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REVIEW

Nature-Based Water Treatment Systems: Global Progress, Performance Metrics, and Sustainability Outcomes

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ABSTRACT

Nature-based water treatment systems are becoming a promising substitute to conventional wastewater treatment technologies because of their potential to advance water quality while providing larger environmental and socio-economic benefits. This review provides a comprehensive synthesis of global performance metrics, progress, and sustainability aids linked with these systems. The study tracks a structured narrative review approach, drawing on peer-reviewed literature from the main scientific databases published primarily over the past decade. Articles were chosen based on their relevance to system typology, treatment performance, implementation context, and sustainability assessment. The review evaluates a wide range of systems, including constructed wetlands, biofiltration and bioretention systems, riparian buffers, floodplain restoration interventions, floating treatment wetlands, and hybrid nature-engineered solutions. In different climatic and socio-economic conditions, these systems establish substantial pollutant removal capability, generally obtaining organic matter and suspended solids removal efficiencies above 70–90%, nutrient reductions normally ranging from 40–80%, and variable pathogen attenuation depending on hydraulic and environmental conditions. Performance, however, is strongly influenced by design configuration, hydraulic loading, substrate properties, vegetation composition, and climatic variability. Beyond treatment effectiveness, the synthesis highlights the multifunctional sustainability outcomes of nature-based systems, including reduced energy and chemical inputs, enhanced biodiversity, climate resilience, and improved social and landscape values. By combining global execution trends with relative sustainability perspectives, this review provides new insights

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into the scalability, long-term performance, and ecosystem-service integration of nature-based water treatment systems within future resilient water management strategies.

Keywords: Nature-Based Water Treatment; Constructed Wetlands; Water Quality Performance; Sustainability Outcomes; Ecosystem Services

1. Introduction

The high rate of population growth, the fast rate of urbanization, industrialization, and increasing agricultural activities have all contributed to pressure on the fresh water resources around the globe in a way that has never been experienced before[1]. The contamination of surface and groundwater systems in the world is expanding rapidly and is characterized by organic matter, nutrients, pathogens, heavy metals, and emerging pollutants, which threaten the integrity of the ecosystem and human health[1–4]. Traditional centralized water and wastewater treatment technologies have been quite instrumental in enhancing the quality of water over the last century but their use has often been limited due to high capital and operating costs, excessive energy and chemical needs, low flexibility in variable loading, and heightened susceptibility to climatic extremes. These restrictions have inspired the increasing concern in alternative and complementary treatment approaches that are not only environmentally sustainable, economically viable, and socially acceptable[1,2].

In that regard, nature-based water treatment systems have become an attractive option that aims at enhancing water quality by relying on the natural processes and ecosystem operations[4–6]. These systems take advantage of physical, chemical as well and biological processes that take place in soils, sediments, plant cover, and microbial populations to eliminate or convert the contaminants contained in the water[6]. Among them are constructed wetlands, biofiltration and bioretention systems, riparian buffer zones, restored floodplains and floating treatment wetlands[7]. In contrast to engineered-based treatment systems, nature-based systems are normally defined in relation to low energy requirements, low levels of chemical additives, and the ability to produce numerous co-benefits not directly related to the removal of pollutants, which include the creation of habitats, carbon capture, water control, and improved aesthetic landscape appearance[8–10].

Within this context, nature-based water treatment systems (NBWTS) have emerged as promising solutions for improving water quality by harnessing natural ecological processes. These systems utilize physical, chemical, and biological mechanisms occurring in soils, sediments, vegetation, and microbial communities to remove or transform contaminants in water. Common examples include constructed wetlands, biofiltration and bioretention systems, riparian buffer zones, floodplain restoration interventions, and floating treatment wetlands. Compared with conventional engineered systems, NBWTS typically operate with lower energy demand, minimal chemical inputs, and the potential to deliver multiple co-benefits such as habitat creation, carbon sequestration, flood mitigation, and improved landscape aesthetics[1,4,6,7].

Beyond treatment performance, the evaluation of NBWTS increasingly requires a broader sustainability perspective[8]. These systems operate within complex socio-ecological environments and generate multiple outcomes that extend beyond pollutant removal. From an environmental standpoint, NBWTS may contribute to reduced energy consumption, carbon sequestration, enhanced biodiversity, and improved hydrological regulation[11–13]. Economically, they are often considered cost-effective alternatives to conventional treatment technologies, particularly in decentralized settings, although comprehensive life-cycle cost assessments remain limited. Socially, nature-based systems can enhance public spaces, promote community engagement in water management, and provide recreational and educational opportunities. However, potential trade-offs must also be recognized, including land-use competition, greenhouse gas emissions in certain wetland systems, and variability in performance across environmental conditions[5,6].

The global distribution of NBWTS implementation reflects significant regional differences influenced by regulatory frameworks, financial resources, technical capacity, and environmental conditions. In high-income regions, adoption is often driven by stringent environmental policies and the promotion of green infrastructure within urban planning. In contrast, low- and middle-income countries frequently adopt nature-based systems as cost-effective decentralized solutions for improving sanitation and water quality in areas lacking conventional treatment infrastructure. Understanding these contextual differences is essential for assessing the scalability and long-term viability of nature-based approaches [14].

Although numerous studies and reviews have examined individual types of NBWTS, such as constructed wetlands or stormwater biofilters, most existing syntheses focus on specific system types, pollutant categories, or regional applications. Comprehensive global assessments that simultaneously evaluate treatment performance and broader sustainability outcomes across multiple nature-based systems remain limited. This review addresses that gap by providing an integrated analysis that combines: (i) a comparative typology of major NBWTS, (ii) an evaluation of global implementation trends, (iii) a synthesis of key performance metrics and treatment effectiveness, and (iv) an assessment of environmental, economic, and social sustainability outcomes [15,16].

By linking treatment performance with sustainability considerations within a global comparative framework, this review aims to provide new insights into the role of nature-based water treatment systems in advancing resilient and sustainable water management strategies.

2. Typology and Functional Principles of Nature-Based Water Treatment Systems

Nature-based water treatment systems refer to a wide range of interventions that involve natural or semi-natural processes that are used to enhance the quality of water. These systems are diverse in nature, size, and use but have a common basis; they are all aimed at removing, transforming, or immobilizing contaminants using ecological structures and biogeochemical processes. An evident typology framework is needed to comprehend the performance of the system, compare the outcomes in different studies, and make a suitable choice and design in treating certain objectives [11,16].

2.1. Conceptual Classification of Nature-Based Water Treatment Systems

As **Figure 1** demonstrates, NBWTS can be divided broadly by three primary criteria, namely the extent of engineering interventions, hydrological structure, and functional treatment goal. Systems that are found at the natural end of the continuum tend to work on the landscape scales and seek to intercept diffuse sources of pollution. Engineered systems, on the other hand, are designed to treat more concentrated flows like municipal wastewater or urban stormwater. Hybrid systems are a kind of system between these two classes, that is, they harmonize ecological functioning with control, which is engineered to enhance the reliability of treatment in fluctuating conditions of loading mass [17,18].

There are also differences in functional objectives in different types of systems. Some systems are mostly used in the treatment of wastewater, and others are aimed at the treatment of stormwater, mitigation of agricultural runoff, and nutrient control at the watershed level. Influential characteristics, treatment targets, space limitations, and socio-economic setting are therefore the determinants of the kind of system to be selected. **Figure 1**'s typological framework gives a convenient reference point for comparison of the system performance and knowing the contribution of various configurations towards water quality improvement [19].

2.2. Constructed and Treatment Wetlands

Constructed wetlands are the most researched and the most common type of nature-based water treatment systems. Such systems are designed to mimic the natural wetland's ability to remove pollutants, but they have a higher ability to control the hydraulic loading and retention time. Common approaches have been free water surface wetland, horizontal subsurface flow wetland, vertical flow wetland, and combinations of these two. Every setting has its unique benefits and drawbacks of oxygen delivery, nutrient dynamics, and clogging vulnerability [20].

The processes of constructed wetlands that lead to the removal of pollutants are sedimentation, filtration, microbial degradation, uptake by plants, and adsorption by substrates. Physical settling and microbial oxidation are the main processes to eliminate organic matter and suspended solids, whereas the removal of nitrogen occurs via complex mechanisms, which include nitrification, denitrification, and assimilation by plants. The retention of phosphorus highly depends on the nature of the substrates, and in most cases, it becomes saturated after a certain time. Constructed wetlands are thus prone to design variables, climatic conditions, and long-term management of operations[22].

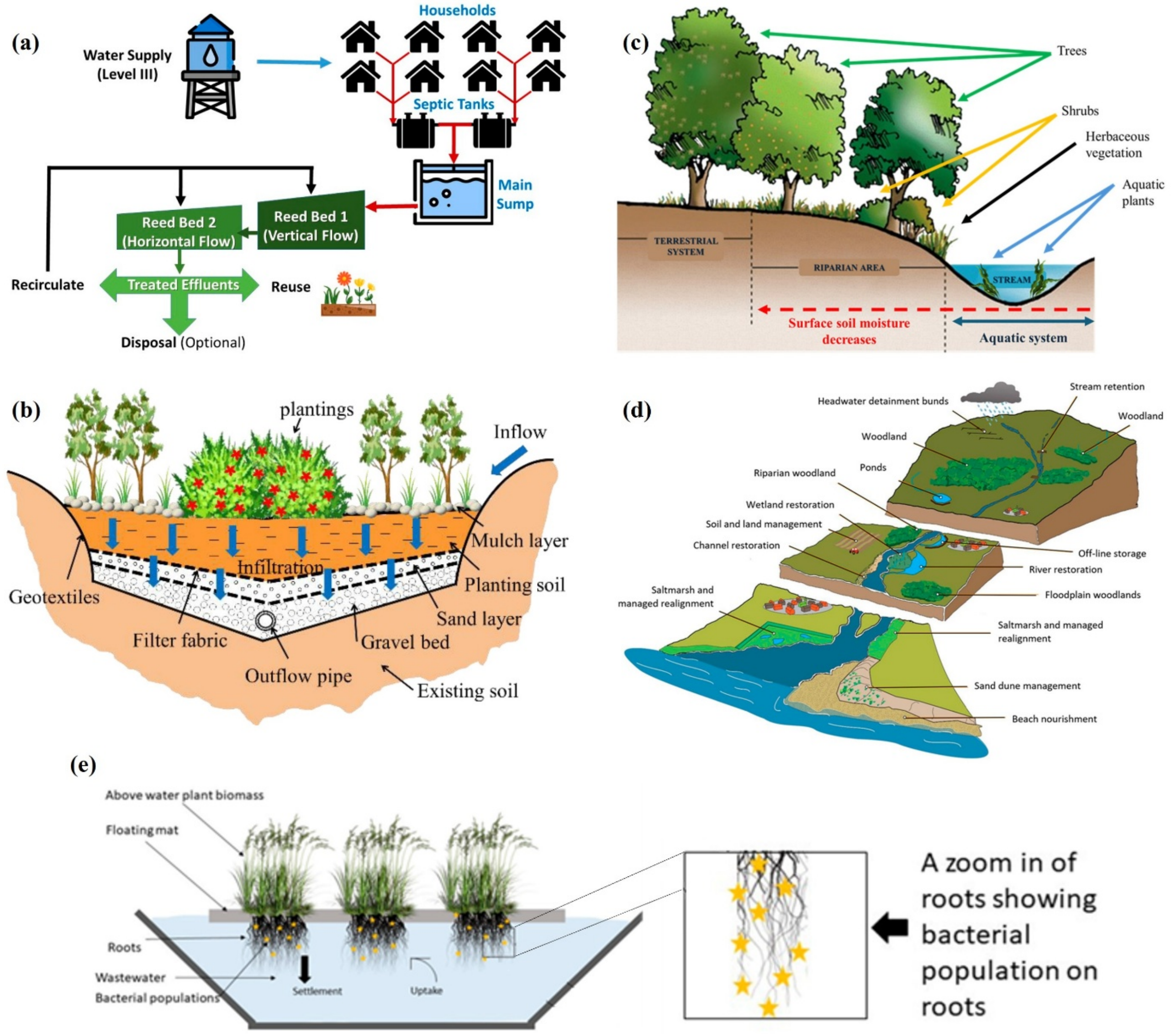

Figure 1. Conceptual schematic of major nature-based water treatment systems: (**a**) constructed wetlands, (**b**) biofiltration/bioretention, (**c**) riparian buffers, (**d**) floodplain restoration, and (**e**) floating treatment wetlands[19–23].

2.3. Biofiltration and Bioretention Systems

The use of bioswales, rain gardens, and vegetated infiltration basins (also known as biofiltration and bioretention systems) is now being used more frequently to treat decentralized stormwater in urban settings. They are usually created to be able to intercept runoff, enhance infiltration, and eliminate pollutants via filtration, sorption, and biological activity in engineered soil media. Plant life is important in increasing the hydraulic conductivity, media stability, and microbial habitat[23].

These systems are specifically applicable in the removal of suspended solids, hydrocarbons, metals, and particulate-bound nutrients. The effectiveness of dissolved nutrients and emerging contaminants, however, is very variable, relating to the media composition and hydraulic residence time. Although biofiltration systems tend to be small and not too bulky in urban environments with limited space, their efficiency to treat the water may go down when they are not looked after, and this may therefore indicate the need to have long-term management to maintain the system performance[20,22,23].

2.4. Riparian Buffers and Vegetated Filter Strips

Landscape-scale nature-based systems to intercept and treat diffuse agricultural and urban runoff pollutants before entering surface water are known as riparian buffers and vegetated filter strips. They depend on vegetation, soil, and the interaction with shallow groundwater to reduce sediment, nutrients, and agrochemicals. This is in contrast to engineered treatment units that are complex components of watershed hydrology and ecology[24].

Riparian buffers usually remove nitrogen with the help of denitrifying anaerobic soils, whereas phosphorus is retained through the deposition of sediments and sorption. Buffer width, vegetation type, soil properties, and hydrological connectivity strongly affect the effectiveness of these systems. Although the ecological benefits of riparian buffers are well known, the performance of the buffer treatment is necessarily uneven and strongly determined by the conditions of the sites[25].

2.5. River, Floodplain, and Wetland Restoration for Water Quality Improvement

Another wider ecosystem-based strategy to enhance water quality is the restoration of rivers, floodplains, and natural wetlands. These interventions enhance hydraulic residence time and permit biogeochemical processing of pollutants by restoring natural flow regimes through reconnecting rivers to the floodplain and recreating hydraulic residence time. Such systems are especially good at reducing nutrient loads on a watershed scale and at enhancing ecological integrity[26].

In contrast to engineered systems, restored landscapes are not focused on removing specific pollutants, but on providing an ecosystem; thus, performance evaluation is more complicated. The benefits of water quality are usually implicit and are realized over a longer time and space. However, restoration-based strategies have huge co-benefits, such as habitat improvement, flood control, and greater resiliency to climate variability[27].

2.6. Floating Treatment Wetlands and Hybrid Systems

Floating treatment wetlands involve using buoyant platforms with emergent vegetation and the roots go into the water column. They are also used more often in lakes, reservoirs and city waters where interventions based on sediments are inconvenient. Root-associated biofilms, plant absorption, and augmented sedimentation under the floating mats aid in the removal of the pollutants[5,8,14].

Hybrid systems like floating wetlands with constructed wetlands or traditional treatment procedures are being considered as being flexible and adaptive. The hybrid designs would improve the removal efficiency by incorporating various treatment pathways and reducing the land needs. They, however, have little empirical evidence on their long-term performance and maintenance requirements[8,12].

2.7. Functional Principles and Cross-Cutting Ecological Processes

NBWTS have multiple fundamental ecological and biogeochemical processes common to their treatment performance, regardless of their configuration and scale. These are hydrologic retention, microbial degradation, nutrient cycling, sedimentation, filtration, and adsorption. The residence time of water in the treatment systems is controlled by hydrological processes that control the amount of time that water remains in the system, which dictates how much time the polluted water is in contact with the reactive media. Microbial communities are very important in the process of changing organic matter and nutrients by means of nitrification, denitrification, and organic mineralization of carbon. Vegetation has a direct and indirect effect by increasing the activity of the rhizosphere microbial activity to promote direct and indirect nutrient uptake[28–30].

In combination with other interlocking mechanisms, NBWTS is capable of eliminating or converting a broad spectrum of contaminants. Their efficacy, however, relies on the interplay between the ecological processes and system design, hence the inconsistency in the performance of treatment systems seen under different environmental conditions and system designs. These common functional principles are thus relevant to maximizing the design of systems and enhancing the stability of nature-based water treatment methods[18].

In identifying these common functional principles, the comparison of different nature-based water treatment systems is possible and the integration of the various systems into sustainable water management approaches is also possible. **Table 1** provides the nomenclature of nature-based water treatment systems, their general applications, general treatment processes, and general design characteristics.

Table 1. Classification and Characteristics of Nature-Based Water Treatment Systems.

System Type	Typical Applications	Key Treatment Mechanisms	Common Design Features
Constructed wetlands[31]	Municipal wastewater, stormwater	Sedimentation, microbial degradation, and plant uptake	Free water surface, horizontal/ vertical subsurface flow, hybrid
Biofiltration/ Bioretention[32]	Urban stormwater, diffuse runoff	Filtration, sorption, microbial processes	Vegetated soil media, flow control structures
Riparian buffers/ Filter strips[33]	Agricultural runoff, diffuse pollution	Sedimentation, nutrient uptake, and denitrification	Vegetation width, soil composition, slope
Floodplain/River restoration[31]	Watershed nutrient control, habitat improvement	Hydraulic retention, microbial and plant processes	Floodplain reconnection, flow management
Floating treatment wetlands[34]	Lakes, reservoirs, urban water bodies	Root-associated biofilms, plant uptake	Floating mats, emergent vegetation
Hybrid systems[35]	Multiple applications	Combined engineered and natural processes	Integrated design, modular components

3. Global Development and Implementation Trends

Nature-based water treatment systems have increasingly grown and been implemented in the past few decades as a reflection of the worldwide tendency to develop more sustainable and resilient approaches to water management. This has been encouraged by the growing awareness of environmental degradation, tougher water quality stipulations, escalated expenses of conventional methods of treatment, and the realization of the multipurpose nature of nature-based methods. Although the incorporation of such systems has been prevalent, they are distributed differently across regions, and the scale and functional goals are highly different, depending on socio-economic factors, governance, and environmental factors[8,16,18].

3.1. Historical Evolution and Policy Drivers

Initial research into nature-based water treatment systems was, to a large degree, driven by the natural observations of attenuation of pollutants in the natural wetlands and riparian areas. These observations over the years were translated into engineered solutions, the most notable one being the constructed wetlands that became prominent as a low-cost treatment of wastewater in rural and peri-urban contexts. Over the last few years, the conceptual framing of nature-based systems has witnessed a shift to become more than just efficient in its treatment, which has been supplemented by a focus on ecosystem services, climate adaptation, and urban livability[8,17,22,36].

Global policy structures and environmental guidelines have been of critical importance to speed up implementation. Regulations that seek to regulate nutrient-polluting factors, enhance the environmental performance of water bodies, and the recovery of urban drainage systems have led to the adoption of nature-based systems in the planning of water infrastructure. Simultaneously, the nature of the problem of climate resilience and biodiversity conservation in the context of global efforts that define the relevance of nature-based solutions as multifunctional interventions able to meet several problems facing society at once has increased the relevance of nature-based solutions[36].

Figure 2 illustrates that policy-driven adoption has often led to large-scale implementation. For example, the introduction of integrated watershed management frameworks and urban green infrastructure policies in the early 2000s accorded with a substantial upsurge in NBWTS projects worldwide. These trends suggest that regulatory support and planning integration are key drivers of technology diffusion.

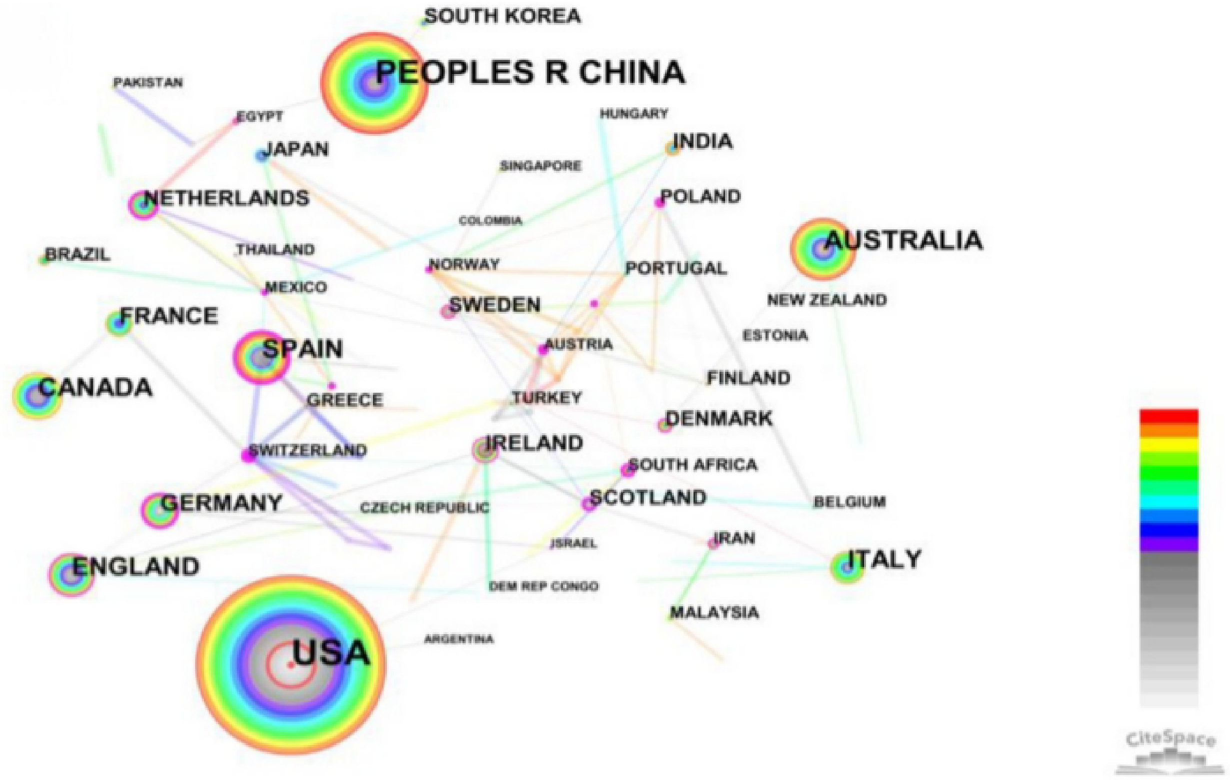

Figure 2. Global Distribution and Implementation Trends [37].

3.2. Regional Implementation Patterns

Even though NBWTS have gained worldwide implementation, the distribution of the technology indicates that there exists a great variation in priorities of environmental importance, regulatory frameworks, and infrastructure demands across regions [11,38,39].

In Europe, the use of nature-based systems in water treatment is common in both municipal wastewater treatment and runoff water from farms. Wetland constructed systems are also quite common, and there are thousands of systems that have been put in place to treat the wastewater in a decentralized manner in rural communities. Green infrastructure urban planning has also increased the rate of adoption of stormwater biofiltration systems within most of the cities across Europe. NBWTS have been largely applied in urban stormwater management systems in North America. Sustainable urban drainage systems are usually incorporated with biofiltration systems, bioswales, and constructed wetlands to minimise volumes of runoffs and enhance water quality. Green infrastructure initiatives are currently used to treat large volumes of urban runoff in a number of metropolitan regions, which indicates the scalability of decentralized NBWTS.

The fast urbanization and industrial growth in Asia have posed growing pressure on the need to adopt alternative treatment of wastewater. Municipal wastewater treatment and river restoration projects are mostly constructed using constructed wetlands and hybrid nature-engineered systems. The NBWTS is becoming relevant in the integrated water management approach of large cities, as evidenced by large-scale urban projects in some of the Asian cities [40]. NBWTS has been commonly implemented in Africa and Latin America as an alternative to centralized treatment infrastructure because it is less expensive [41]. Wetlands and stabilization ponds constructed with vegetated treatment systems are a common practice to enhance sanitation and nutrient load in the surface waters [42,43]. Nonetheless, application in these areas is usually required with the help of extrinsic financing, technical assistance, and community-managed frameworks [37,44–47].

In general, **Table 2** shows that although the same core technologies are utilized all over the world, their functional goals are different. In high-income areas, NBWTS can be part of sophisticated environmental management plans, and in the lower-income areas, they can be a solution to simple wastewater treatment and sanitation.

Table 2. Global Implementation Trends and Regional Adoption.

Region/Country	Common System Types	Primary Drivers	Urban/Rural Application	Notable Policies/ Initiatives
Europe	Constructed wetlands, biofilters	Environmental regulations, SDGs	Urban & rural	EU Water Framework Directive [48]
North America	Biofiltration, wetlands	Stormwater management, non-point source control	Urban & suburban	Green Infrastructure Policies [49]
Asia	Constructed wetlands, hybrid systems	Rapid urbanization, decentralized wastewater	Urban & peri-urban	National wastewater treatment standards [50]
Africa	Constructed wetlands, stabilization ponds	Low-cost sanitation, water quality improvement	Rural & peri-urban	Community-based water projects [51]
Latin America	Constructed wetlands, riparian buffers	Water quality protection, ecosystem services	Rural & urban	Regional environmental programs [52]

3.3. Integration with Conventional Infrastructure and Hybrid Approaches

A key phenomenon of worldwide application is the growing combination of natural water treatment infrastructure with the traditionally designed infrastructure. Nature-based systems are not used as independent standalone solutions but are frequently utilized as supplements to other larger treatment networks. These can be in the form of constructed wetlands used to accomplish tertiary treatment by either a mechanical or biological process or use of bioretention systems to minimize hydraulic loads on sewer systems [8].

The objective of the hybrid approaches is to ensure that the reliability and predictability of traditional technologies meet the sustainability and co-benefits of nature-based systems. The integration improves the resilience of the system, especially during fluctuating load and extreme weather conditions. Nevertheless, to be implemented effectively, both institutional and disciplinary coordination and the provision of clear performance expectations should be observed [5].

3.4. Barriers, Enablers, and Emerging Implementation Trends

Even with the increased awareness regarding the advantages of using NBWTS, there are still multiple challenges that the popularization of NBWTS is likely to encounter. Some of the greatest impediments in the world include the uncertainty about the performance in the long term, insufficient standardized design requirements, and the institutional bias towards the traditional engineered infrastructure. Such obstacles are especially pertinent in those areas where regulatory frameworks are based on predictable and well-established technologies in the field of treatment.

Another constraint is land availability, particularly in high-population urban regions, where competing land uses are more likely to increase the implementation costs. Moreover, a shortage of technical expertise and a lack of maintenance capability can impair the performance of the system in the long term within the resource-constrained environments [3,14,17].

On the other hand, there are also several enabling factors that have promoted the growth of NBWTS across the globe. Favourable policy frameworks, financial inducements, and growing acceptance of ecosystem services in water management planning have come a long way in enhancing the institutional climate of nature-based approaches. Development of monitoring technologies, such as sensor-based water quality monitoring, as well as digital modelling tools are also improving the potential of assessing system performance and system optimization.

Recent developments indicate that the further evolution of NBWTS will be more focused on the adaptive design, the hybridization of infrastructure, and digital monitoring strategies. The use of hybrid systems that are a mixture of natural-inspired and traditional treatment technologies is also being considered as a way of enhancing reliability and still retaining sustainability benefits. On the same note, adaptive management techniques that encompass real-time monitoring and performance feedback can be used to increase system resilience in the changing environmental conditions [6,46].

Combined, the trends depicted in **Figure 2** and the regional analyses as noted in **Table 2** suggest that NBWTS are moving out of the niche into mainstream sustainable water management components. Further development will rely on the advancement of policy support, the enhancement of performance evaluation systems, and the enhancement of interdisciplinary cooperation among engineers, ecologists, and urban planners [53].

4. Performance Metrics and Treatment Effectiveness

To determine the effectiveness of the nature-based water treatment systems, performance metrics are necessary to capture the functionality of the systems as well as the elimination of pollutants in various environmental conditions. In contrast to traditional technology of treatment, whose functionality is usually determined by standardized parameters of operational efficiency, nature-based systems are highly variable because they are dependent on ecological functions. Consequently, there should be a wide scope of water quality parameters, hydrological conditions, and temporal dynamics that performance assessment has to consider [54,55].

4.1. Key Pollutant Categories and Removal Effectiveness

Nature-based water treatment systems are used to treat a broad range of contaminants, such as organic matter, suspended solids, nutrients, pathogens, heavy metals, and emerging pollutants. The efficiencies of removal of organic matter (typically measured by biochemical oxygen demand or BOD and chemical oxygen demand or COD) tend to be high in most types of systems. Biofiltration systems and constructed wetlands have continued to show a significant decrease in organic loads through proper sedimentation and biodegradation by microorganisms. Suspended solids can also be effectively treated using physical filtration and settling, which commonly leads to substantial increases in the level of water clarity and the ecological status downstream [55].

It is more complex and variable in terms of nutrient removal and in particular, nitrogen and phosphorus. There are several biogeochemical processes of nitrogen removal such as nitrification, denitrification, plant uptake, and microbial assimilation. Hybrid wetlands and other systems that have alternating aerobic and anaerobic zones have been found to be more effective in removing nitrogen than one configuration. Sorption to substrates and sedimentation are the main processes in phosphorus removal and thus performance is greatly influenced by media properties and the age of a system. Saturation of adsorption sites may consequently reduce the level of phosphorus retention over time hence the need to evaluate the performance over the long term [53,56].

Another less frequently reported but important performance of nature-based treatment is pathogen attenuation. Some removal mechanisms are sedimentation, predation, exposure to ultraviolet light, and competition among microbes [57]. Although significant decreases of indicator organisms (e.g., fecal coliforms and *Escherichia coli*) can be achieved, removal efficiency may vary significantly depending on temperature, hydraulic loading and system design. The efficacy of nature-based systems to control pathogens is relative and should be viewed with caution in situations where the systems are to be used to protect the health of the populace [58,59].

In most cases, the heavy metals are eliminated by a mixture of sedimentation, adsorption to organic matter and mineral substrates, and in some instances, plant uptake. Particulate matter which is linked to metals, is normally removed more effectively than those metals that are in a dissolved state. Developing pollutants, such as pharmaceuticals, personal care products, and per- and polyfluoroalkyls, are an increasing concern. It has been indicated that nature-based systems have the capability to reduce some emerging contaminants by sorption and biodegradation, but overall removal efficiencies are highly compound-selective and often incomplete which has been pointed out as a critical area of future research [29,45,58].

4.2. Performance Indicators and Reporting Metrics

A combination of concentration-based and load-based measures is usually used to report the performance of nature-based water treatment systems. The most commonly used is the removal efficiency which is defined as the percentage of reduction in the influent and effluent concentrations. Although this metric is convenient in understanding the effectiveness of treatment, it may give inaccurate results in cases where the influent levels are low or highly fluctuating. As a result, mass removal per unit area or per unit time is becoming a more accepted load-based metric that is more robust as a performance measure in a system[16].

The hydraulic parameters such as the hydraulic retention time and hydraulic loading rate are pertinent contextual parameters which have a powerful effect on treatment results. These parameters dictate the level of contact of water with reactive media and therefore control the level of physical, chemical, and biological processing. Another significant performance indicator is system footprint (also sometimes in terms of area needed per unit of treated flow or per population equivalent)[15].

Temporal performance indicators are needed to capture system dynamics. Removal efficiencies may, in principle, be largely affected by seasonal variability, start-up periods and long-term aging effects. Short-term monitoring can overestimate the performance because it does not consider such factors, but long-term monitoring offers less biased information on the reliability and resilience of the systems.

4.3. Variability and Uncertainty in Performance Assessment

The nature-based water treatment systems have a characteristic of variability. The variability in performance is due to seasonal changes in temperature, fluctuating influent loads, hydrological perturbation and ecological succession in the system. As an illustration, cold temperatures can decrease microbial action during winter seasons, decrease the efficiency of nutrient removal, whereas large-flow events decrease retention periods and reduce treatment efficacy.

The uncertainty is also increased in that there are differences in the system design, the practices involved, and the monitoring protocols among different studies. The differences in sampling rate, choice of parameters, and analytical procedures do not allow the direct comparison of the results reported. Such discrepancies emphasize the necessity of uniform performance reporting models allowing the synthesis of meaningful results across a variety of systems and situations.

4.4. Comparative Performance across System Types

Comparative studies reveal that engineered nature-based systems, including constructed wetlands and bioretention cells, are more predictable and controllable in terms of performance than landscape-scale interventions, such as riparian buffers and floodplain restorations. The second, though with major ecological benefits, is more likely to provide more diffuse and transient water quality improvements[5,16].

Hybrid systems which combine several nature-based parts or merge nature-based and standard procedures, usually exhibit greater treatment efficiency. Hybrid designs can also address the weaknesses of each system and enhance the overall strength of the system through the use of complementary mechanisms. Nonetheless, it is also possible that higher complexity leads to new operation-related issues and expenses[11].

4.5. Toward Improved Performance Evaluation

The development of the assessment of nature-based water treatment systems should be based on the transition to more transparent performance indicators. The inclusion of concentration-based and load-based measurements, reporting of hydraulic and design parameters, as well as treatment outcomes and recording of temporal variation are all critical measures towards enhancing comparability and reliability of reported outcomes. In addition, extending the performance evaluation to non-conventional water quality indices to incorporate the emerging contaminant and system resilience will be of crucial importance in harmonizing nature-based treatment with the changing regulatory and social standards[5,13].

Overall, there is a high potential in nature-based water treatment systems to enhance water quality in a variety of different applications. Their behaviour with regard to treatment efficiency is so context-specific and dependent on complicated interactions among design, operation, and environmental conditions. Strong and standard performance measures are thus the basis of determining their role properly under sustainable water management strategies. A summary of normal performance measures and pollutant removal efficiencies of significant nature-based water treatment systems, as well as significant influencing factors and areal requirements, is also given to aid comparison in **Table 3**.

Table 3. Performance Metrics and Typical Treatment Efficiencies.

System Type	Pollutants	Typical Removal Efficiency (%)	Key Influencing Factors	Footprint/Areal Requirements
Constructed wetlands [60]	BOD, COD, TSS, N, P	60–90 (BOD/COD), 40–80 (N), 50–80 (P)	Hydraulic retention time, substrate, vegetation	2–5 m^2 per PE (Population Equivalent)
Biofiltration/ Bioretention [61]	Total Suspended Solids (TSS), metals, nutrients	50–85	Media composition, inflow characteristics	1–3 m^2 per 10 m^3 runoff
Riparian buffers [62]	N, P, sediment	30–70 (N), 20–60 (P)	Buffer width, soil type, and vegetation	Variable, landscape-scale
Floodplain restoration [63]	N, P, suspended solids	25–65	Hydraulic connectivity, flow regime	Large, watershed-scale
Floating treatment wetlands [64]	Nutrients, TSS	30–70	Plant species, root depth	Limited water surface coverage

5. Design, Operation, and Long-Term System Performance

The design configuration, management of the operation, and its ability to sustain the performance of nature-based water treatment systems are very critical determinants of its efficacy as well as longevity. In contrast to traditional types of treatment technologies, which are based on highly regulated mechanical and chemical reactions, nature-based systems are based on the dynamic ecological processes that change with time. Therefore, to obtain credible treatment results, it is essential to pay close attention to the design parameters and match them to the conditions of the site and long-term operation [14,17].

5.1. Design Parameters Governing Treatment Performance

The hydrological design is one of the main predeterminants of system performance, which regulates the contact time between the water and reactive surfaces. Parameters, including hydraulic retention time, hydraulic loading rate, and flow distribution also determine the degree to which physical settling, microbial transformation and biogeochemical cycling may take place. With an incompetent retention time, the systems might not attain the anticipated pollutant removal, whereas if the retention time is too long, it might pose the risk of anaerobic conditions and secondary emission [47,57].

The substrate selection is also very crucial to pollutant attenuation, especially to phosphorus and metals. The composition of media influences the adsorption capacity, redox, and colonization by microbes. Iron rich, aluminium-rich, and calcium-rich materials have been linked with improved phosphorus retention and organic-rich materials stimulate microbial activity and denitrification. Substrate saturation and physical degradation may lower treatment efficiency over time, though and thus it has been suggested that when going through system design, it is important to look at media longevity [9,12,42].

Another important design factor is vegetation, with the effect it has on the treatment processes and stability of the system. The selection of plant species influences the root architecture, exchange of oxygen to the rhizosphere, nutrient uptake and environmental stress tolerance. A greater variety and adaptation of vegetation communities can increase resilience of systems through the provision of broader microbial processes and decreasing susceptibility to pests, disease and climate fluctuation. Nevertheless, the growth of plants can be too high and hinder the movement of water, which will be necessary to manage the ecological process and hydraulic performance.

5.2. Operational Factors and Performance Stability

Treatment effectiveness in nature-based systems requires operational management to endure. Hydraulic and pollutant-based influent loading rates should not exceed the design capacity because it will result in overloading of the system and reduced performance. Disruptions in the microbial community can be caused by sudden shifts in the composition of influent, like shock loads of organic material or toxic substances that can interfere with treatment processes [65].

Seasonal fluctuation is one of the key operational factors that may pose a significant challenge, especially during temperate and cold conditions. Change in temperature affects the metabolism of microorganisms, growth, and oxygen movement in plants, resulting in seasonal variation in the elimination of pollutants. As an example, spring and fall seasons can easily decrease the total nitrogen uptake through the reduced rates of nitrification and denitrification, whereas the uptake of nitrogen by plants is curtailed during the out-of-season periods. Scheduling systems that have adequate buffering capacity and redundancy can be used to address seasonality in performance variability[66,67].

Regular maintenance procedures such as vegetation control, sediment control and control inspection of hydraulic structures play a major role in the long-term operation of the system. Failure to maintain may lead to clogging, short circuit and diminished hydraulic conductivity which eventually affects the performance of treatment. Nature-based systems, in spite of being reputed as low-maintenance solutions, can only be effective with constant management[67,68].

5.3. System Aging and Longevity

System maturation and aging are processes that affect the long-term nature of water treatment systems based on their nature. In the early periods of operation, there may be an improvement in treatment efficiency due to the establishment of a microbial community and the full development of vegetation. This stage of maturation is normally preceded by a time of stable performance, whereby the pollutant-removing mechanisms are functional in their normal loading conditions[69,70].

With long durations of time, however, the processes of aging may contribute to slow deterioration in performance. The build-up of sediments and organic matter will decrease porosity and hydraulic conductivity, especially within subsurface systems of flow. Saturation of the substrates, particularly with regard to phosphorus saturation, prevents subsequent retention of the pollutants unless replaced or regenerated. The vegetation succession can change the composition of species and system hydraulics and requires adaptive management plans[71].

These temporal dynamics are necessary for realistic performance expectations and life-cycle planning. Sustainability can be improved by monitoring the system and responding proactively to its maintenance requirements, which will extend its life span and postpone the decline in performance.

5.4. Resilience to Climate Variability and Extreme Events

Nature-based water treatment systems have a challenge and an opportunity with climate change. High occurrence of extreme events in precipitation may lead to hydraulic overloading, decrease in the retention times, and bypass flows, which decrease the treatment. On the other hand, long periods of drought could negatively affect the performance of wetlands and limit their ability to absorb pollutants with insufficient water[71].

Simultaneously, nature-based systems have natural adaptive benefits because they are flexible and have the ability to self-organize. The more adaptive systems to climatic variability are those with variable flow paths, adequate storage and a range of vegetation communities. By incorporating nature-based treatment into wider landscape and watershed management systems, the resilience may be even better by spreading treatment functions with various interdependent elements[26].

5.5. Trade-Offs between Efficiency, Footprint, and Manageability

Developing nature-based water treatment systems entails considering the balance between the efficiency of treatment and land needs, the complexity of operation and expenses. The large removal efficiencies frequently require large footprints of systems or engineered designs, which are not feasible in space-restricted environments. On the other hand, small systems might be more intensively managed or be less resilient to fluctuating loading[8].

The trade-offs between these treatments can be resolved to maximize their performance and reduce land utilization by using hybrid methods that bring together nature-based and conventional aspects of treatment. Nonetheless, there can be more operational and institutional challenges due to the increased level of system complexity. Proper articulation of treatment goals and situational limitations is thus necessary to make the right system configurations[8].

Overall, the ecological and engineering factors are all interrelated, and determine the design, functioning, and sustainability[7,21] of nature-based water treatment systems. These interactions are difficult to realize in practice unless there is a comprehensive view of how they are involved and of the dynamics of time and an investment in an adaptive management process. These considerations are vital in addressing the fact that nature-based systems can provide reliable and sustainable benefits to water quality throughout the lifetimes of their operations.

6. Sustainability Outcomes and Co-Benefits

Nature-based water treatment systems are also gaining more importance due to their ability to enhance water quality along with other sustainability benefits. Compared to traditional treatment technologies, where most are usually constructed to meet specifically set effluent targets, nature-based systems exist in socio-ecological environments and produce various environmental, economic, and social gains. A sustainability lens approach to the evaluation of these systems thus entails both the intended functions of treatment and other co-benefits which are incidental and any trade-offs and unintended outcomes.

6.1. Environmental Sustainability Outcomes

Another important environmental benefit of nature-based water treatment systems is that they have relatively low energy and chemical needs. These systems typically use less external energy when compared to mechanical or chemical treatment technologies by utilizing natural biogeochemical processes which contribute to lower operational emissions and a higher energy efficiency of the system. This is a key feature, especially in the areas where power is expensive or where the accessibility of sound power infrastructure is restricted[44,65].

Another way in which nature-based systems can help in mitigating and adapting to climate change is through their contribution to climate change. Planted treatment systems[46,47], like constructed wetlands and riparian buffers, can capture carbon in plant biomass and soils, and at the same time increase the ability to endure hydrological extremes. This is because their ability to reduce peak flows and store water during storm events lessens flood risks and enables climate-adaptive management of water. Biofiltration systems and green roofs are instances of green infrastructure that also regulate microclimate and reduce urban heat island effects in an urban environment.

Another significant environmental co-benefit is biodiversity improvement. Nature-based water treatment systems provide or rehabilitate habitats of aquatic and terrestrial species, which aids in promoting richness and ecological connectivity of the species. Specifically, wetland-based systems can be key to habitat provision of birds, amphibians, and invertebrates, which play a role in the bigger conservation agenda. These ecological processes are frequently not confined to the immediate area of the treatment, which adds to the importance of nature-based systems in the restoration of the environment on a landscape scale[72].

Nevertheless, a couple of environmental trade-offs should not be disregarded. Some systems particularly the wetlands that exist in an anaerobic environment, are also capable of spewing out greenhouse gases like methane and nitrous oxide. Although these emissions tend to be less than those of the energy-intensive conventional treatment, they bring the net climate benefits into the realm of uncertainty. Also, improperly operated systems can be the carriers of invasive species or collect contaminants in the sediments and biomass and represent a potential ecological threat[73].

6.2. Economic Sustainability and Cost Considerations

Economically, the nature-based water treatment systems have often been thought of as cost-effective solutions to traditional treatment, especially in terms of decentralized and small-scale water treatment. There is lower capital expenditure, lesser energy usage, and less chemical use that leads to positive cost profiles in the system life cycle. These properties are particularly beneficial in the low- and middle-income areas, where financial and technical resources are limited[54,74].

In addition to direct treatment cost, nature-based systems are also economically valuable in terms of the ecosystem services which are generally not counted in the conventional cost evaluation methods. Flood control, recreational use, aesthetic improvement and higher property values are some benefits that can greatly enhance the overall economic functioning of such systems. In cases where these co-benefits are factored the nature-based solutions tend to fare better than the conventional technologies in cost-benefit analysis[75].

However, long-term maintenance needs and land availability affect economic sustainability. Operation costs would be low in most cases, but a lack of proper maintenance might result in the degradation of performance and the high cost of rehabilitation. In cities, the cost of acquiring land and opportunity costs might reduce viability, the planning and development with the available infrastructure should be well-planned. Nature-engineered approaches that can make use of hybrid methods can be useful in maximizing economic efficiency but may also add complexity.

6.3. Social and Societal Benefits

Nature-based water treatment systems have been characterised by social sustainability. These systems would not only increase people's comprehension of water management by making treatment functions visible and available within visible landscapes, but would also create more positive relationships between communities and their immediate surroundings. Parks, wetlands, and green corridors connected with water treatment can be used as a recreational and educational area, which helps to enhance the quality of life[76].

The key factors of long-term success are community acceptance and participation. Nature-based systems are seen as much more aesthetically pleasing and culturally oriented than traditional treatment facilities in most settings and support this in a way that is acceptable to the populace. In rural and decentralized systems, local ownership and technical capacity development through community participation in planning, construction and maintenance can assist in the sustainability of the system[73].

Another way through which nature-based systems can be used with regard to social equity is by enhancing water treatment and sanitation in underserved regions. They are informal settlements and remote communities because their adaptability and scalability make them practical in places that cannot have the normal infrastructure. Nonetheless, to attain fair results, one should consider governance frameworks and focus on the local socio-cultural processes.

6.4. Trade-Offs, Risks, and Uncertainties

The nature of the water treatment systems, however has limitations despite their numerous advantages. The issues of variability in performance, land requirements, and uncertainties concerning long-term contaminants fate are challenges in the large-scale adoption. Co-benefits can also be incompatible with treatment goals in certain situations, e.g., the hydraulic efficiency of the habitat can be lost by maximizing habitat complexity[77].

There is also the risk of institutional and regulatory systems obstructing implementation because they prefer traditional technologies whose performance standards are well defined. The solution to these barriers is more emphasis on multifunctionality and the development of frameworks of evaluation that can encompass the entire spectrum of sustainability outcomes relating to nature-based systems[78,79].

On the whole, the sustainability performance and co-benefits of nature-based water treatment systems far exceed the removal of pollutants (**Table 4**). Through the provision of environmental, economic, and social value, these systems provide an attractive way forward to more holistic, resilient water management. The key to realizing this potential, however, lies in context-sensitive design, active management and explicit recognition of trade-offs and uncertainty in decision-making[9,66,67].

Table 4. Sustainability Outcomes and Co-Benefits.

System Type	Environmental Benefits	Economic Benefits	Social/Societal Benefits	Potential Trade-Offs/ Limitations
Constructed wetlands[80]	Low energy use, carbon sequestration, and biodiversity	Lower O&M costs, long-term cost-effective	Recreational value, community acceptance	Land requirement, seasonal performance variability
Biofiltration/ Bioretention[81]	Runoff attenuation, habitat creation	Reduced stormwater infrastructure cost	Urban aesthetics, educational opportunities	Maintenance needs, space limitations

Table 4. *Cont.*

System Type	Environmental Benefits	Economic Benefits	Social/Societal Benefits	Potential Trade-Offs/ Limitations
Riparian buffers [82,83]	Nutrient retention, flood mitigation	Low maintenance cost	Supports local agriculture, ecosystem service valuation	Variable performance, land-use conflicts
Floodplain restoration [84]	Watershed nutrient control, habitat restoration	Cost-saving from flood mitigation	Community resilience, biodiversity	Large footprint, long implementation time
Floating treatment wetlands [85]	Water quality improvement, habitat for aquatic life	Low infrastructure cost	Public engagement, aesthetic value	Limited contaminant removal, seasonal plant growth

7. Conclusions

Nature-based water treatment systems (NBWTS) are currently being recognized as significant elements of sustainable water management. Through a combination of the ecological process and the design, these systems are providing alternatives or supplements to traditional water treatment infrastructure. This review is a synthesis of existing information about the typology, worldwide deployment, performance, and sustainability of the large NBWTS, such as constructed wetlands, biofiltration systems, riparian buffer interventions, floodplain restoration interventions, and floating treatment wetlands.

The data points to the fact that NBWTS is capable of realizing significant water quality improvements in a variety of environmental settings. Removing organic matter and suspended solids is often reported to occur with high removal efficiencies, and nutrient removal and pathogen attenuation are more likely to vary based on system configuration, hydraulic conditions, and climatic conditions. Notably, the performance of the treatment is not something that can be measured out of context. The efficiency of NBWTS is directly associated with the overall outcomes of sustainability, such as the reduced use of energy, increased biodiversity, flood management, and better landscape quality. Simultaneously, various interplaying factors influence implementation results, among which are the variability of performance, availability of land, governance systems, and maintenance needs in the long-term. These interdependencies demonstrate the necessity to consider NBWTS in the context of the overall socio-ecological and infrastructure planning as opposed to technical treatment units.

This synthesis has many practical implications for practitioners and decision-makers. First, standardized measures of performance and monitoring procedures should be developed to enhance the comparability of studies and enhance confidence in NBWTS as effective modes of treatment. Second, there is a potential to utilize hybrid treatment configurations that can stabilize the nature-based systems with conventional infrastructure to achieve promising opportunities in terms of improving the reliability without compromising the sustainability it provides. Third system design and operation should include long-term monitoring and adaptive management to consider changes in time, aging of systems, and changing environmental conditions. Such actions can inform better planning, investment, and policy-making regarding sustainable water infrastructure.

There are many areas that future studies should lay emphasis on. Further research in long-term studies would be required to clarify the aging of the systems, their maintenance needs, and the stability of the treatment within the multi-decadal timeframes. More emphasis must also be given to greenhouse gas emissions and carbon balance in wetland-based systems to better determine their net effects on the climate. Moreover, the studies that will be essential in assessing resilience in the changing environment will be those that investigate system performance in the case of climate extremes, including extreme storm events or long periods of drought. Lastly, evidence-based selection of nature-based solutions in various socio-economic and climatic conditions requires comparison of life-cycle assessment and integrated sustainability assessment of various types of systems.

In general, NBWTS is a promising avenue for more resilient and versatile water infrastructure. They will be able to be incorporated effectively into the water management strategies of their future, relying on better performance assessment, better governance structures, and more interdisciplinary research that cuts across the engineering, ecology, and policy perspectives.

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The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

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