CONFIDENTIAL
FINAL REPORT

NICHES DELIVERABLE D1.2 v3

BOUNDARY CONCEPTS: UNDERSTANDING IMPACTS OF COMBINED SEWER OVERFLOWS AND NATURE-BASED SOLUTIONS FOR URBAN WATER MANAGEMENT IN NICHES CITIES

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1. EXECUTIVE SUMMARY

1. This report examines framing, using the social-ecological-technical systems (SETS) concept, through the lens of urban water management – and surrounding infrastructures, interventions and institutions – including the application of nature-based solutions and conventional infrastructures of combined sewer systems and combined sewer overflows (CSOs).
2. Mapping of key issues, concepts, regulatory frameworks and impact assessment regimes was undertaken in conjunction with partners in the cities of Rotterdam (Netherlands), Berlin (Germany), Barcelona (Spain), Boston (USA) and Sheffield (UK). The research then explored characteristics of urban water management systems and contexts in each city.
3. The research indicates that each city's relevant priorities for urban water management – and the state of progression with impact assessment – are shaped by their infrastructures, interventions and institutions (linked with their geographies, histories and governance), and vice versa. The SETS model shines a light on these contextual specificities and gives insights into the applicability of alternative framings of measures of success, such as NBS impact assessment frameworks. However, the emerging picture also highlights limitations in using this approach.
4. The results provide insights that have shaped the development of the conceptual framework and impact assessment framework applied in subsequent workpackages and tasks in the NICHES project. In particular, the research has informed the development of thinking in relation to the project's investigation of change pathways.

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2. INTRODUCTION

Background, purpose and overview of the research

Pollution and flooding from CSOs have increased with the impacts of climate change and biodiversity loss, and interest is increasing in the development of improved measures of success for future responses. This accompanies mounting awareness of impacts of CSOs and a growing recognition that existing metrics based on numbers of overflow events and volumes alone are no longer sufficient.

This research investigates boundaries between different infrastructures, institutions and interventions of relevance to nature-based solutions (NBS) for urban water management in NICHES cities. The report studies different values and benefits of NBS and conventional drainage systems applied in urban areas served by combined sewer networks**.** It does to in order to seek to understand narratives of change in diverse settings, within the social, cultural, environmental, political, and economic institutions relevant in each context. The report applies the theme of urban stormwater management to explore the social-ecological-technical systems or SETS framework. In particular the research involved identifying different indicators, who uses them and for what purpose, with a view to considering their substance in terms of societal challenges and impacts.

Techniques employing NBS such as sustainable urban drainage systems (SUDS - D'Arcy, 1998) rely on infiltration, retention, detention and progressive treatment of urban water in stormwater management trains, employing vegetated interventions such as swales and rain gardens. These techniques were drawn from systems developed in the USA known as urban water best management practices, which were often implemented in separate drainage networks. The thinking around SUDS was developed with the intention to address water quality, water quantity, amenity and biodiversity benefits, drawing on 'nature's way' including the various processes outlined above (treatment through vegetation and substrates, infiltration, detention and retention). Whilst the knowledge employed was largely based on techniques associated with diffuse pollution control and separate drainage networks, calls have strengthened over the years implement SUDS in combined systems in order to control CSO impacts.

The approach in NICHES workpackage 1 has been to consider SUDS, and D'Arcy's (1998) SUDS triangle in the light of other research including Langemayer & Connolly's (2020) work on justice in ecosystem services and Depietri & McPhearson's (2017) interpretation of SETS, with subsequent research also drawing on Woroniecki et al. (2023). The research reported here examines perceptions of interventions, institutions and infrastructures in the five NICHES cities of Rotterdam, Berlin, Barcelona, Boston, Sheffield. The core issues considered are represented in Figure 1 (Wild, 2024) developed in NICHES task 1.1.

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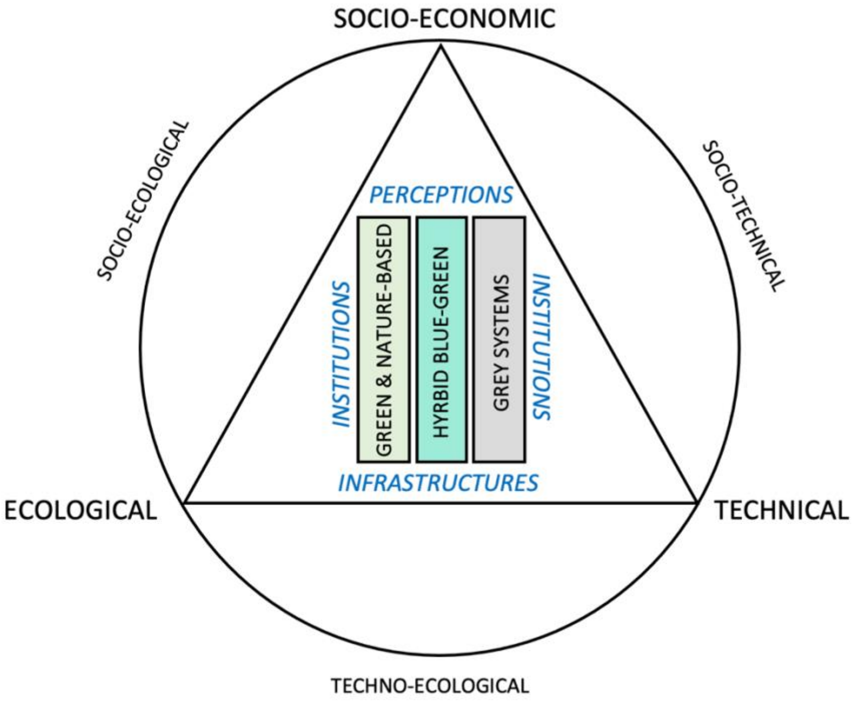

Figure 1. NICHES framing of NBS for urban water management (after D'Arcy, 1998, Depietri & McPhearson, 2017, Langemayer & Connolly, 2020)

Methods and materials used in this research are detailed in NICHES deliverable T1.1 report, and in Wild et al. (2024). The research drew on three main sources of information: (1) interviews undertaken by NICHES partner organisations; (2) mind-mapping pertaining to the impact assessment frameworks, models and metrics applied in each city to understand CSO impacts; (3) restricted literature reviews tailored to each city.

Drawing on the results of 1-3 above, key impacts were identified in each city, according to understandings of the types of indicators and impact assessments applied, through a limited set of key criteria for each place. In particular, the research was concerned with the interplays between the different socio-economic, technical and ecological impacts. The findings of the interviews, mind-maps and literature reviews were used to establish which were the main facets represented in the impact criteria, bearing in mind that several involved an interplay between each of the axes.

Assessment criteria were plotted on to a ternary diagram to represent the relative make-up of each of them in terms of their socio-economic, technical and ecological characteristics. Ternary plots are useful when the purpose of enquiry is to analyse compositional data where three variables need to be plotted in a two-dimensional graph (i.e. in three-dimensional cases).

The state of development or readiness of each impact criterion was also considered based on the literature, mapping and interview findings. These are represented using a familiar red, amber, green (traffic light) motif, for each resulting SETS diagram for each city. Thus, where an impact assessment criterion is considered well established and applied meaningfully, this is marked green, whereas a red notation indicates that the criterion is not well understood or developed enough to support meaningful application. The remainder of this report is structured according to the findings for each of the five cities, with an introduction for each context.

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3. SHEFFIELD

Sheffield is largely served by a combined sewer network, with only peripheral areas being on a separate drainage system. SUDS and green roofs have been heavily promoted and implemented in the city for a wide range of reasons, including goals to reduce CSO spills, with the removal of rainwater from the combined sewer network being a key factor. However it is important to bear in mind that there exists in Sheffield a complex interplay between receiving water flows, flooding and CSO discharges, due to the city's steep, flashy catchment and other factors including river culverts. CSO pollution is back up the agenda in Sheffield due to worsening river water quality in the 2010-20s, following several decades of improvements in ecological status (Wild et al., 2008; Wild, 2022).

Sewerage in England and Wales is provided by ten private companies (Water and Sewerage Companies - WASCs) established through the Water Industry Act 1991 (HM Government, 1991). These companies are responsible for maintaining and expanding the public sewer system, including the provision of drainage and sewage treatment. Regulation of these companies is primarily overseen by two bodies:

- Ofwat - regulates economic aspects, setting prices, and ensuring customer protection (Ofwat, 2025). Price Reviews (PRs) occur every five years, with Ofwat monitoring company spending, profit and service levels.
- The Environment Agency (EA) - environmental protection and regulation is undertaken by the EA. It implements environmental directives including water quality regulation, works to reduce flood risk and monitors compliance, issuing permits for discharges to surface waters and groundwaters (HMG, 2025). The EA also handles pollution incidents and complaints, and takes enforcement action.

Sewage discharge limits in England are calculated based on the type of treatment, the receiving water body, and potential impact on water quality. The EA sets limits using two main types of sewage discharge limits through permits (previously called consents to discharge):

- General Binding Rules - smaller discharges from homes and businesses, with limits are based on sewage volume and the type of treatment plant (applies to septic tanks and small sewage treatment plants only).
- Environmental Permits - larger discharges, from larger wastewater treatment works, industrial sites and combined sewer overflows – limits are tailored to discharge flows, contents, receiving water flows and environmental quality standards.

The EA monitors sewage discharges to ensure compliance. If limits are exceeded it can take legal enforcement action. In issuing permits, The EA sets conditions including discharge limits, based on Environmental Quality Standards (EQSs) - legally binding limits for pollutants in the environment. EQSs cover a wide range of pollutants found in sewage, including: bacteria, nutrients, metals, organic matter, and hazardous substances. Permits also set conditions specific to each regulated facility based on treatment technology used and receiving waterbody flow rates, water quality, and ecological condition including the presence of protected species and habitats. Where permit conditions are breached, the EA can - and should - take enforcement action, with the level of legal action being appropriate to the seriousness and persistence of offences (HMG, 2025).

Monitoring of sewage discharges is via two routes: (1) inspections and sampling by the EA; and (2) monitoring and control systems used by the discharger to optimise and control treatment works and hence discharge flows and qualities. Citizens and community groups also play an important role in monitoring

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water quality and reporting pollution incidents - during the 2010s pollution levels increased - after decades of improvements - and levels of civic action are currently high.

The previous UK Government and the EA were criticised for reducing levels of inspections and monitoring effectiveness through the 2010s (EAC, 2022). In turn, the EA has criticised the Conservative Government for its austerity programme and budget cuts, affecting EA staffing levels (EAC, 2022) and especially monitoring staff. More details on pollution levels in Sheffield rivers, including the worsening of receiving water quality and ecological status, can be found in Wild (2022).

While there is not one universally recognised 'industry standard' software in use for modelling water quality and sewage discharges, SIMCAT is widely used by the EA. Such catchment-scale modelling software is used to assess water quality, addressing hydrological conditions, point and diffuse pollution sources, and environmental quality standards. Pollution sources and discharge attributes are identified, and modelled using source apportionment to assess likely pollution impacts and to predict resulting ecological status. According to Defra, SIMCAT is the main river water quality simulation tool for water management and permitting in the UK (Defra, 2025). However, UKWIR (2024) contends that SAGIS - a system of interconnected tools and processes – is now embedded in business-as-usual processes and serves as the go-to approach. WASCs and environmental consultancies use a range of other software models to predict and assess treatment plant performance and discharge scenarios (including flows, quality and receiving water impacts). The regulator and WASCs work closely together in exchanging data and model outputs, and for Barcelona, CSO systems management depends heavily on WASC owned real-time monitoring data.

Some voices have called for more radical reform of the water industry in the UK partly due to concerns that the water industry and regulators have become too closely entwined, including through such collaborative approaches to modelling, data sharing and discharge monitoring (UK Parliament, 2024).

WASCs in England recently had to publish 25-year plans for wastewater services, including more ambitious investment plans to address CSOs, with water bills being allowed to rise significantly (ca. £100 per annum per household, driven by the Asset Management Planning process AMP, and the Pricing Review 2029 PR29). Yorkshire Water, which is the WASC for Sheffield, is one of the companies that has been most heavily criticised for poor performance on CSOs. Some WASCs, such as Severn Trent have put SUDS central to their responses, accompanied by more advanced integrated catchment modelling bringing together microscale models such as Infodrainage and AutoCAD with river models (building on a significant heritage of such approaches as the Urban Pollution Manual (UPM). In the case of Severn Trent, Mike-II is used to establish flows, spill qualities and volumes. However, not all WASCs have such a science-based approach, and have instead followed a more simplistic target of reduction to10 spills/year without thought given to environmental contexts.

In Sheffield, progress with implementing SUDS has largely been driven by the public sector, especially the local authority, working in partnership with NGOs and community groups through the Sheffield Waterways Strategy Group (Conexus, 2022; Wild, 2022; Interlace, 2023). This includes the high-profile Grey to Green scheme, delivered through ERDF funding enabled by Sheffield City Region's Sustainable Urban Development Strategy (Morley & Wild, 2017; HM Government, 2017) and implemented in partnership under the auspices of the Sheffield Waterways Strategy (Wild et al., 2014). Zac Tudor and Nigel Dunnett's ambitious design scheme for Grey to Green has been widely celebrated (Dunnett & Tudor, 2020) and the SUDS have been well maintained.

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Biodiversity impacts have been monitored through the Conexus project, and increasing attention is being given to how to target the biodiversity benefits of such SUDS schemes featuring the full stormwater management train approach (CIRIA, 2000). Stakeholders have identified the need for SUDS impact assessment to address wider co-benefits, including aesthetics and biodiversity as well as the more usual hydraulic and water quality assessments, in line with D'Arcy's (1998) vision in represented in the SUDS triangle. Biodiversity indicators in particular are receiving more attention due to the complex interplay between England's Biodiversity Net Gain (BNG) policy and SUDS.

Sheffield City Council's draft local plan (spatial plan) includes proposals to limit discharges of surface water from new developments. It is important to note that Yorkshire Water (the WASC for Sheffield) has no strategy for de-paving or to increase permeability in urbanised areas. Since water companies receive income for connections from paved areas of surface water drainage to the sewer, this is unlikely to change – at least until SUDS are made mandatory by Government for new developments in England, bringing it into line with Scotland and Wales.

Flows and flooding in drainage networks and SUDS have been well researched in Sheffield (Stovin et al., 2008; 2010; 2013; Newman et al., 2011; Poë et al., 2015; Johannessen et al., 2017; Goodchild et al., 2018; Richards et al., 2020). Pollution loads, including industrial pollutants, sewage and runoff, are of major concern in Sheffield; sewage discharge pollution loads and concentrations have been the focus of considerable research (Clarke, 1990; Amisah et al., 2000a; 2000b; Saul et al., 2003; Robson et al., 2006; Wild, 2022). Environmental quality impacts in rivers have also been relatively well researched, with river water quality having begun to degrade again since the 2010s after sustained improvements over the preceding decade; CSO impacts have come back up the agenda (Clarke, 1990; Amisah et al., 2000a;2000b; Robson et al., 2006; Rotherham, 2021, Wild, 2022).

Other well-researched aspects involve indicators and impacts relating to: governance, participation and learning (Gill et al., 2010; Newman et al., 2011; Goodchild et al., 2018; Wild et al., 2019; Connelly et al., 2020); access and associated cultural ecosystem services (Gill et al., 2010; Shaw et al., 2010; Shaw et al., 2016b); and biodiversity, ecological quality and habitat connectivity (Shaw et al., 2016a; 2021; Angelopoulos et al., 2018; Amisah et al., 2000a;2000b; Richards et al., 2020; Rotherham, 2021). Related to the latter, through the complex interplay in Sheffield between receiving water flows, flooding and CSO discharges, are the themes of hydrogeomorpholgy and river restoration (Angelopoulos et al., 2018; Wild et al., 2019; Richards et al., 2020).

Less well-established criteria in relevant Sheffield-focussed research pertain to aesthetics including sewage derived objects and receiving waters (Saul et al., 1998; Gill et al., 2010), water resources, including drought and groundwater (Afzal et al., 2020); and cost-benefit and valuation (Wild et al., 2017). It is particularly surprising that aesthetics of CSO discharges have received relatively little attention in the literature, because this is a hotly debated topic in the mainstream media and in popular culture in Sheffield.

For Sheffield, indicators considered in the SETS analysis (Fig.2) are therefore: (1) Flood risk management and retention (FRM for short, see Fig.2); (2) Receiving water quality (WQ) (3) Biodiversity and ecology (BIO); (4) Governance and participation (GOV); (5) Pollution loads (POL); (6) Access to blue/greenspace (ACS); (7) Hydrogeomorphology and river restoration (GEO); (8) Aesthetics (AES); (9) Cost-benefit and valuation (CBA); and (10) Water resources including groundwater (WR).

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Figure 2. SHEFFIELD SETS analysis of impact assessment criteria for urban water management

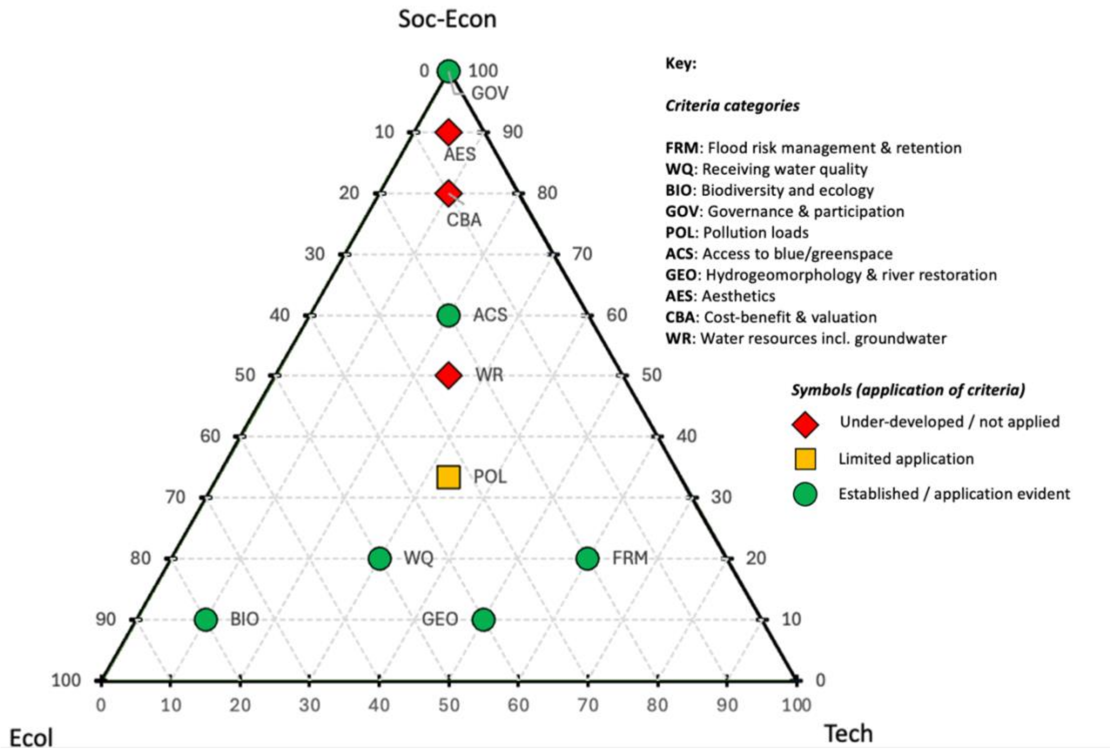
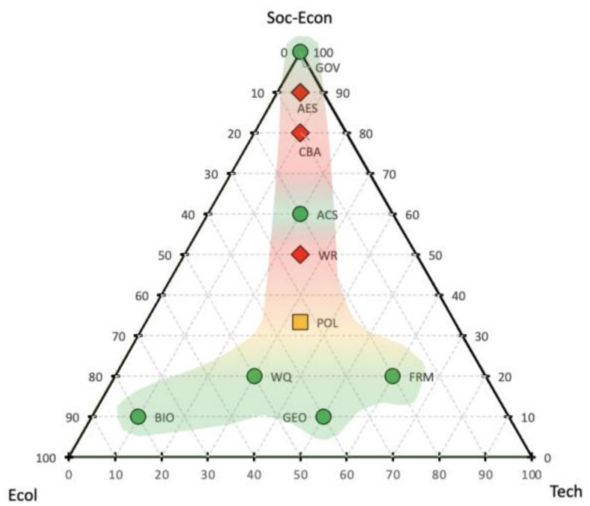
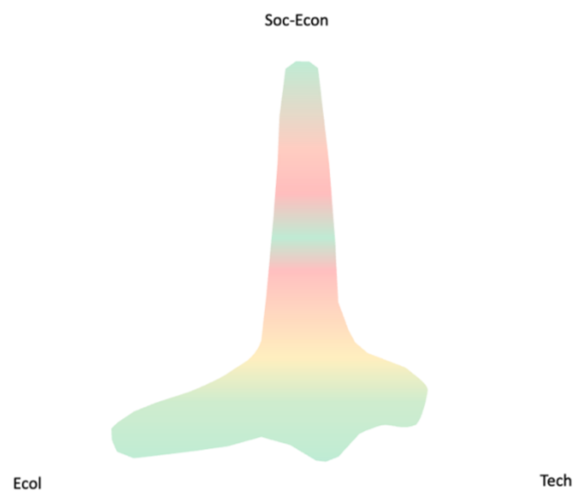


Figure 2 shows for Sheffield the criteria least well developed or where application is not well established relate primarily to social and economic impacts, notably comprehensive valuation, water resources, and aesthetic aspects of sewage discharges, but also pollution loads. Heatmaps in Figures 3a-b highlight these trends in terms of gaps and potential transformative action more clearly. The city has the opportunity to draw on strong governance networks and other socio-economically relevant criteria such as non-motorised access, to address key gaps. However the heatmap also flag up the core sustainability concerns at the heart of SETS interfaces.

Figs. 3a & 3b. Heatmaps for SHEFFIELD SETS analysis *(see also Fig.2)*





4. BOSTON

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Approximately 70% of the city of Boston, Massachusetts is served by combined sewer systems. Key water service providers include the Boston Water and Sewer Commission (BWSC) and the Massachusetts Water Resources Authority (MWRA**)**.

MWRA supplies water and sewer services to 61 communities in the greater Boston area, including Boston itself. It operates drinking water treatment plants and the major wastewater treatment facility on Deer Island. BWSC is responsible for water distribution and wastewater collection within the city of Boston. BWSC purchases treated water and wastewater treatment services from MWRA. In essence MWRA handles the production and treatment of water and wastewater, whereas BWSC delivers and collects the water/effluents.

Sewage discharge limits in Boston are controlled through a combination of federal, state, and local regulations. In the US the primary federal legislation governing water pollution is the Clean Water Act or CWA (US EPA, 1972). This law establishes national standards for wastewater discharges, including limits on pollutants such as biochemical oxygen demand (BOD) and suspended solids.

The US EPA and Massachusetts Department of Environmental Protection (MassDEP) jointly administer surface water discharge permits in Massachusetts. Those responsible for the discharge of pollutants into surface waters must obtain a National Pollutant Discharge Elimination System (NPDES) permit. Since June 2020, the NPDES permit program has been administered by the US EPA, which considers various factors when setting discharge limits, including:

- Receiving water quality: Limits are set to protect receiving water bodies and designated uses including drinking water supply, recreation and aquatic life. According to the US EPA (2023), "Water quality standards set the acceptable levels of various pollutants in surface waters."
- Discharge type: discharge limits are set for specific pollutants and flow rates associated with different industries and water uses.
- Water treatment technology: The effectiveness and cost of treatment technologies influence discharge limits.
- Water quality standards: Discharge limits are set according to the receiving body water quality standards (state and federal): Discharge limits must ensure that the receiving water body meets state and federal water quality standards.

The US EPA employs various tools and models to assess discharges and set permit limits, including the Storm Water Management Model (SWMM) for modelling stormwater runoff quality, control effectiveness and water quality impacts; EPANET is used to model water distribution systems, including flows, pollutant concentrations and impacts (US EPA, 2023)**.** Other, more complex and bespoke models may be used to assessing transport and fate and transport of pollutants in the environment (depending on specific pollutants and the complexity of pathway/ receiving water environment). MIKEII is used for modelling river impacts with SWMM being used to model land drainage elements (Eckelman, pers.comm.).

Previously, MassDEP was solely responsible for implementing and enforcing the CWA at the state level, setting specific discharge limits for various industries and wastewater treatment plants based on the designated uses and quality of receiving water bodies. MassDEP now administers a parallel surface water discharge permitting programme. Both programmes control water pollution by regulating point sources that discharge pollutants to surface waters (MassDEP, 2025). Discharge limits may be adjusted over time based on monitoring data and changes in environmental conditions.

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MassDEP uses various approaches to determine acceptable sewage discharge levels (Mass DEP, 2025):

- Water quality standards are used to **set** limits for pollutants including biochemical oxygen demand (BOD); total suspended solids (TSS); nutrients (nitrogen and phosphorus); pathogens (bacteria, viruses); and metals (e.g., lead, copper).
- Receiving water conditions are assessed and used in setting permit limits, covering (a) flow rate and dilution; (b) water quality, whereby existing conditions and pollution levels influence discharge impacts; and (c) ecology – stricter limits are set to protect sensitive species and/or habitats where present.

In the Charles River, total mean daily limits are set on phosphorous discharges in order to try to control nutrient levels; bathing is prohibited due to levels of toxins associated with algal blooms (Eckelman, pers comm). The city and regulators are aiming to get to the point where bathing will be allowed again. In the Neponset River polluted sediments in the river associated with industry (e.g. PCBs) mean that these should not be disturbed. Large volumes of underground storage have been created to reduce pollution levels (e.g. COD and BOD) In the Bay.

Boston's aging sewer system results in significant CSO discharges during heavy rainfall events. The Boston Harbour Cleanup campaign and problems associated with pollution have led to more stringent regulations to protect the harbour ecosystem and recreational uses (US EPA, 2022). The US EPA compels private landowners discharging stormwater runoff into major rivers to install green infrastructure or other treatment and storage measures to manage pollutant loads (US EPA, 2025).

Boston has been the subject of relatively extensive research relevant to CSOs. In terms of key impacts, pollution has been investigated as regards CSO discharges and levels of bacteria, nutrients and other pollutants (Scaramuzzo et al., 1995; Eganhouse et al., 2001; Siegener et al., 2002; Hellweger, 2007; Hurley et al., 2011; Gamache et al., 2013; Liu et al, 2015). With an active civic society mobilised towards the cleanup, the issues of governance, participation and education are also well researched (Kempe, 1989; Cheng et al., 2017; England, 2017; Feingold et al., 2018; Lu et al., 2019; Frankić, 2022). Flooding is also a common theme in research and this aspect has gained more attention in recent years due to climate change impacts (Bedoya et al., 2016; Cheng et al., 2017; Wescoat et al., 2021; Clemente, 2022).

Perhaps surprisingly, river water quality and waterbody condition has been slightly less well covered (Devenis, 1986; Hellweger, 2007; Hurley et al., 2011). Other areas which have received some attention including cost benefit analysis and land values (Shea, 2007; Wang et al., 2013; Lu et al., 2019), and resource efficiency (Pinck, 1993; Feingold et al., 2018; Saha & Eckelman, 2014). Under-represented research themes include heat (Feingold et al., 2018; Millward, 2024), biodiversity and ecological quality (Frankić, 2022), aesthetics and recreation (Hurley et al., 2011) and *access* (Clemente, 2022*: cycling*)

Impact indicators addressed here in the SETs analysis are thus: (1) pollution (discharge loads and contents); (2) governance, participation and education; (3) flooding; (4) receiving water quality and waterbody condition; (5) cost-benefit analysis including land values; (6) resource efficiency; (7) heat; (8) biodiversity and ecological quality; (9) aesthetics including recreational use of waters; (10) access – e.g. for cycling.

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Figure 4. BOSTON SETS analysis of impact assessment criteria for urban water management

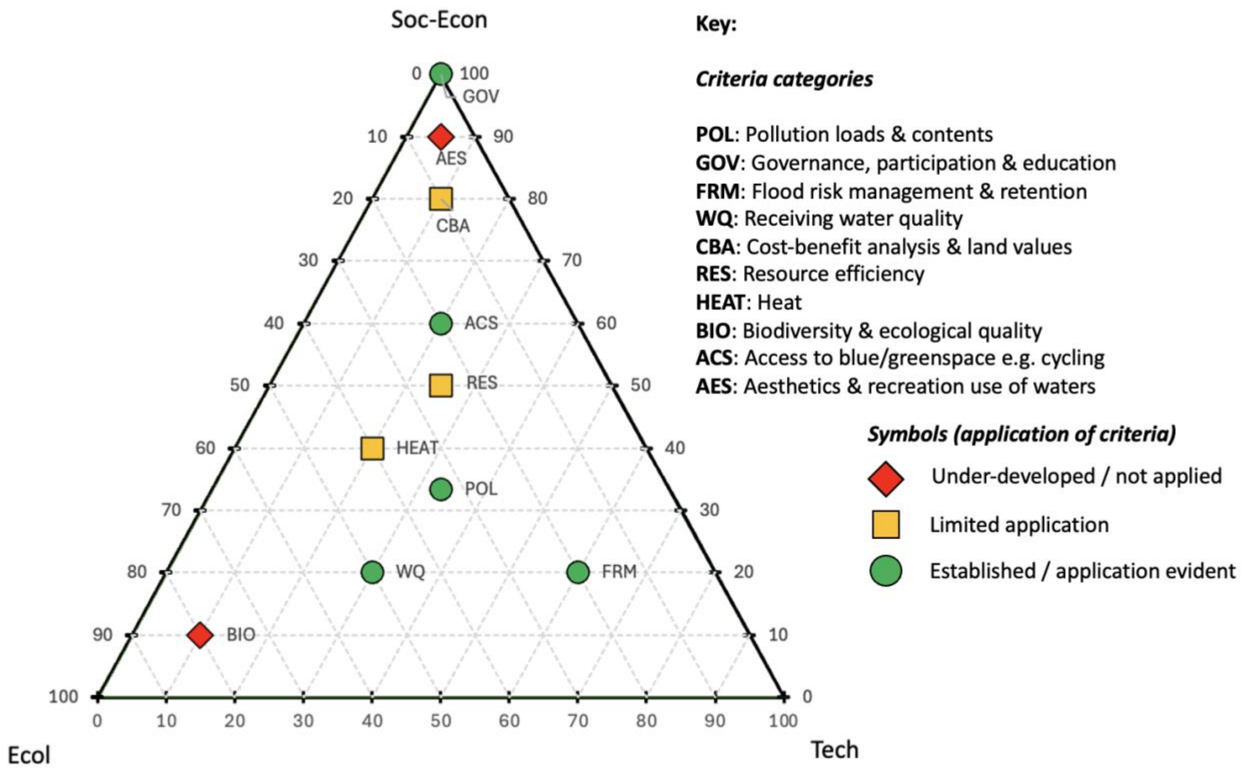
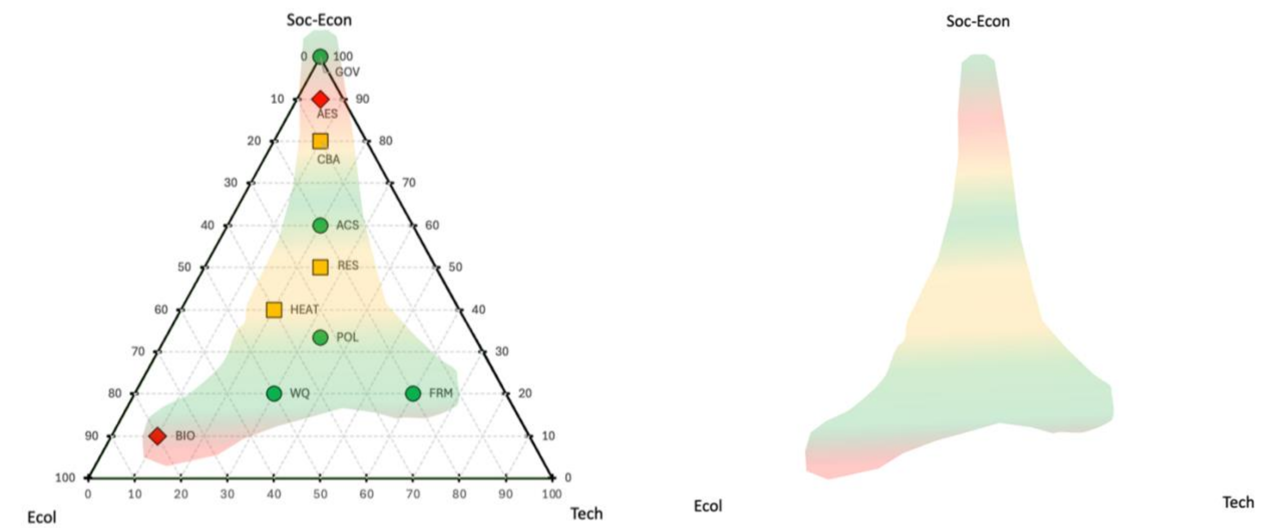


Figure 4 highlights that for Boston, less well-developed urban water management criteria are relatively spread out, apart from within the technical realm. Aesthetics, biodiversity, heat and resource efficiency are less well covered. Heatmaps in Figures 5a-b show this relatively complex picture, where technical impact assessment criteria dominate. Whilst there are many overlaps with Sheffield criteria, heat is an issue in Boston whereas hydrogeomorphology is less relevant (compared with Sheffield where numerous weirs and waterbody modifications are key concerns).

Figs. 5a & 5b. Heatmaps for BOSTON SETS analysis *(see also Fig.4)*



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5. BARCELONA

The regulation of CSO discharges in Barcelona is driven by European, national and community-level frameworks. At the EU level, the Urban Wastewater Treatment Directive (UWWTD), sets minimum standards for the collection, treatment, and discharge of urban wastewater across member states. The Water Framework Directive (WFD) puts in place requirements to achieve Good Ecological Status of water bodies, including coastal and transitional waters. Water regulation at the national level in Spain is rooted in the Ley de Aguas (Water Law) of 1985 (MITECO, 2025). It established the framework for water management, encompassing water resource planning and allocation, protection of water quality, and wastewater management. The Law outlines requirements for wastewater collection, treatment, and discharge, including treatment standards, discharge permits with tailored conditions and limits, and monitoring and enforcement responsibilities. The Spanish Ministry for the Ecological Transition and the Demographic Challenge (MITECO) sets national environmental policy frameworks and ultimately oversees and approves major environmental permits, including those related to wastewater discharges.

Catalunya has its own specific legislation on wastewater management. Licensing and permitting for sewage discharges in Barcelona is carried out by Catalan authorities, including the Departament de Territori i Sostenibilitat and the Agència Catalana de l'Aigua (ACA)**.** Elsewhere in Spain, Regional water authorities, Confederaciones Hidrográficas (CHs), oversee water management within their respective basins. Their responsibilities include enforcing environmental regulations related to water quality, issuing and monitoring discharge permits, and developing water resource plans that consider the impact of wastewater discharges. However, Catalonia has a unique system whereby the ACA holds the primary responsibilities for catchment-level management of water including water treatment.

The ACA's key responsibilities include • planning and managing water use; • protecting water quality; • controlling floods; • conserving aquatic ecosystems; and • promoting sustainable water use practices. The ACA has held these responsibilities since 2000. It plays a key role in planning, implementing, and enforcing wastewater regulations. Regional regulations establish discharge limits for certain pollutants to provide enhanced protection for the receiving water bodies, particularly the Mediterranean. The ACA also is responsible for water quality modelling in Barcelona to set discharge limits and control sewage pollution.

In 2014, Ajuntament de Barcelona (Barcelona City Council) established Barcelona Cicle de l'Aigua (BCASA) as a public company responsible for managing the water cycle in the city. BCASA's functions include water supply, wastewater treatment, managing sewage infrastructure, water conservation promotion and implementation, and environmental protection. BCASA's activities are regulated by ACA.

As regards CSO regulation, ACA assesses ecological risks to identify pollutants of concern and establish site-specific discharge limits, addressing receiving water sensitivity, aquatic ecology impacts and the cumulative effects of multiple discharges. Discharges in sensitive areas and areas deemed as having higher ecological value face more stringent regulation (protected areas, spawning grounds, habitats for vulnerable species etc).

ACA undertakes water quality monitoring, partly to ensure compliance with discharge limits, whereby breaches in discharge limits can result in financial penalties and enforcement action. ACA has encouraged the use of advanced wastewater treatments and real-time control of sewage treatment and storage in combined systems (Puig et al., 2009; BCASA, 2017).

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Research into the impacts of nutrients, emerging contaminants, pharmaceuticals and other micropollutants in Catalan waters (see below) has informed the development of specific discharge limits, more intensive monitoring and analysis of additional parameters to provide a deeper understanding wastewater characteristics and environmental impacts (Generalitat de Catalunya, 2024). The 1997 'Special Plan' for Barcelona's sewer system - updated in 2006 under the 'Comprehensive Plan' - resulted in the installation of many storm sewage retention tanks in the city with a total capacity of nearly ½ million m^3 storage. In 2019, Barcelona City Council established a SUDS Commission within the Urban Ecology Division, to "*divulge knowledge and advance the application of these techniques with the objective of promoting environmental policies... with respect to the resilience of its green infrastructure and water management*." (Martí et al., 2019). Barcelona has undertaken large-scale retroffiting of SUDS (Cabezas et al., 2024). Despite advances in combined sewer modelling and control in Barcelona, concerns over environmental, ecological, social and economic impacts remain, each with relevant sets of indicators.

Bathing water contamination, including viral and bacterial pollution levels are of concern in marine and riverine systems in Barcelona (Neves et al., 2010; Locatelli et al., 2020a&b; Martínez-Gomariz et al., 2021; Blanch et al., 2024). Sewage discharge pollution loads and concentrations have been the focus of considerable research (Sempere-Torres et al., 1999; Neves et al., 2010; Ocampo-Martínez et al., 2013; Llopart-Mascaró et al., 2015; Locatelli et al., 2020a; Locatelli et al., 2020b; Sun et al., 2020;2021; Teixidó et al., 2023; Labad et al., 2025). Receiving water quality impacts are also very well researched in Barcelona, including in contemporaneous studies; in other words, environmental impacts of CSO discharges remain relevant (Díez et al., 2006; Prat et al., 2006; Navarro et al., 2007; Damásio et al. 2008; Neves et al., 2010; Vázquez-Suñé et al., 2010; Köck-Schulmeyer et al., 2011; López-Serna et al., 2012; Locatelli et al., 2020b; Bolívar-Subirats et al., 2021; Blanch et al., 2024; Domínguez-García et al., 2024; Itarte et al., 2024).

Other well established fields of investigation that relate to indicators applied in CSO regulatory practice include flood risk management (including measures relating to hydraulics, rainfall-runoff, real-time control - Sempere-Torres et al., 1999; Cembrano et al., 2004; Ocampo-Martinez, 2006; Puig et al., 2009; Neves et al., 2010; Saurí et al., 2017; Gómez et al., 2019; Carriquiry et al., 2020; Locatelli et al., 2020a; Monjo et al., 2023; Sánchez-García et al., 2024) and water resources, including groundwater (Vázquez-Suñé et al., 2010; Frijns et al., 2016; Martí et al., 2019; Echevarría et al., 2022; Teixidó et al., 2023).

Less-well established indicators relate to social impacts. Relevant research has considered impacts linked with governance, community involvement and communication (Frijns et al., 2016; Carriquiry et al., 2020; Martínez-Gomariz et al., 2021; Ramírez-Agudelo et al., 2022), and aesthetics linked with sewage-derived objects - Locatelli et al., 2020a; Martínez-Gomariz et al., 2021). Cost-benefit has been considered primarily in terms of sewage treatment - wider CBA methods covering more diverse environmental and social benefits - beyond usual cost-effectiveness studies of storage and treatment costs - are rare (Locatelli et al., 2020a; Echevarría et al., 2022). Other fields of research of relevance to CSOs, but less well researched and where CSO performance indicators are lacking include: heat (urban heat island and thermal comfort - Cortinovis et al., 2022; Vasconcelos et al., 2024); biodiversity (Martí et al., 2019; Cortinovis et al., 2022); carbon storage and access to green/blue space associated with urban water (Cortinovis et al., 2022).

Potential indicators of interest considered here are thus: (1) Flood risk management; (2) Receiving water quality; (3) Pollution (load); (4) Water resources including groundwater; (5) Governance and participation; (6) Biodiversity; (7) Aesthetics; (8) Cost-benefit analysis; (9) Heat; (10) Access to blue/greenspace; and (11) Carbon storage (climate mitigation).

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Figure 6. BARCELONA SETS analysis of impact assessment criteria for urban water management

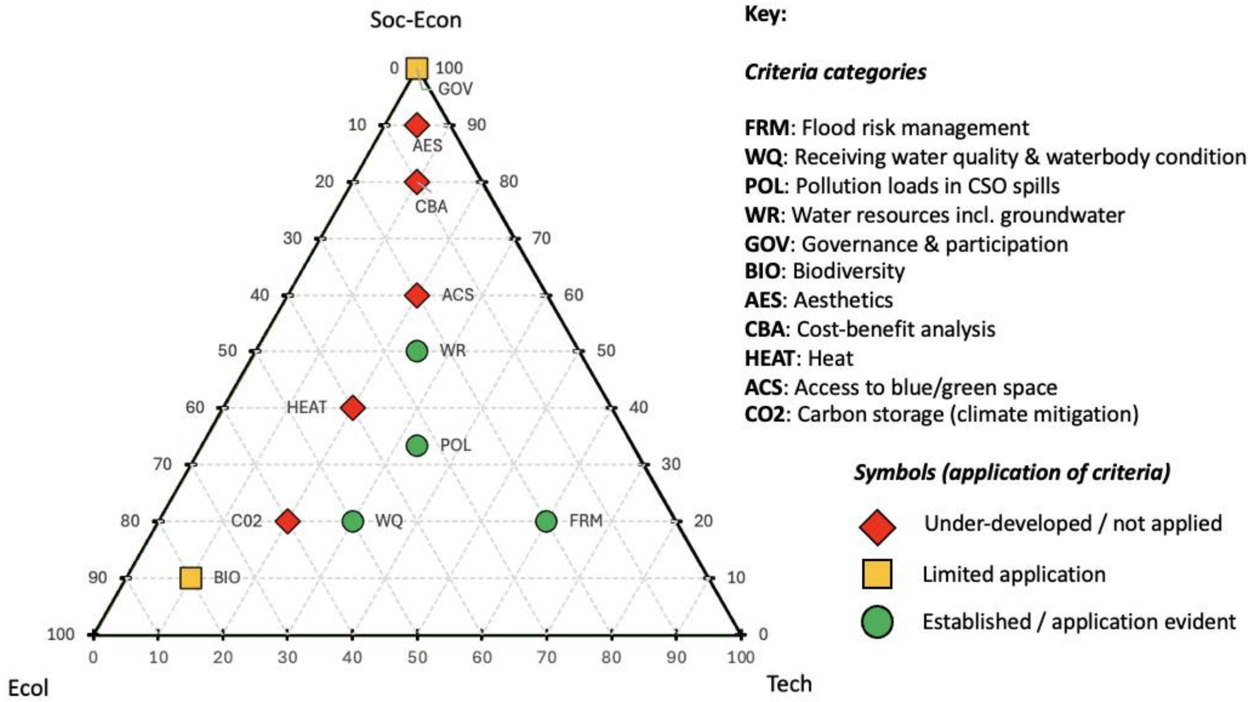
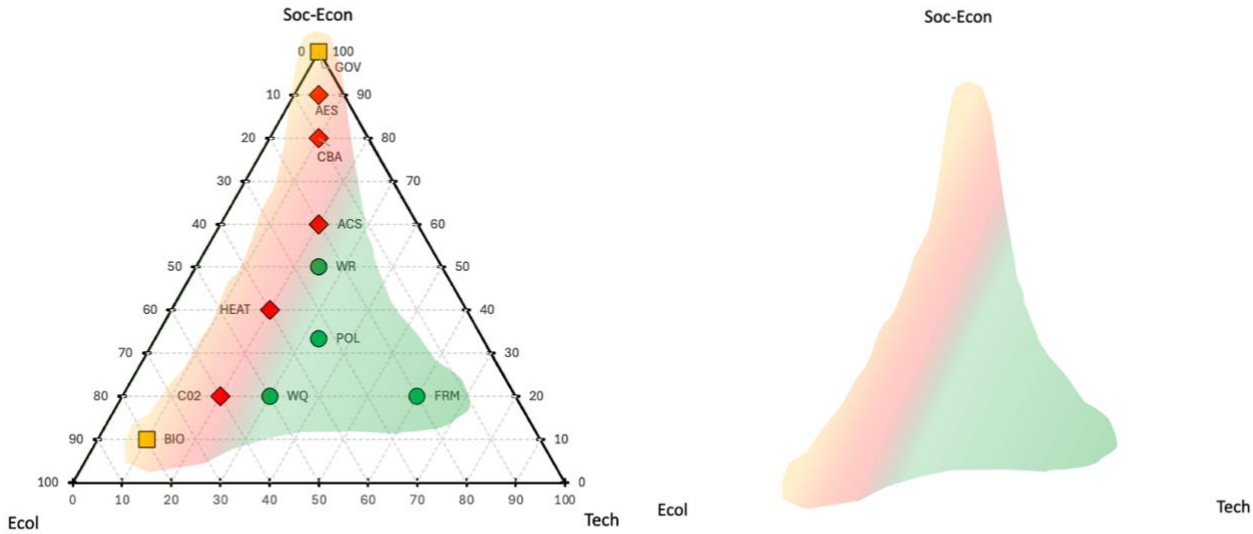


Figure 6 shows for Barcelona the criteria least well established and applied criteria relate primarily to socio-economic and ecological axes. There are a cluster of impact assessment criteria that appear to be less well developed at the socioeconomic-ecological nexus, spanning mitigation, heat, access and aesthetics. The heatmaps (Figs 7a-b) highlight these patterns from the literature, interviews and mind-mapping, where indicators appear to be less well developed or applied in practice (as compared with technical measures).

***Figs. 7a & 7b. Heatmaps for BARCELONA SETS analysis** (see also Fig.6)*



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6. ROTTERDAM

Sewage discharge limits in Rotterdam's rivers, lakes and harbours are primarily governed through EU and national level legislation. In common with the Barcelona and Berlin cases, the key European frameworks include the Urban Waste Water Treatment Directive (UWWT) and the Water Framework Directive (WFD), setting standards for water quality and good ecological status for water bodies including rivers and lakes (EC, 2000; EC, 1991). Discharges to the sea, which are not within the scope of this task, are also regulated by the Port Authority e.g. effluents from ships (Port of Rotterdam, 2023).

As regards national legislation, The Netherlands has in place specific regulations that implement and augment the requirements of the WFD. These laws outline permitted discharge levels for various pollutants. Until 2024, the Water Act (Waterwet) was the primary Dutch legislation addressing WFD requirements. This act provided the overarching framework for water management in the Netherlands. In summary, it included provisions for water quality standards, wastewater discharge permitting, river basin management, monitoring and enforcement, as well as linking with nature conservation and general environmental management regulations (Rijkswaterstaat, 2021). The Waterwet set specific quality standards covering chemical pollutants, nutrients, and biological indicators. It governed the permitting of wastewater discharges, codifying allowed quantities and types of pollutants as well as compliance with those permits. This Act provided for the monitoring of water quality and the enforcement of regulations empowering authorities to take action in relation to breaches as regards discharge limits and control of unlicensed polluters (Rijkswaterstaat, 2021). The Water Act interacted with other legislation, including The Wet Milieubeheer and Wet Natuurbescherming (environmental management and nature conservation acts, respectively). The latter included provisions to protect and restore natural habitats (Government of the Netherlands, 2017). All of these laws are now combined in de omgevingswet as of January 1, 2024. Information on this Environment and Planning Act (Omgevingswet) can be found at https://iplo.nl/regelgeving/omgevingswet/english-environment-and-planning-act/

At the regional level, water authorities are responsible for water resource management and water quality standards enforcement. Regional water authorities set specific discharge limits for wastewater treatment plants within their jurisdiction, including those serving Rotterdam's rivers and lakes.

There are three Regional Water Authorities active in the region of Rotterdam, i.e. Hoogheemraadschap van Schieland en de Krimpenerwaard, HHSK (HHSK, 2023) Hoogheemraadschap Delfland as well as Waterschap Rijnland. In addition, Rijkswaterstaat, as the executive agency of the Ministry of Infrastructure and Water Management, is the manager of national waters, including the rivers such as the river Maas that runs through Rotterdam (Rijkswaterstaat, 2021). Relevant in this context is the Waterkracht Alliantie - a platform for collaboration between municipality, the water boards, and the drinking water company https://www.h2owaternetwerk.nl/h2o-actueel/samenwerking-in-regio-rotterdam-capelle-aan-den-ijssel-krijgt-nieuwe-impuls

Rotterdam has nine sewage treatment works, owned and managed by HHSK. Treated effluents and untreated storm flows are discharged into the receiving waters of the rivers Nieuwe Maas and Nieuwe Waterweg. Rotterdam’s sewerage system comprises 1,711 km of combined sewers (of a total of 2,678 km), owned and operated by Gemeentewerken Rotterdam, the Municipality of Rotterdam (van der Graaf et al., 2010; 2023); the system already incorporates 10 infiltration reservoirs, 4 water squares, and 2 retention squares (Tillie et al., 2016). The Municipality maintains that the use of green infrastructure solutions should be scaled up (Gemeente Rotterdam, 2025).

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A key strategy of the Municipality is to promote green roofs in privately owned housing (Martens, 2016). Rotterdam has also integrated rain gardens and other types of SUDS in public spaces, residential areas, and street sides; however, no current literature describes all types of NBS operating in the city (van der Graaf et al., 2023).

More sewage overflows and increasing inundation depths are predicted to occur in Rotterdam due to the increasing occurrence of extreme weather events (Deltares, 2023; Balsells et al., 2013). HHSK sets limits on sewage discharges in Rotterdam through permitting, monitoring, collaboration, and adaptability measures (HHSK, 2023). The amount of sewage overflows in Rotterdam can vary significantly in practice, with theoretical models aiming for 3-8 times per year. According to interview participants, climate change is expected to increase the occurrence of sewer overflows, with the removal of surface water from CSO systems being a slow process expected to take ca. 43 years at current rates. Rotterdam has incorporated green infrastructure and NBS in order to prevent CSO discharges and to provide co-benefits such as heat island mitigation and recreation.

Wider strategies for water cycle management and waterway regeneration have proposed broader sets of objectives and indicators. Van Leeuwen et al. (2012) put forward 24 indicators in eight numbered categories of (1) water security; (2) water quality; (3) drinking water; (4) sanitation; (5) infrastructure; (6) climate robustness; (7) biodiversity and attractiveness and (8) governance, including public participation. De Urbanisten's Watercity 2035 proposed key outcomes of flood risk management, public realm enhancement, public access, ecosystem restoration (riverbanks and estuaries); see also https://www.c40.org/case-studies/c40-good-practice-guides-rotterdam-climate-change-adaptation-strategy/ Interestingly, biodiversity receives a higher priority in the latter, rather than being combined together with aesthetics. Thus, indicator sets further examined here separate out biodiversity from aesthetics and consider economic value rather than just costs.

Reviewing the Rotterdam literature reveals significant urban water research of relevance to stormwater management and application of NBS type approaches. Overflow volume remains centrally important alongside pollution loads (van der Werf et al., 2023a&b), including nutrients especially nitrogen (Lotti et al., 2015), and also bacteria and viruses (Muller et al., 1986). Flood risk management is a critical issue (Tuijinder et al., 2017; Salinas-Rodriguez et al., 2018). Plastic pollution is also of concern (Blondel et al., 2022). Ricci et al. (2024) highlight the importance of soil permeability and unsealing, as well as achieving socio-economic development outcomes beyond risk management. Tillie et al. (2016) and Zhang et al. (2024) emphasise access i.e. walking and biking routes, framed in terms of blue space quality. From a biodiversity perspective, opportunities for restoration go beyond protection of aquatic organisms and fish kills. Ecosystem restoration is in focus in terms of habitat corridors for van de Haterd et al. (2016) and restoration of soft-sediment estuarine habitats as highlighted by Paalvast et al. (2014). The latter stress total economic value as a potential measure of success.

Indicators to be considered in SETS analysis in Rotterdam are therefore as follows:

(1) Flood risk management; (2) pollution – nutrients, bacteria, viruses, plastic, contaminants of emerging concern etc.; (3) receiving water quality; (4) water resources, including soil permeability; (5) biodiversity; (6) aesthetics; (7) governance including public participation; (8) access; (9) cost/benefit including economic opportunity.

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Figure 8. ROTTERDAM SETS analysis of impact assessment criteria for urban water management

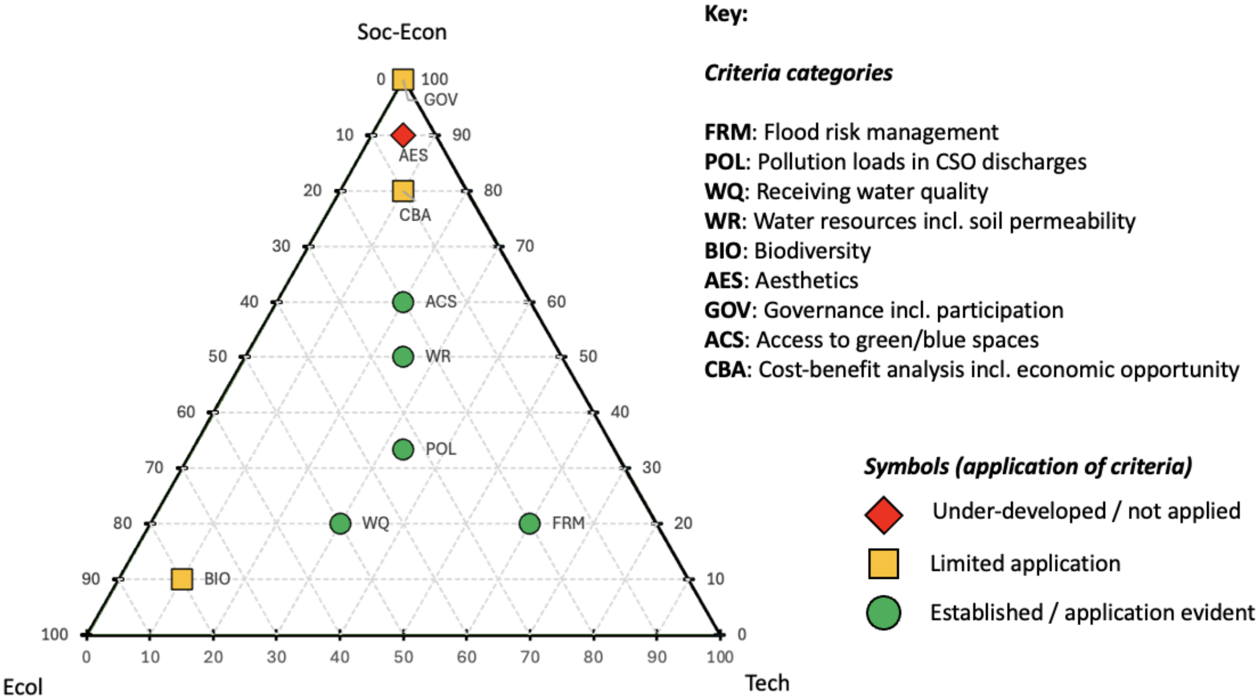
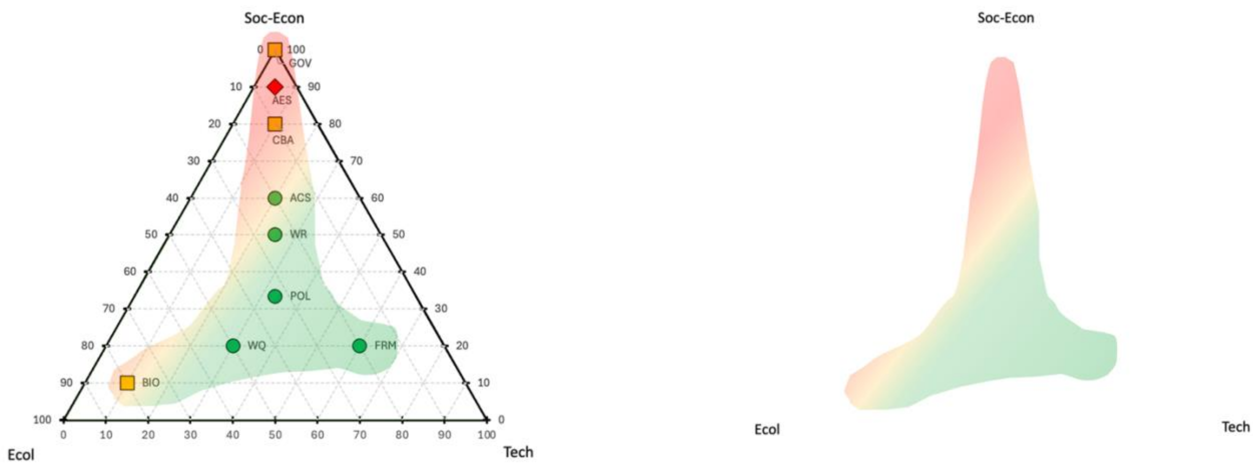


Figure 8 indicates that Rotterdam also has well developed criteria relating to more technical aspects of flood risk management, pollution and its impacts on receiving water quality. Water resources and access are also relatively well catered for. Socio-economic criteria however are relatively underdeveloped (Figs 9a and 9b) including for aesthetics of urban water management and receiving water impacts, in common with the other cities. Overall, criteria for impact assessment cover a narrower range of aspects.

Figs. 9a & 9b. Heatmaps for ROTTERDAM SETS analysis *(see also Fig.8)*



7. BERLIN

The issues surrounding CSOs, their regulation and their impact in Berlin were explored in depth by NICHES in Wild et al. (2024), and so for the sake of brevity are not repeated here. Key indicators considered in the SETs analysis for Berlin are as follows: (1) Governance, management & planning; (2) Receiving water quality

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& waterbody conditions; (3) Pollution from CSO spills & reductions using SUDS; (4) Access to greenspace and blue-green infrastructure; (5) Water resources, unsealing and permeability; (6) Biodiversity & urban ecology; (7) Citizen engagement, environmental activism & education; (8) Flood risk management; (9) Transformation, futures and change; and (9) Aesthetics of stormwater systems and receiving water.

Figure 10. BERLIN SETS analysis of impact assessment criteria for urban water management

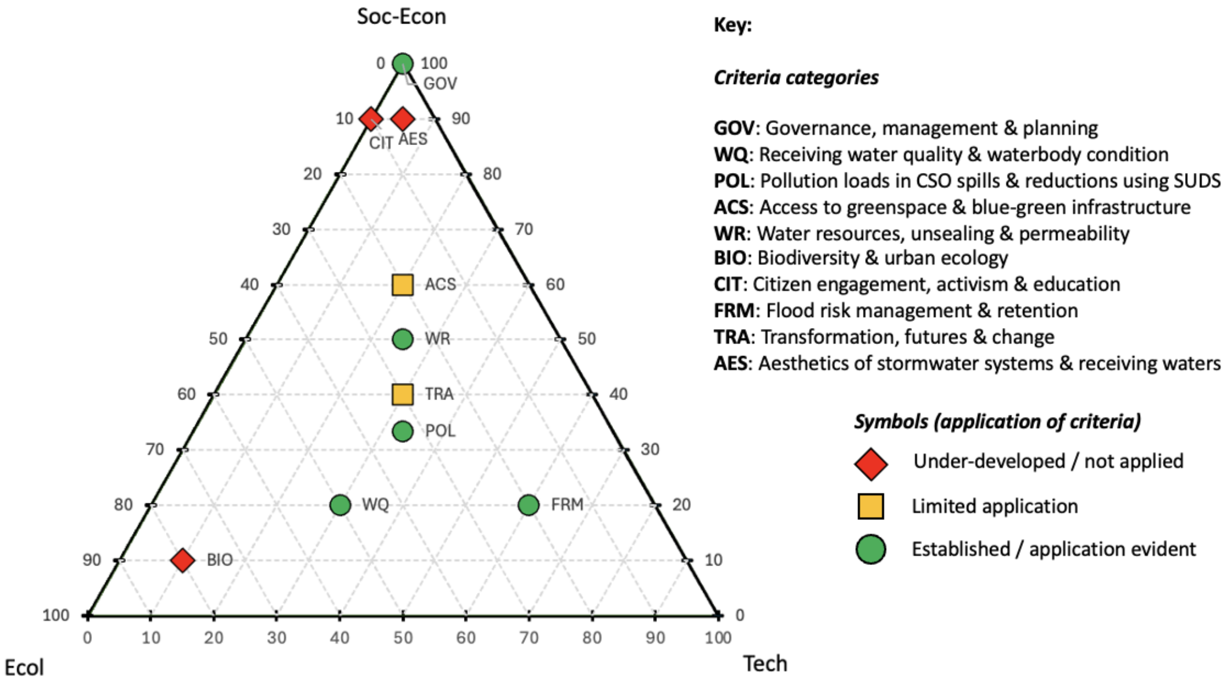
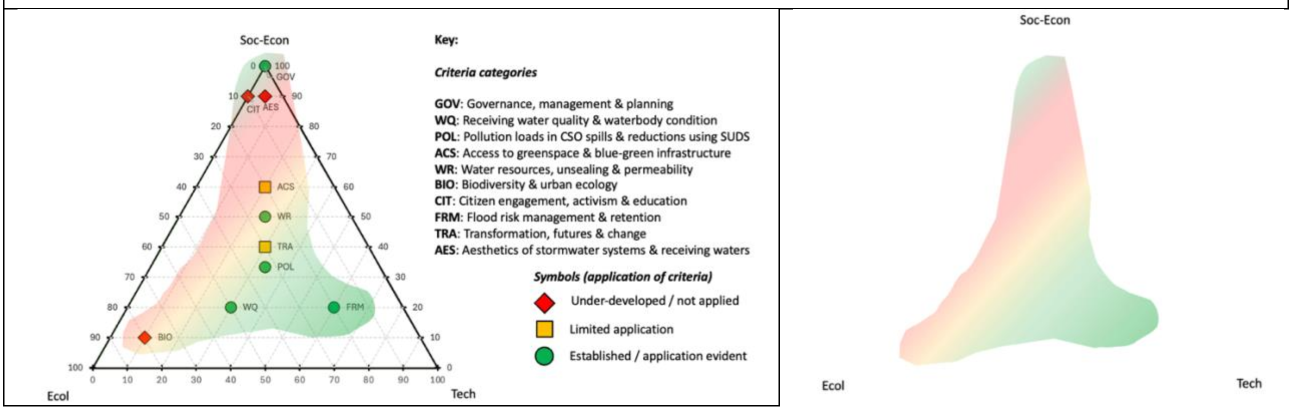


Figure 9 illustrates how in Berlin, more problematic impact assessment criteria relate to the socio-ecological nexus, and particularly the social themes of citizen engagement and aesthetics (and to a lesser extent, access), where the limited application of impact assessment criteria also matches with key urban water management tensions in the city (see Wild et al., 2024). In this respect there is some commonality with Barcelona. Governance criteria are well developed, as are the more technical elements, in common with Sheffield and Boston. Interestingly, hydrogeomorphological aspects seem to be less central, which is surprising for a city water network dominated by canalisation. Heatmaps (Figs 10a-b) highlight these key themes for potential transformative action.

Figs. 11a & 11b. Heatmaps for BERLIN SETS analysis *(see also Fig.10)*



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8. UNDERSTANDING IMPACTS & SETS IN NICHES CITIES

This research set out to explore how the SETS approach could provide new insights into combined sewer systems and NBS water management in cities. It is therefore important to reflect on the SETS model through this lens of urban water management, and to consider the relationships between different impact assessment criteria in each city (as well as the relationship between those criteria across the five cities).

An important initial reflection is that several core impacts, which are perhaps not entirely surprising, were found to be common to all five cities, despite their diverse contexts. Several of these themes, including flooding, water quality, pollution loads, biodiversity, aesthetics and amenity have been central to research and innovation in sustainable urban drainage systems from the beginning (D'Arcy, 1998). These are also impacts that have featured strongly in NBS research, along with another common criteria across the NICHES cities, i.e. governance. In this respect, it is possible to view an important evolution in the core paradigms, which is also evident in the NBS definitions of the EC, IUCN and UNEA (EC, 2020; UNEA, 2022). Bearing in mind that NBS are intended to address societal challenges one would expect to see such themes strongly represented. It can also be observed that, in the main, governance themes are relatively well addressed in each of the five cities, perhaps reflecting their participation in NICHES.

Drawing on the literature, it is interesting to note that part of the development of the SETS concept incorporated research into grey, green and blue in cities (Depietri & McPhearson, 2017). In this, the 'social-behavioural domain' does not explicitly address economic criteria (although the paper does make references to socio-economic processes, activities and impacts). Here, an early decision was made to incorporate economic aspects within the 'S' of SETS, i.e. with an explicit socio-economic framing.

SETS mapping of impact assessment criteria drawing on the reviewed literature, mapping and interviews highlighted that technically oriented measures are consistently dominant themes. Areas that tended to be under-developed included those along the S-E axis. In some instances this involved less well-developed biodiversity impact assessment measures. As regards NBS, this is perhaps a cause for concern, bearing in mind the strengthened imperative for restoration of biodiversity and ecosystem services in the EC definition (see Wild et al., 2020). In some cities, the less well represented themes were at the social-ecological interface, such as aesthetic impacts of pollution and ecological degradation, or non-motorised access to green/blue spaces, or urban heat island impacts. It would appear that this socio-ecological nexus may be particularly vulnerable or liable to neglect where urban water management impacts are considered.

Another key insight is that certain impact assessment criteria may serve to flag up potential blindspots in the literature and action on urban water management systems development. Themes unique to just one or two cities may prove to be useful in considering what other key criteria have been absent in other NICHES cities' debates about urban water management. Examples include climate mitigation, heat, resources, and physical modification of waterways.

A final reflection on the substance of the SETS mapping methodology is that in this research, fitting monetary or economic values within the framework proved problematic. Bearing in mind that investment in hard- or blue/green- infrastructures for urban water management is a central topic, this is a potential downside of the SETS analysis. In particular, examination of the economic-technical nexus (for instance, investigating how drainage models relate to future investment plans) may have been better facilitated using some other theoretical framework. Whilst the prospect of 3D representation may be alluring in developing a wider social-economic-ecological-technical model, doing so was beyond the scope of the research and the NICHES approach. That being said, the SETS approach has yielded new insights into the key nexuses operating within urban water management systems, and especially the interconnectedness between relevant infrastructures, institutions and interventions, future change, and measures of success.

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