities, we conducted an examination to determine the availability of spatially explicit indicators. These indicators were then processed and analyzed using software tools such as QGIS and ArcGIS. Below we present all the indicators considered for the cities analysed among the ones identified in the table, and the respective description of the spatial map, as well as of the rationale behind their creation. We categorised the indicator values into three standardised groups, where 0 = not feasible; 0.5 = feasible, but with severe S, E, and/or T constraints; 1: feasible with low SETs constraints.

3.2.1. Social feasibility

a. Existing zoning policies

Description of the raster map:

Feasibility	**Color**	**Value**
1	Green	Parks
0.5	Yellow	No parks

Rationale

Regulatory frameworks can either promote or hinder the implementation of NBS (Zuniga-Teran et al., 2020). For instance, the recently published Metropolitan Urban Planning Directive (PDU) in AMB establishes the regulatory framework and guidelines for urban planning. Any NBS that involves changes in land use not covered by the PDU is considered less feasible, as it necessitates additional regulatory adjustments.

b. Current land use

Description of the raster map

Feasibility	Color	Value
1	Green	Parks
0.5	Yellow	Streets
0	Red	Buildings

Rationale
Changing current land-use has been identified as a barrier to NBS implementation (Johns, 2019). For example NBS are less socially accepted by certain groups in society when they reduce parking lots (Everett et al., 2018). Building on this, we assume that unused land may be easier to transform whereas major changes in function will make a development less likely. Nevertheless, we don’t rule out functional changes as impossible, since changes might lead to perceived benefits and usage patterns can vary in the future.

3.2.2. Ecological feasibility

a. Slope
Description of the raster map

Feasibility	Color	Value
1	Green	Slope < 6°
0	Red	Slope > 6°

Rationale
Slope creates higher runoff speed and prevents infiltration, which reduces the effectiveness of Sustainable Drainage Systems (SUDS). Accordingly the Barcelona SUDS commission recommends a maximum slope of 6° (Comissió de SUDS de l’Ajuntament de Barcelona, 2020).

b. Soil permeability
Description of the raster map

Feasibility	Color	Value
1	Green	Moderately drained, well drained, rapidly drained soil
0.5	Yellow	Imperfectly drained
0	Red	Saturated

Rationale
The choice to use soil permeability parameters as a proxy for the soil's ability to infiltrate water is rooted in the principle that the level of drainage in the soil is inversely proportional to its capacity for water infiltration. In other words, the more effectively a soil can drain excess water, the better it can accommodate the infiltration of water into its structure.

c. Polluted water for land use

Description of the raster map

Feasibility	Color	Value
1	Green	d > 60 m
0	Red	d < 60 m

Rationale

The inclusion of a buffer distance for major roads (highways, primary, secondary, and tertiary) when implementing NBS that do not effectively filter pollutants from water serves the purpose of preventing polluted rainwater from high circulation streets from infiltrating into the soil without adequate filtration. This measure safeguards against soil and groundwater contamination, preventing pollution from affecting these vital resources. The choice of a 60-metre buffer distance is based on a conservative approach, considering the uncertainty of street widths and aiming for a 10-metre buffer on each side of the street, even for larger major roads typically around 40 metres in Spain.

3.2.3. Technological feasibility

a. Distance to buildings

Description of the raster map

Feasibility	Color	Value
1	Green	Above 3m buffer from buildings
0	Red	Within 3m buffer from buildings

Rationale

Increased infiltration and saturation of the soil can lead to damages and destabilisation of buildings and other structural bases. An appropriate distance should thus be kept between newly installed NBS and existing structures (Comissió de SUDS de l'Ajuntament de Barcelona, 2020). This distance is typically chosen depending on the width of the building. Since we could not find available data on building width, we assumed a 3m buffer using the Open Street Map (www.openstreetmap.org) buildings database.

b. Underground structures

Description of the raster map

Feasibility	Color	Value
1	Green	No underground structures
0	Red	Presence of underground structures

Rationale

Similarly, underground infrastructures can get damaged or destabilised by increased infiltration of water and pollutants. Besides, a high density of underground structures and services limits the availability of space for additional underground infrastructure needed for the NBS, such as underdrains (Comissió de SUDS de l'Ajuntament de Barcelona, 2020).

3.3 Scenario Development

The presented flowchart (Fig.1) outlines a systematic approach designed to be replicable in multiple urban settings, making it a versatile tool for urban water management. Considering socio-ecological-technological limitations within cities is essential for developing feasibility maps. Locations where NBS implementation was not feasible were assigned a value of 0, areas where it was absolutely feasible received a value of 1, and those where it was feasible but not likely were assigned a value of 0.5. For our spatial elaborations, we used QGIS and ArcGIS software.

A feasibility map is individually crafted for each NBS and is designed to offer a spatially detailed assessment of the viability of implementing that specific NBS in various locations. The map uses a color-coded system, typically employing green, yellow, and red, to indicate different levels of feasibility and likelihood for implementing the chosen NBS out of the eight considered options.

- Green: Areas highlighted in green on the feasibility map represent locations where the implementation of the NBS is deemed entirely feasible. These areas are well-suited for the selected NBS, requiring minimal interventions or changes to make it a viable option.

- Yellow: The yellow areas signify regions where the NBS is considered feasible but not highly likely. These locations may require more extensive interventions, adjustments, or considerations compared to the green areas to successfully implement the chosen NBS.

- Red: In contrast, the red areas on the map indicate places where implementing the NBS is not deemed feasible. These areas may have inherent characteristics or limitations that make the NBS incompatible or impractical.

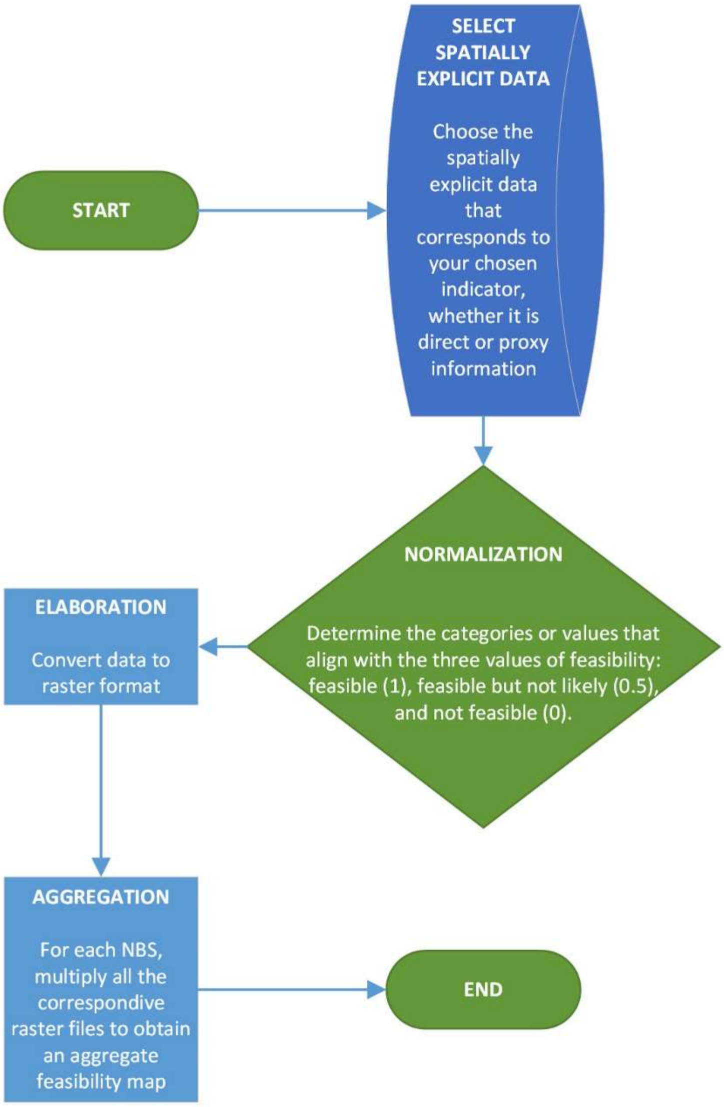

Figure 1: Flowchart of the scenario development methodology

4 Results

For each study site, we present the indicator to the NBS map and the relative feasibility maps.

4.1. Barcelona

For the city of Barcelona, we selected the indicators presented in Table 2, based on data availability. Indicators sharing similar characteristics were grouped as follows:

- 1st group: Rain garden, vegetative swale, urban parks, agricultural land
- 2nd group: Bioretention cell, infiltration trench, porous pavement (all with underdrain)

This resulted in a total of eight feasibility maps. The following maps illustrate the elaboration of both the SET framework and the sub-groups of social, ecological, and technological feasibility.

Table 2: Indicators-NBS correspondence for Barcelona

		Social		Ecological			Technological	
	INDICATORS / NBS	Existing zoning policies	Current land use	Ground Slope	Soil Permeability	Polluted water for land use	Distance Buildings	Underground Structures
1	Rain garden	✓	✓	✓	✓	✓	✓	✓
2	Vegetative swale	✓	✓	✓	✓	✓	✓	✓
3	Bioretention cell (with underdrain)	✓	✓	✓	x	x	x	x
4	Infiltration trench (with underdrain)	✓	✓	✓	x	x	x	x
5	Porous pavement (with underdrain)	✓	✓	✓	x	x	x	x
6	Urban parcs	✓	✓	✓	✓	✓	✓	✓
7	Agricultural land	✓	✓	✓	✓	✓	✓	✓

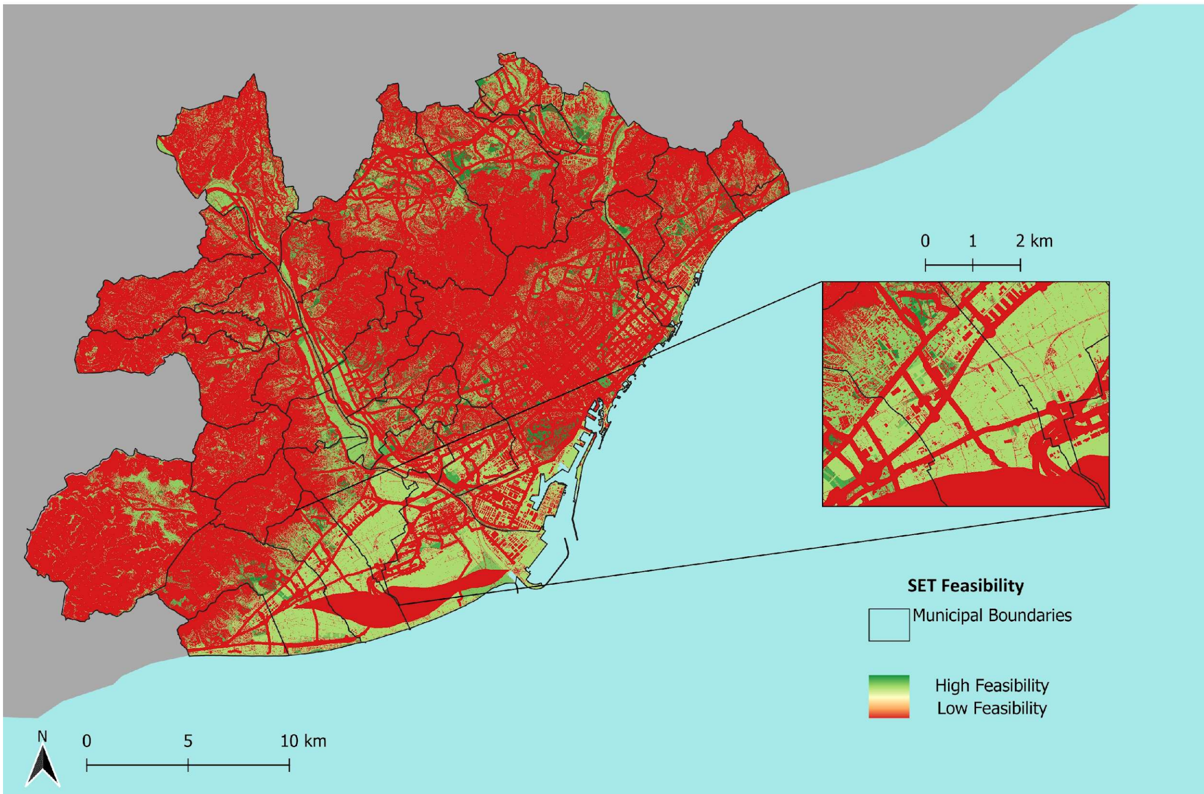

Figure 2: SET feasibility map for NBS (Barcelona): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

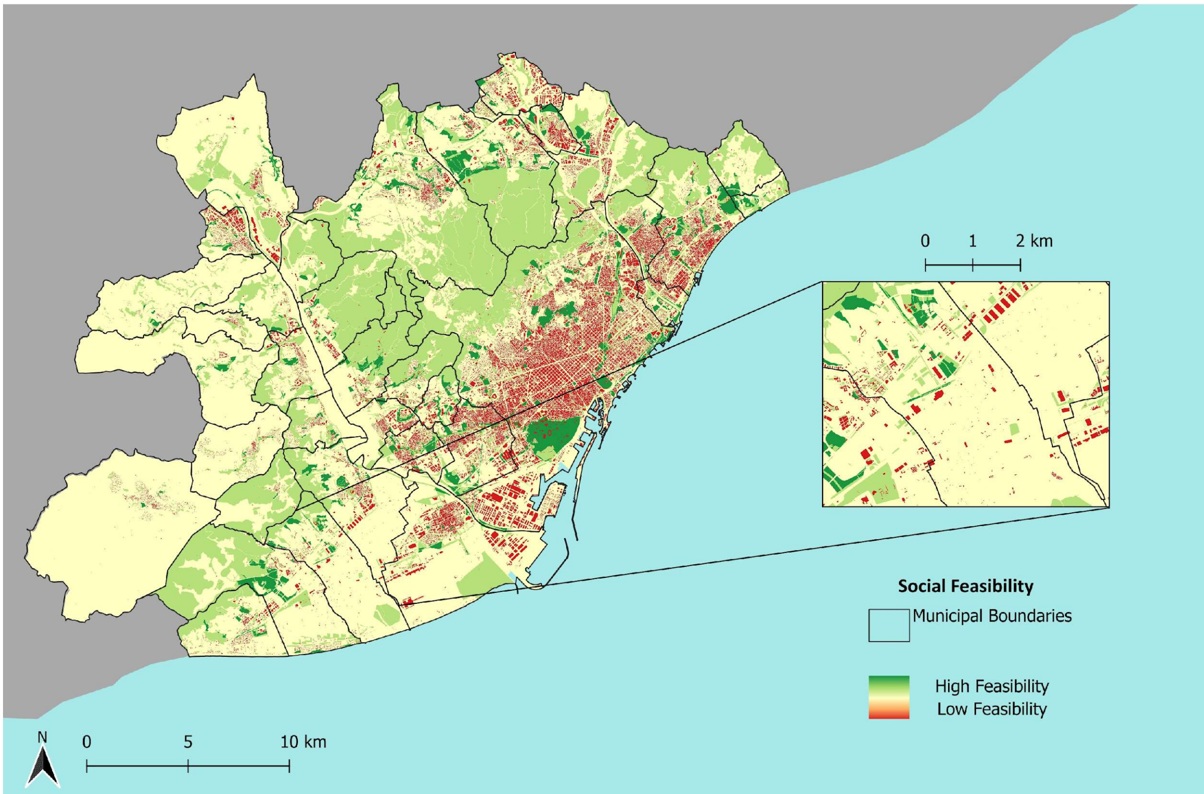

Figure 3: Social feasibility map for NBS (Barcelona): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

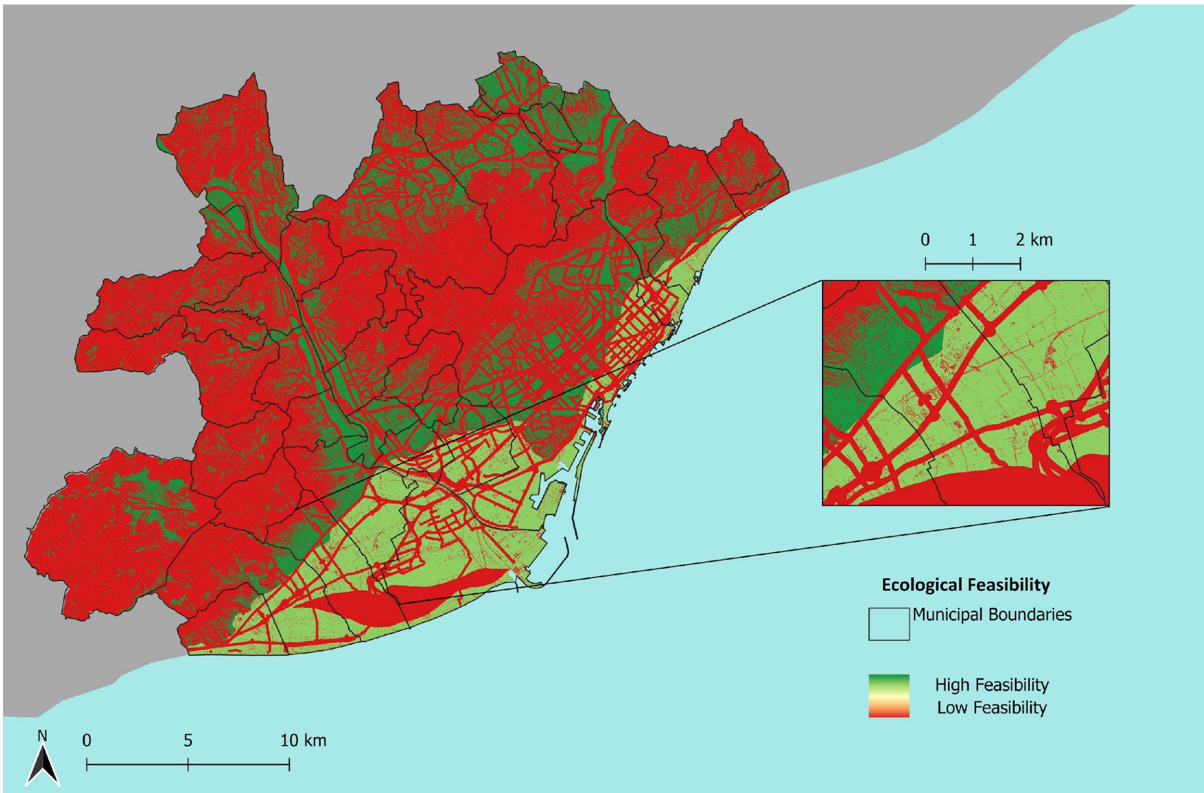

Figure 4: Ecological feasibility map for NBS (Barcelona): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

Technological feasibility map for NBS: Rain garden, Vegetative swale, Urban parks, Agricultural land

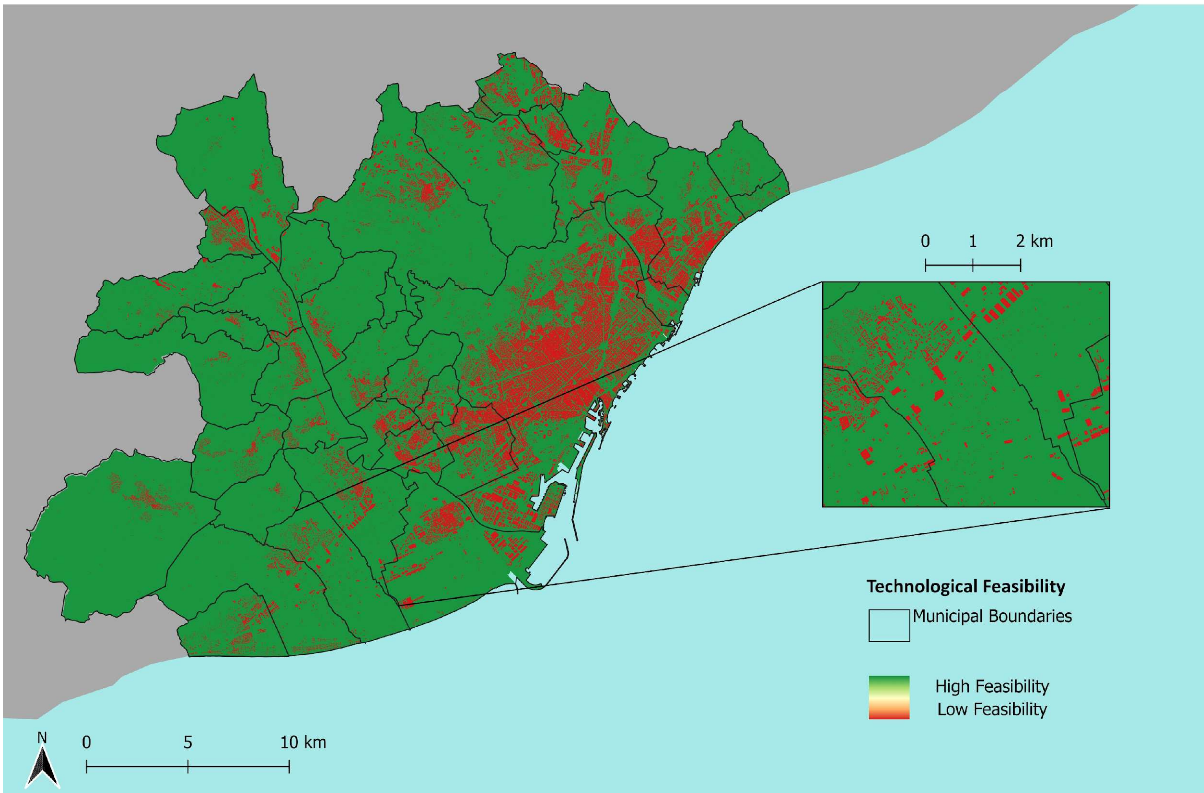

Figure 5: Technological feasibility map for NBS (Barcelona): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

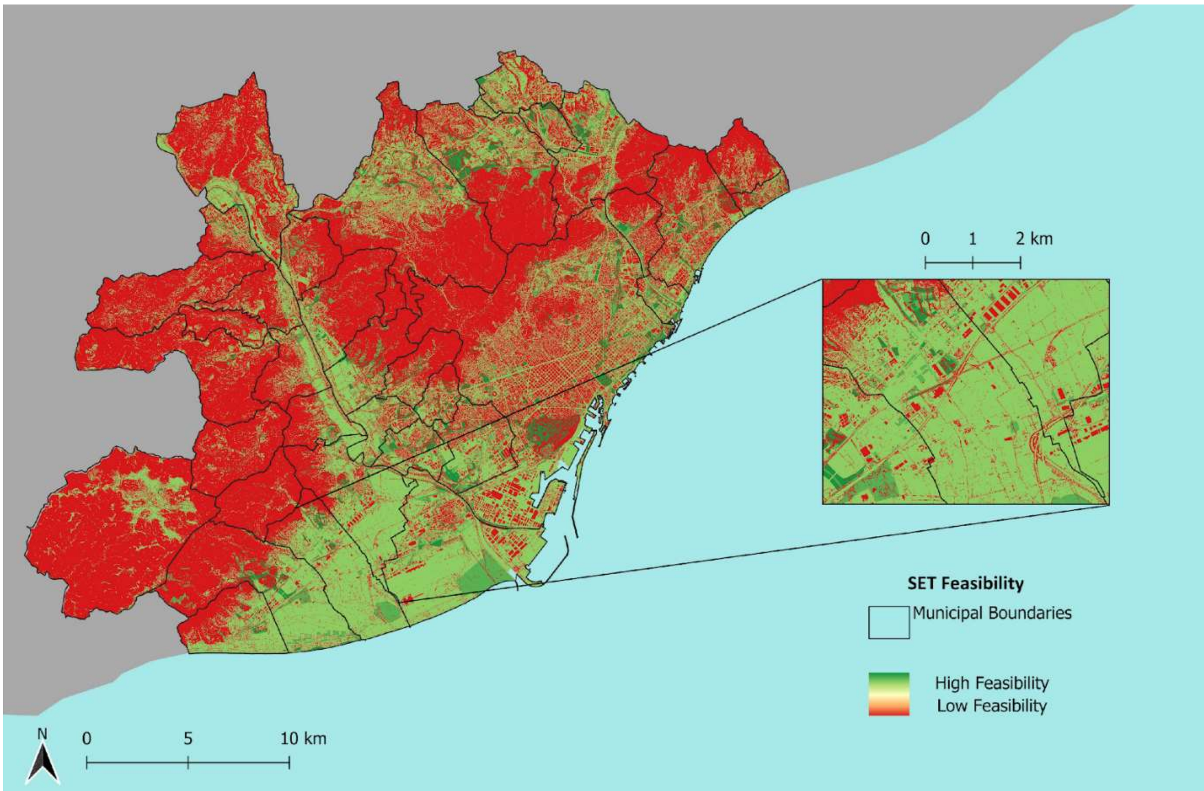

Figure 6: SETs feasibility map for NBS (Barcelona): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

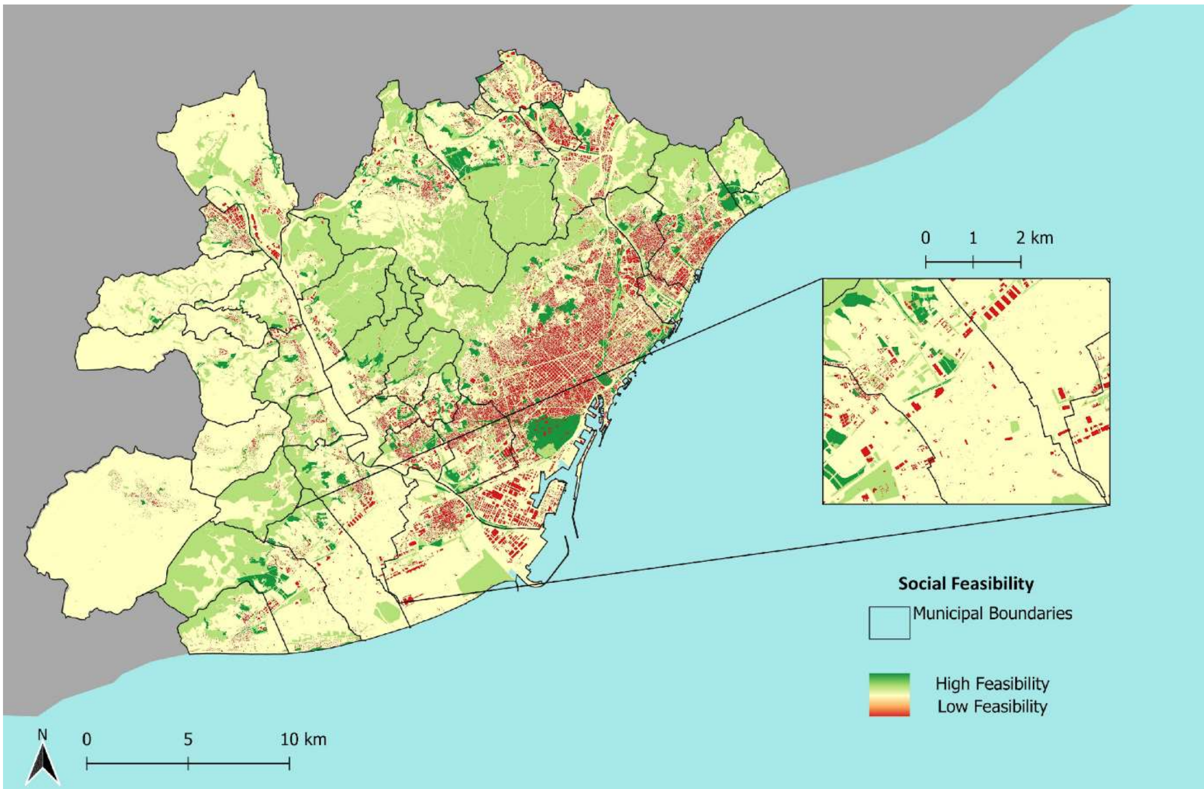

Figure 7: Social feasibility map for NBS (Barcelona): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

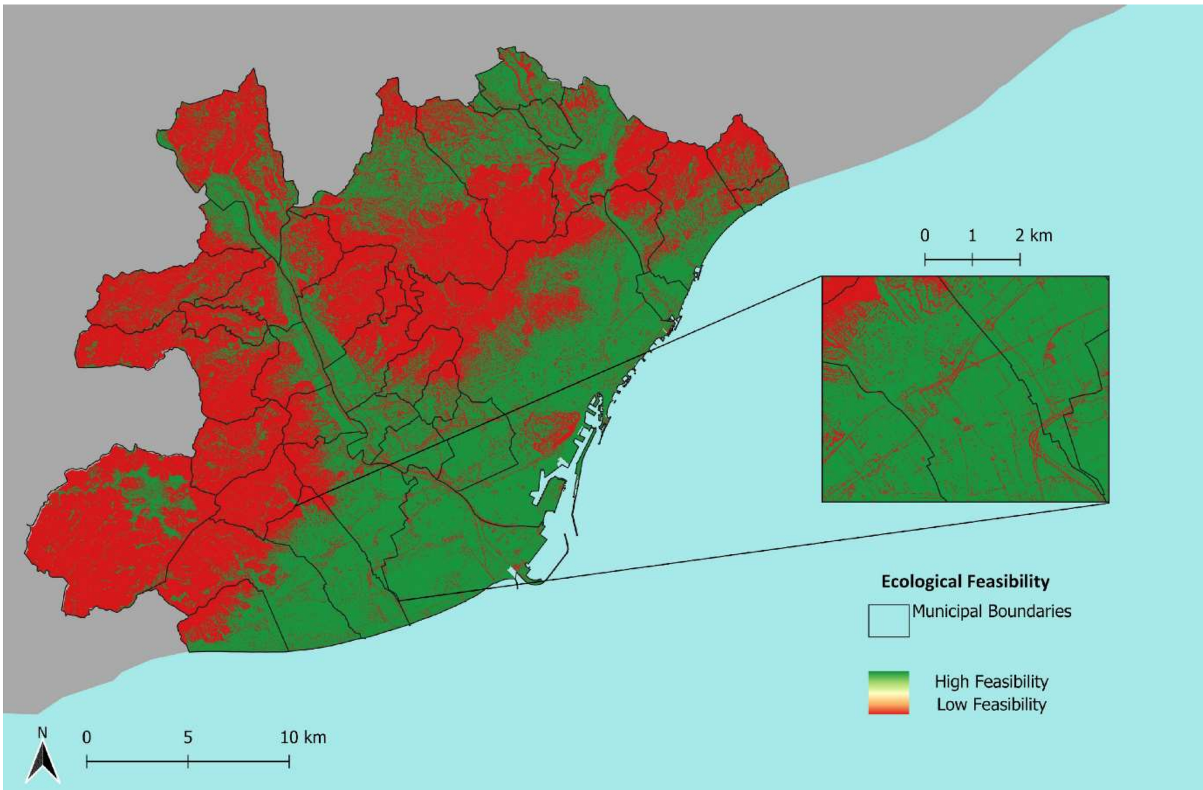

Figure 8: Ecological feasibility map for NBS (Barcelona): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

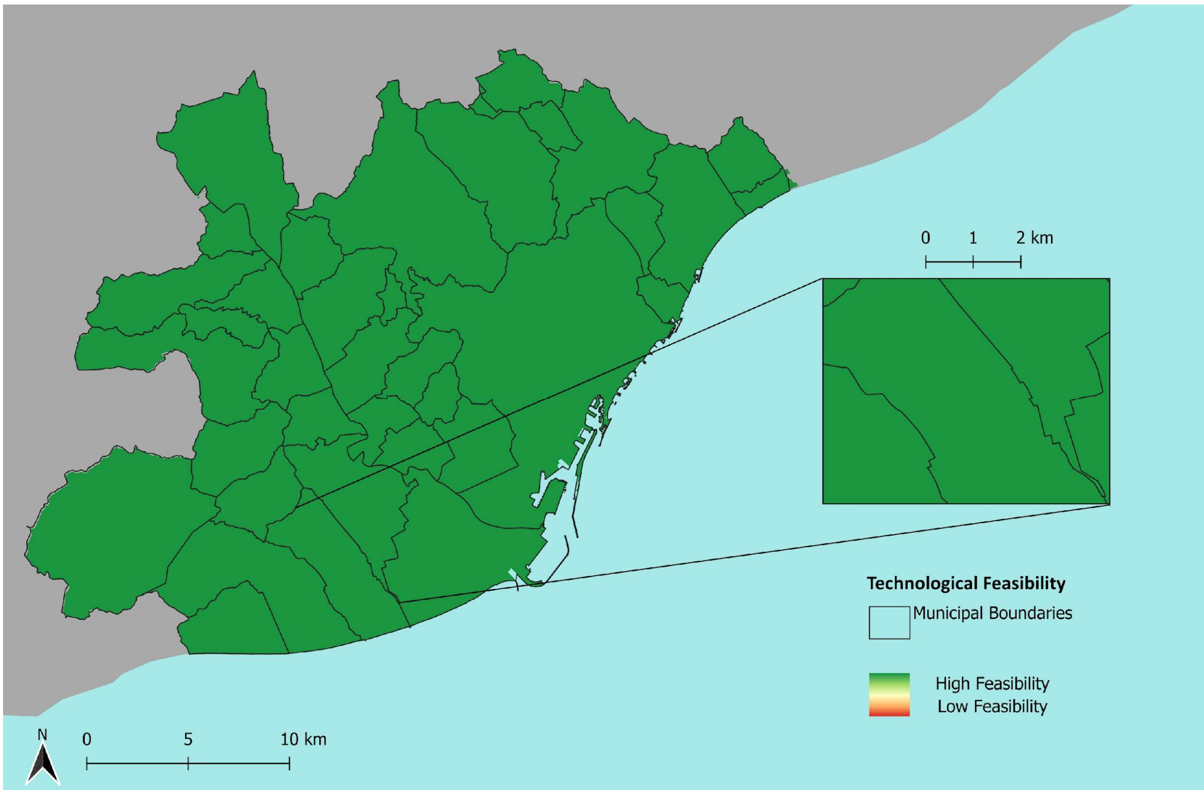

Figure 9: Technological feasibility map for NBS (Barcelona): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

4.2. Boston

For the city of Boston, we selected the indicators presented in Table 3, based on data availability. Indicators sharing similar characteristics were grouped as follows:

- 1st group: Rain garden, vegetative swale, urban parks, agricultural land
- 2nd group: Bioretention cell, infiltration trench, porous pavement (all with underdrain)

This resulted in a total of eight feasibility maps. The following maps illustrate the elaboration of both the SET framework and the sub-groups of social, ecological, and technological feasibility.

Table 3: Indicators-NBS correspondence for Boston

		Social		Ecological		Technical
	INDICATORS / NBS	Existing Zoning Policies	Current Land Use	Polluted water from land use	Ground Slope	Distance Buildings
1	Rain garden	✓	✓	✓	✓	✓
2	Vegetative swale	✓	✓	✓	✓	✓
3	Bioretention cell (with underdrain)	✓	✓	x	✓	x
4	Infiltration trench (with underdrain)	✓	✓	x	✓	x
5	Porous pavement (with underdrain)	✓	✓	x	✓	x
6	Urban parcs	✓	✓	✓	✓	✓
7	Agricultural land	✓	✓	✓	✓	✓

In the subsequent maps, we have similarly analysed both the SET and sub-groups of social, ecological, and technological feasibility for the city of Boston. The chosen indicators for Boston have led to the same combinations as those for Barcelona, but the determining factor in this similarity is the presence of underdrains in some of the NBS. Specifically, the combinations include: i. Rain garden, Vegetative swale, Urban parks, Agricultural land and ii. Bioretention cell, Infiltration trench, Porous pavement (all with underdrain). This results in a total of eight feasibility maps for the city of Boston, mirroring the approach we took for Barcelona.

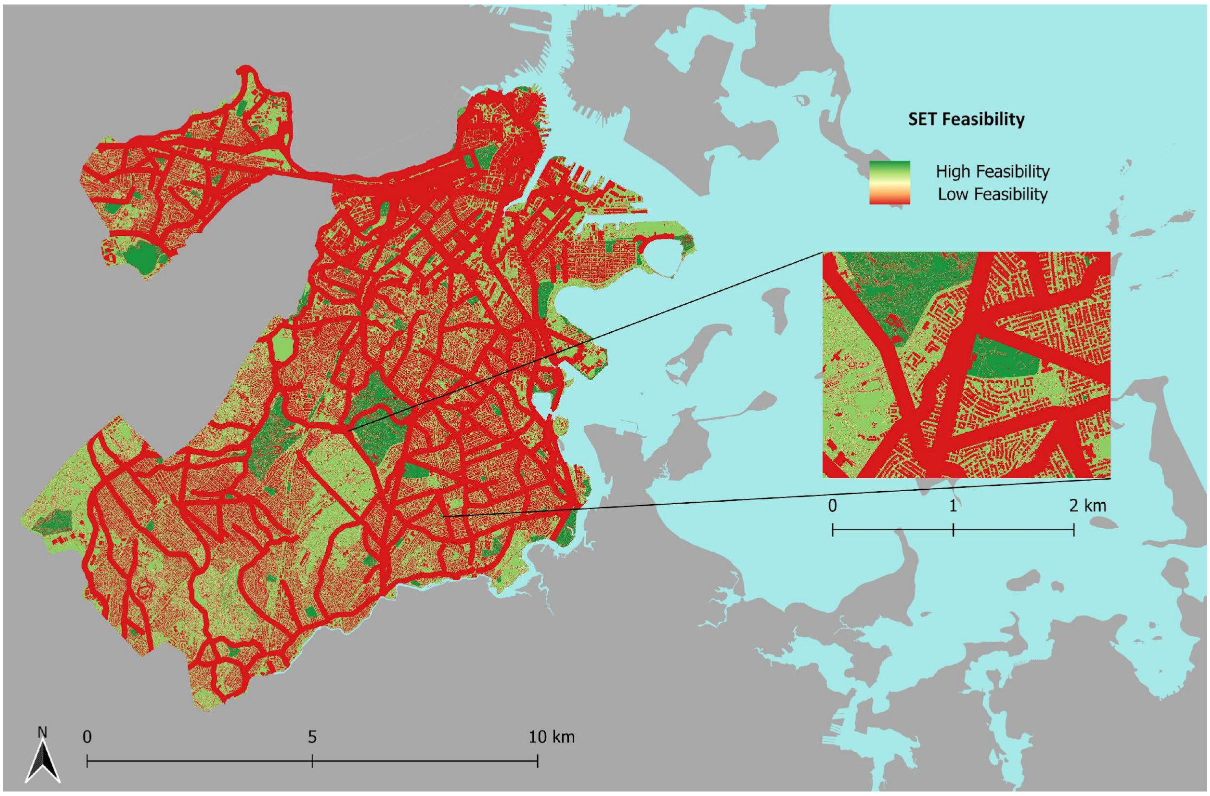

Figure 10: SET feasibility map for NBS (Boston): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

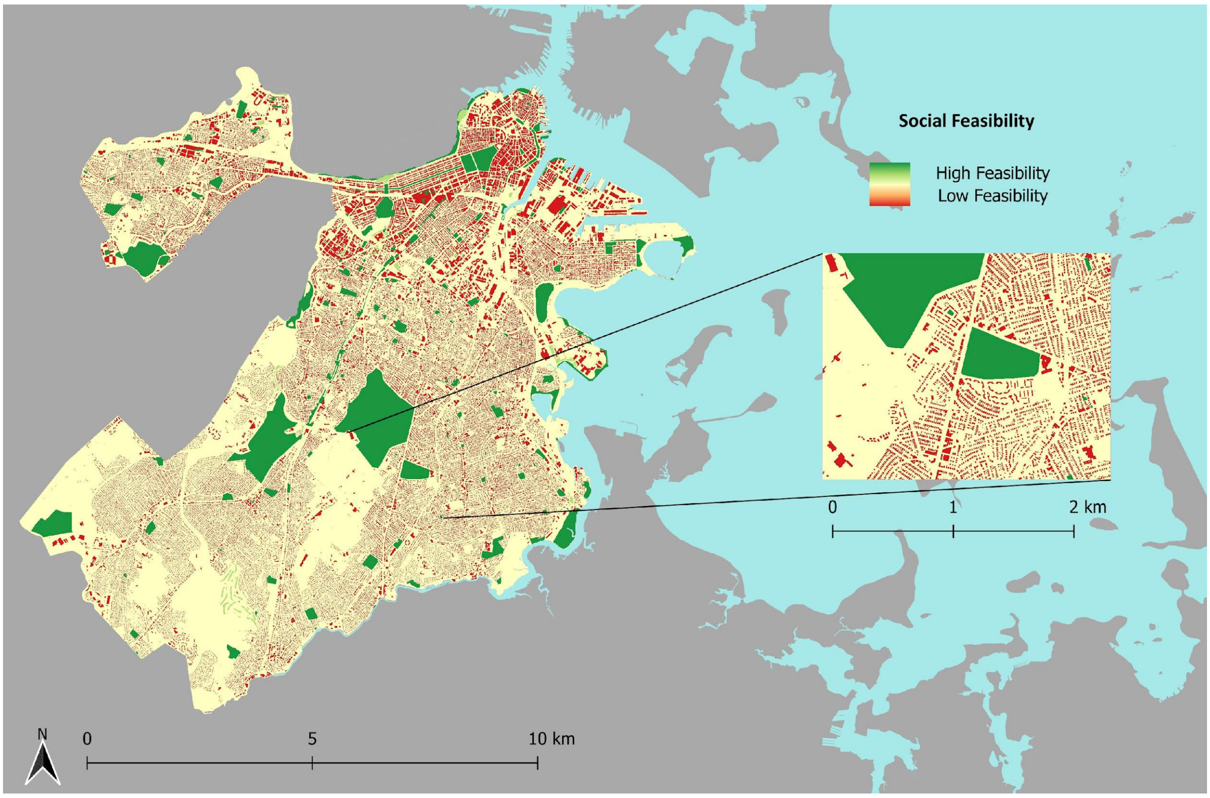

Figure 11: Social feasibility map for NBS (Boston): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

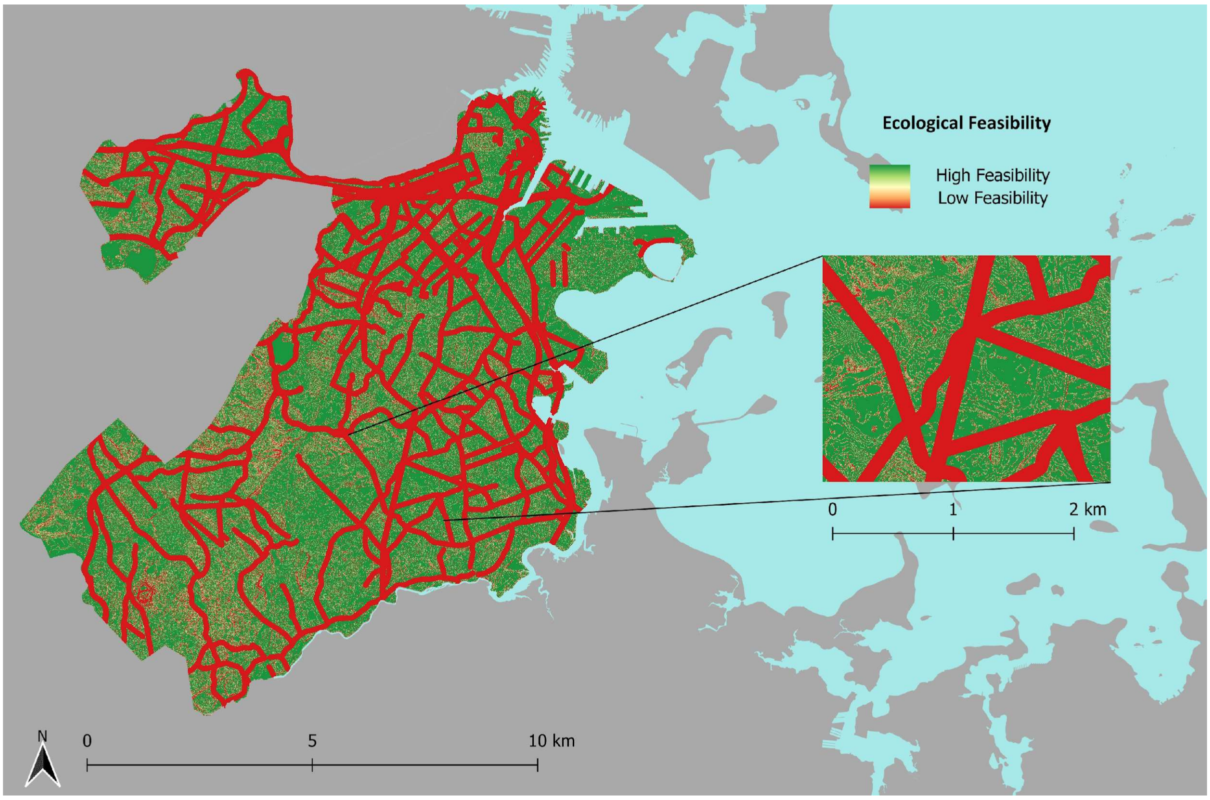

Figure 12: Ecological feasibility map for NBS (Boston): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

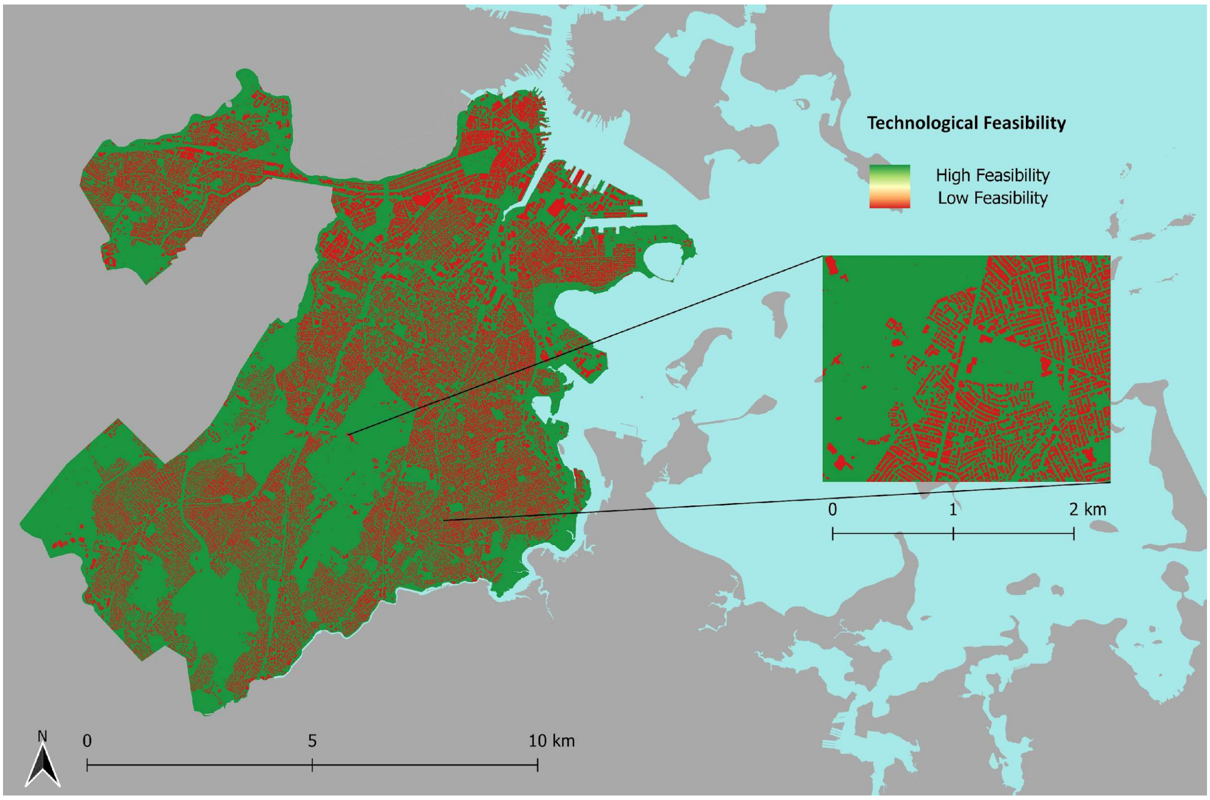

Figure 13: Technological feasibility map for NBS (Boston): Rain Garden, Vegetative Swale, Urban Parks, Agricultural Land.

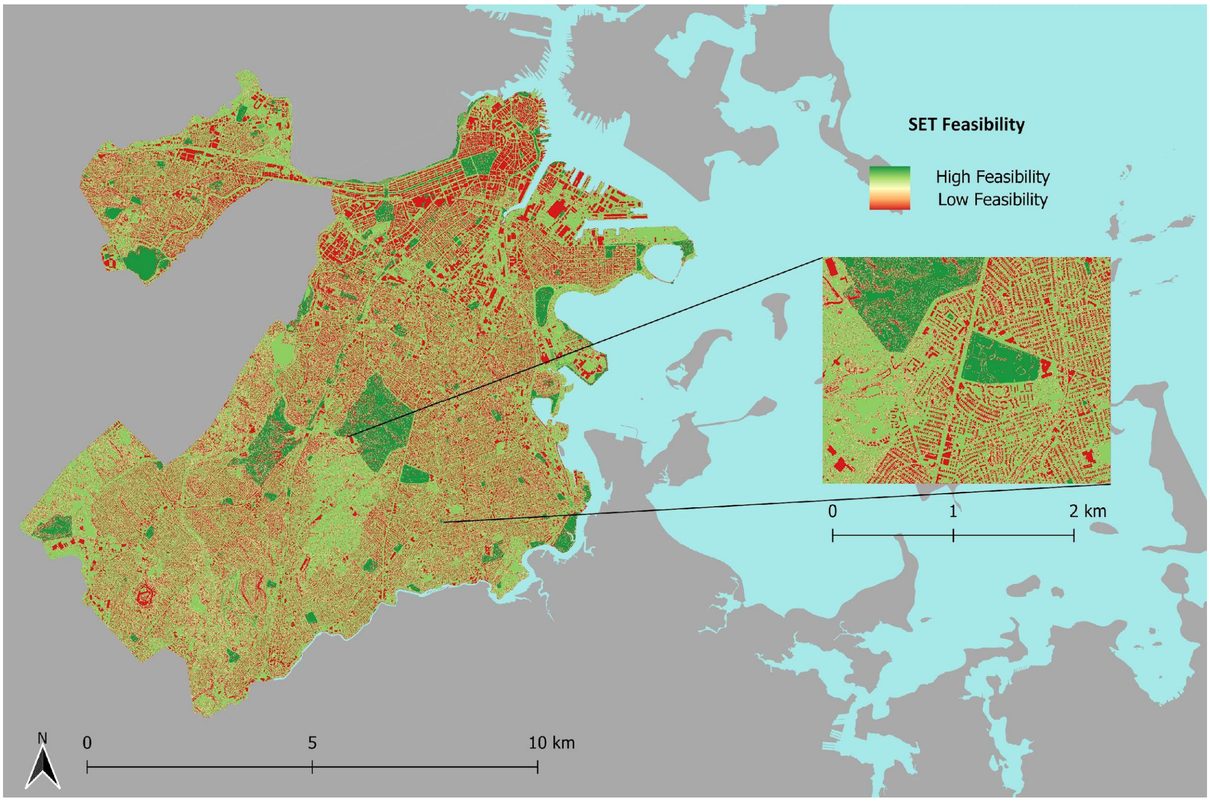

Figure 14: SETs feasibility map for NBS (Boston): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

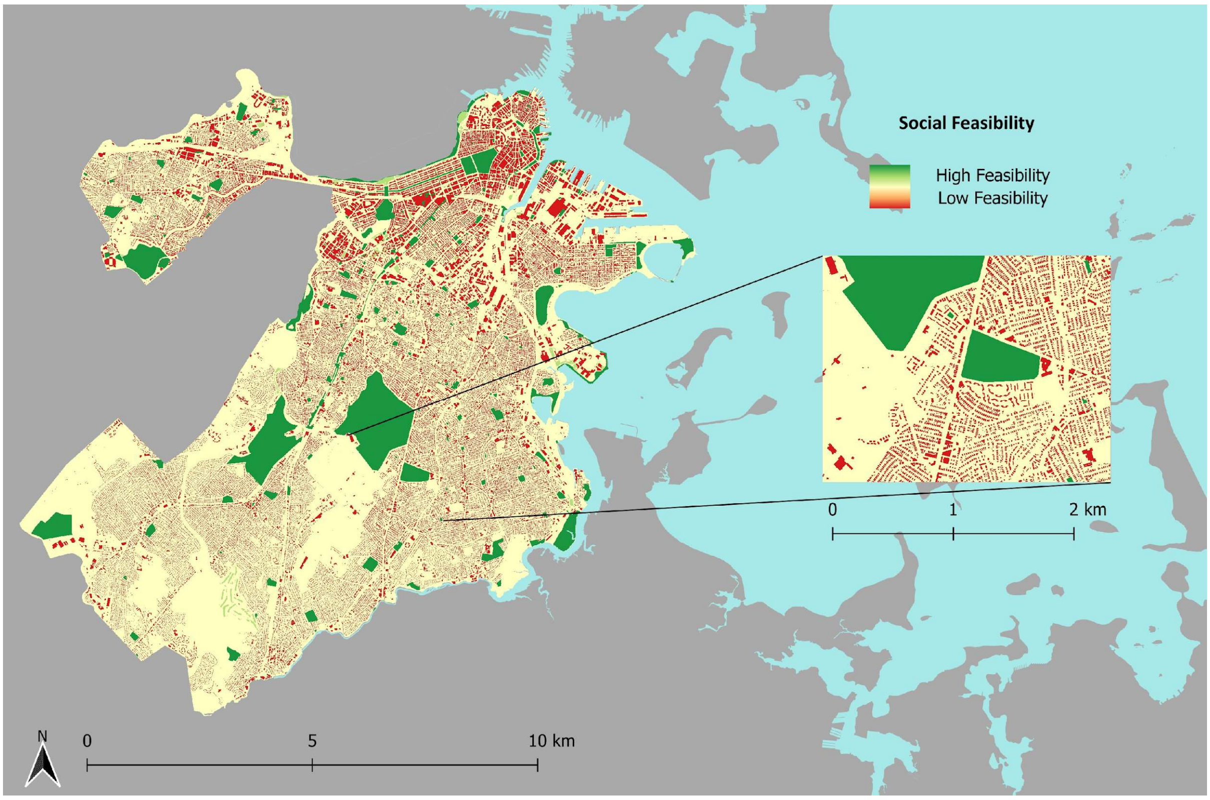

Figure 15: Social feasibility map for NBS (Boston): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

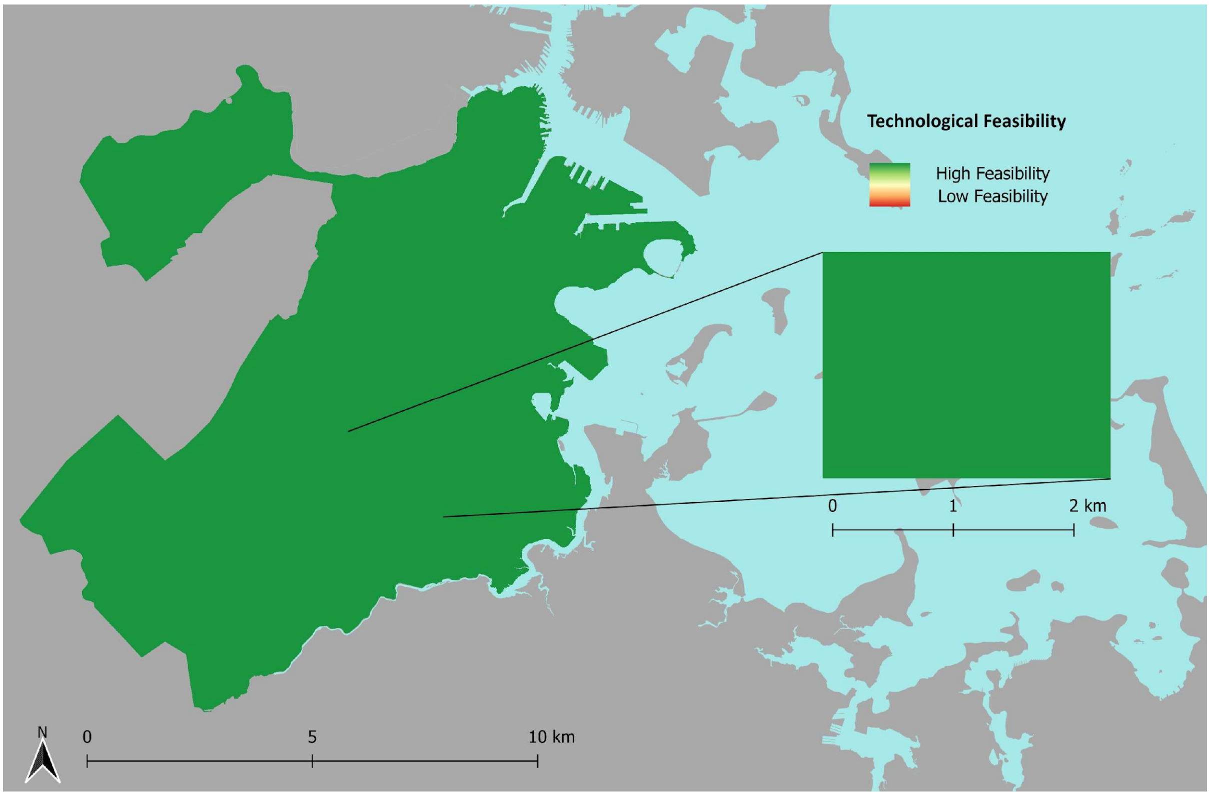

Figure 17: Technological feasibility map for NBS (Boston): Bioretention Cell, Infiltration Trench, Porous pavement (all with underdrain)

5 Conclusion

The purpose of this approach is to guide urban administrations in a systematic manner when considering NBS implementation specifically aimed at improving water infiltration and reducing flood risks. Administrations are encouraged to follow a stepwise approach, starting with areas marked as green, which are the most feasible and require the least intervention. Subsequently, they can progress to the yellow areas, acknowledging that more effort may be needed to make the NBS work effectively for infiltration and flood mitigation. The red areas, on the other hand, serve as clear indicators of infeasibility for these specific objectives. Moreover, these output maps serve as an input for the climate modelling scenario to assess, more in depth, where the considered NBS are most needed.

6 References

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