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

D2.4 Estimates of stormwater flow and nutrient loading mitigation potential

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2 Summary of Deliverable

This report is Deliverable D2.4 'Estimates of stormwater flow and nutrient loading mitigation potential' and describes the technical modelling undertaken to characterize the maximum potential extent and benefits of nature-based solutions (NBS) in each of the three NICHES core cities: Barcelona, Boston, and Rotterdam.

For each city, parcel-level geospatial data on land use and land cover were obtained or derived to estimate the total extent of land that would be potentially suitable for installation of NBS. Validated reduced-form hydraulic and costing models were used, specifically the USEPA BATT model, to calculate stormwater infiltration, runoff, and nutrient loading associated with a current scenario and a maximum potential NBS implementation scenario.

These two scenarios will serve as lower and upper bounds against which community co-created scenarios for improvements through restorative NBS will be evaluated (D3.3). These bounding estimates will also serve as a scaffold for estimation of ecosystem services provided by NBS in each city (D3.2), which are ultimately a function of NBS land area, extent, and connectivity.

3 Abbreviations and Nomenclature

ac	Acre (unit of area)
ASCE	American Society of Civil Engineers
BATT	BMP Accounting and Tracking Tool
BMP	Best Management Practice
BOD	Biological Oxygen Demand
CSO	Combined Sewer Overflow
ES	Ecosystem Services
gal	gallon (unit of volume)
GIS	Geographic Information System
lb	pound (unit of mass)
MS4	Municipal Separate Storm Sewer System
N	Nitrogen
P	Phosphorus
NBS	Nature-Based Solutions
NPS	Non-Point Source
NICHES	Nature’s Integration into Cities’ Hydrologies, Ecologies, and Societies
NRCS	Natural Resource Conservation Service
RCN	Runoff Curve Number
SCS-CN	Soil Conservation Service Curve Number (
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency

4 NICHES: Project Background

Increased stormwater runoff in urban areas, as a consequence of climate change-induced
heavy rainfall events, pose critical threats to aquatic biodiversity. Specifically, combined drainage systems which transport wastewater, stormwater and urban water together can flood after heavy rainfall, causing a combined sewer overflow (CSO) event: a discharge of wastewater and contaminated runoff directly into rivers, streams, or other nearby water bodies, introducing a mix of pollutants such as organic matter, total suspended solids (TSS), metals, pesticides, polybrominated diphenyl ethers, phthalates, alkylphenols, and bisphenol A (Dembele 2010; Zgheib et al. 2012). Previous studies show that CSO impacts on receiving waters lead to harmful effects like algal blooms, species extirpation, trophic chain contamination, and stream eutrophication (Casadio et al. 2010; Passerat et al. 2011). Which pose significant risks to the environment, public health, and economic imbalances.

The NICHES project ('Nature's integration into cities' hydrologies, ecologies, and societies')
recognises this threat and aims to showcase the potential of nature-based solutions (NBS) to mitigate the negative impacts of such combined sewer overflow events on society and the environment. NBS, such as riverbank restoration, sustainable urban drainage systems, and the regeneration of urban green belts, can act as an alternative to the cost-intensive renewal of wastewater systems and as a supplementary element to existing stormwater management systems.

Despite this potential, the use of NBS for urban water management remains limited (Busscher et al. 2018). This is in part due to low awareness of NBS opportunities and benefits among key stakeholder groups. To build awareness and support, there is a need to gather evidence, demonstrate practical approaches and provide targeted guidance to decision-makers, practitioners, and other relevant groups. NICHES aims to bridge this gap by defining a holistic framework for understanding the social, ecological, and technical aspects of applying restorative NBS for urban runoff mitigation and the resultant benefits for aquatic systems. Using global cities as co-design arenas, the project will support the development of recommendations for integrating NBS in urban policies.

5 Current State of NBS in NICHES Cities

In each of the three NICHES core cities of Barcelona, Boston, and Rotterdam, there are already installations and programs for green infrastructure or Nature-Based Solutions (NBS) for stormwater management. The core cities share some basic topographical and hydrological characteristics: all are coastal cities that are bounded by rivers, meaning that poor water quality can impact both local freshwater systems and coastal marine waters. The freshwaters around Boston and Rotterdam are both heavily managed hydrologically, which maintains water levels but has major effects on flow rates and residence times in local freshwater systems.

As with most older cities, all three NICHES core cities have a history of poor water quality of surface waters due to combined sewer overflow (CSO) events during periods of heavy rainfall, which bring pollutants including biological oxygen demand (BOD), nitrogen (N), and phosphorus (P) into local waterways, causing poor water quality in terms of pathogens and eutrophication. In all three cities, there have been extensive, multi-decade efforts to install municipal separate storm sewer systems (MS4) and large detention basins to reduce the frequency and severity of CSO events. Despite these investments, all three cities still experience CSO events. Figures 1-3 show the location of existing CSO outfalls in each city. Barcelona is arguably most impacted financially because of its extensive beachfront and the negative impacts for tourism and recreation when these beaches must be closed. The local governmental body Ajuntament de Barcelona quantified the annual damages caused by CSO to be 48 M€ to properties, 13 M€ to commercial activities and 39 M€ to the environment (Ajuntament de Barcelona, 2021).

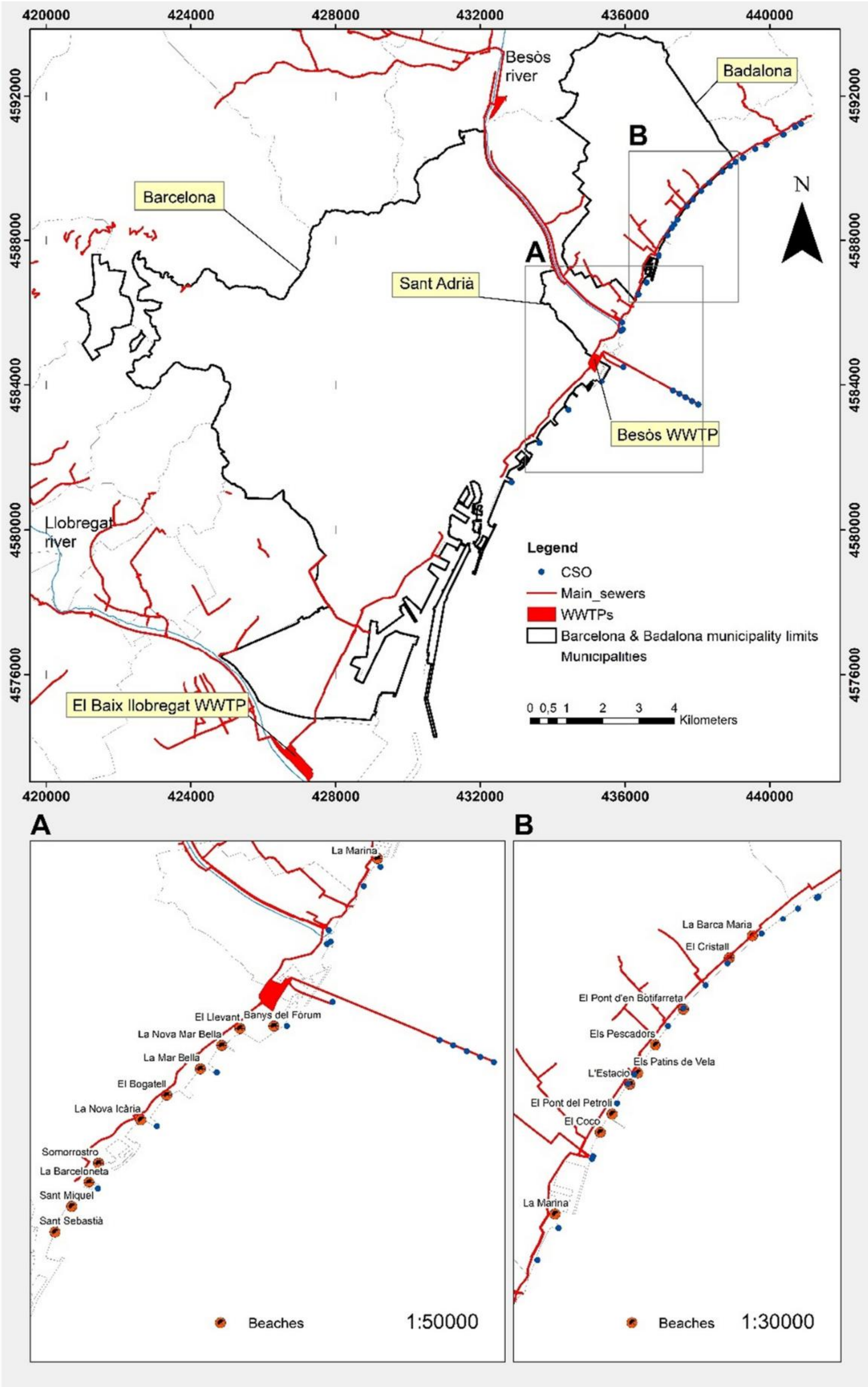

Figure 1. Map of Barcelona main sewers, beaches, and CSO points (Martinez-Gomariz *et al.*, 2021).

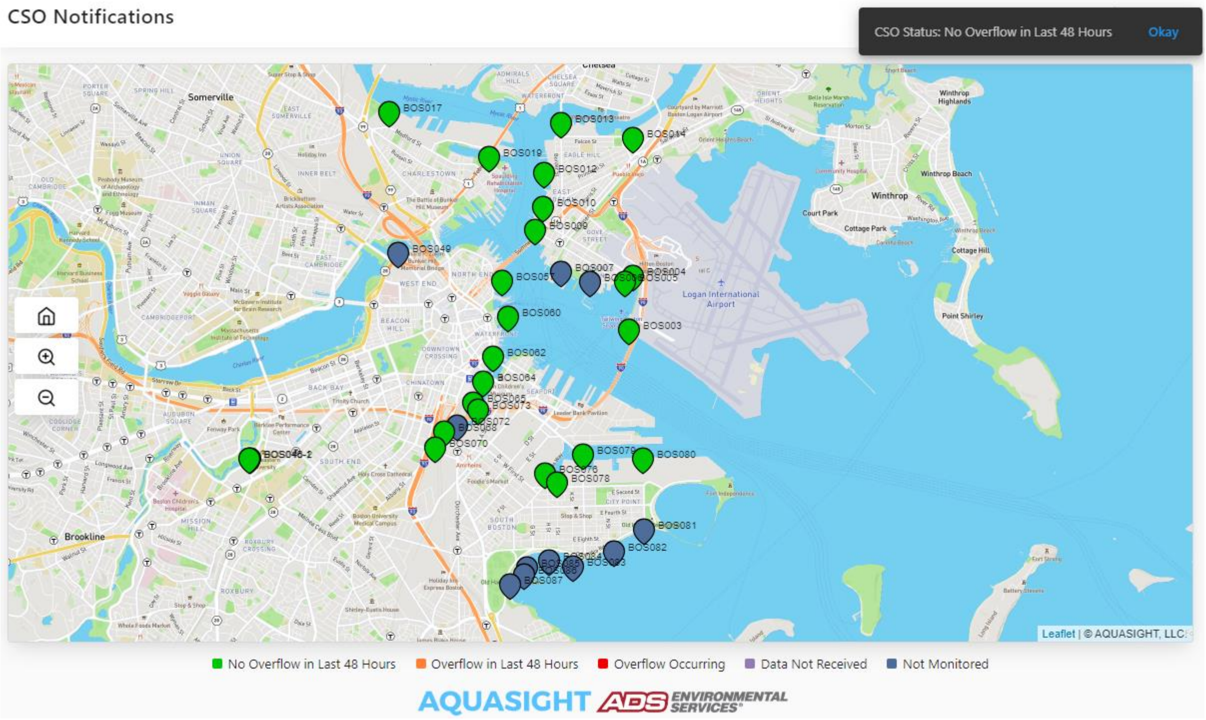

Figure 2. Map of Boston CSO points (Boston Water and Sewer Commission, 2023). Of 34 mapped points, green points are monitored continuously while blue points are not monitored because overflows do not occur anymore due to earlier mitigation actions.

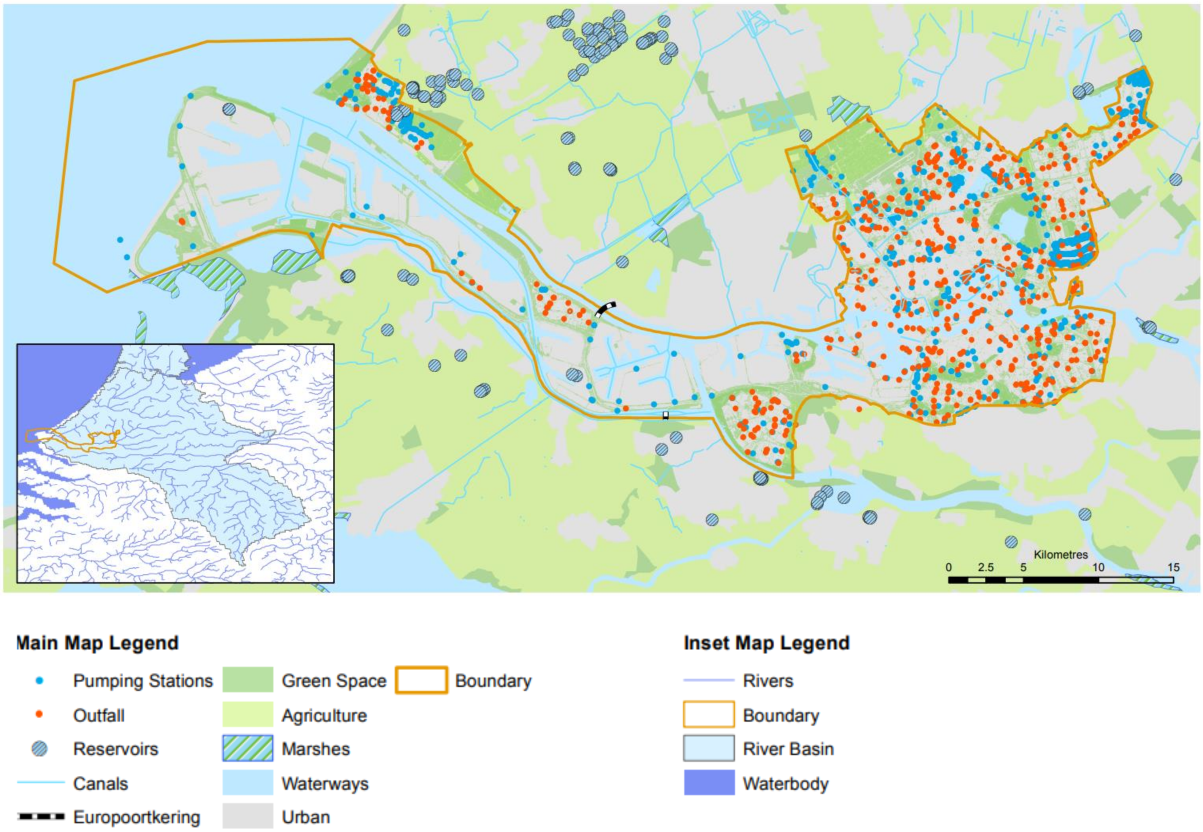

Figure 3. Map of Rotterdam reservoirs, pumping stations, and outfalls (Arup, 2019).

In addition to separating storm sewers, the cities have also implemented varying levels of green infrastructure to try to increase natural infiltration, provide stormwater detention volumes, and treat pollutants such as N and P that are present in surface runoff, before nutrients are carried into the conventional storm sewer system. Focusing on the Boston case, Figure 4 shows a map of downtown Boston green infrastructure installations, coloured by different types. The area of each circle represents a relative measure of the area that each installation can manage for a 1 inch (~25 mm) rainfall event (BWSC, 2023)

Figure 4. Map of green infrastructure installations in Boston. The size of each circle indicates the relative area that the installation can manage fir a 1 inch (approx. 25mm) rainfall event.

Boston's Climate Action Plan, launched in 2007, aims to reduce greenhouse gas emissions and build resilience against climate impacts. As part of this plan, Boston has implemented various green infrastructure measures, such as constructing green roofs, installing rain gardens, and promoting permeable pavements to manage stormwater runoff and reduce the urban heat island effect. The City of Boston has also just implemented new design guidelines for streets (City of Boston, 2022) that also include measures for stormwater infiltration, including:

- Right-of-way (ROW) Bioretention: Curb extensions may incorporate green infrastructure in the form of Rain Gardens, Bioswales, etc.
- Infiltration Tree Pit/Tree Trench: Curb extensions may incorporate green infrastructure in the form of Infiltration Tree Pits or Infiltration Tree Trenches.
- Porous Paving: Curb extensions may incorporate Porous Asphalt, Permeable Pavers, Porous Paver Installations, and Porous Concrete Slabs.
- Subsurface Infiltration Area: Curb extensions may incorporate Stone Subsurface Infiltration Areas (with or without perforated pipe).
- One-time Seeding: The area within the curb extension may be seeded once with a groundcover, low-grow fescue or wildflower mix.

Comparative studies of the costs and benefits of different stormwater management measures have shown that urban greening has an order of magnitude higher benefit/cost ratio than traditional grey infrastructure because of the many additional benefits to communities and ecosystems that are introduced (Quaranta *et al*., 2022).

Some good examples of the NBS tool for stormwater management could be bioswales. Integrated into urban planning, they are essentially vegetated channels designed to slow, collect, and filter stormwater. As runoff flows through the bioswale, vegetation and engineered soil facilitate the removal of pollutants, including phosphorus and nutrients, through processes like absorption and microbial degradation. This green infrastructure not only enhances water quality by preventing pollutants from reaching water bodies but also helps replenish groundwater and promotes the overall health of urban ecosystems. By seamlessly blending into urban landscapes, bioswales showcase the harmonious synergy between nature and infrastructure, providing a sustainable and aesthetically pleasing approach to managing stormwater and mitigating the environmental impact of urbanization.

Some potential benefits of NBS for stormwater management include (USEPA, 2023):

- **Climate Resilience**: Nature-based solutions such as green infrastructure and urban forests help enhance the city's resilience to climate change impacts. They mitigate flooding by absorbing and storing stormwater, reducing the burden on drainage systems. Green spaces also act as natural cooling agents, mitigating the urban heat island effect and reducing energy consumption for cooling.

- **Improved Air Quality**: Vegetation and green spaces contribute to improved air quality by adsorbing and/or absorbing gaseous pollutants and filtering out particulate matter.

- **Biodiversity Conservation**: Nature-based solutions promote biodiversity conservation by providing habitats for various plant and animal species. Boston's green spaces support diverse ecosystems and contribute to the preservation of native flora and fauna. Protecting biodiversity is crucial for maintaining ecosystem services and the overall health of the environment.

- **Enhanced Water Quality**: Green infrastructure, including rain gardens, bioswales, and vegetated buffers, helps filter and purify stormwater runoff before it enters water bodies. This reduces the number of pollutants and contaminants that reach rivers, lakes, and the ocean, thereby improving water quality. Clean water supports aquatic ecosystems, enhances recreational opportunities, and protects public health.

- **Social and Health Benefits**: Nature-based solutions provide numerous social and health benefits to residents. Access to green spaces and parks promotes physical activity, mental well-being, and community interaction. Green spaces also offer opportunities for recreation, relaxation, and stress reduction, contributing to a higher quality of life.

6 Prior Work Characterizing Water Quality Benefits of NBS

There has been some prior work to model the potential benefits of different NBS implementation scenarios. In Barcelona, Locatelli *et al*. (2020) analysed the benefits of proposed green infrastructure plans based on published planning documents including green roofs, bioretention cells, as well as a retention and detention basins (Figure 5). Proposed green roofs covered 5% of all available roof area, based on an earlier feasibility study. The study found that damages caused by flooding could be reduced by approximately half through the planned investment in green infrastructure, and almost completely in the neighbouring municipality of Badalona. Additional modelled benefits were the reduction of CSO volumes by approximately 28% and a reduction of beach closures by 16%.

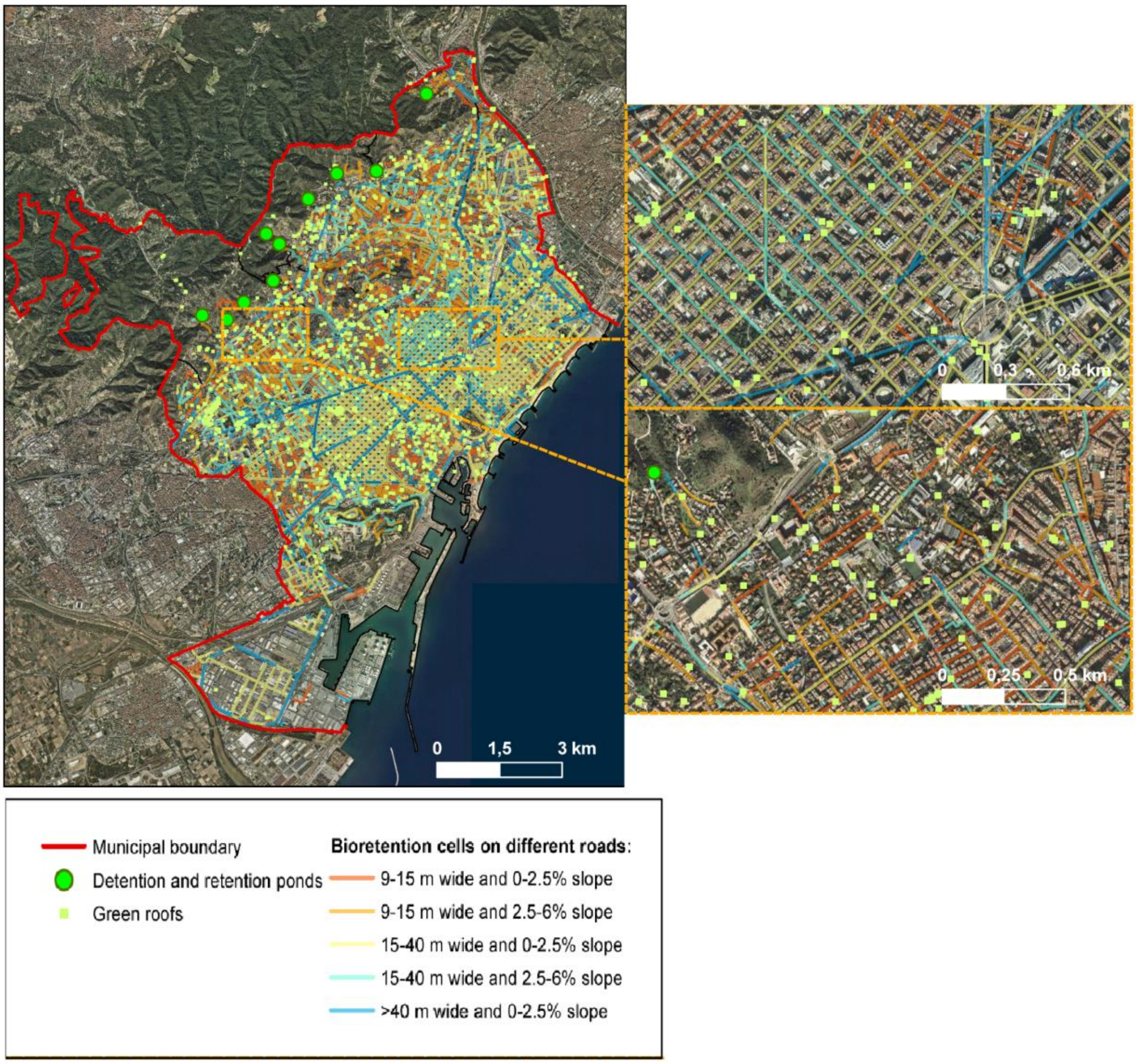

Figure 5. Location of proposed green infrastructure installations in Barcelona (Locatelli et al., 2020).

Additional hydro-chemical modelling assessed the efficacy of Barcelona’s green infrastructure in protecting water quality in its underlying aquifers. While installations such as porous pavement may increase infiltration and can capture some pollutants through sorption to engineered media, NBS is widely recognized to be more effective at mitigating water quality impacts through phytoremediation and uptake of nutrients. This prior research found that there is low vulnerability of the area's aquifers to water quality degradation from infiltrating surface waters, with the possible exception of the interfacial zone between the Besós River and the Barcelona Plain aquifers (Scheiber *et al*., 2022).

7 NICHES Modelling of NBS Total Potential and Benefits

Technical modelling of the total technical feasibility of NBS in each of the three NICHES cities was conducted in three steps. First, parcel-level geospatial data on land use and land cover were obtained from public geodata sites or derived from remote sensing data. Second, those land use and land cover types that are amenable NBS were characterized and summed to estimate the total extent of land that would be potentially suitable for installation of NBS. Finally, a reduced-form hydraulic and costing model was used, specifically the USEPA BATT model, to calculate the benefits of stormwater infiltration, runoff, and nutrient loading associated with a current scenario and a maximum potential NBS implementation scenario.

7.1 Parcel-Level Data

For Boston, parcel-level data layers were obtained from MassGIS (a state-level agency), which are already differentiated by pervious-impervious land cover type. In the case of Barcelona, land use data was obtained from the city administration. Raster data were converted into a range of 0 to 1 (representing pervious-impervious) based on NDBI (Normalized Difference Built-Up Index). Data were then vectorized, creating SHAPE files, and overlapped with land use data with the impervious layer to classify the pervious-impervious categories into specific land use types. For Rotterdam, CORINE land-cover data were combined with remote-sensing data, through the same process as for Barcelona. Data layers were vectorized, normalized using the NDBI, and then the raster was differentiated into pervious-impervious types. Figure 6 shows an example shapefile of land use / land cover types in Boston.

7.2 Area Calculations

For each city, .shp files were processed using the QGIS field calculator ($area) for automatic calculation of the total area of each land use category. Bioswales and porous pavements were modelled for all suitable areas corresponding to the maximum implementation extent. Tables 1-3 show the area calculations, soil types, and runoff characteristics for each land use type.

7.3 Hydrologic Modelling

The USEPA's BMP Accounting and Tracking Tool (BATT) is a "spreadsheet-based tool that provides accounting, tracking, and reporting for pollutant (nutrients and sediment) load reduction. The purpose of this tool is to provide permittees, developers and watershed managers means to account for and track over time the pollutant load reductions (total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN)) associated with implementing stormwater and Non-Point Source (NPS) controls, and to track net increases or decreases in nutrient loading associated with changes in land uses within the area of interest (an MS4 area, specific watershed, etc.)." (USEPA, 2023).

For each NICHES city, BATT outputs were calculated on an annual basis, shown in Table 4.

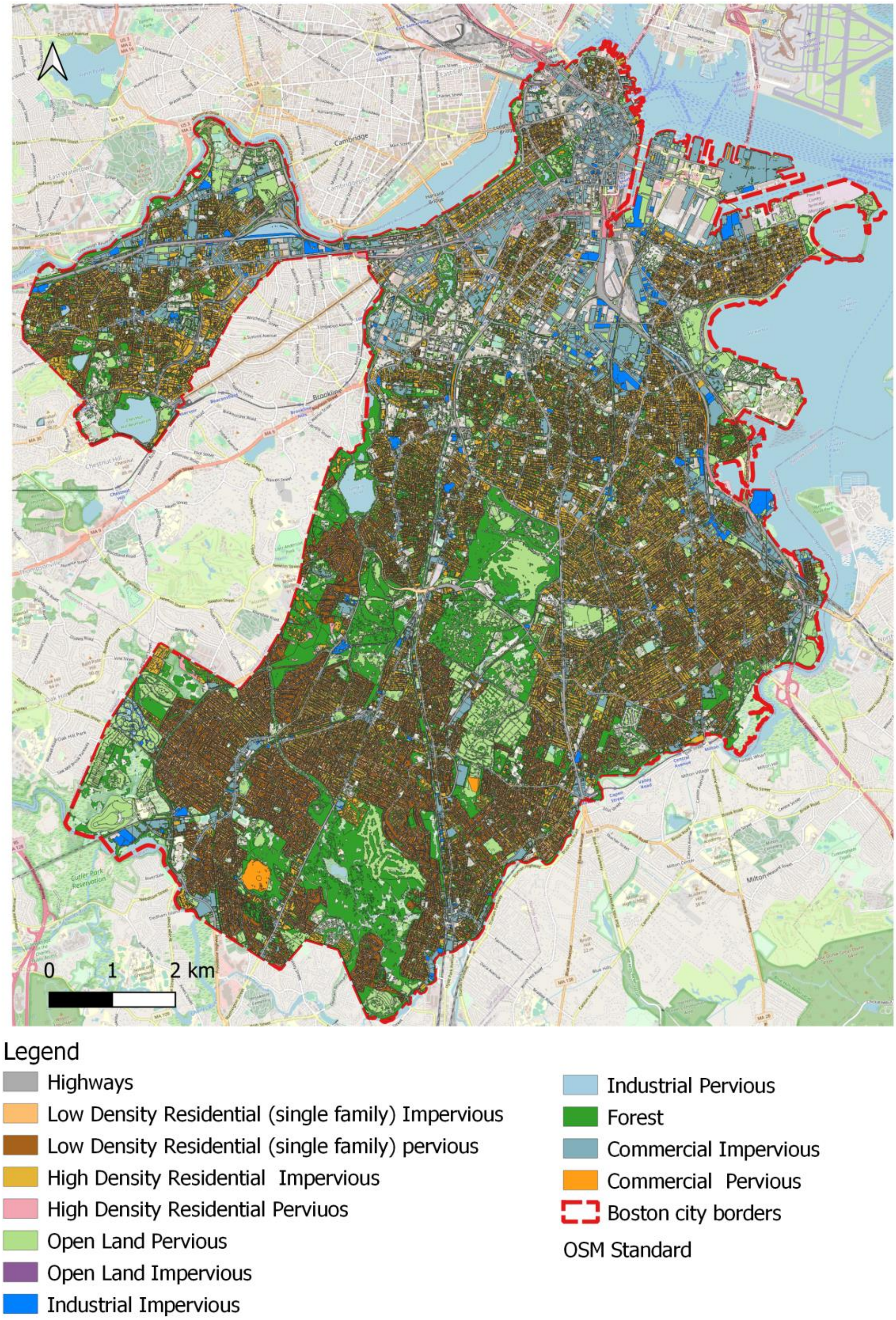

Figure 6. Land use / Land cover map for Boston showing pervious and impervious areas. (Based on MassGIS Data: 2016 Land Cover/Land Use)

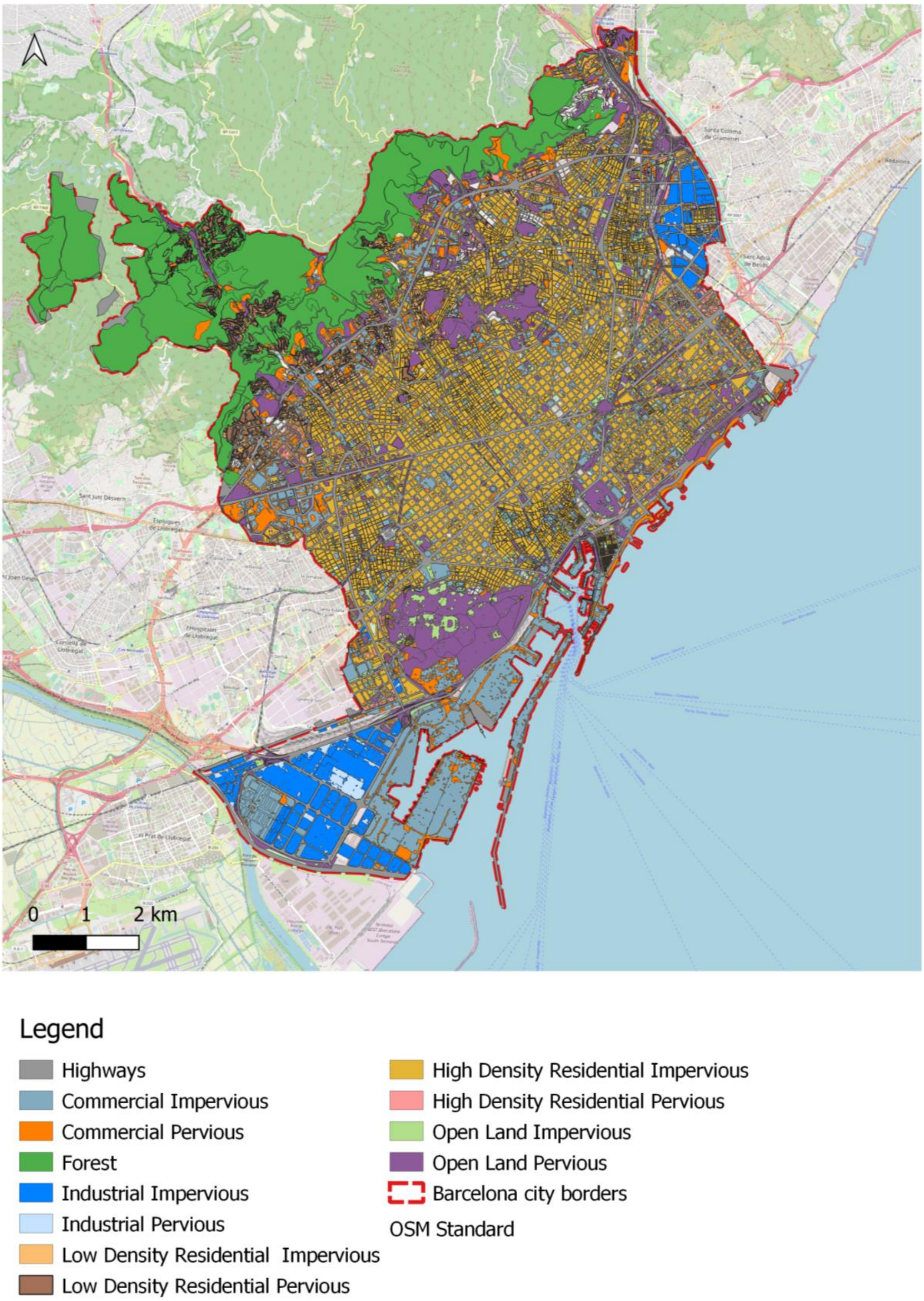

Figure 7. Land use / Land cover map for Barcelona showing pervious and impervious areas. (Based on Institut Cartogràfic i Geològic de Catalunya Data: 2018 Land Use and Remoted Sensed (Landsat 8) data process into pervious / impervious categories for Land Cover)

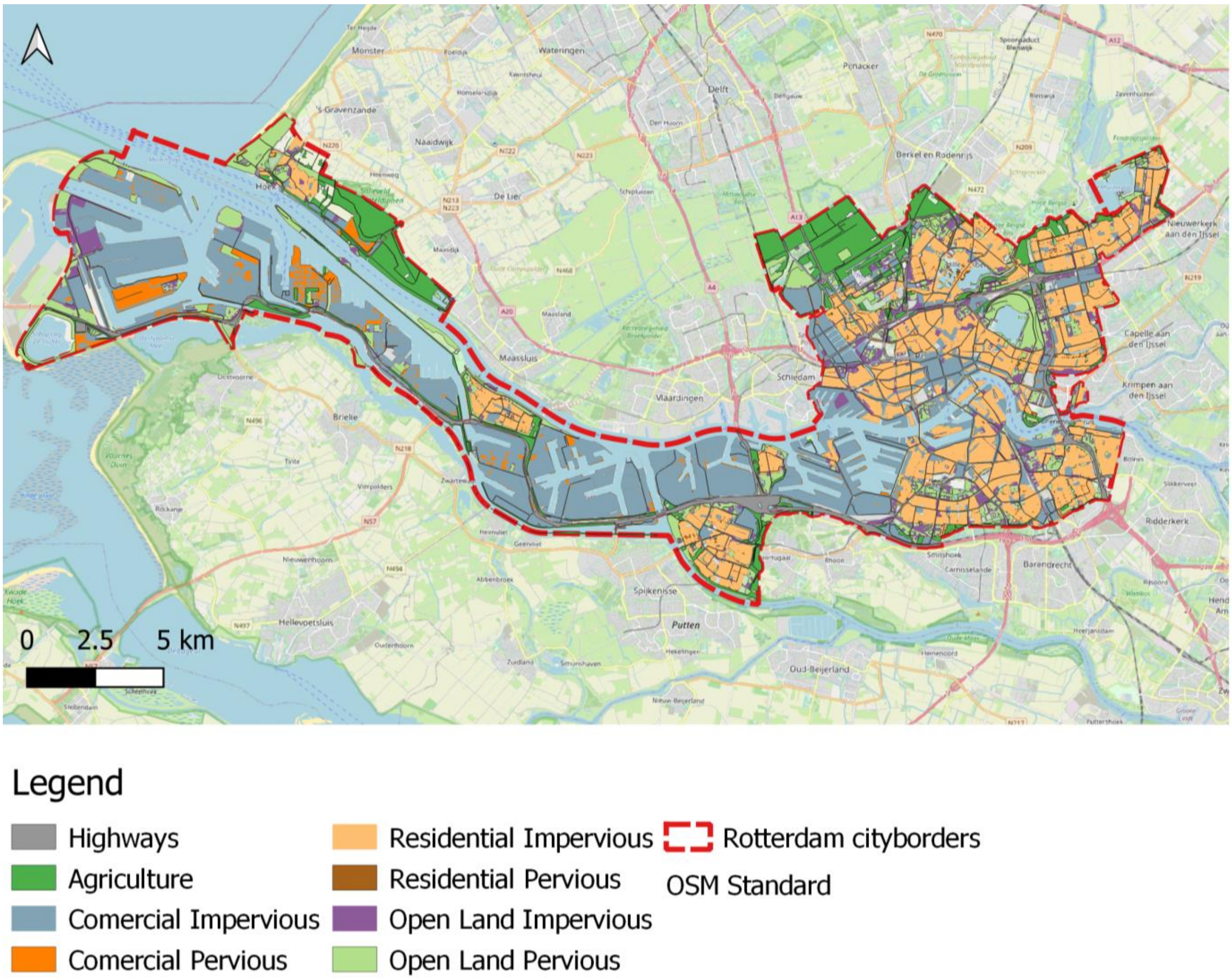

Figure 8. Land use / Land cover map for Barcelona showing pervious and impervious areas. (Based on Corine: 2018 Land Use and Remoted Sensed data (Landsat 8) process into pervious / impervious categories for Land Cover)

Table 1. Boston land area calculations, soil types, and runoff characteristics for each land use type.

Land use	Type of Land cover impervious/pervious	Area (ac)	Area(ha)	% of total area	Hydrological soils type	Phosphorous Loading (lb/ac/yr)	Nitrogen Loading (lb/ac/yr)	Runoff coefficient (average)	Runoff Curve Numbers	The potential maximum retention (SCN, mm)	Direct surface runoff (mm)
Highways	I	6074.36	2458	23.9	N/A	1.34	10.17	0.85	88	34.6	1059.50
Agriculture	P	0.003	0.001	0.0	N/A	0.45	2.59	0.15	82	55.8	1035.81
Commercial	I	1943	787	7.6	N/A	1.78	15.08	0.75	94	16.2	1080.78
Commercial	P	523	212	2.1	C	0.21	2.41	0.17	74	89.2	999.71
Forest	P	6507	2633	25.6	N/A	0.12	0.54	0.15	60	169.3	920.01
High Density Residential	I	3165	1281	12.4	N/A	2.32	14.1	0.67	90	28.2	1066.84
High Density Residential	P	2022	818	8.0	C	0.21	2.41	0.17	74	89.2	999.71
Industrial	I	319	129	1.3	N/A	1.78	15.08	0.65	91	25.1	1070.42
Industrial	P	214	87	0.8	C	0.21	2.41	0.17	74	89.2	999.71
Low Density Residential (single family)	I	1333	539	5.2	N/A	1.52	14.1	0.40	90	28.2	1066.84
Low Density Residential (single family)	P	1936	783	7.6	C	0.21	2.41	0.17	74	89.2	999.71
Open land	I	405	164	1.6	N/A	1.52	11.33	0.85	98	5.2	1093.80
Open land	P	994	402	3.9	C	0.21	2.41	0.17	74	89.2	999.71
Total		**25437**	**10294**	**100**						**809**	**13,393**
Notes:	Defined in QGIS (Based on MassGIS Data: 2016 Land Cover/Land Use)	Calculated in QGIS (Based on MassGIS Data: 2016 Land Cover/Land Use)			Refer to Table 1 of Appendix A	USEPA BATT setting	USEPA BATT setting	Refer to Table 1 of Appendix B	Refer to Table 1 of Appendix C	Refer to Equation 1 of Appendix D	Refer to Equation 2 of Appendix D

Table 2. Barcelona land area calculations, soil types, and runoff characteristics for each land use type.

Land use	**Type of Land cover impervious/pervious**	**Area (ac)**	**Area(ha)**	**% of total area**	**Hydrological soils type**	**Phosphorous Loading (lb/ac/yr)**	**Nitrogen Loading (lb/ac/yr)**	**Runoff coefficient (average)**	**Runoff Curve Numbers**	**The potential maximum retention (SCN, mm)**	**Direct surface runoff (mm)**
Highways	I	5564	2252	22.5	N/A	1.34	10.17	0.85	88	34.6	560.3
Commercial	I	2717	1100	11.0	N/A	1.78	15.08	0.75	94	16.2	581.0
Commercial	P	1243.3	503	5.0	C	0.21	2.41	0.17	74	89.2	504.8
Forest	P	4030.49	1631	16.3	N/A	0.12	0.54	0.15	60	169.3	435.8
High Density Residential	I	5216	2111	21.1	N/A	2.32	14.1	0.67	90	28.2	567.4
High Density Residential	P	541.43	219	2.2	C	0.21	2.41	0.17	74	89.2	504.8
Industrial	I	1068.34	432	4.3	N/A	1.78	15.08	0.65	91	25.1	570.9
Industrial	P	193.32	78	0.8	C	0.21	2.41	0.17	74	89.2	504.8
Low Density Residential (single family)	I	185.44	75	0.7	N/A	1.52	14.1	0.40	90	28.2	567.4
Low Density Residential (single family)	P	442.57	179	1.8	C	0.21	2.41	0.17	74	89.2	504.8
Open land	I	756	306	3.1	N/A	1.52	11.33	0.85	98	5.2	593.8
Open land	P	2783.77	1127	11.3	C	0.21	2.41	0.17	74	89.2	504.8
Total		**24741.66**	**10013**	**100**						**753**	**6400**
Notes:	Defined in QGIS Automatic Detection of Impervious Surfaces from Remotely sensed data	Calculated in QGIS (Based on Institut Cartogràfic i Geològic de Catalunya Data: 2018 Land Use)			Refer to Table 1 of Appendix A	USEPA BATT setting	USEPA BATT setting	Refer to Table 1 of Appendix B	Refer to Table 1 of Appendix C	Refer to Equation 1 of Appendix D	Refer to Equation 2 of Appendix D

Table 3. Rotterdam land area calculations, soil types, and runoff characteristics for each land use type.

Land use	**Type of Land cover impervious/pervious**	**Area (ac)**	**Area (ha)**	**% of total area**	**Hydrological soils type**	**Phosphorous Loading (lb/ac/yr)**	**Nitrogen Loading (lb/ac/yr)**	**Runoff coefficient (average)**	**Runoff Curve Number (CN)**	**The potential maximum retention (SCN, mm/yr)**	**Direct surface runoff (mm)**
Highways	I	3776.12	1528	8.1	N/A	1.34	10.17	0.85	73	94	732
Agriculture	P	5329.26	2157	11.5	A	0.45	2.59	0.15	66	131	696
Commercial	I	14210.04	5751	30.6	N/A	1.78	15.08	0.75	89	31	798
Commercial	P	2082.75	843	4.5	A	0.03	0.27	0.17	49	264	585
Middle Density Residential	I	10650.04	4310	22.9	N/A	1.96	14.1	0.50	77	76	750
Middle Density Residential	P	937.43	379	2.0	A	0.03	0.27	0.17	49	264	585
Open land	I	2612.04	1057	5.6	N/A	1.52	11.33	0.85	98	5	829
Open land	P	6812.96	2757	14.7	A	0.03	0.27	0.17	49	264	585
Total		**46410.64**	**18782**	**100**						**1130**	**5559**
Notes:	Defined in QGIS Automatic Detection of Impervious Surfaces from Remotely sensed data	Calculated in QGIS (Based on Corine: 2018 Land Use)			Refer to Table 1 of Appendix A	USEPA BATT setting	USEPA BATT setting	Refer to Table 1 of Appendix B	Refer to Table 1 of Appendix C	Refer to Equation 1 of Appendix D	Refer to Equation 2 of Appendix D

The BATT modelling showed that maximum implementation of porous pavements and bioswales in each of the three cities will have substantial mitigation potential.

Table 4. Mitigation potential of maximum NBS scenario in NICHES core cities

City	TN mitigation (kg)		TP mitigation (kg)		Additional storage volume (Mm^3)
	Porous Pavement	Bioswales	Porous Pavement	Bioswales	
Boston	37414	112400	4589	2253	25.2
Barcelona	777393	233522	95099	46685	58.2
Rotterdam	556478	N/A	646187	N/A	61.0

The differences in the modelled value of additional storage volume, total phosphorus mitigation, and total nutrient mitigation between Barcelona, Boston, and Rotterdam could be attributed to various factors related to the cities size, geographical, environmental, and urban characteristics of each location. Each city has its own unique geography and climate, which can influence factors such as precipitation patterns, temperature, and soil composition. These variations can impact the rate and manner in which runoff occurs, as well as the transport of nutrients. Differences in urban planning, land use, and infrastructure can affect the amount of impervious surfaces (such as roads and buildings) in each city. Higher levels of impervious surfaces can lead to increased runoff and altered nutrient transport pathways.

For context, the reductions needed to meet the total maximum daily load (TMDL) for the Lower Charles River in Boston, defined as the level of nutrient inputs that would maintain healthy water quality for ecosystem function, is less than 20,000 kg of TP annually.

This BATT modelling indicates that NBS, when implemented at its maximum extent in the NICHES core cities, could have substantial water quality benefits. This maximum extent only considers technical potential, based on land area and land cover types, and not any socioeconomic considerations. Actual practical scenarios that are co-created with stakeholders will have implementation plans that are likely much smaller extent, and these will be modelled in subsequent stages of the NICHES project. The results modelled here provide an upper bound for what is technically possible.

8 Discussion

These findings indicate that implementing NBS to its maximum extent in the NICHES core cities could yield significant water management benefits. The preliminary assessment using the BATT spreadsheet model provided an initial understanding of the relationship between NBS implementation, runoff reduction, and nitrogen and phosphorus capture. However, it is crucial to acknowledge that the spreadsheet model employed in this study was simplistic and served as a starting point in evaluating NBS effectiveness. Furthermore, the maximum extent considered in the modelling exercise was solely based on technical potential derived from land area and land cover types, without considering socioeconomic, technical, and ecological feasibility factors.

In contrast, hydrological modelling offers a more comprehensive and representative approach to evaluating the effectiveness of NBS. By incorporating factors such as the urban drainage/ sewer system, topography, and rainfall patterns, hydrological modelling provides a more robust understanding of how NBS implementation influences runoff and pollutant capture. Utilizing advanced tools like MIKE+ with the ECOLLAB component enables to capture the intricate interactions and complexities of the system, resulting in more reliable and detailed assessments. When comparing the spreadsheet model approach to hydrological modelling, it becomes evident that the spreadsheet model falls short in capturing the full range of factors that influence NBS performance. The hydrological modelling approach provides a more accurate representation of the hydrological processes and considers various parameters, such as flow velocities, infiltration rates, and pollutant transport mechanisms. This enables a more realistic evaluation of NBS effectiveness and its potential impact on mitigating runoff and capturing pollutants.

The findings of this study align with previous research conducted by Selbig and Bannerman (2008), Koch et al. (2014), and Duan et al. (2016). These studies, including paired watershed studies and site-specific analyses, have shown that NBS design techniques significantly reduce runoff, sediment, and nutrient pollutant loads compared to traditional designs. They have also highlighted the effectiveness of implementing NBS in a series or as part of treatment trains for maximizing pollutant removal.

While this study contributes to the existing knowledge on NBS effectiveness, it is important to acknowledge the limited number of studies in this field and the need for further research. Pennino et al. (2016) have all called for additional field-based research and comprehensive data collection to enhance our understanding of NBS performance and its potential for pollutant removal. Future studies should prioritize the use of advanced hydrological modelling approaches to provide more accurate and representative assessments of NBS effectiveness in urban water management contexts.

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10 Appendix

Appendix A: Hydrologic Soil Groups Classification

The following table presents the classification of soils into four Hydrologic Soil Groups (HSGs) based on their respective runoff potential. (Ross et al. 2018) This classification system is established by the Natural Resource Conservation Service (NRCS) to assist in understanding and managing the hydrological characteristics of different soil types. The four HSGs, namely A, B, C, and D, indicate varying levels of runoff potential, with Group A having the smallest runoff potential and Group D possessing the greatest.

Please note that the "N/A" category is not included in the input due to the presence of impervious cover, which can significantly alter the soil's hydrological behavior and is not considered in this classification.

Table A1: Classification of Soils into Hydrologic Soil Groups (Ross et al. 2018)

Soil Group	**Runoff Potential**	**Description**
A	Lowest	Soils with the smallest runoff potential. These soils typically have excellent infiltration rates, effectively absorbing and retaining rainfall. They exhibit high water-holding capacity and minimal risk of surface runoff.
B	Moderate	Soils with a moderate runoff potential. While they are not as well-drained as Group A soils, they still exhibit decent infiltration rates and can store a moderate amount of water. Some surface runoffs may occur during intense or prolonged rainfall events.
C	High	Soils with a relatively high runoff potential. These soils have reduced infiltration rates compared to Groups A and B, leading to a higher likelihood of surface runoff. They can store less water and are more susceptible to erosion and runoff.
D	Highest	Soils with the greatest runoff potential. Group D soils typically have very low infiltration rates, resulting in significant surface runoff even during small rainfall events. They have limited water storage capacity and are highly vulnerable to erosion and runoff.

Appendix B: Recommended Runoff Coefficients for Different Land Uses and Soil Types

The following table provides recommended values for the runoff coefficient, which is a measure of the ratio of runoff to rainfall, for different land use categories and soil types. The runoff coefficient serves as an essential parameter in estimating the amount of rainfall that is converted into runoff in a watershed. It is influenced by various watershed characteristics, including land use patterns and soil properties. Taken average coefficient for each Land use group.

Table B1: Runoff Coefficients (Innovyze, 2021)

DESCRIPTION OF AREA	RUNOFF COEFFICIENT
Business	
Downtown	0.70 - 0.95
Neighborhood	0.50 - 0.70
Residential	
Single-family	0.30 - 0.50
Multiunits, detached	0.40 - 0.60
Multiunits, attached	0.60 - 0.75
Residential (suburban)	0.25 - 0.40
Apartment	0.50 - 0.70
Industrial	
Light	0.50 - 0.80
Heavy	0.60 - 0.90
Parks, Cemeteries	0.10 - 0.25
Playgrounds	0.20 - 0.35
Railroad yard	0.20 - 0.35
Unimproved	0.10 - 0.30
CHARACTER OF SURFACE	
Pavement	
Asphaltic and concrete	0.70 - 0.95
Brick	0.70 - 0.85
Roofs	0.75 - 0.95
Lawns, sandy soil	
Flat, 2%	0.05 - 0.10
Average, 2-7 %	0.10 - 0.15
Steep, 7%	0.15 - 0.20
Lawns, heavy soil	
Flat, 2%	0.13 - 0.17
Average, 2-7 %	0.18 - 0.22
Steep, 7%	0.25 - 0.35

Appendix C: Runoff Curve Numbers for Predicting Direct Runoff or Infiltration

The following table presents recommended values for Runoff Curve Numbers (RCNs), which are empirical parameters used to predict the amount of direct runoff or infiltration from rainfall excess. These values are based on the methodology established by the American Society of Civil Engineers (ASCE) in 1992 and Rossmiller in 1980.

The Runoff Curve Number represents the runoff potential of a land surface based on its land use and land cover characteristics. It is a dimensionless parameter ranging from 0 to 100, where higher values indicate a higher runoff potential. A higher RCN suggests less infiltration and more direct runoff. The RCN is influenced by factors such as soil type, land cover, land management practices, antecedent moisture condition, and hydrological response characteristics.

Table C1: Runoff Curve Numbers (ASCE, 1992)

Land Use	Cover		Hydrologic soil group			
	Treatment or practice	Hydrologic condition	A	B	C	D
Cultivated	Straight row		76	86	90	93
Cultivated	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
Cultivated	Contoured &	Poor	66	74	80	82
	Terraced	Good	62	71	77	81
Cultivated	Bunded	Poor	67	75	81	83
		Good	59	69	76	79
Cultivated	Paddy		95	95	95	95
Orchards	With understory cover		39	53	67	71
	Without understory cover		41	55	69	73
Forest	Dense		26	40	58	61
	Open		28	44	60	64
	Scrub		33	47	64	67
Pasture	Poor		68	79	86	89
	Fair		49	69	79	84
	Good		39	61	74	80
Wasteland			71	80	85	88
Roads (dirt)			73	83	88	90
Hard surface areas			77	86	91	93

Appendix D: Potential Maximum Retention (SCN) and Direct Surface Runoff based on SCS-CN Method

The following equations represent the calculation of the potential maximum retention (SCN) and direct surface runoff using the Soil Conservation Service Curve Number (SCS-CN) method. The SCS-CN method was developed by the Soil Conservation Service (SCS), and the equations are based on the work of Yen and Chow (1983).

Equation 1: Potential Maximum Retention (SCN)

$$S = \frac{25400}{CN} - 254 = 254\left(\frac{100}{CN} - 1\right)$$

Equation 2: Direct Surface Runoff (Pe)

$$Pe = \frac{(P - Ia)^2}{P - Ia + S} = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad ; \text{ for } P > \lambda S$$

$$Pe = 0 \quad for\ P \leq \lambda S$$

Where Pe = Average direct surface runoff per year (all in units of volume occurring in time Δt) Ia= initial abstraction (I a = S × λ) S= potential maximum retention

For Boston:
Average rainfall per year (P) = 1100 mm
λ value = 0.2 (standard)

For Barcelona:
Average rainfall per year (P) = 600 mm
λ value = 0.2 (standard)

For Rotterdam:
Average rainfall per year (P) = 835 mm
λ value = 0.2 (standard)

The potential maximum retention (SCN) is a dimensionless parameter ranging from 0 to 100, where higher values indicate a higher potential for water retention and lower runoff potential. It is calculated using Equation 1, where the CN value is used as an input (refer to Table 2 of Appendix A)

The direct surface runoff (Pe) represents the volume of water that flows over the surface of the land and does not infiltrate into the soil. It is calculated using Equation 2, where P represents the total rainfall and Ia represents the initial abstraction. The initial abstraction represents the volume of water that is initially retained or absorbed by the soil before any runoff occurs.

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