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Built environment solutions

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Abstract

Monitoring biodiversity and ecohydrology of aquatic nature-based solutions in urban areas

In the face of climate change, cities have started to restore their degraded small-water bodies (streams and ponds) or build new aquatic ecosystems which can be regarded as aquatic nature-based solutions (aquaNbS). Aimed at helping to adapt cities to climate change, these freshwater habitats provide numerous services and functions related to water-cycle, stormwater, flooding and microclimate regulation, while providing aesthetic and recreational values, and supporting local biodiversity – which in turn underpins the services provided. Still, urban aquaNbS such as infiltration ponds, constructed wetlands, rewilded urban streams, are frequently neglected in biodiversity monitoring, and are thus not systematically monitored. However, to ensure their long-term ecological success and functioning, there is an urgent need to evaluate their biodiversity and ecological functionality.

This report provides practical information and guidelines for developers, planners and designers of how to monitor biodiversity and functioning of urban aquaNbS. The report is based on research results and experiences from the project "Bringing nature back – biodiversity-friendly nature-based solutions in cities (BiNatUr)" in five European cities (Antwerp, Berlin, Helsinki, Lisbon and Poznań) where a monitoring framework targeting aquaNbS biodiversity and functioning metrics was developed and used. The report gives guidelines for conducting in-situ monitoring on hydromorphological conditions, vegetation (both terrestrial and aquatic), microbial communities, macroinvertebrate communities, hydrological processes and water quality. In addition, the report gives examples on how such collected data can be analyzed and used as an indicator for ecohydrological quality and biodiversity values of urban aquaNbS.

By using research-based monitoring methods and indicators, it is possible to support the design, implementation and long-term maintenance of restoration interventions and aquaNbS, and to enhance their comprehensive management contributing both to the production of ecosystem services and to supporting local biodiversity.

Keywords: Aquatic nature-based solutions, biodiversity, ecosystem services, monitoring, urban areas

Tiivistelmä

Akvaattisten luontopohjaisten ratkaisuiden monimuotoisuuden ja ekohydrologian seuranta kaupungeissa

Ilmastonmuutoksen edetessä kaupungit ovat ennallistaneet ekologiselta laadultaan jo lähes kokonaan menetettyjä ja huonokuntoisia pienvesiään, kuten puroja ja lampia, tai rakentaneet uusia hulevesien hallinnan luontopohjaisia ratkaisuja (akvaattiset luontopohjaiset ratkaisut, aquaNbS). Kaupunkien pienvedet ja akvaattiset luontopohjaiset ratkaisut auttavat kaupunkeja sopeutumaan ilmastonmuutokseen tuottamalla lukuisia ekosysteemipalveluita, kuten hulevesien hallintaa, tulvasuojelua ja mikroilmaston säätelyä. Samalla ne tuottavat esteettisiä ja virkistyksellisiä arvoja sekä tukevat paikallista luonnon monimuotoisuutta, joka puolestaan varmistaa ekosysteemipalveluiden toimivuuden.

Akvaattiset luontopohjaiset ratkaisut – kuten imeytysaltaat, rakennetut kosteikot, ennallistetut puro- ja jokiuomat – jäävät usein biodiversiteettiseurannan ulkopuolelle, eikä niiden ekologista tilaa seurata systemaattisesti. Jotta akvaattisten luontopohjaisten ratkaisuiden pitkän aikavälin ekologinen laatu ja ekosysteemin toiminta voidaan varmistaa, on välttämätöntä arvioida kohteiden hydrologista kiertoa, biotoopin ekologista laatua ja paikallislajistoa säännöllisesti.

Tämän ohjekirjan tavoitteena on antaa yleiskuva akvaattisten luontopohjaisten ratkaisuiden monimuotoisuusarvoista ja ekologisesta laadusta sekä miten niitä voidaan paikallisesti arvioida. Raportin tulokset perustuvat kansainvälisen ”Bringing Nature Back – Biodiversity-friendly Nature-Based Solutions in Cities (BiNatUr)” hankkeen kokemuksiin, jossa tutkittiin ennallistettujen kaupunkien pienvesien ja rakennettujen akvaattisten luontopohjaisten ratkaisuiden lajistollista monimuotoisuutta, niiden tuottamia säätelypalveluita ja kehitettiin menetelmiä pienialaisten vesiekosysteemien seurantaan viidessä Euroopan kaupungissa (Antwerpen, Berliini, Helsinki, Lissabon ja Poznań). Seurannassa arvioitiin vesielinympäristöjen laatua, kasvillisuutta, mikrobiyhteisöjä, hydrologisia prosesseja ja vedenlaatua. Lisäksi ohjekirjassa annetaan esimerkkejä, kuinka aineistoja voidaan hyödyntää kaupunkien akvaattisten luontopohjaisten ratkaisuiden ekohydrologisen laadun ja monimuotoisuuden indikaattorina.

Hyödyntämällä tutkimukseen perustuvia seurannan menetelmiä ja indikaattoreita voidaan tukea ennallistamisen ja akvaattisten luontopohjaisten ratkaisuiden suunnittelua, toteutusta ja pitkäaikaista ylläpitoa sekä tehostaa niiden kokonaisvaltaista hallintaa – mikä edistää sekä ekosysteemipalveluiden tuottamista että paikallisen luonnon monimuotoisuuden tukemista.

Asiasanat: Akvaattiset luontopohjaiset ratkaisut, ekosysteemipalvelut, kaupunkialueet, luonnon monimuotoisuus, seurantamenetelmät

Sammandrag

Uppföljning av mångfald och ekohydrologi i akvatiska naturbaserade lösningar i städer

I takt med klimatförändringen har man i städerna restaurerat bäckar, tjärnar och andra småvatten i dåligt skick samt byggt naturbaserade lösningar för hantering av dagvatten (akvatiska naturbaserade lösningar, aquaNbS). Städernas småvatten och akvatiska naturbaserade lösningar bidrar till klimatanpassning genom att producera ett stort antal ekosystemtjänster som dagvattenhantering, översvämningsskydd och reglering av mikroklimatet. Samtidigt ger de estetiska och rekreationella värden samt stöder den lokala biologiska mångfalden, som i sin tur säkerställer ekosystemtjänsternas funktion.

Akvatiska naturbaserade lösningar – såsom infiltrationsbassänger, byggda våtmarker samt restaurerade bäck- och flodfåror – hamnar ofta utanför biodiversitetsuppföljningen, och deras ekologiska status bedöms sällan systematiskt. För att säkerställa deras långsiktiga ekologiska kvalitet krävs regelbunden bedömning av objektens hydrologiska kretslopp, habitatens ekologiska kvalitet och lokala artförekomster.

Denna handbok ger en översikt över de akvatiska naturbaserade lösningarnas mångfaldsvärden och ekologiska kvalitet samt praktiska råd om hur dessa kan utvärderas lokalt. Resultaten bygger på erfarenheter från det internationella projektet "Bringing Nature Back – Biodiversity-friendly Nature-Based Solutions in Cities (BiNatUr)". I det projektet undersökte man artmångfald i städernas restaurerade småvatten och byggda akvatiska naturbaserade lösningar, regleringstjänster som dessa producerade samt utvecklade metoder för uppföljning av småskaliga vattenekosystem i fem städer i Europa.

Övervakningen omfattade vattenmiljöernas kvalitet, vegetation, mikrobsamhällen, hydrologiska processer och vattenkvalitet. Handboken ger också exempel på hur dessa data kan utnyttjas som indikatorer för akvatiska naturbaserade lösningars ekohydrologiska kvalitet och biodiversitet.

Genom att tillämpa forskningsbaserade metoder och indikatorer kan man stödja planering, genomförande och långsiktig förvaltning av akvatiska naturbaserade lösningar samt effektivisera deras helhetsmässiga hantering. Det gynnar både produktionen av ekosystemtjänster och bevarandet av lokal biologisk mångfald.

Nyckelord: Akvatiska naturbaserade lösningar, ekosystemtjänster, stadsområden, naturens mångfald, uppföljningsmetoder

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Highlights of this report:

- **Nature Restoration Regulation and Biodiversity Strategy 2030 encourage cities and municipalities to restore degraded water ecosystems and establish nature-based solutions**
- **Aquatic nature-based solutions (aquaNbS) in urban areas are expected to provide regulating ecosystem services and support biodiversity, but continuous monitoring is poor or totally missing**
- **The report presents standardized monitoring methods for small-water bodies and urban aquaNbS to evaluate their biodiversity values and ecohydrological functions**
- **The report also raises awareness of the role of ecological quality and species diversity in urban aquaNbS among planners but also among the wider interested public**

Preface

The project “Bringing nature back – biodiversity-friendly nature-based solutions in cities (BiNatUr)” studied the role of biodiversity and its linkages with regulating ecosystem services (ES) in urban water-related nature-based solutions (aquaNbS) in five European cities (Antwerp, Berlin, Helsinki, Lisbon and Poznań). The overall aim of the project was to analyze how different social, ecological and technological factors influence to ecological functions and biodiversity of aquaNbS to support biodiversity-friendly planning, building, restoration, and maintaining of aquaNbS and develop standardized monitoring methods suitable for urban small-water ecosystems and constructed aquaNbSs.

The first part of the report provides an overview of the project results, and the second part presents six different in-situ monitoring methods to evaluate ecohydrological quality, hydrological functions and biodiversity of urban aquaNbS. The report gives examples and recommendations about the monitoring methods and how these can be applied to evaluate aquaNbS. We hope that the report also strengthens our overall understanding on biodiversity and ecological functions of aquaNbS in urban areas. The report can also guide and support strategic planning, design, implementation and maintenance of aquaNbS. The document is targeted to researchers, developers, managers and practitioners in the public and private sectors who are working with aquaNbS in urban environments.

We would like to acknowledge all our international and national founders. This study is funded through the 2020–2021 Biodiversa and Water JPI joint call for research projects, under the BiodivRestore ERA-NET Cofund (GA N°101003777), with the EU and the national funding organisations as the National Science Centre (Poland) UMO-2021/03/Y/NZ8/00100, Research Foundation Flanders (Belgium), Research Council of Finland, Bundesministerium fur Bildung und Forschung (Germany), Federal Ministry of Education and Research (Germany) and Fundação para a Ciência e Tecnologia (FCT, Portugal). PP: 10.54499/2020.03415.CEECIND/CP1595/CT0006, PP, VD: 10.54499/DivRestore/0001/ 2020. JS thanks the Bijzonder Onderzoeksfonds of the University of Antwerp for research funding (Project no. 44158). Special thanks to colleagues and researchers who partly joined the project and helped us by collecting data or making analyses.

18th December, Helsinki, Finland

Kati Vierikko and co-authors

Contents

1 Nature-based solutions for climate resilient cities

Many cities have ambitious climate adaptation policy goals, supported by blue and green infrastructures. The European Union's Biodiversity Strategy 2030 and Nature Restoration Regulation have set up specific goals to protect biodiversity and achieve no net loss of blue and green areas in urban environments. This includes restoration of degraded natural habitats and implementing new nature-based solutions. To estimate the successes and failures of these policy goals, regular monitoring of restoration and implementation actions are urgently needed.

1.1 Restoration vs. nature-based solutions in aquatic ecosystems

Climate change has a significant impact on the urban water cycle and on biodiversity and ecosystem functioning. Major changes in water quantity, quality, and seasonal distribution are projected across Europe and worldwide. Urban areas thus will be subject to increasing periods of water scarcity and excess, reduced water quality, flash flooding, and soil erosion, among other risks (Egerer et al. 2021). Furthermore, climate change threatens ecological conditions of urban blue and green infrastructure leading to decreasing distribution of native species and favoring alien or introduced species (Knapp et al. 2021). Surface water in the natural landscape flows through interconnected ecosystems (ponds, streams, rivers, lakes and marine areas), but in cities these systems are usually destroyed or disrupted and existing local habitats (e.g. ponds and streams) are degraded. Urban freshwater ecosystems have largely been eliminated, with surface waters diverted into subterranean drainage infrastructure. Therefore, there is a need to bring water back to cities by re-introducing removed surface water by **restoring destroyed or degraded water ecosystems** and implementing **water-related nature-based solutions** (Kowarik et al. 2025, Szoszkiewicz et al. 2025, Warter et al. 2025, Martín Muñoz et al. 2024, Pinho et al. 2023).

The European Union's Nature Restoration Regulation (NRR) and Biodiversity Strategy 2030 encourage cities and municipalities to restore degraded water ecosystems or establish novel nature-based solutions. There are some fundamental differences between ecological restoration and nature-based solutions interventions that are crucial to understand. They are commonly used simultaneously, but they are not identical in terms of planning goals and outcomes (Carbonari & Solari 2025, Waylen et al. 2024). Ecosystem or ecological restoration has various definitions, and it can be defined as supporting and assisting the recovery of degraded or destroyed ecosystems by improving their natural functions, processes and structure, with the overall goal of improving resilience of ecosystem (Carbonari & Solari 2025, Waylen et al. 2024, Carver et al. 2021, Gann et al. 2019). The main restoration actions are clearly driven by ecological goals. It can include the removal of anthropogenic stressors, regenerating or rewilding natural processes sometimes through engineered interventions (Waylen et al. 2024, Shackelford & McDougall 2023, Gann et al. 2019). Many times, despite the focus is on ecology, restoration actions of degraded water ecosystem provide multiple societal benefits and ecosystem services, but not necessarily always as the ecological goals are prioritized (Waylen et al. 2024).

Nature-based solutions (NbS) is a broad concept that has been introduced, defined and supported by several global institutions, (e.g. European Commission IUCN). UNEA (2022) defines NbS as "… actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits …". The two concepts can be similar, but their essential goals are different as restoration aims to repair nature itself, whereas the main goal of NbS is in fulfilling societal needs (Waylen et al. 2024). Both concepts of restoration and NbS can also be seen as a continuum between ecological and technological orientation, with potentially shifting and overlapping with each other (Fig. 1).

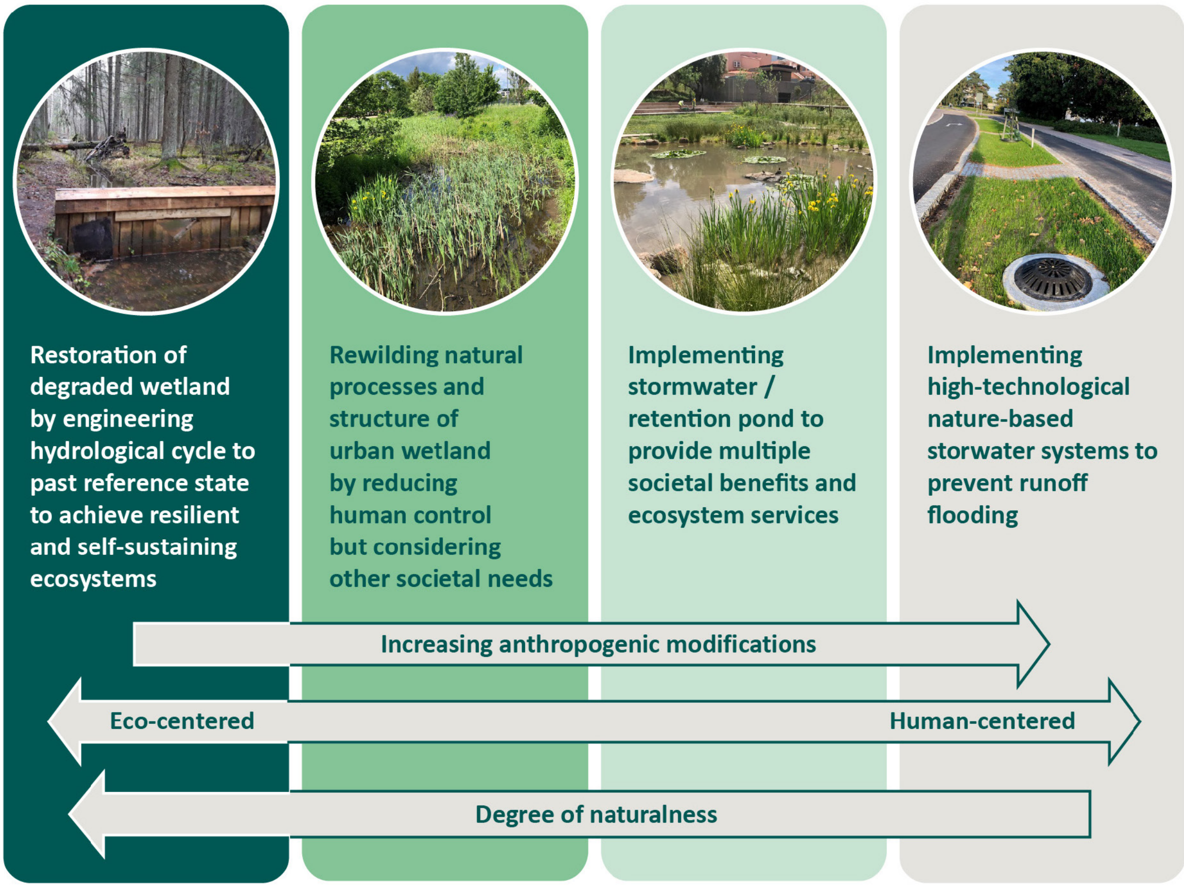

Figure 1. Examples of different measures targeting either restoring nature itself or delivering benefits for society. All these examples can be considered as water-based NbS but to a different degree. The restoration actions are clearly driven by ecological goals and sometimes human pressures need to be excluded (e.g. recreational use), while high-tech hybrid NbS interventions are strongly driven by societal needs and technology can have an important role in the system.

In this report, the focus is on **water-based NbS** i.e. **aquatic NbS** interventions that provide ecosystem services and support local biodiversity in urban areas. Below, we will give a short overview of what we mean by these urban aquaNbS, how they have been implemented in cities and what their role is in supporting local biodiversity.

1.2 **Aquatic nature-based solutions in urban areas**

Water-based or aquatic nature-based solutions (hereafter: aquaNbS), have a crucial role in urban environments. They support the adaptation of cities to climate change, increase local biodiversity and provide recreational and aesthetic experiences for residents (Pinho et al. 2023, Sowińska-Świerkosz et al. 2021, Kabisch et al. 2017). Today grey - or engineered – drainage systems are being partly replaced with aquaNbS through restoration of degraded water habitats by re-establishing natural water flow and habitat structure or bringing back entirely lost ecosystems by implementing novel aquaNbS. The type, form and functions of aquaNbS can vary greatly and often they are hybrid systems of engineered and natural elements. Sometimes technological elements have a major role in e.g. purifying and filtering urban runoff water, especially in densely built urban environments where stormwater is directed to sewer systems after the treatment (EEA 2021, Seddon et al. 2019). These tecno-oriented and micro-scale types of NbS are usually located along the roadside or heavily built environments such as parking lots and are not considered important to support local biodiversity values (see right-hand side in Fig. 1).

Usually, aquaNbS are planned and designed to deliver multiple ecosystem services, such as stormwater regulation, recreation, human well-being and climate change mitigation, simultaneously supporting biodiversity (Rodrigues et al. 2022, Cuenca-Cambronero et al. 2023, Oertli et al. 2023, Ryfisch et al. 2023). In most cases regenerated or novel constructed aquaNbS can be classified as a freshwater ecosystem. By definition, freshwater ecosystems are standing (lentic) and running surface water (lotic) bodies supporting nutrient cycling and energy flows among inland aquatic microbial, plant, and animal communities and where multiple species can co-exist (Wetzel 2001a). Therefore, aquaNbS can also be classified as a freshwater ecosystem especially if there have also been ecological restoration goals (see Fig. 1, first two on left-hand side). For example, general ecosystem typology of the EU National Restoration Regulation (NRR) classifies many anthropogenic (linear and non-linear) water bodies, such as canals or water reservoirs, as part of freshwater ecosystems (BISE 2025).

In many European cities, implementation of aquaNbS has become an important policy goal, with the aim of improving adaptation to climate change while supporting local biodiversity. NbS are considered essential to achieve climate resilience in a more efficient and cost-effective way than only relying on engineered-based grey solutions (Frantzeskaki 2019, Kabisch et al. 2017). For example, in Finland many municipalities have implemented nature-based stormwater systems (e.g. artificial wetlands, stormwater ponds and streams) that also support the existence of different taxonomic groups e.g. amphibians, macroinvertebrates, birds and vegetation (Kopperoinen et al. 2021). The Vauhtitie artificial wetland in Helsinki, Finland (Fig. 2) was implemented in a public park to improve stormwater flooding in the catchment area, but also to support local biodiversity.

In Belgium, there are entire public parks developed for stormwater management. One example is Zuid Park in Antwerp, Belgium, which is a redevelopment of a parking space near the Scheldt estuary. The park includes various play and sport facilities, multifunctional lawn, rain gardens, water basins and ponds. Water can easily seep into the ground, a crate system irrigates the trees, there are rainwater cisterns, the gardens and the grass meadow serve as a water buffer, the water is reused for play and for buffering water in the wadi.

Wuhle in Berlin, Germany, is an example on restoration of degraded freshwater ecosystems, by removing grey infrastructure (i.e. weirs) and implementation of still water zone and reactivating of wetlands. Other activities include removal of invasive vegetation, mowing channel vegetation, introducing deadwood and restoring natural stream structures (i.e. boulders), development of near-natural channel structure and geomorphic conditions.

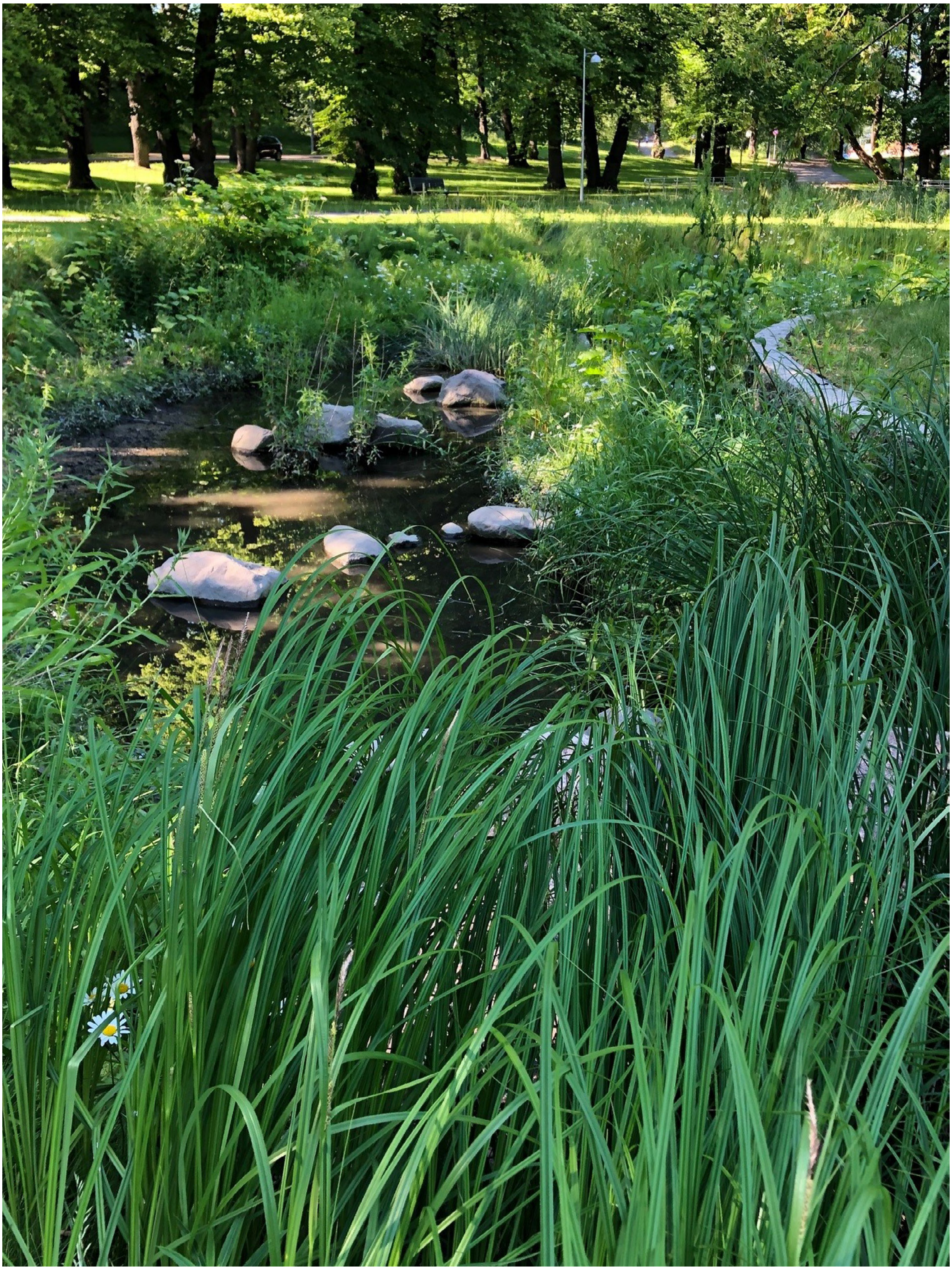

Figure 2. Example of aquaNbSs studied in BiNatUr project. Vauhtitie artificial wetland in Helsinki, Finland. Despite being constructed, this wetland can be classified as a freshwater ecosystem. Photo: Kati Vierikko

In Poznan, Poland “The Ratajski Newts” project created an aquaNbS in cooperation with the city of Poznan and University of Life Sciences to protect the population of amphibians (Fig. 3). One objective of the NbS was to increase biodiversity and thus impacts were observed to reveal the changes in the environment after the implementation of the NbS were made. This type of cooperation between municipalities and universities can support long-term monitoring, although funding and formalization of such partnerships might remain a challenge.

In Lisbon, Portugal, the municipality has implemented aquaNbS with different aims. At the Praça de Espanha, at the upper city area, the land restoration in a densely urbanized area led to the creation of a small retention pond, in the end point of a dry riverbed, aimed at flash flood regulation, water infiltration, relax zone and aesthetics (Fig. 4). At Monsanto, the city’s largest urban forest, a permanent pond was built surrounded by local vegetation, to support local biodiversity, providing water year-round, a scarce resource in Mediterranean climate.

Figure 3. Modified Bogdanka stream in Poznan, Poland. This aquaNbS type can be classified as a freshwater ecosystem. Photo: Szymon Jusik.

Figure 4. A small retention pond at the Praça de Espanha in Lisbon, Portugal, is providing multiple ecosystem services such as flood regulation, water infiltration and aesthetics. Photo: Vladimíra Dekan Carreira.

1.3 Biodiversity values of aquatic nature-based solutions

It has been shown that urban small water bodies (ponds and streams) can reach high plant biodiversity, support endangered species, provide resilience to flooding and drought, and improve the aesthetic appearance (e.g. Martín Muñoz et al. 2024, Cuenca-Cambronero et al. 2023, Vierikko & Niemelä 2016). Urban aquaNbS, particularly in densely built areas, face significant anthropogenic and environmental pressures. These include high concentrations of nutrients and other pollutants, severe hydromorphological alterations, and declining streamflow. Such pressures adversely affect biodiversity, including the species abundance, leading to habitat degradation (Warter et al. 2025, Oswald et al. 2023). Within the BiNatUr project, we analyzed biodiversity values of urban aquaNbS. We used a SET (Social-Ecological-Technological) systemic framing to study urban aquaNbS (Pinho et al. 2023, McPhearson et al. 2016, Wellmann et al. 2023) and as a conceptual framework to test the general hypothesis that social actors (planning and valuing aquaNBS), ecological attributes of aquaNBS and surrounding environment (habitat condition, vegetation), and technological elements (e.g. soil sealing, artificial elements in NbS) are the key drivers that determine biodiversity of aquaNBS (Table 1).

The research focused on aquaNBS in five European cities: Antwerp (Belgium), Berlin (Germany), Helsinki (Finland), Lisbon (Portugal), and Poznań (Poland). Study locations were selected through a stratified random sampling method, considering factors, such as aquaNBS type (lotic and lentic water bodies), water availability throughout the year (temporary or permanent), and the level of naturalness. In addition, all selected sites provided ecosystem services (e.g. water regulation, recreation, aesthetic) to consider them as aquaNbS (Szoszkiewicz et al. 2025). Study sites were selected along a gradient of artificialization (from near natural to heavily artificial), with established submerged plants and bank vegetation (built to last for more than 5 years), with public access and with small to medium size (streams up to 50 m wide, ponds up to 500 m2 area). This resulted in 96 sample sites in 60 urban aquaNbS across four different biogeographical and climatic regions in Europe. Field sampling methods are described in detail in chapter 3.

Most urban aquaNbS are relatively small, shallow and intensively modified. The median width of studied aquaNbS in BiNatUr project varied between 2 and 10 m for streams and the median depth was less than 0.7 m. The ponds designed for stormwater or retention ponds are usually small in surface area, in our study the median size was 2.064 m^2, and shallow (median depth of 1 m, maximum 6 m). During our field monitoring of vegetation in five cities, a total of 103 aquatic plant species (macrophytes) were identified, showing considerable variation in species richness and abundance across locations (Szoszkiewicz et al. 2025). Helsinki recorded the highest richness, averaging 7.25 species per site, while Berlin had the lowest, with 3.54 species per site (Table 2). Average macrophyte cover per site was greatest in Helsinki (44.8%) and Poznań (35.7%), and lowest in Berlin (12.2%). Comparing the number of species recorded in aquaNBS with other studies is challenging, as total species counts strongly depend on sampling effort. Nevertheless, the 103 taxa observed in our research exceed those reported for urban ponds (Bubíková & Hrivnák 2018a) and other freshwater habitats across Central Europe (Bubíková & Hrivnák 2018b) and the UK (Williams et al. 2004). This comparison reinforces that aquaNBS systems play a vital role in supporting urban biodiversity. Overall species richness differed only slightly between sites with limited and intensive hydromorphological modification. This modest influence aligns with previous studies (Kutyła et al. 2025, Bubíková & Hrivnák 2018a), some of which suggest that modified aquaNBS can function comparably to natural systems and provide valuable secondary habitats for macrophyte persistence and development (Bubíková & Hrivnák 2018b).

Table 1. Example of different SET factors produced for the analyses. Bioclimatic variables LST: Land Surface Temperature, NDVI: Normalized Difference Vegetation Index. Regional bioclimatic variables related to air temperature and precipitation were only used at the variation between cities due to the low spatial resolution. Ex-situ monitoring of vegetation is described in chapter 3.1.8, the in-situ field monitoring of water parameters in chapter 3.1.6 and habitat conditions in chapter 3.1.1. (Dekan Carreira et al. 2025).

Climate	Landscape	Water parameters	Habitat
Bioclimatic variables	NDVI spring NDVI summer (°C)	Water temperature (°C)	Type of habitat (stream/pond)
Snow cover (%)	Tree cover (%)	pH	Water availability (permanent/temporary)
LST spring LST summer (°C)	Tree height (m)	Oxygen concentration (mg/L)	Average depth (m)
	Impervious surface (%)	Conductivity (µS/cm)	Bottom material (%)
		d-excess (‰) *a proxy of the humidity of the water source region*)	

Table 2. Number of macrophyte species recorded in five studied cities in the BiNatUr project and average macrophyte diversity of a single NBS: species richness, Shannon and Simpson diversity, evenness and average cover (Szoszkiewicz et al. 2025)

City	Total number of species	Species richness per site	Shannon diversity	Simpson diversity	Evenness	Macrophyte cover (%)
Antwerp	30	3.88	0.67	0.35	0.43	21.3
Berlin	35	3.54	0.60	0.31	0.38	12.2
Helsinki	47	7.25	1.15	0.56	0.64	44.8
Lisbon	29	4.46	0.97	0.50	0.68	24.4
Poznań	48	5.92	0.82	0.42	0.47	35.7
Total	**103**	**5.02**	**0.84**	**0.43**	**0.52**	**27.8**

We examined macroinvertebrate communities in urban ponds and streams designed as aquaNbS across 48 sites in four of the cities: Antwerp, Helsinki, Lisbon and Poznań (Dekan Carreira et al. 2025). We further assessed how environmental factors—climate, vegetation, water characteristics, and NbS design—affect biodiversity at both the variation between (all cities together) and within cities (cities considered separately). In Antwerp, we identified 7,062 individuals from 40 taxa, dominated by Baetidae and Physidae. Helsinki hosted 30,859 individuals from 45 taxa, with Asellidae and Baetidae as the most abundant families. Lisbon yielded 12,404 individuals from 43 taxa, dominated by Baetidae and Chironomidae. Poznań showed the greatest diversity, with 50,422 individuals from 67 taxa, where Chironomidae and Oligochaeta were most abundant (Dekan Carreira et al. 2025).

At variation between cities, macroinvertebrate community composition was primarily influenced by climate and bottom material. At the variation within cities, communities were associated by the type of aquaNbS (lentic vs lotic) regardless their clime differences, followed by several city specific drivers, namely water (temperature, oxygen, water residence time), aquaNbS (bottom material, depth) and vegetation (Normalized Vegetation Index) related variables. Climate, as the main factor in our study, cannot be managed, but it should be considered when projecting broad-scale aquatic community responses (Bonada et al. 2017), especially when climate change and extreme events are expected to increase (Boersma et al. 2016). Our findings also showed strong relationships between macroinvertebrate communities, bottom substrate characteristics and vegetation structure. Bottom material, in general, provides niches, food resources and refugia for macroinvertebrates and other European studies (Barnes et al. 2013, Schröder et al. 2013) have emphasized the importance of substrate in shaping freshwater biodiversity. Riparian vegetation affects ecosystem dynamics connected to macroinvertebrate communities (Jiang et al. 2006, Li et al. 2019) by decreasing of light and water temperature through shading and increasing organic matter for decomposition. While understanding of impact of environmental factors on macroinvertebrate communities is well known for natural and seminatural aquatic ecosystem, this is not well known for urban aquaNbS. However, this knowledge is essential to design appropriate actions in management and conservation of urban freshwaters. Overall, we found that different macroinvertebrate communities depend mostly on different bottom materials and aquaNbS type (lentic or lotic); thus, ensuring the presence of a wide range of habitats can boost higher variability in macroinvertebrate biodiversity.

2 Towards biodiversity-sensitive planning and maintenance of aquatic nature-based solutions

Increasing biodiversity enhances ecosystem resilience and the services they provide in the face of perturbations from anthropogenic pressures and long-term environmental changes. Our studies on macrophyte and macroinvertebrate diversity highlighted the significance of aquatic nature-based solutions in supporting local biodiversity in urban areas. Therefore, there is a need for biodiversity-sensitive planning, implementation and maintenance of urban aquaNbS to ensure their long-term resilience and capacities to deliver ecosystem services.

2.1 Understanding constraints and enablers

Urbanization, soil sealing, and intensified anthropogenic and climatic pressures have significantly impacted macroinvertebrate and microbial diversity at the examined sites, as reported by Dekan Carrera et al. (2025) and Water et al. (2025). These studies highlight the critical need for monitoring to inform strategic planning, implementation, and maintenance of aquaNbS in urban settings. The effectiveness of aquaNbS in delivering their intended ecosystem services can be compromised without adequate long-term planning and adaptation to specific goals and objectives. Consequently, planning, maintenance, and monitoring must be integrated. As part of the BiNatUr project, we engaged with 33 local experts to identify common challenges and facilitators for the successful planning, implementation, and maintenance of aquaNbS across Finland, Poland, Belgium, and Portugal. Furthermore, we conducted walking workshops and field trips with key stakeholders (e.g., city planners, water engineers, practitioners, environmental experts) at the study sites to foster knowledge exchange, present findings, and discuss strategies to support biodiversity-sensitive planning and maintenance of aquaNbS (Fig. 5).

Experts have unanimously emphasized the critical importance of monitoring various aspects of aquaNbS to ensure their successful implementation. Monitoring is crucial for gaining insights into ecological dynamics, including seasonal changes and succession, which inform vegetation management practices. The primary rationale for monitoring, as outlined by experts, is to verify whether aquaNbS operates as intended, meaning they meet established objectives and expected outcomes. Maintenance is seen as a means to uphold these target achievements. However, defining and communicating clear objectives for aquaNbS is essential to determine success, as the term 'successful' can be ambiguous, especially when multiple, potentially conflicting targets such as water management and biodiversity enhancement are in play. This complexity underscores the need for transparent and well-defined goals.

The multifunctionality of aquaNbS presents significant challenges for practitioners, requiring a careful balance between various co-benefits and design objectives. For example, prioritizing biodiversity in planning can conflict with the recreational needs of urban residents. Furthermore, focusing on water regulation services does not guarantee solutions that are both ecologically rich and suitable for recreation. The limited physical space available often restricts the consideration of diverse benefits, values, and objectives. Insufficient funding for managing and monitoring aquaNbS emerged as a critical issue, with many systems not being monitored at all, leading to ambiguous impacts and a lack of understanding regarding their long-term performance and the evolution of plant communities. Santos (2025) highlighted that this data gap can result in misleading assessments of NbS effectiveness.

Figure 5. Knowledge exchange and discussions between researchers and experts responsible of planning, implementing, maintaining and monitoring is crucial to support changes in current practices. Photo: Kati Vierikko, Finland.

2.2 Supporting adaptive management for aquatic nature-based solutions

Achieving and maintaining positive ecological outcomes, including enhanced water quality and support for native species, necessitates site-specific management and restoration strategies that are tailored to local biotic and abiotic conditions (Warter et al. 2025). Monitoring is critical for increasing process understanding and shifting from static management practices to more dynamic and adaptable planning and maintenance approaches. Adaptive management acknowledges the functional dynamics and natural changes in species composition, allowing for adjustments to seasonal and climatic variations. Santos (2025) has developed a dynamic, climate-resilient evaluation framework that underscores the interaction between vegetation, hydrology, and climate. Backcasting is recommended as a method to comprehend and define the requirements for monitoring and data, beginning with the desired future outcomes of aquaNbS. Contrarily, interviews conducted in Portugal revealed that monitoring does not equate to routine maintenance. AquaNbS does not require constant upkeep but rather targeted monitoring to facilitate informed management decisions, such as selective manual weeding.

Furthermore, monitoring is crucial for identifying harmful management practices, prompting necessary adjustments. Polish experts underscore the importance of consulting specialists in specific taxonomic groups when planning maintenance activities. Belgian interviews highlighted the necessity for post-implementation ecological analyses to evaluate species presence and alignment with biodiversity objectives. The data obtained from monitoring can validate nature-based solutions during planning and decision-making, emphasizing the value of empirical knowledge in building public support. Such solutions offer benefits like biodiversity enhancement and water purification, fostering community empathy towards local ecosystems and justifying investments to decision-makers. For instance, a Belgian expert noted that monitoring data could mitigate the perception of aquaNbS as “mosquito magnets” by confirming the presence of dragonflies, natural predators of mosquitoes. Assessing impacts and benefits, along with associated costs and savings pertinent to city goals, can enhance social acceptance and garner greater political support.

3 In-situ monitoring methods for aquatic nature-based solutions

There are limited resources for maintaining and monitoring aquatic nature-based solutions. Too often, systematic and long-term monitoring is missing. However, urban aquatic ecosystems, especially in densely built areas, are under strong anthropogenic and environmental pressures such as high concentrations of nutrients and other pollutants, severe hydro-morphological alterations and a declining streamflow. Therefore, systematic and regular monitoring is needed to understand the underlying processes and follow the wanted and unwanted changes within the ecosystem.

The more information we gain about aquaNbS, the more we can optimize their planning, design and maintenance practices serving especially those experts who are responsible for designing and implementing the aquaNBS. Unfortunately, post-hoc monitoring of changes in environmental qualities, species composition, or ecosystem functions is also very limited and often conducted only a few times after the implementation or as a part of time-limited, externally funded projects (Bartrons et al. 2024, Costadone & Vierikko 2023, Oertli & Parris 2019).

Our report presents different in-situ monitoring methods for six different target variables (1) habitats, (2) vegetation, (3) macroinvertebrates, (4) microbes, (5) hydrological processes and (6) water quality to evaluate ecological quality, ecosystem functions and species diversity that can be conducted independently but ideally in an integrated way with each other. First, we give a short introduction on each monitoring method, then present the field methods followed by analysis and use as an indicator. Benefits, costs, expertise needed, feasibility (in time and effort needed) that can have an impact for selecting and conducting the monitoring are discussed in Chapter 4.

3.1 Hydromorphological conditions

In freshwater ecosystems, habitat quality is determined by a combination of hydromorphological conditions shaped by natural processes and human activities. Key habitat factors include variables that influence hydrological conditions, such as water level, water sources, pathways, flow velocity, as well as morphological features. These features include channel characteristics such as the bottom substrate and natural formations (e.g., physical parameters, dimensions, bars, and riffles), along with macro-, meso-, and microhabitats, as well as in-channel vegetation and woody debris. Additionally, habitat quality is impacted by human modifications such as restricting, reinforcements, or other artificial structures. Bank and riparian zone characteristics (e.g., bank material, vegetation structure) and floodplain features (e.g., land use) are also vital components of habitat conditions (Argillier et al. 2025, Belletti et al. 2015, Fisher et al. 2012).

A comprehensive assessment of ecosystem health can only be accomplished by considering both abiotic and biotic elements. Therefore, the importance of habitat and hydromorphological conditions has been highlighted through their inclusion in the Water Framework Directive as supporting components of ecological status evaluation (Directive 2000/60/EC). Furthermore, many biological assessment methods include a brief description of the habitat, emphasizing the need to gather at least some information about these environments (e.g., Adamczyk et al. 2017, Armitage et al. 1983). The vital role of habitat quality for supporting organisms, especially for the most valuable species, is also well represented in the Habitats Directive, which was established to protect valuable and threatened biodiversity by safeguarding crucial ecosystems, their resident species, and habitats (Council Directive 92/43/EEC).

Any abiotic changes occurring in ecosystems, whether due to natural processes or human activities, will result in alterations to the associated plant and animal communities. These changes will continue until a certain balance is achieved between the habitat and the organisms that inhabit it. Consequently, in monitoring species composition or diversity in aquaNbS it is important to understand habitat conditions (Li et al. 2025, Reid. et al. 2018, Geist & Hawkins 2016).

3.1.1 Field monitoring of hydromorphological conditions

Currently, through the implementation of the Water Framework Directive, there are various methods available for assessing the hydromorphological status (Belletti et al. 2015), along with comprehensive guides and standards (Argillier et al. 2025) that outline habitat characteristics and facilitate quality assessments. However, many of these methods relate to larger freshwater ecosystems — whether entire water bodies or their various parts — and may not be directly suitable for evaluating small aquaNbS. To address the limitations of existing methods, we developed a monitoring method designed to characterise relatively small aquaNbS by incorporating elements from the River Habitat Survey method (Environmental Agency 2003). This assessment centred on the entire pond of any study and on 100-meter sections of each stream (Fig. 6). The various habitat parameters are categorised into the riverbed and the banks. The protocol for habitat monitoring can be found in Appendix I.

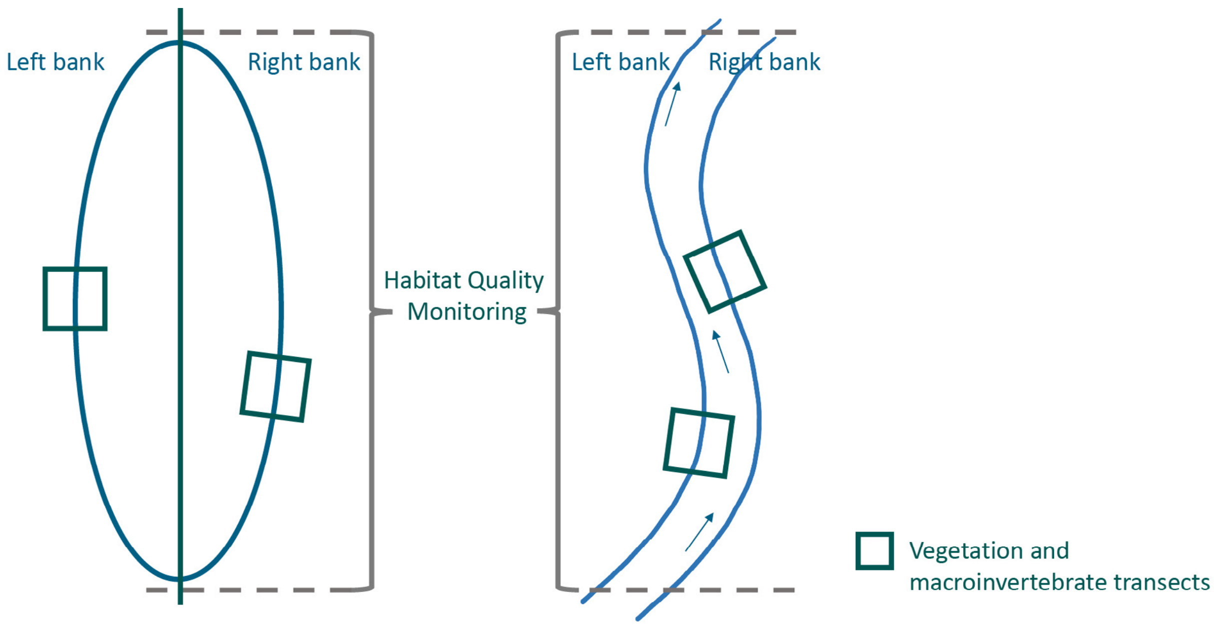

Figure 6. The locations of sampling sites (red quadrats) in the pond (left-hand side) and along research transects (100 m) in the small river or stream.

The protocol for habitat monitoring comprised six substantive sections and information about the site (Section I of the protocol). The monitoring includes recording the dimensions of rivers and ponds (Section II), noting aspects such as depth, width, and anthropogenic features, including embankments.

Section III includes 15 substrate categories, featuring natural substrates such as bedrock and boulders, as well as gravel and sand, more characteristic of lowland areas. Additionally, section III addressed various anthropogenic materials, including concrete and sewers, and some of which can be introduced as part of restoration efforts (e.g., wood piling). A three-point scale of estimation was used in this section and across all subsequent sections to evaluate the presence of various elements, ranging from "none" to "present" (1-33% share) and "extent" (>33% share). Section IV focuses on the channel zone and described natural morphological features that enhance the diversity of flow types and channel structures, including different types of bars, islands, and cliffs. The bank assessment Section (V) records various bank profiles, encompassing both natural (e.g., vertical, steep) and human-made (e.g., resected, reinforced) types. The final two Sections (VI and VII) focus on morphological elements associated with bankside trees (such as woody debris and underwater tree roots – and land use, both of which are crucial for creating habitats in aquatic ecosystems and in areas directly adjacent to them.

3.1.2 Analysis and use as an indicator

In-situ monitoring of habitat qualities of aquaNbS primarily allow for a semi-quantitative characterisation of hydromorphological conditions. This information can be utilised in various statistical analytical methods to explore the relationships between different habitat elements or to examine the links between habitat conditions, ecosystem functions and the organisms present. Additionally, the findings from hydromorphological monitoring can be valuable in assessing and predicting how habitat quality of aquaNbS over time.

3.2 **Vegetation**

Vascular plants play a key role in aquaNbS. In urban areas, planted vascular plant species are very often selected according to their capacity to bind pollutants and nutrients, based on their resistance towards changes in water flow or provide other expected ecosystem functions of aquaNbS. Management practices of aquaNbS are especially targeted to vegetation through planting, mowing, and removing unwanted species. Despite vegetation of aquaNbS often being strongly controlled, wild species and spontaneous vegetation are common. Therefore, aquaNbS can provide suitable habitats for many macrophytes and wetland species, and drier bank zones also for mesic species and flora attracting pollinators. Macrophytes, as a vital component of aquatic ecosystems, play an important role in aquatic environments by providing physical structure, food and shelter for various aquatic organisms (Thomaz & Cunha 2010), increasing habitat complexity and heterogeneity which strongly affects other aquatic communities, such as benthic macroinvertebrates (Błachuta et al. 2014), fish (Meschiatti et al. 2000), zooplankton, microalgae and birds (Kuczynska-Kippen & Joniak 2016). Therefore, macrophytes are good bioindicators for ecological quality as many aquatic plants respond to various environmental factors such as light, temperature, and substrate (Bornette & Puijalon 2011, Dengler et al. 2023). Overall, species composition of vascular plants and water mosses indicates ecological quality of aquaNbS, helping to detect eutrophication (Haury et al. 2006, Szoszkiewicz et al. 2020), and to some extent also acidification (Tremp & Kohler 1995) and morphological degradation (Haury et al. 2006).

3.2.1 Field monitoring of vegetation

100 m long stretches were established for sampling vegetation in two vegetation survey sites: a more natural section, typically characterized by well-developed vegetation along the banks, and a more modified section, where bank vegetation has often been disturbed or even removed (Fig. 7). We acknowledge that a stretch of 100 m is relatively short but often contains most of the variation in urban streams. This scale is commonly used in the biological assessment of rivers for some quality elements (between 50-100 m) (Campos et al. 2024). Each survey site was based on 10-meter quadrats, which were divided between the bank and the aquatic zone. Vegetation was identified at the species level including both terrestrial and macrophyte species. If a field worker has the relevant expertise, it is useful to identify also aquatic bryophytes as they are good indicators of ecological quality (Gecheva & Yurukova 2014). Total cover of vegetation was estimated for each species within the quadrat (the sum can be higher than 100%) and reported in a nine-point ordinal scale: <0.1% (1), 0.1–1% (2), 1–2.5% (3), 2.5–5% (4), 5–10% (5), 10–25% (6), 25–50% (7), 50–75% (8), and >75% (9) (Szoszkiewicz et al. 2020). The most suitable time for field surveys is summer, spanning from early May to September, depending on biogeographical location and climate (Mediterranean, temperate, boreal, arctic).

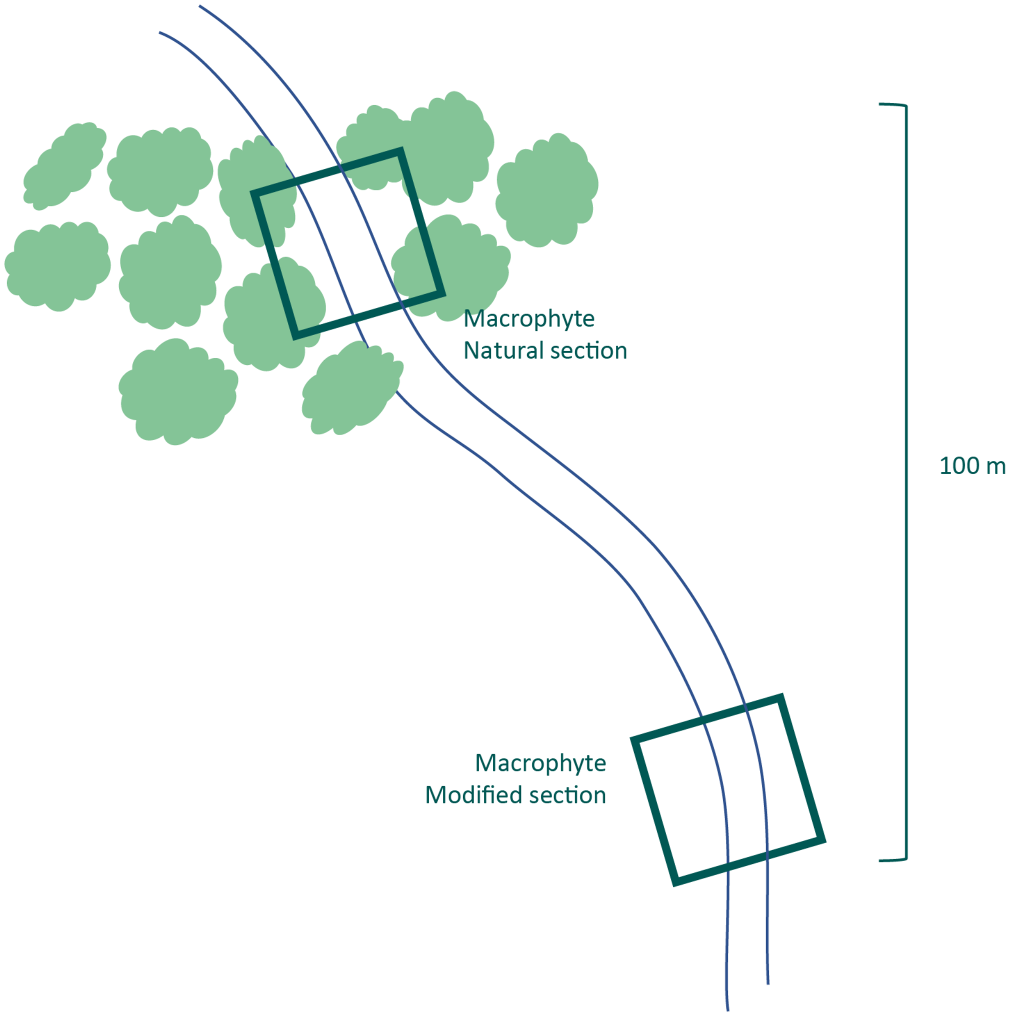

Figure 7. Example of sample area and single sampling site (10x10m red quadrats). This is an effective sampling size in a small aquaNbS (Szoszkiewicz et al. 2025).

3.2.2 Analysis and use as an indicator

There are several diversity metrics that incorporate relative species abundance such as Shannon diversity (Allaby 2018, Shannon and Weaver 1949), Simpson diversity (Simpson 1949), and evenness (Pielou 1966). Functional traits (emergent, submerged, and floating-leaved) or species' indicator values are useful for estimating biodiversity values and whether the variation among functions that vegetation provides in aquaNbS. The most commonly used metric for macrophytes is the Ellenberg Indicator Values (EIV), which expresses plant preferences for various environmental factors. These values assess species' environmental preferences, including light availability, temperature, soil moisture, pH, and trophy based on nitrogen availability (Ellenberg 1974). EIVs are among the most widely used methods for biological monitoring, particularly effective in bioindication through analyzing the species composition of communities (Di Biase et al. 2023). However, a deeper analysis of EIV can also be used to examine the role of filtering mechanisms in shaping plant communities according to species' ecological preferences (Di Biase et al. 2023).

In the BiNatUr project, the diversity of macrophyte abundance was also analyzed, considering their sensitivity to various ecological parameters. We based this on six EIVs expressing plant preferences for temperature, light, continentality, moisture, pH, and trophy (Dengler et al. 2023), which are widely used to investigate the importance of filtering mechanisms in shaping plant communities (Di Biase et al. 2023).

3.3 **Macroinvertebrates**

Aquatic macroinvertebrates contribute to many processes in freshwater ecosystems, including nutrient cycling and food webs (Huryn & Wallace 2000). Since they show a high variability in terms of environmental tolerances and habitat preferences (Sumudumali & Jayawardana 2021), they represent a useful tool for assessing the ecological status of ecosystems (Dallas 2000). Thus, to improve conservation and understand the effects of environmental policies, studying which environmental factors impact their communities is essential (Van Looy et al. 2017). Macroinvertebrate monitoring in urban aquatic habitats is challenging but provides valuable understating to improve the management of urban aquaNbS.

3.3.1 Field monitoring of macroinvertebrates

There are several methods for monitoring macroinvertebrates, including qualitative sampling focused on community diversity, such as kicking method using kick net, and quantitative sampling focused on the number of individuals per area using samplers, such as Surber sampler (Ghani et al. 2016). To determine the community structure, it is recommended to sample in spring and autumn or dry and wet seasons, depending on biogeographical and climate region.

Due to the small size of most urban aquaNBS, adaptations from the EU Water Framework Directive 2000/60/EC (WFD) are necessary. In general, we recommend sampling within a time limit, e.g. 2 minutes per site, within a comparable area (e.g., 10 x 10 m). To account for the diversity of bottom substrate, which can be highly diverse even in small size habitats, we recommend using a kick-sampling method (e.g., using a D-frame kick-net, 500 µm mesh size), covering the substrates proportionally to their area in the square (Fig. 8). This method can be supplemented by hand-collecting under rocks and sweeping in areas with macrophytes. Special attention should be made to cover all possible habitats in which macroinvertebrates could be present, such as sand, clay, gravel, pebbles and stones. Collected specimens should be stored in a preservation solution for identification in the laboratory. Furthermore, physicochemical parameters of water should be also measured, using a portable multiparameter probe measuring water temperature, pH, conductivity and dissolved oxygen.

3.3.2 Identification and use as an indicator

The identification of macroinvertebrates relies on both national guidelines (e.g. De Pauw & Vanhooren (1983) for Belgium) and available determination keys. The identification level is usually chosen according to the national indices used to assess biodiversity and water quality and can be country dependent. In the BiNatUr project, we identified macroinvertebrates communities to the sub-class, order, family or genus level, using the binocular magnifying glass and microscope (Fig. 9). Importantly, the higher the taxonomic level identified, the better understanding of biodiversity and trophic dynamics can be gathered. However, identifying species to the lowest possible level - species level - can be time-consuming and labor-intensive. Thus, we recommend at least identifying macroinvertebrates to the family or genus level and whenever possible and necessary, to the species level.

Figure 8. Macroinvertebrate sampling in Lisbon, Portugal. Photo: Pedro Pinho

Monitoring of macroinvertebrates, used as indicators, is crucial for promptly intervening in the mitigation of the negative changes in ecosystems (Carignan & Villard 2002), especially in urban areas. Simple monitoring uses biodiversity metrics like species richness, Simpson and Shannon diversity indices, representing basic understanding of species distribution in a community. More sophisticated indices are recommended since they provide a comprehensive assessment of water quality by combining taxonomic diversity and pollution tolerance (Marques 2009), such as EPT Index (the number of different taxa; species, genera or families observed in Ephemeroptera, Plecoptera and Trichoptera (Kitchin 2005)) and Biological Monitoring Working Party Score System (BMWP, Armitage et al. 1983) based on WFD classification. To assess the environmental drivers of communities it is important to focus on bioclimatic variables, affected by air temperature and precipitation, and local conditions, such as riparian vegetation, macrophytes and water variables, namely water temperature, pH, oxygen concentration, conductivity, isotope composition, water depth and bottom material.

Figure 9. Individuals from the family Baetidae were identified under a binocular magnifying glass and counted. Photo: Vladimíra Dekan Carreira.

3.4 **Microbial patterns**

Environmental DNA (eDNA) offers a step-change for biodiversity assessments of terrestrial and aquatic species. eDNA provides a snapshot of the organisms present in a specific environment and can be interpreted as an indicator for diversity. Microbial patterns can be linked to hydrological functioning and water quality and provide an integrated overview of current conditions in an aquaNbS system. The use of novel genetic techniques for understanding ecological systems provides technological advances for biodiversity monitoring that allow fast and efficient recovery of biodiversity signals (Deiner et al. 2016, Bagley et al. 2019). Water eDNA can be used to analyze the presence, distribution and evolution of species within aquatic environments (Altermatt et al. 2023). Environmental DNA metabarcoding captures signals from macro and microorganisms - ranging from planktonic bacteria to diatoms and algae, land plants and fungi. Compared to traditional species sampling methods, eDNA offers the advantage of being minimally invasive, relatively quick, and globally applicable. Through metabarcoding analysis, multiple species can be detected at the same time, including rare and invasive species. This gives the potential for biodiversity assessments in aquaNBS at high spatial and temporal resolution if needed.

3.4.1 Field monitoring of water eDNA

Sampling of water eDNA usually occurs as a two-stage process. For assessing aquatic diversity, a liquid water sample is required. Necessary sampling equipment includes: i) Eppendorf tube (2ml) filled with 96% ethanol, ii) tweezers, iii) Isopore polycarbonate membrane filter (ø 47mm, pore size 0.22µm), iv) bucket for capturing water, v) Nalgene vacuum pump (Thermo Fisher), vi) filter holder with 500ml receiver (Thermo-Fisher), vi) Latex Gloves, vii) tissue and alcohol for disinfection.

First, a grab sample is collected from the desired water body. To collect a genetic sample for eDNA analysis, a certain amount of water (150 – 400ml) is filtered through an Isopore polycarbonate membrane filter, which is placed in the center of the filter holder (Fig. 10). Using a vacuum pump, water is drawn from the upper to the lower compartment of the filter holder, pushing water through the membrane filter which in turn retains the genetic material. Depending on the abundance of organic material in the water, this process may be relatively quick, with water passing through the filter relatively fast (<1 min). If there is a lot of organic material or suspended solids this can take some time (30min - 1hr). It is recommended to filter at least 200ml of water sample. Once the filter process is complete, the top part of the filter holder is removed and using tweezers and sterile gloves, the filter paper is folded and placed in the Eppendorf tube, which is filled with 96% ethanol. Filters must be placed in a freezer at -20°C as soon as possible. If sampling multiple locations on the same day, samples can be stored in a portable cooler and placed in the freezer at the end of the day. Filters can be stored in -20°C until analysis. Extraction of genetic materials involves different steps done by the responsible laboratory (i.e. see Warter et al. 2024 for detailed step by step procedure of eDNA extraction).

Figure 10. Sampling of environmental DNA in the field. A water sample is filtered through a filter apparatus which contains a polycarbonate membrane filter. The filter is then placed in an Eppendorf tube, which is filled with ethanol. Photo: Maria Warter.

3.4.2 Analysis and use as an indicator

Sampling over extended spatial or temporal scales can provide insights into landscape-scale influences and seasonal variability, tracking changes in species presence, appearance of invasive species or loss of native ones. Relative abundance of species can be used to estimate alpha diversity indices, such as species richness (total number of species present), Shannon Diversity Index or Simpson Index. Beta diversity measures can also be estimated such as turnover (change of species composition over time) or nestedness. These indices can provide valuable insights into local ecological conditions as well as a link to water sources and water quality. It is recommended to sample at least on a seasonal basis and if possible, across a diverse spatial scale. Principal component analyses and non-metric multidimensional scaling can help to illustrate spatio-temporal patterns and linkages to hydrological or water quality conditions.

3.5 **Hydrological processes**

As naturally occurring tracers of the water cycle, the stable water isotopes of water (δ18O and δ2H) can be used to differentiate contrasting water sources across catchment, regional and global scales and characterize fundamental hydrological processes and water fluxes (Ehleringer et al. 2016, Tetzlaff et al. 2015). Oxygen has three naturally occurring stable isotopes (16O, 17O, 18O) while hydrogen also has three isotopes, two of which are stable (1H, 2H), and the third is radioactive (3H) (Jasechko 2019). Isotopic signatures can be used as "fingerprints" of water and are conservative which means their signature does not change through any other processes than mixing or evaporative fractionation. They vary between different water sources (i.e. precipitation, groundwater, runoff) and allow to investigate water sources and flowpaths, connectivity between landscapes and freshwater ecosystems, as well as climate-water-ecosystem interactions between natural and anthropogenic systems (Kirchner, 2016). Sampling of multiple water sources, such as surface water, groundwater, precipitation or soil water, can give valuable insights into how water is stored and released in the landscape and to the aquaNbS, which water sources dominate in a system (i.e. groundwater, soilwater rainfall) and which hydroclimatic processes are relevant (i.e. evaporation, groundwater recharge or discharge). Analysis of stable water isotopes across extended spatial and temporal scales or hydroclimate gradients offers an integrated lens through which to understand the role of hydrology in aquaNbS, potential dependencies on certain water sources and sensitivities to hydroclimate changes (Warter et al. 2025).

3.5.1 Field monitoring of stable water isotopes

Sampling of stable water isotopes can be done across different temporal or spatial scales. Either low-frequency approaches (i.e. seasonal or monthly) can be done over short or extended time periods at multiple sites or as part of high-resolution intensive campaigns that collect data on a weekly, daily or even sub-daily basis. It is recommended to take samples at least on a seasonal basis (spring, summer, autumn, winter) over the period of one year, to generate a broad characterization of local hydrologic processes and accounting for effects of climatic variability. If possible, monthly sampling over the period of one year or up to 18 months, can provide even more detailed information on hydroclimate impacts and ecohydrologic functioning of ecosystems.

Typically, grab sampling is recommended if no automatic sampling is possible as it is easy and cheap. Using a bucket, water can be collected on-site from a stream or pond of interest (Fig. 11). Attention needs to be taken to not disturb the water to be samples by stirring up sediment, which can contaminate the sample. Either a larger volume (~1 liter) can be collected and taken to the lab, or a smaller volume can be filtered and decanted into 1.5 ml glass vials (with screw top) on site. Filtering of all liquid samples using a 0.2 µm cellulose acetate filter and syringe is highly recommended to remove organic material and suspended solids and avoid contamination of analyzing equipment. Samples should be tightly sealed and can be stored in a refrigerator until analysis. Between sampling, it is recommended to rinse the sampling bucket once or twice at each location, to avoid mixing water from previous sampling.

It is recommended to also collect water samples from local precipitation and groundwater as reference. If this is not possible, one can refer to the data from Global Network of Isotopes in Precipitation (GNIP) or the Global Network of Isotopes in Rivers (GNIR) by the International Atomic Energy Agency (IAEA).

3.5.2 Analysis and use as an indicator

Analysis of δ18O and δ2H is usually done using a Picarro L2130-i cavity ring-down water isotope analyzer (Picarro Inc., Santa Clara, CA, USA). Analysis of δ18O and δ2H is generally done relative to internal laboratory standards, which are themselves calibrated against international standards such as the Vienna Mean Standard Ocean Water (VSMOW) by the International Atomic Energy Agency (IAEA).

Isotopic signatures of each water source are placed relative to a meteoric water line – linear regressions describing local precipitation variations in δ18O and δ2H. Different water sources are characterized by variable isotopic signatures, which are induced by processes such as evaporation, mixing, seasonal changes, elevational changes (Jasechko 2019). Variables like Deuterium excess (d-excess) can help identify the impact of evaporation on a water body (Dansgaard 1964). Simple transit time proxies, such as young water fractions (i.e. the fraction of water that entered the stream or pond within the last 2-3 months) or damping ratio (i.e. the dampening of stream or pond isotopes in comparison to local precipitation), can be used as semi-quantitative proxy measures to assess general trends in transit and residence times, as well as precipitation-runoff responses and mixing processes (Kuhlemann et al. 2022, Kirchner 2016).

Figure 11. Grab samples are taken for isotope analysis directly from the stream using a bucket. The water is filtered through an acetate filter using a syringe and decanted directly into a vial (1.5 ml). Photos: Maria Warter.

3.6 **Water quality**

Monitoring water quality in urban streams is important for evaluating chemical and biological conditions of a stream or pond system and can help identify suitable locations for aquaNbS and improvement opportunities. Regular monitoring of water quality parameters has the added benefit of providing information on potential pollution sources, urban influences and ecological boundary conditions. Indicators such as pH, salinity, water temperature, nutrients, oxygen concentration and turbidity can help identify pollution pathways, stormwater runoff processes, and water sources and flowpaths, which can support a systematic assessment of the conditions for an aquaNbS and provide an understanding of aquatic ecosystem health. Systematic water quality monitoring before and after the implementation of an aquaNbS can also provide evidence of the success and functioning of the aquaNbS in the long-term.

3.6.1 Field monitoring and analysis of water quality

Basic water quality parameters such as temperature, salinity (electric conductivity), pH and oxygen concentrations can be measured in-situ with handheld devices at fair prices (i.e. WTW Multi 3630 IDS Set). It is recommended to sample basic water quality parameters at the same time when taking stable water isotopes, eDNA or macroinvertebrate samples. For nitrogen (i.e. ammonium (NH4, nitrate NO3) and other parameters such as dissolved inorganic/organic carbon (DIC/DOC), phosphorus (soluble reactive phosphorus SRP, total phosphorus TP) or other major ions (i.e. calcium (Ca), sodium (Na), iron (Fe)) water samples need to be analyzed in the laboratory. In addition, there are nowadays quite cheap water quality probes available which are not handheld but can just be installed for long-term high-resolution monitoring.

Water quality parameters can be analyzed through simple statistical methods. Analyses of spatio-temporal variability, seasonal patterns can support the interpretation of aquatic diversity patterns – from macroinvertebrates and macrophytes, to microbial patterns. Cluster analyses or principal component analyses can help to disentangle spatio-temporal patterns and interlinkages with hydrological and ecological processes.

3.7 **Selection of in-situ monitoring methods**

In the previous chapters, various monitoring methods have been presented and discussed to monitor different aspects of ecological quality, ecohydrological processes, and biodiversity of aquaNbS. A well planned and prepared sampling design is essential to optimize sampling efforts and ensure that valuable and reliable data is collected. There are many practical issues that are limiting systematic in-situ monitoring of aquaNbS such as costs, staff efforts and time needed for monitoring, and whether there are restrictions and permissions to access the sites. In addition, to ensure representative data collection, at least the following aspects need to be considered: (i) season and frequency of sampling; (ii) number of sampling sites; and (iii) spatial representativeness of the sampling sites. Climatic conditions need to be considered when deciding what time of the year to carry out sampling. Table 3 below gives an overview of benefits, feasibility, costs, staff effort and time required for in-situ monitoring of different methods relevant for urban aquaNbS.

Table 3 shows that different monitoring methods have their own benefits. Monitoring of water quality and hydrological processes of different aquaNbS can provide baseline information on physico-chemical characteristics, external stressors, and pollutants affecting the habitat and microbial diversity in different aquaNbS. Stable water isotope analysis is a particularly valuable tool for quantifying water partitioning, tracing flow paths, and understanding ecohydrological interactions within aquaNbS. Short-term reconnaissance-style isotope surveys can generate robust datasets across spatial and temporal gradients, allowing for the comparison of hydrological processes such as runoff, baseflow, infiltration, and evapotranspiration. Incorporating isotopic methods into NbS assessment can improve understanding of their hydrological and ecological dynamics, thereby supporting the sustainable design, implementation, and long-term management of urban aquaNbS.

Table 3. Benefits, feasibility, efforts required and suggestions for regularity of data collections

Monitoring method	Benefits	Feasibility and efforts	Data collection
Hydro-morphological conditions	Allow for a semi-quantitative characterisation of hydro-morphological conditions that can have impact to ecological functions and biodiversity.	Need specific expertise, equipment costs are low. Hydromorphological characterization made in the field. Use of citizen science as a supporting approach is acceptable – e.g. photographs of important hydromorphological elements.	Data collection every 4-5th year, ideally in summer but also possible and acceptable in spring and autumn. After any major changes/ modifications every year during first 2-3 years.
Plants, including terrestrial and aquatic species.	Plants are the bases of the regulation ecosystem functions and services. Special attention for invasive alien species is needed.	Need specific expertise, equipment costs are low. Identification made in the field and laboratory for the more difficult taxa.	Data collection ideally twice in a summer season every 3-4th year. After the strong changes/ modifications every year during first 2-3 years. If invasive alien species are found, check-in and removing on annual base.
Macro-invertebrates	Biological indicators of ecosystem's ecological and biological conditions. Can help identify sources of disturbances (e.g. pollution) and locations for aquaNbS restoration.	Samples need to be collected by experts and identification needs specific expertise, equipment and sampling costs are relatively low. Relatively high costs for monitoring and identification after the sampling.	Data collection in summer season at least every 3-4th year.
Microbial patterns with eDNA	Multiple species can be detected at the same time, including rare and invasive species.	Relatively quick, and globally applicable. Samples can be easily collected by non-expert with manuals. Specific expertise required for laboratory analysis of data. Laboratory costs are moderate.	Data collection ideally twice a year, or at least once per year every 3-4th year.
Hydrological processes	Provides core insights into physical structure and processes of water within aquaNbS, and origin of water and dependency on rain, groundwater or other sources.	Samples can be easily collected by non-expert using simple guidelines. Specific expertise required for laboratory analysis of data. No high-tech equipment required. Manuals available for sampling. Low costs for sampling, moderate for laboratory analysis.	Strongly driven by climate, therefore data collection four times / year ideally annually based.
Water quality	Gives an overview of water quality and changes in pollutants	Samples can be easily collected by non-expert using simple guidelines. Carry-on equipment available giving results directly in the field.	Annual based basic monitoring of water quality.

For more ecologically oriented aquaNbS, where supporting biodiversity may be an important goal, more specific species monitoring is needed to ensure that aquaNbS can maintain their biodiversity and conservation values. As these are relatively expensive and need specific expertise, it is important to identify and map those aquaNbS where systematic and regular multispecies monitoring is crucial.

It should be noted that the proposed monitoring frequencies may deviate from established national practices under the Water Framework Directive. The frequencies suggested here represent minimum recommendations; more frequent monitoring is encouraged when it better fits ongoing national or regional practices.

3.8 Ex-situ monitoring and use of remote data

In addition to in-situ monitoring, ex-situ monitoring using remote sensing can provide important information about the surrounding environment, land cover and land use types of aquaNbS (Assiri et al. 2024). Aerial photographs, satellite and radar data, and aircraft- or drone-borne hyperspectral images enable continuous and objective observation of easily accessible and difficult-to-access water bodies throughout the year. However, limitations are set by snow cover, shadows or cloud cover.

In regard to aquaNbS monitoring, remote sensing can be used to assess (i) surrounding vegetation parameters and (ii) climatic variables, as well as to monitor (iii) the surrounding urban matrix, among other things. These variables are at the foundation of ecosystem service assessments. Due to the small scale of the water bodies, water quality monitoring is difficult to obtain using remote sensing. Vegetation metrics were derived from remote sensing data reflecting current vegetation structure and productivity, using imagery from Landsat 8 and 9, Sentinel-2, and PlanetScope platforms (Liu et al. 2023). PlanetScope-based products included estimates of tree cover, tree height, and biomass using a combination of optical and Lidar data. Normalized Difference Vegetation Index (NDVI) across seasons are also obtained from PlanetScope imagery.

All PlanetScope datasets provide a spatial resolution of 3 m. Sentinel-2 based indices include the NDWI (Normalized Difference Water Index) and the Normalized Burn Ration using band 8A at 20 meters resolution. The latter indices are indicative for water stress in plants. Land Surface Temperature (LST) was obtained from remote sensing data using Landsat Level-2 Surface Temperature products. These datasets were derived from the Thermal Infrared Sensor (TIRS) instruments onboard Landsat 8 and 9 satellites (Liu et al. 2023). LST values were computed at a 120 m spatial resolution by applying the standard scaling factors described by EROS (2020) and were used for analyses at the city scale and to fine tune climatic model data. As an example, for monitoring the surrounding urban matrix, Surface imperviousness data were obtained from the Copernicus High Resolution Layer on impervious surfaces, which provides pan-European estimates of sealing density (0–100%) for the reference year 2018 at 10 m spatial resolution, primarily based on Sentinel-2 imagery (Copernicus Land Monitoring Service, 2018). All variable values were extracted at the pixel corresponding to each sampling location. A new Copernicus backbone data (10 m spatial resolution) was published in 2025.

4 Conclusions

Monitoring data is increasingly important to all aspects of urban aquaNbS success. Nonetheless, the lack of long-term monitoring data remains a challenge across various European countries implementing NbS for water management (Santos 2025). It is essential to note that a lack of monitoring does not imply a lack of maintenance or management; rather, the focus may not align with the unique characteristics of aquaNbS—both as technical structures and landscape features intertwined with vegetation and natural elements, balancing ecological goals with technical functionality. To mitigate funding shortfalls in monitoring and maintenance of aquaNbS, citizen involvement represents a promising avenue for cost-effective monitoring. In Finland, for example, standardized methods and guidelines for citizen-led water quality monitoring have been established (www.mappa.fi). Belgian and Portuguese experts also presented cases of citizen participation in biodiversity monitoring data collection, complementing more traditional technical monitoring efforts. Citizens typically have a strong interest in their local water ecosystems (Vierikko & Niemelä 2016). Fostering a sense of ownership and stewardship for aquaNbS within local communities can facilitate volunteer participation in ecological monitoring (Fig. 12), especially with novel techniques such as eDNA, that do not necessitate specific taxonomic expertise (Battisti et al. 2024).

Ultimately, monitoring aquaNbS is not only an ecological or a technical task but it should be also seen as a tool serving social aspects and participative governance of urban NbS (Hafferty et al. 2025). Integrated monitoring schemes for NbS can provide valuable insights and evaluate success for biodiversity-sensitive governance starting from planning, spanning from implementation phase to practical management tasks. Ideally, such schemes ensure that aquaNbS remain effective, resilient, and support transformative change aligned with their initial goals.

Figure 12. Volunteer monitoring and citizen science can provide valuable information and support citizens stewardship towards nature. Photo: Kati Vierikko.

Lexicon

AquaNbS — Water-based or aquatic nature-based solutions that are planned and designed to deliver multiple ecosystem services, such as stormwater regulation, recreation, human well-being and climate change mitigation, simultaneously supporting biodiversity (Pinho et al. 2023). The type, form and functions of aquaNbS can vary greatly and often they are hybrid systems of engineered and natural elements.

Backcasting — Backcasting is a scenario approach utilized for instance developing innovative urban climate adaptation actions (Wübbelmann & Kabisch 2025). Backcasting focuses on "what should happen" and takes desirable future as a starting point. From which different strategies, targets, pathways and actions - e.g. here nature-based solutions for water-management - that are needed to the desired future are then developed backwards from to the present (Vergragt & Quist 2011).

Ecohydrology — Ecohydrology - Interdisciplinary science studying the interactions between water (hydrology) and living organisms (ecology) within ecosystems. The field of ecohydrology encompasses aquatic (in-stream) and terrestrial processes and revolves around examining water's critical role in influencing biological communities in aquatic and terrestrial habitats, to plant life (i.e. vegetation water needs), and how in turn they affect the availability of water and the water cycle (Baird & Wilby 1999).

Hydromorphology — Hydromorphology refers to the physical features and processes of a river, lake, or other waterbody, including water flow, water levels, and their dynamics. It also covers the shape and structure of the channel, banks, and riparian zone (EPA 2024). The Water Framework Directive (WFD) defines hydromorphological conditions as considering the hydrological regime, continuity, and morphological conditions (Directive 2000/60/EC).

Lentic water — Lentic water refers to standing water i.e. aquatic bodies of water with no essential flow. Lentic freshwater water bodies include ponds, lakes and reservoirs (Waterinfo 2025).

Lotic water — Lotic ecosystems refer to flowing freshwater environments, such as streams and rivers, characterized by unidirectional water movement along a slope in response to gravity (Wetzel 2001b).

Restoration — Ecological restoration also called as ecosystem restoration refers to supporting and assisting recovery of degraded or destroyed ecosystems by improving their natural functions, processes and structure, with the overall goal of improving resilience of ecosystem (Gann et al. 2019). The primary focus of restoration practices is on ecology, but it can also provide societal benefits (Waylen et al. 2024).

Rewilding	Process of rebuilding, following major human disturbance, a natural ecosystem by restoring natural processes and the complete or near complete food web at all trophic levels as a self-sustaining and resilient ecosystem with biota that would have been present had the disturbance not occurred (Carver et al. 2021). Rewilding natural processes sometimes need engineered interventions.
SETS framing	Social-Ecological-Technological Systems (SETS) framework illustrates the importance of coordinating natural, technological, and socioeconomic systems when designing, planning, and managing urban nature-based solutions to enable optimal social-ecological outcomes in the context of complex urban-systems dynamics (Pinho et al. 2023, McPhearson et al. 2021)
Urban biodiversity	Variability among living organisms within city and its administrative limits, from genes to species to ecosystems to urban land-use types, including all native, spontaneous, cultivated or domesticated organisms regardless of their origin (Kowarik et al. 2025, Knapp et al. 2021).

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Appendix I. Protocol for habitat monitoring developed based on the River Habitat Survey method

River Habitat Survey based field protocol				Page 1 of 2
Section I – Site details				
City/Country:	aquaNBS construction year:			
Site number:	aquaNBS role:			
GPS beginning:	Watercourse ☐	Lake ☐		
GPS wnd:	Natural ☐	Artificial ☐		
Site name:	Permanent ☐	Temporary ☐		
River/lake name:				
Date ……../……../……../	Managing authority:			
Surveyor name:				

Section II – Dimensions					
Left bank		Channel		Right bank	
Banktop height (m)		Bankful width (m)		Banktop height (m)	
Is banktop height also bankful height? (Y or N)		Water width (m)		Is banktop height also bankful height? (Y or N)	
Embankment (m)		Water depth (m)		Embankment (m)	

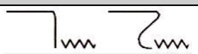
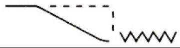
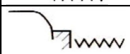
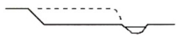
Section III – Bottom and Bank Material (tick one box for each feature) record if >1%									
	Bottom material			Left bank material			Right bank material		
	None	Present	E(≥33%)	None	Present	E(≥33%)	None	Present	E(≥33%)
Bedrock	❑	❑	❑	❑	❑	❑	❑	❑	❑
Boulder	❑	❑	❑	❑	❑	❑	❑	❑	❑
Cobble	❑	❑	❑	❑	❑	❑	❑	❑	❑
Pebble	❑	❑	❑	❑	❑	❑	❑	❑	❑
Gravel	❑	❑	❑	❑	❑	❑	❑	❑	❑
Sand	❑	❑	❑	❑	❑	❑	❑	❑	❑
Earth	❑	❑	❑	❑	❑	❑	❑	❑	❑
Sicky clay	❑	❑	❑	❑	❑	❑	❑	❑	❑
Concrete	❑	❑	❑	❑	❑	❑	❑	❑	❑
Sheet piling	❑	❑	❑	❑	❑	❑	❑	❑	❑
Wood piling	❑	❑	❑	❑	❑	❑	❑	❑	❑
Gabion	❑	❑	❑	❑	❑	❑	❑	❑	❑
Brick/laid stone	❑	❑	❑	❑	❑	❑	❑	❑	❑
Rip-rap	❑	❑	❑	❑	❑	❑	❑	❑	❑
Silt	❑	❑	❑	❑	❑	❑	❑	❑	❑

River Habitat Survey based field protocol	Page 2 of 2

Section IV – Extent Of Channel and Bank Features (tick one box for each feature) *record even if <1%

	None	Present	E(≥33%)		None	Present	E(≥33%
*Free fall flow	❑	❑	❑	Exposed bedrock	❑	❑	❑
Chute flow	❑	❑	❑	Exposed boulders	❑	❑	❑
Broken standing waves	❑	❑	❑	Vegetated bedrock/boul-	❑	❑	❑
Unbroken standing waves	❑	❑	❑	Unvegetated mid-channel	❑	❑	❑
Rippled flow	❑	❑	❑	Vegetated mid-channel	❑	❑	❑
Upwelling	❑	❑	❑	Mature island(s)	❑	❑	❑
Smooth flow	❑	❑	❑	Unvegetated side bar(s)	❑	❑	❑
No perceptible flow	❑	❑	❑	Vegetated side bar(s)	❑	❑	❑
No flow (dry)	❑	❑	❑	Unvegetated point bar(s)	❑	❑	❑
Marginal deadwater	❑	❑	❑	Vegetated point bar(s)	❑	❑	❑
				Eroding cliff(s)	❑	❑	❑
				Stable cliff(s)	❑	❑	❑

Section V – Bank Profiles Use ❑ (present) or E (> 33% bank length)

Natural/unmodified		L	P	Artificial/modified		L	P
Vertical/undercut				Resectioned (reprofi-			
Vertical with toe				Reinforced – whole			
Steep (>45)				Reinforced - top only			
Gentle				Reinforced - toe only			
Composite				Artificial two-stage			
Natural berm				Poached bank			
				Embanked			
				Set-back embankment			

Section VI – Extent Of Trees And Associated Features*record even if <1%

Trees (tick one box per bank)	Left	Right	Associated Features (tick one box per feature)	None	Present	E(≥33%)
None	❑	❑	Shading of the channel	❑	❑	❑
Isolated/scattered	❑	❑	*Overhanging boughs	❑	❑	❑
Regularly spaced, single	❑	❑	*Exposed bankside roots	❑	❑	❑
Occasional clumps	❑	❑	*Underwater tree roots	❑	❑	❑
Semi-continuous	❑	❑	Fallen trees	❑	❑	❑
Continuous	❑	❑	Large woody debris	❑	❑	❑

Section VII – Land-Use on Banktop and Within 50m of Banktop Use ❑ (present) or E (> 33% bank length)

	Banktop		Within 50 m			Banktop		Within 50 m	
	L	R	L	R		L	R	L	R
Broadleaf/mixed woodland (semi-					Artificial open water				
Broadleaf/mixed plantation					Natural open water				
Coniferous woodland (semi-natu-					Rough/unimproved grassland/pasture				
Coniferous plantation					Improved/semi-improved grass				
Parkland or gardens					Tall herb/rank vegetation				
Scrub & shrubs					Rock, scree or sand dunes				
Orchard					Suburban/urban development				
Wetland (e.g. bog, marsh, fen)					Tilled land				
Moorland/heath									

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