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Nature-based solutions for urban stream restoration and water quality enhancement: A review

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ABSTRACT

Urban watercourses are often affected by hydrological, chemical and ecological degradation, driven by increased impervious surface cover in an urban environment, impact on flow regimes, and diffuse pollution. Among the most persistent challenges are elevated loads of total suspended solids, heavy metals, nutrients, organic micropollutants, and microbial contaminants transported by stormwater runoff. These pollutants contribute to oxygen exhaustion, eutrophication, bioaccumulation of toxic substances, and substantial losses in aquatic biodiversity. In response to these pressures, nature-based solutions are increasingly applied as decentralised and ecologically integrated strategies for improving water quality. This review presents full-scale applications of NbS, analyzing their technical characteristics, pollutant removal efficiencies, and ecosystem service benefits. The results indicate that the removal of TSS often exceeds 80%, while the reductions vary depending on the design of the system, the type of vegetation, and hydraulic loading rates. In addition to improving water quality, these systems contribute to flood retention, habitat creation, temperature regulation, and carbon sequestration. Despite their multifunctionality, the implementation of NbS remains challenging due to regulatory fragmentation, design uncertainty under changing climate scenarios, and the lack of standardized monitoring protocols. The primary objective is to provide a comparative overview of full-scale nature-based systems applicable to improving water quality and supporting the ecological restoration of urban streams affected by climate change and intensive land use.

Keywords: constructed wetlands, climate change adaptation, nature-based solutions, stormwater runoff, urban stream restoration, water quality improvement.

INTRODUCTION

In the context of climate change, stormwater management is becoming an increasingly important challenge. Projected climate change, such as an increase in the intensity and frequency of precipitation, leads to serious problems of overloaded drainage systems and an increased risk of flooding (Boukalová et al., 2020; Stefanakis et al., 2021). On the other hand, prolonged droughts, increasingly driven by anthropogenic climate change, are transforming the hydrology of urban and peri-urban streams. As natural base flows decrease, many watercourses become hydrologically disconnected, sustained primarily by anthropogenic inputs such as urban drainage and stormwater runoff (Gu et al., 2023; Ribeiro Neto et al., 2022). In heavily modified catchments, such artificial inflows become dominant during dry periods, leading to fundamental shifts in flow patterns and ecological function. (Moss et al., 2024) emphasise that these changes not only alter the biogeochemistry but also reduce ecological resilience, making freshwater ecosystems more vulnerable to future drought cycles. Furthermore, the resulting re-evaluation of how urban streams are managed in the context of climate extremes and increasing landscape artificiality.

Traditional stormwater drainage systems, based on 'grey' infrastructure, are insufficient to effectively manage stormwater, resulting in increased surface runoff, soil erosion, and deterioration of surface water (Boukalová et al., 2020; Li et al., 2019). The increase in extreme weather events is forcing the search for new and more effective solutions to treat stormwater, especially in urbanised areas, where there is a greater risk associated with rapid surface runoff and the accumulation of pollutants (Matos and Roebeling, 2022).

Drought significantly threatens surface water quality, especially in urban environments where intensive urbanisation reduces natural retention and infiltration processes (Payus et al., 2020). A prolonged lack of rainfall results in reduced flows in rivers and streams, leading to concentrations of pollutants such as heavy metals, nutrients, and organic matter. Lower water levels also contribute to an increase in the temperature of receiving waters, which can exacerbate eutrophication and a decrease in dissolved oxygen, thus worsening living conditions for aquatic organisms (Agarwal and Bharat, 2023; Bak and Barjenbruch, 2022). In cities, drought affects the decline in groundwater levels, which in turn contributes to higher surface temperatures and increased water demand among residents, and hinders the functioning of green infrastructure (Jakubowicz et al., 2022; Wojciechowska et al., 2015; Zhang et al., 2020). In this context, drought not only worsens environmental conditions but also puts pressure on urban water management systems, reducing their resilience to climate change (Kasprzyk et al., 2022; O'Donnell et al., 2020; Oral et al., 2020).

Climate change is further intensifying the phenomenon of 'urban stream syndrome', which describes the degradation of river ecosystems in urbanised areas. The increase in stormwater infiltrating urban watercourses contributes to reduced biodiversity and hydrological destabilisation of watercourses (Hale et al., 2016). In addition, stormwater transports large amounts of pollutants, including heavy metals, nutrients, microplastics, pharmaceuticals, and other emerging pollutants that can accumulate in water bodies, causing harmful ecological effects (Balu et al., 2023; Li et al., 2019). The treatment of stormwater is therefore becoming a key challenge in climate change adaptation, as inadequately managed stormwater can lead to degradation of surface water quality, eutrophication, and loss of biodiversity (EEA, 2014; Boukalová et al., 2020; European Environment Agency, 2015; Hale et al., 2016).

Nature-based solutions (NbS) such as wetland systems and green infrastructure are being developed in response to these challenges (Stefanakis et al., 2021). These technologies can effectively retain, infiltrate, and treat stormwater before it enters river ecosystems. Examples of effective applications include rain gardens, which contribute to water retention and infiltration, reducing peak loads on wastewater systems and improving surface water (Bak and Barjenbruch, 2022). The use of bioretention in many cities around the world has contributed to significant reductions in surface runoff, an example of effective adaptation to climate change (Li et al., 2019). Mathematical models show that NbS can significantly improve surface water quality, even in the context of future climate change (Matos and Roebeling, 2022).

With further climate change projected, the integration of nature-based solutions into stormwater management becomes essential to ensure the long-term resilience of cities and the protection of aquatic ecosystems (Stefanakis et al., 2021). In addition to hydrological benefits, NbS can support biodiversity conservation and improve urban microclimates, making them integral to sustainable urban development (Bak and Barjenbruch, 2022).

Constructed wetlands (CW), increasingly referred to as treatment wetlands (TW) systems, are one of the key nature-based solutions used to treat wastewater, stormwater, and protect aquatic ecosystems (Dotro et al., 2017). Their growing importance is due to their ability to mimic the natural processes of wetland ecosystems, enabling effective water treatment in a sustainable and environmentally friendly manner. In this study, we retain the designation CW to emphasize their engineered origin and distinction from natural wetland systems.

Constructed wetlands use physical, chemical, and biological mechanisms such as filtration through soil layers, adsorption of pollutants, and biochemical degradation of organic matter by microorganisms with different trophic preferences. Through these processes, constructed wetlands can efficiently remove a wide range of pollutants, including organic matter, nutrients (nitrogen, phosphorus), heavy metals, and microorganisms (Regelsberger et al., 2020). Long-term studies show that CWs can effectively remove up to 89% of total nitrogen and 98% of phosphorus from landfill leachate (Waara and Wojciechowska, 2019).

One of the main strengths of wetland systems is their versatility. They can be used to treat different types of wastewater, including municipal wastewater, industrial wastewater, landfill leachate, and stormwater. They are exceptionally effective in removing nutrients to reduce eutrophication of surface water, as well as in managing stormwater in the context of changing climatic conditions (Vymazal, 2011).

Constructed wetland systems are also an important component of a circular economy, as they support the recovery of resources such as water, nutrients (e.g., nitrogen and phosphorus), and organic matter. As a result, they can be used for irrigation and improving soil conditions in agriculture, which fits in with the concept of sustainability (Masi et al., 2018).

In addition to their role in water purification, constructed wetland systems also have a significant positive impact on biodiversity. The creation of wetlands in the urban environment promotes the development of habitats for different species of flora and fauna, which supports the recovery of ecosystems degraded by human activities. In the context of climate change, they additionally act as retention systems that prevent flooding and mitigate the effects of heavy rainfall (Stefanakis et al., 2021). This study aims to review possible nature-based solutions applicable for urban stream restoration and improvement of urban stormwater quality before discharge into receiving waters. This review focuses on:

- identifying effective treatment systems that enhance stormwater quality by removing key pollutants;
- supporting aquatic ecosystem protection through pollutant load reduction;
- promoting biodiversity by integrating habitat-enhancing nature-based solutions;
- reducing the risk of eutrophication through nutrient management;
- highlighting the role of resilient stormwater treatment strategies in adapting to changing climatic conditions.

Furthermore, the study aims to synthesize existing knowledge to support developing sustainable, resilient, and ecologically beneficial urban water management practices.

DEGRADATION OF URBAN WATERCOURSES

Degradation of streams in urbanised areas refers to a set of typical negative changes observed in rivers and small watercourses exposed to intensive land-use changes. These alterations are reflected in both the physical structure and ecological functioning of the streams. As urbanisation increases, watercourses experience a range of changes in hydrology, morphology, water quality, and biodiversity (Booth et al., 2016). Hydromorphological changes to a watercourse often occur as a result of catchment modifications, including channel regulation, bank reinforcement, partial or complete stream development, and the removal of floodplain terraces. Channel regulation, which usually involves straightening the course of the channel, eliminating natural meanders, buffer zones, and increasing the gradient of the bed to accelerate water runoff, especially in urban areas, leads to serious consequences. The acceleration of stormwater runoff from the catchment and the reduction in channel capacity, is associated with a reduction in the ecological and functional quality of streams and rivers in urban areas (Ladson et al., 2007; Lewicki, 2015; Walsh et al., 2005; Walsh et al., 2005).

Stormwater in a natural, non-urbanised catchment, which normally infiltrates deep into the ground and slowly makes its way into rivers and streams, is discharged directly into watercourses. This results in more rapid and frequent flows in the watercourses, leading to degradation, including channel erosion, bank destabilisation, and reduced water retention, as well as changes in aquatic ecosystem structure, leading to the disappearance of sensitive species (Askarizadeh et al., 2015; Booth et al., 2016). Urban streams are often characterised by rapid, short-term increases in flows, especially during times of intense rainfall, which adds to their instability (Roy et al., 2009; Walsh et al., 2004; Walsh, Fletcher, et al., 2005; Walsh, Roy, et al., 2005).

Urbanisation primarily affects hydrology through the introduction of large amounts of impervious surfaces such as roads, pavements, and building roofs. These surfaces contribute to an increase in the amount and rate of surface runoff, reducing water infiltration into the ground and disrupting natural hydrological processes (Booth et al., 2016; Ladson et al., 2007; Loperfido et al., 2014). These processes have the effect of simplifying the physical structure of watercourses, which in turn reduces the availability of diverse habitats, especially for organisms associated with different flow types, such as fish species that prefer areas with calmer flows or riparian vegetation (Hale et al., 2016; Kominkova, 2013; Ladson et al., 2007).

Hydromorphological changes also affect the self-purification capacity of waters, which is one of the key elements in the functioning of river ecosystems. Under natural conditions, watercourses can retain and decompose organic and mineral pollutants due to their appropriate structure, thus maintaining high water quality. As a result of intensive erosion and simplification of the river bed and bank structure, the contact area between water and the ground is reduced, which limits the effectiveness of self-purification processes. Impermeable surfaces affect the rapid run-off of water, which reduces the residence time of water in the system, limiting the potential for pollution reduction and suspended solids deposition (Booth et al., 2016; Hale et al., 2016; Kominkova, 2013).

Another critical aspect is the deterioration of water quality. Urban surface runoff carries a complex mixture of pollutants, including heavy metals, organic matter, microplastics, nutrients, and microbiological contaminants. Elevated concentrations of these substances have adverse effects on aquatic ecosystems, leading to reduced biodiversity and increased water toxicity. Organic pollution often results in oxygen depletion and altered redox conditions in the aquatic environment, which may remobilize metals and other pollutants from sediments, thereby increasing their bioavailability. Low dissolved oxygen concentrations further exacerbate the toxic effects of pollutants on aquatic biota. The behavior and distribution of contaminants are also influenced by hydrodynamics, biogeochemical processes, and environmental parameters such as salinity, temperature, and sediment particle size (Kominkova, 2013). In urban streams, toxic metals and other priority pollutants can be more readily assimilated by aquatic organisms. Pollutant concentrations in sediments often exceed those in the water column by three to five orders of magnitude (Bryan and Langston, 1992; Kominkova and Nabelkova, 2007). Higher levels of suspended solids enhance the risk associated with the presence of toxic substances, such as heavy metals and polycyclic aromatic hydrocarbons (PAHs). Runoff from roads and agricultural areas introduces nitrates, nitrites, and sulfates, altering the hydrochemical balance of water and increasing the levels of carcinogenic PAHs, which are toxic to zooplankton (Kominkova, 2013).

Extended dry periods promote the accumulation of pollutants on impervious surfaces, which are rapidly flushed into watercourses during heavy rainfall events. These dynamics have direct impacts on aquatic ecosystems, which are highly sensitive to oxygen deficits and rapid chemical fluctuations. For aquatic organisms, reduced water quality translates into a loss of suitable habitat and diminished adaptive capacity, ultimately leading to population declines and reduced biological diversity (Kominkova, 2013; Wantzen et al., 2019). Pollution- and hydrology-sensitive species are gradually replaced by more tolerant taxa, resulting in a marked decline in biodiversity (Booth et al., 2016; A. R. Ladson et al., 2007; Roy et al., 2009; Walsh, Roy, et al., 2005).

Biodiversity loss in urban aquatic ecosystems also reduces their resilience to environmental changes. The loss of habitat heterogeneity and species diversity diminishes the capacity of ecosystems to recover from disturbances such as abrupt flow variations or pollutant surges. Consequently, these systems become more vulnerable to degradation caused by extreme weather events and increasing anthropogenic pressures, posing a major challenge for urban water management in the face of accelerating global urbanization and climate change (Booth et al., 2016; Hale et al., 2016; T. Ladson et al., 2007).

WATER QUALITY

Key pollutants

Stormwater runoff from urbanised areas carries a wide range of pollutants that can significantly affect surface water quality and the health of aquatic ecosystems. These pollutants are mainly of anthropogenic origin, and their type and concentration are closely related to human activities such as traffic, industrial activities, and urban development. The most important groups of pollutants that predominate in stormwater are described in detail below (Table 1).

Total suspended solids

Total suspended solids are one of the most important parameters characterising stormwater quality and are crucial in the context of pollutant transport. Suspended solids are fine particles of solid matter that, depending on the velocity of the water flow, can remain in suspension or undergo straining and sedimentation. Suspended solids mainly originate from anthropogenic activities, especially in areas of intensive urban development and in industrial regions. These particles can result from the erosion of road surfaces, buildings, and open areas, as well as from the abrasion of vehicle tyres and brakes, which introduce metal fines and dust into the environment. Suspended solids are common in surface runoff, and their concentration increases with the intensity of road and industrial traffic (Gasperi et al., 2022). Due to their large surface area and chemical properties, they can adsorb heavy metals such as zinc, copper, lead, or cadmium, as well as organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). Heavy metals that are associated with suspended solids can be transported over considerable distances, increasing their range and impact on aquatic ecosystems (Eriksson et al., 2007; Gong et al., 2016; Zuraini et al., 2018). In urban runoff, suspended solids can also transport contaminants in the form of microplastics, which are difficult to remove and harm aquatic organisms (Werbowski et al., 2021).

Nutrients

Nutrients such as nitrogen and phosphorus are key pollutants of stormwater, particularly in urban and agricultural areas. The main sources of these pollutants are agricultural fertilisers and surface runoff from urbanised areas, including roads and car parks. Excess of these nutrients leads to eutrophication, i.e. excessive growth of algae and aquatic plants, which in turn lowers the oxygen content of the water, causing the death of aquatic organisms and the formation of dead zones (Li et al., 2015). Nutrients are difficult to remove, but treatment systems such as bioretention and constructed wetlands can effectively reduce their concentrations through biological processes (Aryal et al., 2010).

Microbiological contaminants

Microbiological contaminants in surface runoff include mainly faecal indicator bacteria such as E. coli, Enterococci, and other coliforms. Their sources are mainly animal faeces, sanitary wastewater and pollution from households. Stormwater from urban areas, especially from roofs, roads and car parks, can transport these microorganisms into water systems, posing a threat to public health and aquatic ecosystems. Studies indicate that levels of bacteria such as *E. coli* and Enterococci in surface runoff can vary significantly depending on rainfall intensity and population density (Clary and Leisenring, 2020).

Heavy metals

Heavy metals (Table 2), such as zinc (Zn), copper (Cu), lead (Pb), and cadmium (Cd), are commonly present in stormwater runoff from urban areas. They are mainly the result of anthropogenic activities such as tyre wear, brake abrasion, and corrosion of road infrastructure components (Aryal et al., 2010; Eriksson et al., 2007). These metals are adsorbed onto suspended solids, which increases their mobility and potential for long-distance transport in stormwater. In addition, studies highlight that areas with heavy traffic are particularly prone to high concentrations of these pollutants, requiring special attention when planning stormwater management in such locations (Gasperi et al., 2022).

Emerging pollutants

Emerging pollutants (micropollutants) are a group of chemical compounds that appear in the aquatic environment in very low concentrations

Table 1. Concentration ranges of pollutants in surface runoff

Type of pollutant	Range of values	Reference
Total suspended solids (TSS)	1–40 000 mg/L	(Chocat et al., 2007; Garbarczyk, 2005; Grabarczyk and Gwoździej-Mazur, 2005)
Total dissolved solids (TDS)	38–670 mg/L	(Clary and Leisenring, 2020)
Chemical oxygen demand (COD)	20–1 500 mg/L	(Chocat et al., 2007; Garbarczyk, 2005; Grabarczyk and Gwoździej-Mazur, 2005)
Biological oxygen demand (BOD)	0.7–500 mg/L	
Total nitrogen (TN)	1–10 mg/L	(Aryal et al., 2010; Chocat et al., 2007; Garbarczyk, 2005; Grabarczyk and Gwoździej-Mazur, 2005)
Total phosphorus (TP)	0.05–1 mg/L	
Escherichia coli	48–26 500 MPN/100 mL	(Clary and Leisenring, 2020)
Enterococci	178–24 100 MPN/100 mL	
Coliform bacteria	132–155 000 cfu/100 mL	

Table 2. Concentration ranges of heavy metals in surface runoff

Type of pollutant	Range of values (μg/L)	Reference
Zinc (Zn)	36–932	(Gasperi et al., 2022)
Copper (Cu)	15–570	
Lead (Pb)	5.3–98	
Cadmium (Cd)	0.05–37	
Cobalt (Co)	0.3–6.5	
Arsenic (As)	0.5–2.8	(Clary and Leisenring, 2020)
Chromium (Cr)	1.2–11.8	(Clary and Leisenring, 2020)

(often in the nanogram to milligram per litre range), but can nevertheless have significant impacts on the health of ecosystems and organisms, including humans (Table 3). In the context of surface runoff in urban environments, micropollutants such as microplastics, phthalates, PFASs (per- and polyfluoroalkylated compounds), PAHs (polycyclic aromatic hydrocarbons) and PCBs (polychlorinated biphenyls) pose a significant threat to aquatic ecosystems (Aryal et al., 2010; Gasperi et al., 2014, 2022; Jakubowicz et al., 2022; Miksch et al., 2016; Wicke et al., 2021). They occur at low concentrations, but their toxicity, bioaccumulation capacity, and long-term persistence in the environment make them difficult to remove from stormwater. Studies indicate that their presence in surface runoff is mainly related to industrial and transport activities, highlighting the need for advanced treatment methods and environmental regulations (Lei et al., 2021; Walaszek et al., 2018).

Organic compounds

Organic compounds such as PAHs, PCBs, and phthalates are important pollutants of stormwater surface runoff (Aryal et al., 2010; Eriksson et al., 2007; Gasperi et al., 2022). The sources of PAHs are mainly fossil fuel combustion processes, such as vehicle emissions and industrial heating installations. PCBs and phthalates, on the other hand, are commonly used in the chemical industry as flame retardants and plasticisers. These compounds, like heavy metals, have the ability to adsorb onto suspended solids, which significantly affects their mobility in the aquatic environment.

Microplastics

Microplastics are fine plastic particles smaller than 5 mm that are increasingly detected in urban surface runoff (Venghaus and Barjenbruch, 2017; Wang et al., 2021). In a study by (Werbowski et al., 2021), microplastics were found to be a common pollutant in urban precipitation runoff, with the main sources being tyre wear, rubber particle fragments and synthetic fibres from textiles. It was emphasised that these pollutants are transported in large quantities during rainfall, especially during the first phase of runoff. The highest concentrations of these pollutants were observed in areas with high traffic, highlighting the impact of transport activities on their presence (Treilles et al., 2021). A study (Stang et al., 2022) highlighted that microplastics can be difficult to remove in wetland systems because their small size allows them to pass through filters and physical barriers. Furthermore, smaller microplastic particles (< 100 μm) are particularly problematic because they are more mobile and can more easily enter the aquatic environment, where they can affect aquatic organisms.

Table 3. Concentration ranges of emerging pollutants in surface runoff

Type of pollutant	Unit	Range of values	Reference
Microplastics	particles/m^3	270–22 894	(Hitchcock, 2020; Liu et al., 2019; Olesen et al., 2019; Padervand et al., 2020)
Phthalates	μg/L	0.1–78	(Gasperi et al., 2022)
∑19 PFAS	ng/L	2.0–105	(Gasperi et al., 2022; Munoz et al., 2018)
∑16 PAH	ng/L	1.0–8 000	(Gasperi et al., 2022; Zgheib et al., 2012)
∑7 PCB	ng/L	256–727	(Zgheib et al., 2012)

MITIGATION STRATEGIES

Constructed wetlands are engineered systems that mimic the natural processes of the soil and water environment by mimicking the hydraulic and habitat characteristics of wetland ecosystems (Dotro et al., 2017; Gajewska, 2019; Gajewska et al., 2010; Gajewska and Obarska-Pempkowiak, 2009; Kadlec and WalaceWallace, 2009; Langergraber et al., 2019). Due to field demand, they were initially used mainly in rural areas as domestic wastewater treatment plants. Over time, their use was also extended to the treatment of agricultural runoff, industrial wastewater, landfill leachate, and wastewater from agri-food processing plants (Vymazal, 2005, 2011, 2022; Walaszek et al., 2018).

Constructed wetland systems are based on several key elements related to the hydraulic regime, the type of deposits, and the presence of vegetation (macrophytes). Water flows through the beds either surface or subsurface (vertically or horizontally) and contacts the infill material, such as sand or gravel, which has adequate permeability and sorption capacity. Macrophytes, i.e., plants rooted in the substrate or floating on the water, assist the treatment process through their ability to absorb and transform organic matter and some pollutants (Gajewska, 2019; Langergraber et al., 2019; Saeed and Sun, 2012).

CW systems mimic the natural filtration and biochemical degradation processes occurring in wetlands and coastal zones. The fundamental aim is to use physical, chemical, and biological interactions to effectively treat wastewater. These systems can be used to treat both domestic and industrial wastewater as well as rainfall runoff, making them a flexible and environmentally friendly engineering solution (Dotro et al., 2017; Gajewska, 2011; Gajewska and Obarska-Pempkowiak, 2011; Kadlec and Walace, 2009; Walaszek et al., 2018; Walsh et al., 2004).

The design and technology of constructed wetland systems are still being researched and developed both on a real and pilot scale. Currently, the most common systems are surface flow and subsurface vertical and horizontal flow systems, which use complex unit processes to treat a wide variety of wastewater and water types. Vymazal, (2022) conducted an extensive review on the applications of constructed wetland systems. Constructed wetlands, despite their effectiveness in removing many pollutants, require careful design and maintenance. Regular inspection and maintenance are crucial to prevent clogging, which can significantly reduce treatment efficiency (Dotro and Chazarenc, 2014).

CW can remove various pollutants through well-established physical and biological processes, extensively documented in scientific literature (Dotro et al., 2017; Kadlec and Walace, 2009; Langergraber et al., 2019; Sharma et al., 2021; Tanner and Headley, 2011). Filtration and sedimentation enable the retention of suspended solids within the porous substrate. At the same time, microbial degradation of organic matter occurs in a wide range of redox potential, thus in microzones of both aerobic and anaerobic conditions. Nitrogen is removed via coupled nitrification-denitrification processes. Phosphorus is retained by adsorption onto the substrate and partly assimilated by vegetation. Heavy metals are retained mainly by adsorption on particle surfaces and by their reaction with organic and mineral substances present in the deposit.

MITIGATION MEASURES – CASE STUDIES

Nature-based solutions (NbS) have gained increasing attention as effective and sustainable approaches for improving water quality, enhancing ecosystem services, and providing additional social and environmental benefits in urban landscapes. In the context of degraded urban watercourses – characterized by hydrological alteration, pollutant accumulation, and ecological degradation – NbS offers a suite of strategies that can supplement or restore natural purification processes within highly modified catchments. Numerous NbS typologies can be applied depending on local conditions and water quality objectives. In many cases, combinations of various elements are integrated into multifunctional systems to support pollutant retention, flow regulation, and habitat enhancement in degraded urban streams.

This section presents selected case studies illustrating practical implementations of NbS for the treatment of surface water and stormwater. The examples represent diverse geographic and climatic contexts, but share the common goal of supporting ecological function and water quality in urban watercourses. Key characteristics, targeted pollutants, and observed treatment performances are summarized to facilitate comparative analysis. Table 4 provides an overview of the main system features and outcomes.

Floating treatment wetland (FTW) for surface water (Durham, NC, USA)

To test whether FTWs provide nutrient and total suspended solids removal benefits, they were installed in two ponds in Durham. At the end of March 2010, FTWs were installed as retrofits in both the Museum and DOT ponds (Figure 1). The FTWs act as a hydroponic system in which plants and microorganisms in the plant root system extract nutrients from stormwater. The facility improves the ecosystem above the water table, while the roots are provided with a wetland habitat. In addition, the systems take up excess nutrients from agricultural land. They minimise algal blooms and dead zones. Research indicates that they can be used to reduce the amount of man-made pollution that persists in the environment. The dominant plant species established in the system include Carex stricta, Juncus effusus, and Spartina pectinate (Hunt et al., 2012).

Floating treatment wetland (FTW) for surface water (Fairfax, NC, USA)

This project adapted a standard water quality upgrade to a wet pond on Ashby Road in Fairfax, Virginia, to evaluate FTWs as a potential new treatment technology (Figure 2). FTWs improve water quality by removing nutrients through uptake by plants, microorganisms and increased sedimentation. Four variants with three replicates, were used to assess the impact of floating islands and different plant species in a mesocosm experiment. The four variants included: control trial, floating island without vegetation, water arrow, and soft rush (Sample et al., 2013). Floating islands allow for water purification. Furthermore, it is a facility that enhances the biodiversity of the town of Fairfax. It allows for ecotourism and recreation. In addition, it is a frequent destination for school trips (Sample et al., 2013).

The values achieved are lower than the accepted standards for total phosphorus (50%) and total nitrogen (50%) currently in place for floating islands according to the Virginia Stormwater BMP Clearinghouse (Virginia Department of Environmental Quality 2013). The dominant plant species established in the system include *Pontederia cordata L.*, *Schoenoplectus tabernaemontani.*

Floating treatment wetland (FTW) for surface water (London, England)

BioHaven floating island at Hyde Park, as part of the Royal Parks' wildlife habitat improvement programme, a large FTW floating island has been constructed on Serpentine Lake in London's Hyde Park (Figure 3). Ecologists and landscape architects worked with Salix bioengineers to install the 200 m^2 island in the southern part of the lake to naturally clean the water. FTW on Serpentine helps to improve water quality in a chemical-free way and provide habitat and food

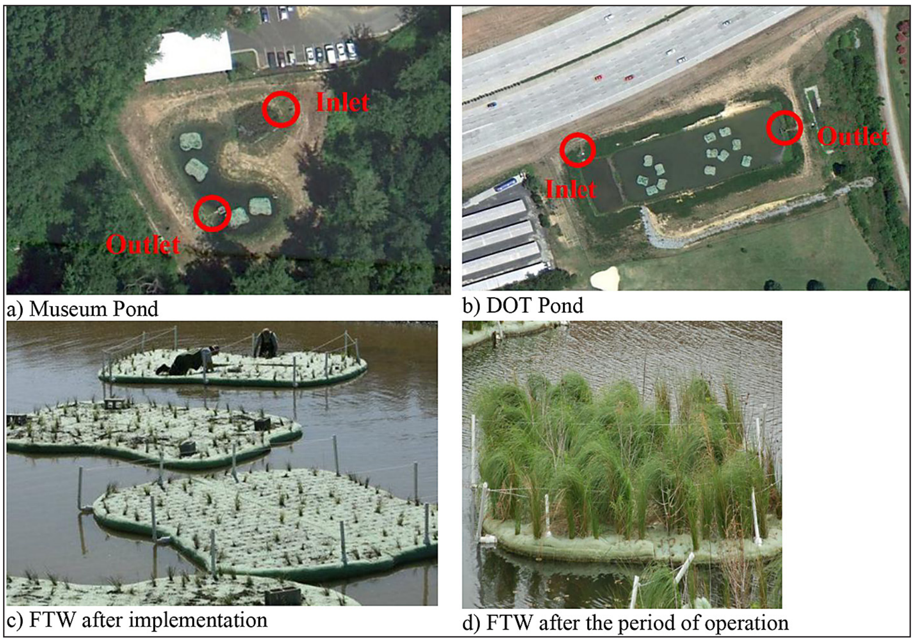

Figure 1. Floating treatment wetland (FTW) for surface water (Durham, NC, USA) (Hunt et al., 2012)

a) FTW after the period of operation b) FTW after the period of operation

Figure 2. Floating treatment wetland (FTW) for surface water (Fairfax, NC, USA) (Sample et al., 2013)

for a variety of wildlife, including insects, waterfowl and amphibians. The facility has rapidly improved the area of habitat provided, which in turn has increased biodiversity. The root systems of plants on the floating islands also recycle excess nutrients in polluted waters. This improves water quality and wider aquatic habitats for insects and fish (Salix, 2014b). FTW mimics the environmental benefits of wetlands in the natural world. Downstream, micro-organisms will naturally accumulate to form a biofilm on the island's surface, cleaning the water and providing food for zooplankton, micro and macro invertebrates such as dragonfly nymphs and snails, and further upstream, food for fish.

Buffer zones for surface water (Dublin, CA, USA)

The Tassajara Creek restoration involved the construction of a dual low-flow channel system with vegetated floodplain terraces (Figure 4). The project replaced a traditional flood control design with a nature-based approach, integrating native plantings to stabilize banks and support ecological functions. The design was developed in collaboration with the California Department of Fish and Wildlife, the US Army Corps of Engineers, and geomorphologists from the University of California, Berkeley. Construction commenced in 1998 along a one-mile reach of the stream targeted for future infrastructure development (Kondolf and Atherton, 2013). The downstream reach of the project was reconstructed into a low-flow channel designed to convey a 2-year event (14–18 m^3/s), with overflow directed to a floodplain terrace accommodating a 100-year flood event. The facility has operated successfully since 1999, fully meeting initial project assumptions. Construction incorporated 208 cubic yards of reclaimed concrete from former military infrastructure as channel substrate, reducing landfill waste and saving approximately $18,800 in material and disposal costs.

Lake shoreline restoration and floating treatment wetland (FTW) (Cwmbran, South Wales)

The recreational lake was a popular tourist attraction and fishing spot. However, the shoreline of the reservoir was in poor condition, almost completely devoid of shoreline vegetation. Floating

a) FTW after the period of operation b) FTW after the period of operation

Figure 3. Floating treatment wetland (FTW) for surface water (London, England) (Salix, 2014b)

Figure 4. Buffer zones for surface water (Dublin, CA, USA) (Kondolf and Atherton, 2013)

islands were used to increase habitat for fish and waterfowl. To create a wide shoreline zone around the lake, pre-grown coir rolls produced and grown in-house were installed (Figure 5). A mixture of native hydrophytic plants was planted behind the coir rolls, using bare-root cuttings. Coconut pallets were placed on the shallow shelves for a quicker visual impact than the cuttings (Salix, 2014a).

Fascine reinforcement was used to elevate the coir rolls where needed. Additionally, 23 modular floating islands (3 × 3 m each) were deployed and interconnected to create an irregularly shaped island with a central open water area. Native hydrophytic plants were used throughout to enhance habitat complexity for fish and waterfowl.

Lake shoreline restoration (Porthcawl, South Wales)

The restoration of Wilderness Lake aimed to enhance water quality, stabilize degraded shorelines, and restore habitat functionality. Over 2,000 m^3 of accumulated sediment was removed using specialized dredging equipment to deepen the lake and create designated angling zones and pool areas. Excavated material was reused on-site to form shoreline shelves and islands, reducing the need for off-site disposal. Stabilization was achieved using woven geotextile fencing to construct 1-meter-deep islands and fascine reinforcement combined with coconut rolls and native shoreline plantings along 350 meters of eroded shoreline biodiversity (Figure 6). A 2-meter-wide vegetated riparian zone composed of native hydrophytic species and field wildflowers was established to enhance (Salix, 2014c).

Lake shoreline restoration (Chicago, IL, USA)

In response to prolonged shoreline erosion and environmental degradation, the Chicago Botanic Garden undertook the restoration of over 75% of its 5.7 miles of lake shoreline. The project aimed to reestablish natural habitat functions by combining innovative bioengineering techniques with ecological landscape design (Figure 7). The restored shoreline habitats effectively reduce erosion, support healthy native ecosystems, and improve lake water quality, while simultaneously providing an aesthetically appealing environment well accepted by the local community. The project also serves an educational function,

Figure 5. Lake shoreline restoration and floating treatment wetland (FTW) (Cwmbran, South Wales (Salix, 2014a)

Figure 6. Lake shoreline restoration (Porthcawl, South Wales) (Salix, 2014c)

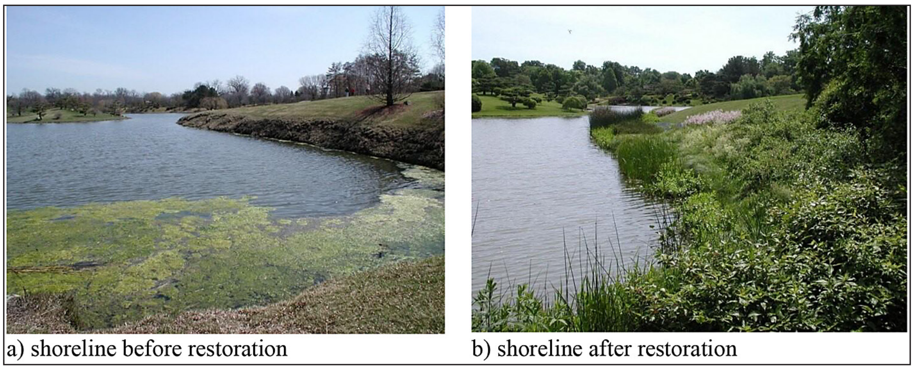

Figure 7. Lake shoreline restoration (Chicago, IL, USA) (Kinki and Whalen, 2013)

demonstrating the potential for shoreline landscapes to be both visually attractive and ecologically sustainable (Kinki and Whalen, 2013).

The project increased the diversity of shoreline vegetation from 23 to 244 species, with 100% consisting of native perennial plants. Restoration efforts created approximately 6.05 acres of new and enhanced habitat supporting at least 217 observed species, including waterfowl, shorebirds, fish, turtles, mussels, frogs, and aquatic insects, with 98% of the species being native. Habitat enhancement measures directly contributed to biodiversity recovery and water quality improvements (Kinki and Whalen, 2013).

Stormwater management facility and stream restoration (Charlottesville, VA, USA)

The Dell is an 11-acre restored landscape located at the University of Virginia, converting a formerly buried and neglected stream into a modern retention pond and pre-reservoir system. Developed as part of the Meadow Creek Stormwater Master Plan, The Dell effectively manages small to moderate stormwater events. Beyond stormwater management, the site reintroduces critical wildlife habitats, provides recreational opportunities, strengthens campus-community connectivity, and serves as a demonstration landscape featuring native Virginia plant species (Hughes and Thatcher, 2011). The Dell manages stormwater runoff from events occurring up to once every two years, with overflow directed via underground piping to a treatment facility 1.2 km downstream (Figure 8). Monitoring data confirms reductions and delays in peak flows, mitigating flash flood risks, and promoting suspended solids settling. Water quality improvements include a 30-92% reduction in total suspended solids, a 23–100% reduction in phosphate concentrations, and a −50% to 89% variation in nitrate concentrations, depending on storm conditions. Restoration efforts significantly increased wildlife habitat availability, as demonstrated by a rise in species observations post-construction (Hughes and Thatcher, 2011).

Reclamation pond for stream treatment (Durham, NC, USA)

The Duke University Water Reclamation Pond was developed to improve the ecological health of a degraded urban stream in Durham, North

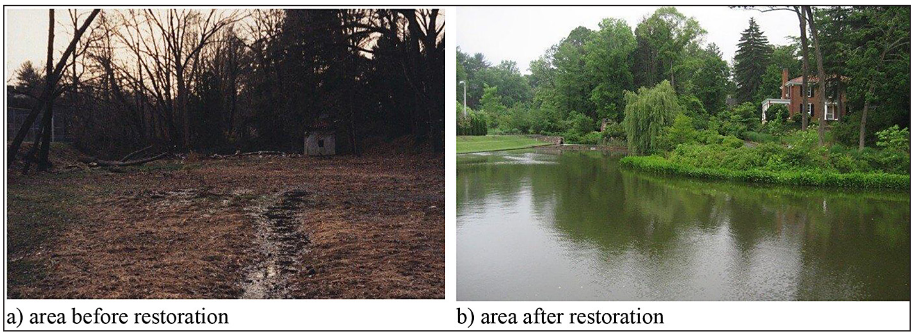

Figure 8. Stormwater management facility and stream restoration (Charlottesville, VA, USA) (Hughes and Thatcher, 2011)

Carolina. Treated stormwater from the pond flows into Sandy Creek and the Jordan Lake watershed, part of the Cape Fear River Basin, where a significant portion of streams were classified as polluted. Constructed within an ecologically degraded Piedmont forest, the project integrates a sediment trap, wetland terraces, and locally sourced materials to restore water quality, biodiversity, and hydrological functions (Figure 9) (Hogge and Pinto, 2020). The project retained 5.000 cubic yards of alluvium and 2.700 cubic yards of existing topsoil. The retention pond stores 16.4 million gallons of water at normal levels. At maximum capacity, it can hold 31.8 million gallons. It provides 85–90 million gallons of reclaimed stormwater per year, equivalent to 16% of the university's total annual potable water needs. Reduces total nitrogen by 30–100%, total phosphorus by 11–100% and total suspended solids by 77–100% during a typical rainfall event, comparing water flowing into and out of the pond. It stores and slows down surface runoff even in a storm lasting 24 hours and occurring once every 500 years. The total discharge rate during the 10-year storm has been reduced by 720 cubic feet per second, or 40% compared to pre-construction projections (Hogge and Pinto, 2020). Ecological enhancements include habitat creation for at least 47 bird species, with 23 species nesting and 24 using the site as a migratory stopover (Hogge and Pinto, 2020).

Wetland restoration for stormwater management (Lincoln, New Zealand)

Te Whāriki is a residential development adjacent to Lincoln University in Canterbury, New Zealand. The project integrates the bicultural heritage of the indigenous Māori and European settlers with the region's ecological characteristics, transforming a former university-owned dairy farm into a high-value, functional residential landscape. Acting as an ecological, educational, and cultural link between the university and the nearby township, the development incorporates a connected system of wetlands, green spaces, stormwater retention systems, and pedestrian networks (Figure 10). As part of the project, historical watercourses were restored, and a new

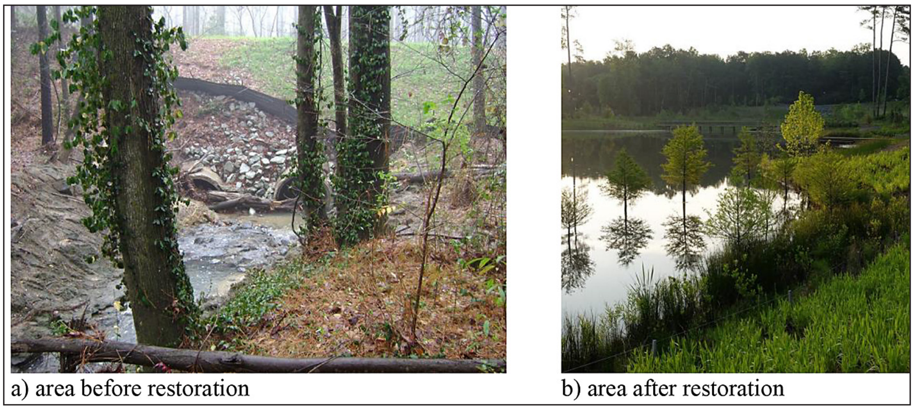

Figure 9. Reclamation pond for stream treatment (Durham, NC, USA) (Hogge and Pinto, 2020)

Figure 10. Wetland restoration for stormwater management (Lincoln, New Zealand) (Bowring and Chen, 2021)

stormwater treatment system was established to improve the water quality of Te Waihora (Lake Ellesmere), a culturally significant and heavily polluted lake due to agricultural runoff. Native vegetation was planted to recreate pre-agricultural biodiversity and provide habitats for local wildlife (Bowring and Chen, 2021).

The integrated stormwater management system captures approximately 5% of total runoff from the area, through vegetated swales and wetland zones. Annual monitoring data indicate a local reduction of approximately 10% in total nitrogen, 19% in total phosphorus, 8% in total suspended solids, and 8% in coliform bacteria concentrations downstream of the site. Biodiversity enhancements include a 400% increase in bird species richness and a 165% increase in mollusk, arachnid, and insect diversity compared to the baseline of a former dairy landscape. The system contributes to microclimate regulation, lowering residential air temperatures by an average of 1.8 °C (3.0 °F) on warm, sunny days compared to adjacent conventional residential zones. Additionally, the newly established vegetation sequesters approximately 239 tons of atmospheric carbon annually (Bowring and Chen, 2021).

Sedimentation pond and a vertical subsurface flow constructed wetland (VSSF CW) for urban stormwater runoff (Strasbourg, France)

The Strasbourg wetland system was developed to improve the quality of stormwater runoff originating from urban areas, including residential neighbourhoods. Previously, stormwater was directly discharged into the Ostwaldergraben urban stream without prior treatment. The main objective of the system was to retain and treat stormwater before its release into the environment, aiming to mitigate negative impacts such as river pollution, eutrophication, and toxicity to aquatic organisms. By effectively removing heavy metals, organic compounds, and nutrients, the system enhances water quality, supports aquatic biodiversity, and strengthens natural self-purification processes in receiving water bodies (Schmitt et al., 2015).

The treatment system consists of a sedimentation pond combined with a vertical subsurface flow constructed wetland (VSSF CW) (Figure 11). Monitoring data indicate that the system achieves removal efficiencies exceeding 90% for total suspended solids (TSS), 70–98% for chemical oxygen demand (COD), over 79% for total nitrogen (TN), and above 77% for total phosphorus (TP). The system significantly reduces pollutant loads, contributing to the protection of aquatic ecosystems and improving overall water quality downstream (Schmitt et al., 2015).

Floating treatment wetland (FTW) for stormwater runoff (Bribie Island, Queensland, Australia)

Constructed in Queensland, Australia, the Bribie Island system is a floating treatment wetland (FTW) designed to improve the quality of surface runoff from a low-density residential area covering 42.3 hectares (Figure 12). The system treats runoff from a 7.46-hectare catchment. The FTW comprises 11 interconnected floating modules, providing a treatment surface of 130 m² within a 5.048 m² pond. The primary objective of the system was to remove suspended solids and phosphorus from stormwater before discharge into receiving water bodies, thereby mitigating eutrophication risks and enhancing aquatic ecosystem health (Walker et al., 2017). The floating

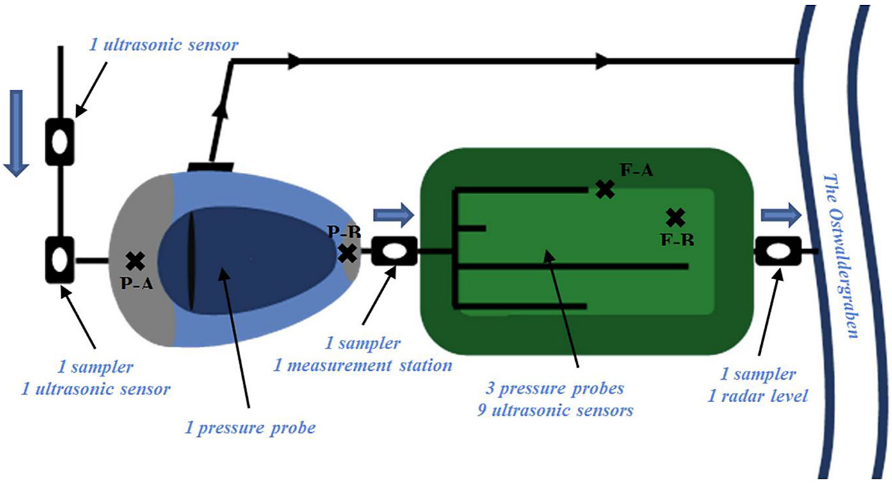

Figure 11. Sedimentation pond and a vertical subsurface flow constructed wetland (VSSF CW) for urban stormwater runoff (Strasbourg, France) (Schmitt et al., 2015)

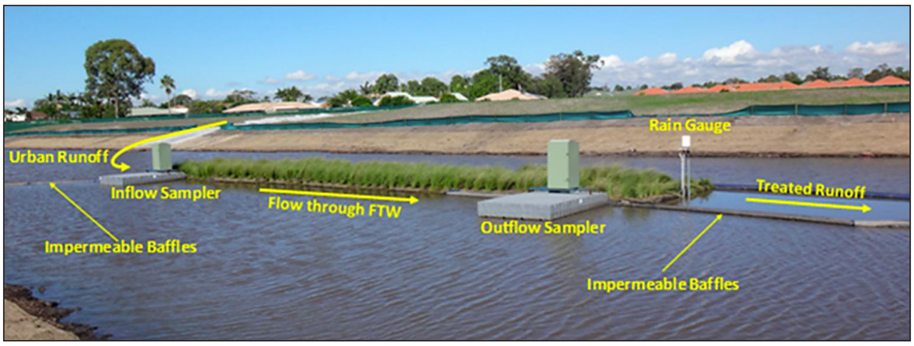

Figure 12. Floating treatment wetland (FTW) for stormwater runoff (Bribie Island, Queensland, Australia) (Walker et al., 2017)

wetland system achieved an average removal efficiency of 81% for TSS, 52% for TP, and 17% for TN, with a 47% removal efficiency specifically for nitrate (NO_3-N) and nitrogen oxides (NOx-N). In addition to pollutant removal, the system contributed to improved surface water quality and supported ecological recovery by reducing nutrient and sediment loads entering downstream aquatic environments (Walker et al., 2017).

Naturally vegetated ditch (an overflow from a fishpond that is fed only by drainage waters from adjacent agricultural fields) (Bohemia, Czech Republic)

A vegetated drainage ditch located in south-central Bohemia serves as an example of NbS applied to improve water quality in agricultural landscapes. The ditch collects overflow water from a nearby fish pond, which is supplied by subsurface agricultural drains. Naturally colonized by hydrophytic vegetation, the system enhances nutrient retention, promotes sedimentation, and provides habitat for aquatic organisms, thus supporting local biodiversity. The design demonstrates the potential for integrating simple vegetated structures into various agricultural settings to mitigate runoff pollution. The drainage ditch is vegetated with *Phragmites australis*, *Typha latifolia*, and *Glyceria maxima*, supporting key ecosystem processes such as nutrient uptake and flow reduction. The monitored floodplain area covers approximately 360 m², with water depths ranging from 5 to 15 cm and flow rates between 0.51 and 0.55 L/s throughout the year (Vymazal and Březinová, 2018).

Water quality improvements recorded include a 38.3% reduction in TN in 2015 and a 52.6% reduction in 2016, with an average annual nitrogen removal rate of 1070 kg N/ha/year, primarily through denitrification (804 kg N/ha/year). TP concentrations decreased by 52.6% in 2015 and

51.3% in 2016, with an annual removal of 142 kg P/ha/year, with plants accounting for 14% of phosphorus uptake. Biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) decreased by approximately 48%, corresponding to annual removals of 1150 kg BOD_5/ha/year and 7000 kg COD/ha/year. Total suspended solids (TSS) content decreased by 86% in 2015 and 76% in 2016, with an annual reduction of 20,437 kg TSS/ha/year (Vymazal and Březinová, 2018). The system's high removal efficiencies are comparable to constructed wetlands, with optimal performance linked to shallow water depths (5–15 cm), dense vegetation, and low water flow velocities. Regular maintenance, including biomass harvesting, is necessary to sustain treatment performance over time (Vymazal and Březinová, 2018).

Surface flow constructed wetland for agricultural drainage water (Bologna, Italy)

A FWS constructed wetland located in northern Italy was designed to treat agricultural drainage water on an experimental farm managed by the Canale Emilia-Romagna Consortium (Figure 13). Operational since 2000, the system treats runoff from a 12.5-hectare farm cultivating fruits, vegetables, and grains. The FWS wetland simulates natural hydrophytic processes through a series of meanders, supporting nutrient removal and water quality improvement while also providing ecosystem services and wildlife habitat (Langergraber et al., 2019; Lavrnić et al., 2018). The wetland is approximately 470 meters long, 8–10 meters wide, with a total water capacity of about 1.500 m³ and a maximum

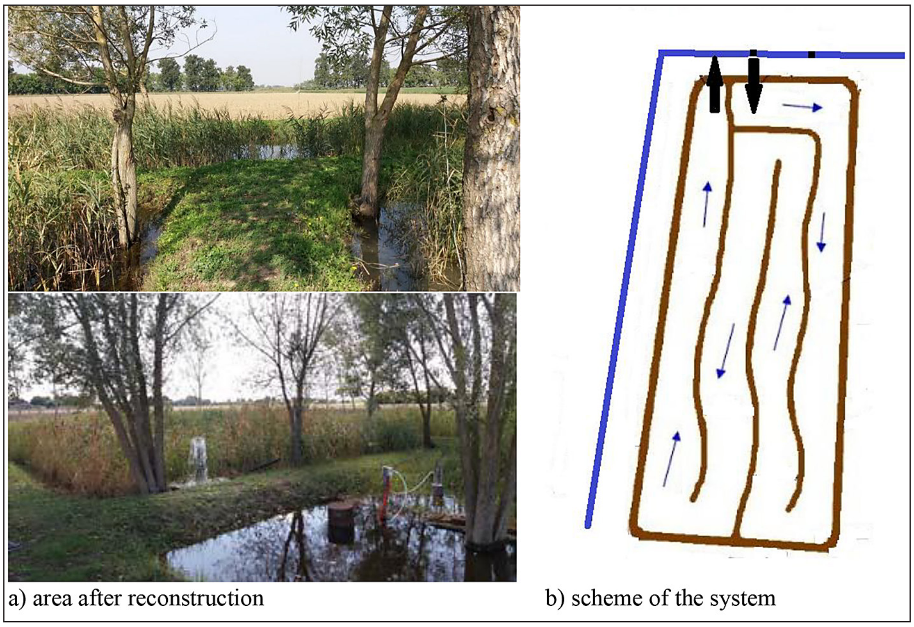

Figure 13. Surface flow constructed wetland for agricultural drainage water (Bologna, Italy) (Langergraber et al., 2019; Lavrnić et al., 2018)

Figure 14. Multifunctional water reservoir (MWR) (Ljubljana, Slovenia) (Langergraber et al., 2019)

water depth of 0.4 meters, covering around 3% of the farm area. Water is pumped from a drainage ditch and flows through the system by gravity, with excess water discharged into a nearby canal. Due to the unsealed nature of the system, water losses occur through infiltration and evapotranspiration, particularly during summer months. Vegetation includes Phragmites australis, Typha latifolia, Typha angustifolia, and occasional plantings of Salix alba and Populus alba for biomass production (Langergraber et al., 2019; Lavrnić et al., 2018).

Long-term monitoring (2003–2017) demonstrated an average reduction of about 50% in TN and TP loads, with variability influenced by seasonal conditions and inflow characteristics. Heavy metals such as Cu and Zn were predominantly accumulated in plant roots and upper soil layers, minimizing bioaccumulation risk in aboveground biomass. Annual inflows varied from 8.400 to 19,500 m^3/year, while outflows ranged from 750 to 9.500 m^3/year, with infiltration and evapotranspiration accounting for significant water losses, especially during the summer period. The highest flows in the system were recorded in autumn and winter (October-December), which was related to precipitation. Runoff flows were much lower in years with low inflows to the system, leading to water accumulation in the system. Nutrient retention was closely linked to water retention times and hydrological conditions. Additional benefits include improved soil organic matter content and carbon sequestration, alongside the provision of habitat for birds, amphibians, and aquatic organisms (Langergraber et al., 2019; Lavrnić et al., 2018).

Multifunctional water reservoir (MWR) (Ljubljana, Slovenia)

The multifunctional water reservoir (MWR) in Ljubljana, Slovenia, represents an integrated water management approach aimed at improving the quality and reuse of urban stormwater (Figure 14). The system treats a mixture of river water, urban runoff, and septic tank overflows, combining retention, ecological restoration, and recreational functions. Implemented in two phases (2006 and 2014), it integrates a sedimentation pond, a vegetated drainage channel (constructed wetland with horizontal flow), and a new meandering riverbed, embedded within a flood protection reservoir. The project addresses multiple objectives, including flood mitigation, pollutant load reduction, enhancement of urban biodiversity, and provision of recreational and educational spaces for the local community (Langergraber et al., 2019). Designed for a flow of 173 m^3/day and a flood event with a 10-year return period, the MWR system promotes sedimentation, nutrient removal, and habitat creation. The drainage channel is divided into three vegetated compartments filled with sand and gravel layers of varying particle sizes, sealed with geomembranes, and planted with *Phragmites australis*. A diverse native vegetation was planted along the riverbanks, including *Typha latifolia, Juncus effusus, Carex* spp., and *Iris pseudacorus*. Further from the waterline, trees and shrubs such *Salix spp., Corylus avellana, Alnus glutinosa*, and *Quercus robur* were established. Regular maintenance is required to prevent the reduction of retention capacity due to sediment accumulation and excessive vegetation growth.

Monitoring results show average removal efficiencies of 68% for NO_3-N, 40% for TN, 7% for NH_4-N, 9% for BOD_5, and 3% for TP. Slight increases were observed for TSS and COD in the final discharge. The vegetated drainage channel was particularly effective in removing NH_4-N (38%) and NO_3-N (63%); however, these parameters increased again in the newly created meandering riverbed. In contrast, the new river channel demonstrated greater efficiency in removing TP (10%) (Langergraber et al., 2019). Although the overall system performance should be evaluated not only based on pollutant removal rates but also on the significant ecosystem services it provides. These include water flow regulation, flood mitigation, water quality improvement, carbon sequestration, habitat creation for amphibians and birds, and provide recreational and educational opportunities. Performance evaluation emphasizes both pollutant removal and broader ecological benefits (Langergraber et al., 2019).

CONCLUSIONS

Effective surface runoff from rainfall is characterized by high variability in both pollutant loads and water volume. Runoff from roads and highways carries relatively high loads of heavy metals and hydrocarbons, while runoff from urban areas is characterized by significant microbiological pollution, such as that caused by animal feces, and sometimes high organic loads resulting from littering and cleaning of streets and markets.

Table 4. Overview of characteristics and performance of case studies applying nature-based solutions for pollutant removal and ecosystem enhancement

System type	Location	Climate (Köppen)*	Year of construction	Treated area	Catchment area	Pollutants and ecosystem impacts targeted	Observed performance	Reference
Floating treatment wetland for surface water	Durham, NC, USA	Cfa	2010	370 m^2 (FTW); 3 600 m^2 (FTW + surface water)	15,500 m^2	Nutrients and total suspended solids	Significant reduction in the content of all pollutants tested	(Hunt et al., 2012)
Floating treatment wetland for surface water	Fairfax, VA, USA	Cfa	2009–2013	8000 m^2	566,560 m^2	Nutrients	Values lower than the assumed standards for TP (50%) and TN (50%)	(Sample et al., 2013)
Floating treatment wetland for surface water	London, England	Cfb	2013	200 m^2	n.a.	Nutrients; biodiversity loss	Habitat and biodiversity enhancement; nutrient uptake and water quality improvement	(Salix, 2014b)
Buffer zone for surface water	Dublin, CA, USA	Cfa	1999	14 000 m^2	60 km^2	Chronic embankment erosion due to livestock grazing	Flood protection (5,200 cfs peak flow); significant reduction of chronic erosion	(Kondolf and Atherton, 2013)
Lake shoreline restoration and FTW	Cwmbran, South Wales	Cfb	2011	20 000 m^2; FTW area 207 m^2	n.a.	Shoreline and biodiversity degradation; loss of riparian vegetation; limited aquatic and avian habitat availability;	Restoration of riparian zones using coir rolls and pallets; 23 FTW to enhance aquatic biodiversity;	(Salix, 2014a)
Lake shoreline restoration	Porthcawl, South Wales	Cfb	2005	lake bottom and 350 m of shoreline	4 acres	Severe sediment accumulation; shoreline erosion; loss of riparian vegetation	Removal of over 2,000 m^3 of sediment; stabilization of banks; 2-m wide riparian zone	(Salix, 2014c)
Lake shoreline restoration	Chicago, IL, USA	Dfa	2012	3 miles of shoreline	6 acres	Shoreline erosion; habitat degradation; native biodiversity loss; poor water quality	Restoration of 75% of a 5.7-mile shoreline; increase plant species; creation of enhanced habitat	(Kinki and Whalen, 2013)
Stormwater management facility & stream restoration	Charlottesville, VA, USA	Cfa	2004	365 m of shoreline; 0,75 acres of stormwater pond	11 acres	Bank erosion; sediment transport; habitat degradation; loss of floodplain connectivity	Minimizing flood risk and bank erosion; decrease TSS: 30–92%, PO_4: 23–99%, NO_3: −50–89%	(Hughes and Thatcher, 2011)
Reclamation pond for stream treatment	Durham, NC, USA	Cfa	2015	5.5-acre pond	12 acres	Nutrients; stream degradation and sediment accumulation; flood risk; loss of aquatic and riparian habitat	Reduction of TN: 30–99%, TP: 11–99%, TSS: 77–99%; peak flow reduction during 10-year storms by 40%	(Hogge and Loaiza Pinto, 2020)
Wetland restoration for stormwater management	Lincoln, New Zealand	Cfb	Phase 1: 2017; Phase 2: 2019	16 connected wetlands (20.5 acres or 8.3 ha)	144 acres (58.4 ha)	Nutrients; surface runoff; agricultural pollution; loss of biodiversity; heat island in residential zones	Annual reduction of TN (~10%), TP (~19%), TSS (~8%), coliform bacteria (~8%); air temp reduction of 1.8°C	(Bowring and Chen, 2021)

Sedimentation pond and VSSF CW for urban stormwater runoff	Strasbourg, France	Cfb	2012	sedimentation pond (45.5 m^2) & 100 m^2 VSSF CW	18 000 m^2	Total suspended solids; organic pollutants; nutrients; heavy metals and urban runoff contaminants;	Removal: TSS >90%; COD 70–98%; TN >79%; TP >77%; reduction of toxic pollutants; biodiversity recovery	(Schmitt et al., 2015)
Floating treatment wetland for stormwater runoff	Bribie Island, Queensland, Australia	Cfa	2015	130 m^2 (11 FTW) on 5048 m^2 pond	7.46 ha	Total suspended solids; nutrients; risk of eutrophication in receiving waters	Removal : TSS: 81%; TP: 52%; TN: 17%: NO_3-N and NO_x-N: 47%; reduction of eutrophication risk	(Walker et al., 2017)
Naturally vegetated ditch	Bohemia, Czech Republic	Cfb	2014	200 m ditch	360 m^2	Total suspended solids; organic pollutants; nutrients; loss of aquatic biodiversity and habitat quality	Removal: TN: 38.3–52.6%; TP: 51.3–52.6%; BOD_5 & COD: 48%; TSS: 76–86%; biodiversity enhancement	(Vymazal and Březinová, 2018)
Surface flow CW for agricultural drainage water	Bologna, Italy	Cfa	2000	4000 m^2 (1500 m^3)	12.5 ha	Nutrients; heavy metals (Cu, Zn); organic matter; agricultural runoff	Removal: 50% TN and TP; accumulation of heavy metals (Cu, Zn) in plant roots, upper soil layers; provision of habitat	(Langergraber et al., 2019; Lavrnić et al., 2018)
Multifunctional water reservoir	Ljubljana, Slovenia	Cfb	Phase 1: 2006; Phase 2: 2014	Sedimentation basin, vegetated drainage ditch; new river bed with meanders	n.a.	Organic pollutants; nutrients; flood risk reduction and habitat loss	Removal: NO_3-N: 68%; TN: 40%; BOD_5: 9%; TP: 3%; flood protection for 10-year flood events; purification capacity and habitat biodiversity	(Langergraber et al., 2019)

Note:[*] (Kottek et al., 2006).

The main objectives of stormwater treatment are to protect surface waters from changes in bottom morphology, increased turbidity, deoxygenation, eutrophication, toxic concentrations of heavy metals, and, in some cases, microbiological contamination. Constructed wetland systems also act as hydraulic buffers and water reservoirs, protecting downstream areas from flooding. Due to the random nature of rainfall, the required storage capacity and treatment capacity are extremely variable. Pollutant concentrations often show patterns of the so-called 'first flush'.

Urban watercourses are subject to the cumulative impact of anthropogenic pressures, resulting in degraded water quality and loss of biodiversity. Among the diverse pollutants, total suspended solids remain the most critical, acting as a carrier for other contaminants such as heavy metals, nutrients, pathogens, and increasingly, microplastics. Their effective removal, therefore, plays a crucial role in improving overall water quality.

NbS, such as constructed wetlands (including vertical subsurface flow – VSSF and free water surface – FWS systems), FTWs, vegetated ditches, and shoreline buffer zones, have demonstrated high potential in this context. Their efficiency in reducing TSS often exceeds 80%, and many systems simultaneously achieve substantial removal of total nitrogen (17–99%), phosphorus (11–99%), and organic matter (as BOD_5 or COD), particularly in VSSF systems and FTWs. In addition to pollutant removal, these systems support multiple ecosystem functions, such as carbon sequestration, thermal buffering, flood regulation, and biodiversity enhancement, transforming degraded urban streams into multifunctional areas.

Despite growing interest, implementation remains constrained by institutional fragmentation, limited regulatory frameworks, and uncertainties in system design under fluctuating hydrological conditions. Further progress requires integrated planning, harmonized monitoring protocols, and greater emphasis on ecological co-benefits. Future research should prioritize performance modelling under climate scenarios and develop site-specific guidelines to support the scalable deployment of NbS in urban catchments.

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