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Review

Mechanisms and Applications of Nature-Based Solutions for Stormwater Control in the Context of Climate Change: A Review

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Abstract: Nature-based solutions (NbSs) are considered to form an innovative stormwater management approach that has living resolutions grounded in natural processes and structures. NbSs offer many other environmental benefits over traditional grey infrastructure, including reduced air pollution and climate change mitigation. This review predominantly centers on the hydrological aspect of NbSs and furnishes a condensed summary of the collective understanding about NbSs as an alternatives for stormwater management. In this study, which employed the CIMO (Context, Intervention, Mechanism, Outcome) framework, a corpus of 187 NbS-related publications (2000–2023) extracted from the Web of Science database were used, and we expounded upon the origins, objectives, and significance of NbSs in urban runoff and climate change, and the operational mechanisms of NbSs (including green roofs, permeable pavements, bioretention systems, and constructed wetlands), which are widely used in urban stormwater management, were also discussed. Additionally, the efficacy of NbSs in improving stormwater quality and quantity is discussed in depth in this study. In particular, the critical role of NbSs in reducing nutrients such as TSS, TN, TP, and COD and heavy metal pollutants such as Fe, Cu, Pb, and Zn is emphasized. Finally, the main barriers encountered in the promotion and application of NbSs in different countries and regions, including financial, technological and physical, regulatory, and public awareness, are listed, and future directions for improving and strategizing NbS implementation are proposed. This review gathered knowledge from diverse sources to provide an overview of NbSs, enhancing the comprehension of their mechanisms and applications. It underscores specific areas requiring future research attention.

Keywords: nature-based solutions (NbSs); hydrology regulation; water quality enhancement; barriers; strategy

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1. Introduction

The burgeoning expansion of global urban landscapes, in conjunction with the multifarious impacts of climate change, is precipitating significant alterations in urban hydrological dynamics [1]. There have been variations in land use/land cover (LULC) during the urbanization process, where natural surfaces such as cropland, grassland, and waters have been largely replaced by impermeable surfaces like buildings and roads [2–4]. This fundamental transformation alters the surface properties of urban areas, resulting in an increase in the imperviousness and runoff coefficient of urban surfaces. The rising imperviousness leads to increased surface runoff, reduced rainwater infiltration, diminished groundwater re-charging, and deteriorating water quality [5]. Simultaneously, natural surfaces and impermeable surfaces exhibit significant differences in the properties of light absorption, heat capacity, and rainfall runoff coefficients [6]. This transition affects the energy budget and water budget of urban areas, leading to changes in the local climate of urban areas, such as abnormal variations in surface temperature and the intensity and duration of heavy precipitation events [2,7]. This has likewise led to the urban heat island (UHI) and convective rainfall initiation generation [7]. Concurrently, climatic fluctuations are inducing changes in precipitation patterns. Over the past few centuries, there have been major changes in climate behavior at global and regional scales, altering the transport patterns and availability of water [8]. The increase in average temperatures due to global warming has accelerated the hydrological cycle, which has had a direct impact on rainfall, particularly in terms of the number and duration of extreme rainfall events [9]. In addition, in the context of climate change, precipitation changes have taken place not only regarding amount, but also distribution and state [10]. Climate change may lead to changes in the distribution and seasonality of rainfall, and, according to previous studies, the proportion of seasonal and snowfall rainfall has a non-negligible impact on the average annual net flow [11]. This confluence of factors amplifies the risk of urban flooding, posing substantial threats to human settlements, infrastructural resilience, and ecological systems [12–14].

In response to these hydrological challenges, various nations have embarked on the implementation of sustainable approaches and technological advancements in urban stormwater management. Prominent examples include the Best Management Practices (BMPs) in the United States, Active, Beautiful, Clean (ABC) Waters in Singapore, and the Sponge City initiative in China [15,16]. In European urban centers, nature-based solutions (NbSs) have garnered increasing attention as a strategy to combat urban issues like climate change, urban decay, and aging infrastructure. NbSs are characterized as strategies that utilize natural elements to address various challenges such as climate change, food security, water resources, and disaster risk management [17]. These approaches involve conserving and utilizing biodiversity sustainably. They include green roofs, bioretention systems, and the construction of wetlands that serve to reduce surface runoff and improve water quality and air quality. Another NbS is the increased provision of urban green spaces such as parks and street trees to ameliorate high temperatures in cities [18]. Whatever the NbS measures, they will be inspired and supported by nature. For example, permeable pavements mimic the natural surface water cycle by allowing rainwater and other precipitation to infiltrate through its surface layers to nourish the groundwater. In bioretention, plants carry out the processes of rainwater retention, uptake, and conversion, and natural surfaces carry out the processes of infiltration. These processes are carried out through a series of chemical, biological, and physical processes that mimic the natural ecology [19].

There has been a global surge in research validating the efficacy of NbSs in improving water quality and reducing stormwater volume [20,21]. For instance, Liu et al. [22] examined the impacts of various NbS approaches at the watershed level, and their study found that different levels and combinations of NBS practices reduced runoff volume by 0 to 26.47%, TN by 0.30 to 34.20%, TP by 0.27 to 47.41%, TSS by 0.33 to 53.59%, Pb by 0.30 to 60.98%, BOD by 0 to 26.70%, and COD by 0 to 27.52%. Thiagarajan et al. [23] explored the comprehensive benefits of NbSs in residential areas and noted that NbSs has the capacity to capture 56 billion liters of stormwater annually if all residential properties used NbSs. The result found by Versini et al. [24] shows that a combination of several NbSs can reduce the runoff volume about 90%. While the ecological services and effectiveness of NbSs are well documented, there remain gaps, particularly in the optimization of their hydrological benefits [25]. Despite the numerous advantages of NbSs, their widespread integration faces challenges, notably the lack of comprehensive guidelines for their design, implementation, and maintenance [26], along with prevalent misconceptions about high maintenance costs and complex application, which hinder their broader acceptance [27,28].

Acknowledging the critical importance of NbSs, this review aims to synthesize the existing body of literature on NbSs in the context of urban stormwater management, highlighting its advantages, challenges, and potential solutions. Specifically, this review seeks to (1) elucidate the origins, objectives, significance, and fundamental processing mechanisms of NbSs in the midst of urban and climatic transformations; (2) critically analyze the effectiveness of several NbS practices (specifically green roofs and bioretention) in reducing surface runoff and improving water quality (the results show that NbS practices can significantly reduce surface runoff, peak flow, and remove pollutants from runoff, including TN, TP, TSS, COD, and heavy metals); and (3) provide examples of the main barriers to NbS implementation in different countries or regions and propose comprehensive strategies for their sustainable integration.

2. Methods

This investigation meticulously appraises the hydrological efficacy of NbSs, primarily focusing on studies that elucidate runoff mitigation and water quality enhancement. To ensure methodological robustness, this review employs a structured research paradigm, enabling an exhaustive reconnaissance of pertinent works in the literature and a meticulous scrutiny of relevant studies. The analytical framework employed is the Context, Intervention, Mechanism, Outcome (CIMO) model, acclaimed for its analytical acumen in systematic literature reviews [29]. Within this paradigm:

- Context delineates the specific environmental or situational backdrop of the study;
- Intervention denotes the specific NbS or practice under examination;
- Mechanism investigates the causative linkages between the intervention and its ensuing effects;
- Outcome encapsulates the resultant effects or consequences engendered by the intervention, as driven by the identified mechanism [30].

The central research inquiry addressed herein is as follows: "In the milieu of urbanization and climatic fluctuations, how do NbS interventions modulate urban hydrological outcomes via their intrinsic mechanisms?"

Operationalizing the CIMO framework involved pinpointing key terminologies such as "Nature-based solutions", "low impact development", "runoff", "rainwater", "urban drainage", "hydrological processes", "flood management", "best management practices", "sponge city", "sustainable urban drainage systems", and "water-sensitive urban design". These terminologies were assimilated into an extensive search protocol, employing Boolean operators (OR within categories and AND between categories) for scrutinizing titles, abstracts, and the core content of seminal papers. The initial screening of articles was predicated on criteria such as article genre (e.g., empirical studies, reviews), publication recency (prioritizing the last decade), and linguistic medium (English). Further refinement of article selection emphasized the caliber and pertinence of the literature [31], with exclusion criteria disqualifying studies that did not directly address NbSs in urban hydrological contexts or those devoid of empirical data.

A systematic analysis of NbS research from 2000 to 2023 was carried out using the core collection database of Web of Science. The principal data repository was the Web of Science database, selected for its comprehensive scope and scientific rigor [32,33]. To augment the scope of the literature search, additional databases such as Scopus and Google Scholar were also perused. The selected articles were subjected to an in-depth content analysis, focusing on the categorization and delineation of NbS practices and their respective benefits. The synthesis approach amalgamated both qualitative and quantitative methodologies, facilitating a nuanced comprehension of NbS applications and outcomes. This hybrid methodology permits an all-encompassing exploration of the multifarious aspects of NbS efficiency in urban stormwater management. The section culminates with an acknowledgment of potential methodological constraints, such as the reliance on published academic literature, potentially excluding grey literature or unpublished studies, and the concentration on English-language articles, which may inadvertently neglect significant research published in other languages.

3. Review Results and Discussion

3.1. Literature Search Results

An advanced query within the SCI–EXPANDED (Science Citation Index Expanded) subset of the Web of Science Core Collection from 2000 to 2023 yielded 1907 documents using key terms such as “Nature-based solution”, “Best management practice”, “Water-sensitive urban design”, “Sponge city”, “Green infrastructure”, “Low impact development”, and SUDS in conjunction with hydrological variables like runoff, rainfall, drainage, and flood. This initial corpus was meticulously refined by excluding non-article document types such as reviews and meeting abstracts, which may not encapsulate a comprehensive NbS practice process. This filtration resulted in 161 articles being excluded. A subsequent thematic culling excluded disparate fields such as computer science and metallurgy, leaving 548 studies in more relevant domains. A closer examination of abstracts and titles further distilled the collection, focusing on studies directly investigating NbSs’ impact on urban hydrology, culminating in 187 studies being selected for in-depth analysis (Figure 1).

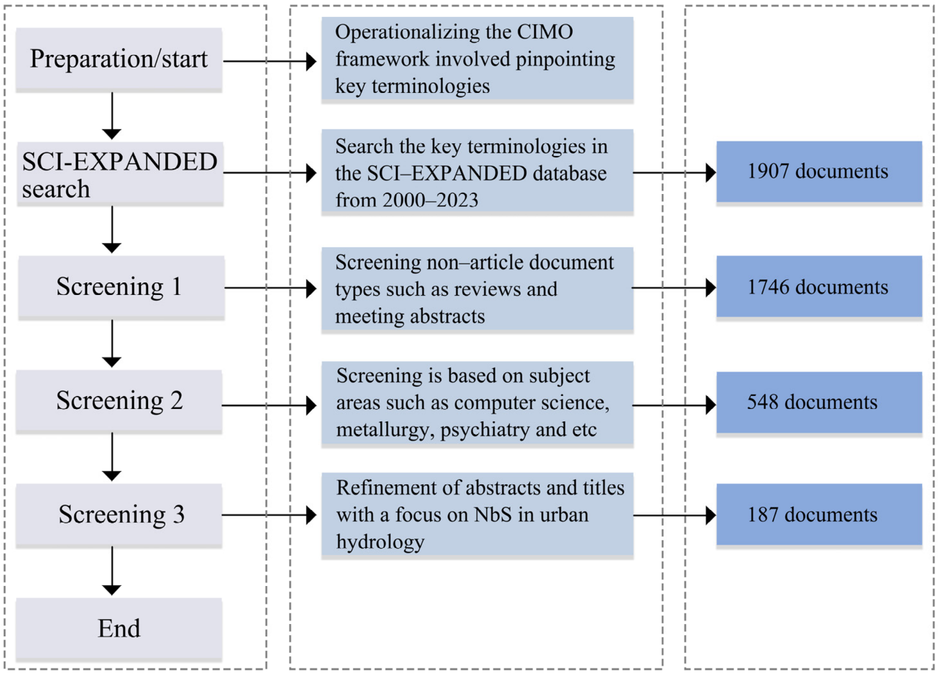

Figure 1. A step-by-step process for filtering relevant articles from search results.

3.2. Overview of Nature-Based Solutions

3.2.1. Historical Trajectory of Nature-Based Solutions

The genesis of NbSs is anchored in the interplay between biodiversity and human welfare, initially surfacing in the ecosystem services discourse of the 1970s [34]. The late 20th century witnessed a pivotal shift in conservation strategies, transitioning from an anthropocentric focus to a more holistic human–nature synergy [35]. This transition marked the evolution from passive nature beneficiaries to active ecosystem stewards. The European Commission’s recent definition encapsulates NbSs as multifaceted, cost-effective approaches that bolster resilience while yielding environmental, social, and economic dividends [35]. This conceptual evolution has been paralleled by a diversification in methodologies, although terminologies vary across different stormwater control frameworks [36,37].

3.2.2. Intervention of Nature-Based Solution Implementations

NbSs are predicated on harnessing natural systems and processes to foster functionally equivalent hydrologic landscapes, eschewing traditional infrastructural approaches. This paradigm emphasizes natural processes like evapotranspiration and infiltration, integrating botanical, geomaterial, and bioengineering elements to modulate stormwater dynamics [38]. Empirical evidence substantiates NbSs' role in addressing urban hydrological challenges, including runoff modulation and flood mitigation, while offering cost-effective alternatives to conventional methods [39,40]. Additionally, NbSs' assimilation into urban landscapes augments ecological vitality, offering a spectrum of ecosystem services [41].

3.2.3. Mechanistic Underpinnings of NbSs for Stormwater and Contaminant Regulation

Deciphering NbSs' mechanics is essential for optimized stormwater management. NbSs orchestrate a suite of processes—such as soil infiltration and vegetative absorption—to effectively mitigate stormwater runoff and modulate peak flows. Specifically, in the case of bioretention, for example, when stormwater runoff enters the bioretention system, it will first pass through the vegetation layer, where the vegetation will absorb and retain some of the water. Then, the residual water flow will enter the soil layer, and through the porous structure and water absorption capacity of the soil, the water will gradually penetrate deep into the soil until it reaches the storage layer for the temporary storage of stormwater. The stormwater is finally either discharged downstream through underdrain pipes or infiltrated into the subsoil below the soil bed [19]. During this process, some of the water may overflow the bioretention system due to soil saturation or unfavorable topography. While some water will be retained in depressions or between vegetation, this water may be absorbed by plants or evaporate directly. Through plant transpiration, water is returned to the atmosphere as water vapor. In the case of green roofs, similar to bioretention, rainfall is intercepted through a vegetative layer, allowed to infiltrate into a substrate layer, and then stored in the storage layer and finally drained through a drainage layer. Concurrently, these systems facilitate pollutant filtration and biotransformation through synergistic interactions among plant species and microbial consortia [42]. This mechanistic insight underscores the importance of strategic species and matrix selection to maximize hydrological efficiency within the NbS framework.

4. Leveraging NbS Techniques for Urban Stormwater Management

NbSs have been empirically validated as potent tools for stormwater management and the enhancement of urban hydrological systems. This review highlights four seminal NbS implementations, each chosen based on a comprehensive set of criteria: Green Roofs, Permeable Pavement Systems, Bioretention Systems, and Constructed Wetlands.

Green Roofs: In the face of escalating urbanization, the proliferation of built structures within cityscapes presents a unique opportunity. The integration of green roofs on these structures offers multifarious benefits. These include the mitigation of surface runoff, the enhancement of urban greenery, the moderation of indoor temperatures, and subsequent energy conservation. The convergence of these factors underscores the criticality of research into green roof technology.

Permeable Pavement Systems: These systems are distinguished by their versatility and minimal land use requirements, negating the need for additional land acquisition [43]. Their adaptability across varied urban contexts and cost-effectiveness compared to traditional pavement materials underscore their practical significance.

Bioretention Systems: Designed as landscaped depressions, bioretention systems not only optimize urban hydrological functions but also integrate aesthetically with urban landscapes. These systems serve a dual purpose of water management and urban beautification.

Constructed Wetlands: Representing a larger-scale NbS intervention, constructed wetlands are paramount in addressing water eutrophication and the removal of heavy metals. They exemplify the capacity of NbSs to tackle complex environmental challenges at a substantial scale.

Collectively, these NbS implementations are instrumental in reducing runoff, thereby mitigating urban flood risks. Their hydrological benefits have been substantiated through extensive field studies and advanced modeling simulations [44], demonstrating their efficacy in urban stormwater management.

4.1. Green Roofs (GRs)

Green roofs, multifunctional components of urban ecosystems, serve as water storage matrices while providing a suite of ecosystem benefits (see Figure 2). These benefits encompass thermal regulation, air pollution mitigation, and urban hydrology enhancement. In densely populated urban areas, where terrestrial green spaces are limited, green roofs emerge as pivotal repositories of urban biodiversity and essential green spaces [45].

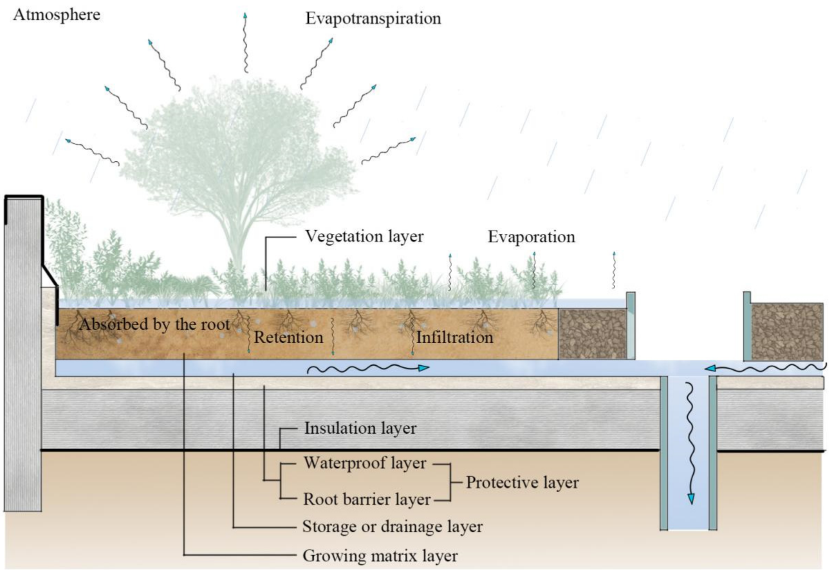

Figure 2. Mechanism diagram of green roof in providing regulation services for hydrological process.

4.1.1. Efficacy in Stormwater Runoff Retention

Table 1 delineates various studies highlighting green roofs' capacity to mitigate stormwater runoff and diminish peak flow. Nonetheless, their hydrological efficacy is subject to a confluence of factors: climatic conditions, geometric design, substrate properties, drainage layer depth, vegetation type, and stormwater metrics [46,47].

Substrate depth and composition are critical in optimizing stormwater retention capabilities [48,49]. Vegetation type plays a salient role, particularly under arid conditions and elevated temperatures [50]. Research by Nagase and Dunnett reveals that grasses outperform other plant types, such as forbs and sedum, in stormwater retention [51]. Carter and Rasmussen report a correlation between rainfall intensity and runoff retention, noting a higher retention rate for lighter rainfall, and that runoff is reduced by just under 90% when rainfall is less than 2.54 cm and by just under 50% when rainfall is greater than 2.54 cm [52]. Villarreal and Bengtsson identified an inverse relationship between rainfall intensity and water retention [53]. Further, Li et al. [54] expounded on the hierarchical impact of various factors on runoff retention and peak flow reduction.

Table 1. The application of green roofs for the reduction of runoff peak flow.

Country	Green Roof Information	Site Characteristics	Runoff/Outflow Reduction (%)	Peak Flow Reduction (%)	Other/Notes	Reference
China	100 cm long × 100 cm wide × 40 cm high Substrates (10 cm in depth)	The mean annual precipitation is 587 mm	81.00–87.00	83.00–87.00	Natural rainfall events	Zhang et al. [48]
China	Mainly refers to the national standard for the technical specifications of green roof construction	Study areas under 2.70 hectares	31.40–69.80	19.80–65.20	In the 5-year period rainfall events	Yao et al. [55]

Table 1. *Cont.*

Country	Green Roof Information	Site Characteristics	Runoff/Outflow Reduction (%)	Peak Flow Reduction (%)	Other/Notes	Reference
Italy	N/A	Residential area, imperviousness of 96.0%	25.90–62.80	31.40–83.80	The rainfall duration was assumed 30 min and the time-to-peak ratio 0.4	Palermo et al. [56]
China	Four types of vegetation cover (Portulaca grandiflora, Sedum lineare, Festuca elata, and bare substrate)	Subhumid continental monsoon climate in north temperate zone	41.70–54.20	50.60–59.10	The heaviest rainfall event during the observation period (81.4 mm)	Ge and Zhang [57]
Greece	Substrate depth is 8 cm or 16 cm while plant species is Sedum or origanum or no vegetation	N/A	22.80–62.00	56.90–79.10	The duration of the studied rainfall events ranged between 50 min and 2640 min	Soulis et al. [58]
England	The test bed (3 × 1 m) comprised a sedum vegetation layer growing in 80 mm of substrate	Located in typical extensive green roof build-up	0.04–99.95	19.81–99.93	Rain depth (mm) between 8.80 mm and 99.6 mm	Stovin et al. [59]

4.1.2. Efficacy in Augmenting Stormwater Quality

Table 2 provides insights into green roofs' proficiency in reducing pollutants such as Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Total Nitrogen (TN), and Total Phosphorus (TP). Green roofs act as contaminant filters, leveraging processes like filtration, sedimentation, adsorption, plant uptake, and biodegradation [60]. However, discrepancies in effluent quality are observed, attributed to design variability, construction methods, substrate types, and environmental factors [61,62]. Studies in diverse geographical locales by Liu et al. [63] and Koc et al. [64] demonstrate significant pollutant reductions. The results of Liu et al. showed that the removal ratios of GR for TSS, COD, and TN reached 31.60%, 25.10%, and 37.8%, respectively, while Koc et al. demonstrated 41.15%, 39.73%, and 29.58%. Moreover, green roofs have shown efficacy in heavy metal sequestration from precipitation, as indicated in Table 3.

Table 2. The attenuation of TSS, COD, TN, and TP in green roofs.

Country	Runoff Source	Scale	Filter Media	Pollutant Removal Efficiency (%)				Reference
				TSS	COD	TN	TP	
Greece	Natural rainfall events	Field	Vermiculite	93.00	91.00	87.00	N/A	Thomaidi et al. [65]
China	Simulated rainfall events	Laboratory	Peat soil, vermiculite and polyaluminum chloride (PAC)	N/A	N/A	6.04	84.33	Zhang et al. [66]
Turkey	Simulated rainfall events	Laboratory	N/A	41.15	39.73	29.58	32.26	Koc et al. [64]
The Netherlands	Simulated rainfall events	Laboratory	N/A	22.00	N/A	19.00	20.00	Dutta et al. [67]
China	Simulated rainfall events	Laboratory	Combined substrate	44.77	N/A	19.60	45.51	Zhang et al. [68]
China	natural rainfall events	Field	Commercial substrate	31.60	25.10	37.80	N/A	Liu et al. [63]
Republic of Korea	natural rainfall events	Field	N/A	77.00	N/A	57.00	53.00	Jeon et al. [69]
China	natural rainfall events	Field	Perlite or recycled bricks	37.85	N/A	14.52	12.93	Chai et al. [70]

Table 2. *Cont.*

Country	Runoff Source	Scale	Filter Media	Pollutant Removal Efficiency (%)				Reference
				TSS	COD	TN	TP	
China	Simulated rainfall events	Laboratory	Peat soil	N/A	30.00	42.00	47.00	Zhang et al. [71]
India	Simulated rainfall events	Laboratory	Sand, brick bats, and gravel	85.00–90.00	88.00	88.00–99.00	92.00	Chandrasekaran et al. [72]
Vietnam	Natural rainfall events	Field	Soil, sand, crushed stone, and gravel	64.30–73.10	77.00–78.00	88.00–91.00	72.00–78.00	Bui et al. [73]
China	Simulated rainfall events	Laboratory	N/A	80.00–90.00	50.00–70.00	50.00–70.00	40.00–70.00	Zhou et al. [74]

Table 3. The attenuation of heavy metals in green roofs.

Country	Filter Media	Runoff Source	Removal Efficiency of Heavy Metal (%)				Reference
			Cu	Zn	Pb	Cd	
China	Loam, perlite, pure cocopeat, and sodium polyacrylate	Simulated rainfall events	N/A	94.55	98.84	N/A	Guo et al. [75]
India	Perlite, vermiculite, sand, crushed brick, cocopeat, and *T. conoides*	Simulated rainfall events	95.50	96.60	98.30	97.80	Kuppusamy and Joshi [76]
India	Perlite, crushed brick, and sand	Simulated rainfall events	99.20	97.40	99.90	99.90	Kuppusamy and Raja [77]
France	Commercial substrate	Natural rainfall events	87.00–90.00	70.00–98.00	N/A	N/A	Seidl et al. [78]
USA	Commercial substrate	Natural rainfall events	50.00	65.80	Nearly 100	N/A	Gregoire et al. [79]
USA	An expanded clay mixed with pine bark	Simulated rainfall events	94.00	65.02	80.46	N/A	Sarah et al. [80]

Conversely, instances of elevated pollutant concentrations, notably total phosphorus and nitrate, have been observed in green roof runoff [47]. For example, Gong et al. [81] noted a doubling of nitrate concentrations following rainfall events on green roofs. Razzaghmanesh et al. [82] reported a significant increase in nitrate concentrations in Adelaide, Australia. Such phenomena may be exacerbated by the use of phosphorus-rich fertilizers, as evidenced by Castro et al. [83], who observed a substantial increase in TP concentrations in Porto Alegre, Brazil.

While green roofs offer a multitude of ecological and hydrological benefits in urban environments, their impact on stormwater quality demands detailed examination. This necessitates comprehensive research to fully understand and optimize the multifaceted roles and benefits of green roofs in urban ecosystems.

4.2. Permeable Pavement Systems (PPSs)

Permeable Pavement Systems (PPSs) represent a forward-thinking approach to stormwater management, distinguished by their capacity to facilitate water percolation into the underlying soil layer. This unique characteristic positions PPSs as a potent tool in mitigating urban flood risks, particularly in densely urbanized areas where conventional green spaces are scarce (Figure 3) [84]. PPSs significantly contribute to urban infrastructural resilience by maintaining natural hydrological cycles, thereby enhancing groundwater recharge and reducing stormwater runoff. Given that pavements account for a substantial portion (20–40%) of urban areas, the transition from traditional impervious surfaces to permeable alternatives marks a critical shift towards sustainable urban water management [85].

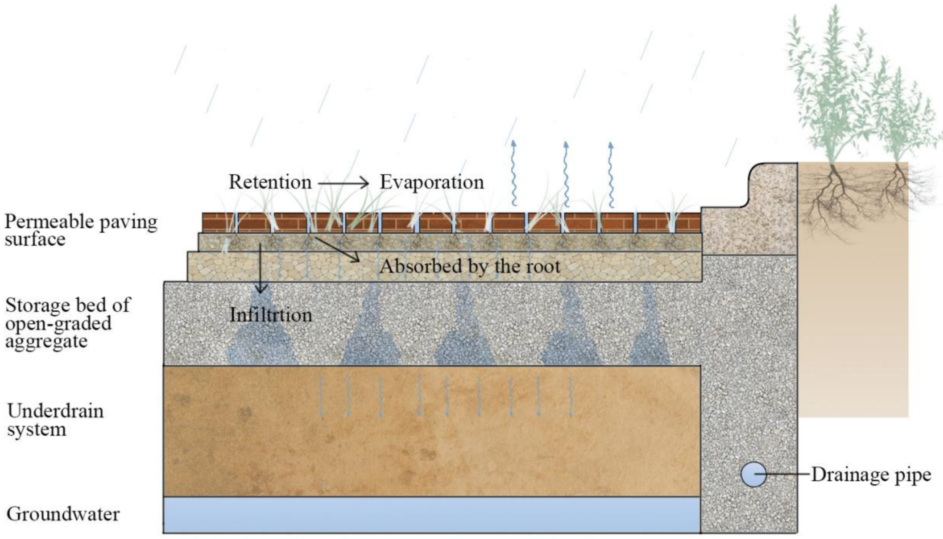

Figure 3. Mechanism diagram of permeable pavement providing regulation services for hydrological processes.

4.2.1. Efficacy in Stormwater Runoff Retention

PPSs demonstrate a variable retention capacity for rainwater, typically between 16 and 66%, resulting in marked reductions in drainage pressure, hydraulic flow rates, and the frequency of stormwater influx [86]. Empirical studies underscore this efficacy: Kumar et al. [87] observed that PPSs in Illinois significantly exceeded regional median rainfall infiltration rates. Computational models by Liu et al. [14] in Beijing's Haidian District indicated the peak flows were reduced 37.9–35.7%, respectively, under 1-, 2-, 5-, and 10-year storm events, attributed to the conversion of impervious surfaces to permeable materials. Park et al. [88], in Busan, South Korea, further demonstrated the varying efficacy of PPS types in reducing total and peak flows. The peak flow decreased by 9.1%, 10.7%, 5.9%, and 15.8%, and the total outflow decreased by 3.6%, 3.1%, 1.4%, and 16.3%, respectively. Wang et al. [89] highlighted PPSs' heightened performance during less intense, shorter-duration rainfall, although its effectiveness diminished under more severe storm conditions.

4.2.2. Efficacy in Augmenting Stormwater Quality

PPSs inherently excel in pollutant sequestration, utilizing mechanisms such as interception, filtration, sedimentation, nutrient transformation, and microbial degradation. This is largely due to their porous structure [90,91]. Removal rates within the PPS matrix are notable, with TSS and COD extraction ranging broadly, and significant reductions in heavy metals such as Cd, Cu, Pb, and Zn. Liu et al. [92] correlated pollutant removal with factors like rainfall intensity and gravel layer size. The results showed that for permeable paving, the removal rates of TSS, Cd and Cu were less affected by rainfall intensity, with removal rates ranging from 93.76 to 98.66%, 92.84 to 95.97%, and 90.49 to 98.26%, respectively. A comprehensive study by Mahmoud et al. [93] in Texas, USA, reported average reductions of 76% for 23 samples, 56% for 19 samples, and 12% for 11 samples in TSS, BOD, and Escherichia coli. However, the variability in PPSs' pollutant removal efficiency is significant, as evidenced by Wang et al. [94], who noted fluctuating removal rates for TP and TN; the TP and TN removal efficiencies of the systems can vary from 6 to 68% and 5 to 99%, respectively. A major challenge for PPSs is substrate clogging, primarily due to TSS accumulation during rainfall events [95]. Substrate composition, particularly concrete with smaller aggregates and higher air voids, has been shown to offer enhanced purification capabilities [96].

4.3. Bioretention Systems (BRs)

Bioretention systems have been acknowledged as a critical on-site intervention for urban stormwater management, principally facilitating permeation and evaporation to replicate pre-development hydrological conditions (Figure 4) [20]. These systems are adeptly integrated into urban landscapes, offering a sustainable alternative to conventional stormwater infrastructure, particularly in densely populated urban areas [97].

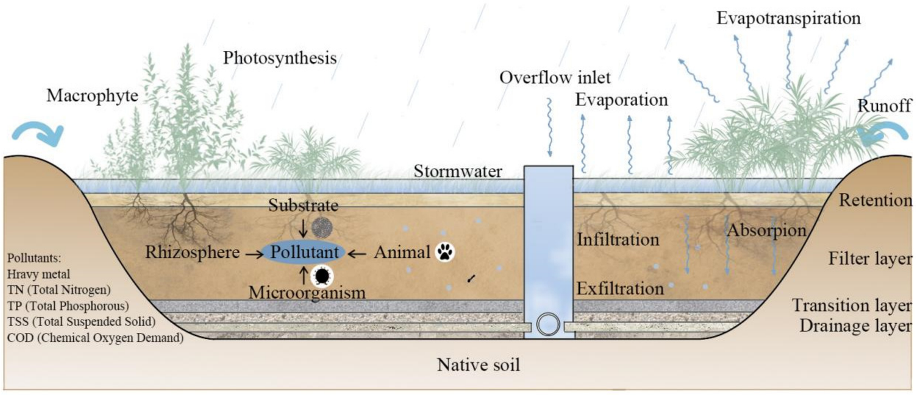

Figure 4. Mechanism diagram of bioretention in in providing regulation services in hydrological processes.

4.3.1. Efficacy in Stormwater Runoff Retention

The proficiency of bioretention systems in stormwater runoff retention is noteworthy, with peak discharge rate reductions ranging from 40% to an impressive 99% [98]. Table 4 delineates the effectiveness of bioretention cells in reducing stormwater runoff and attenuating peak flow. Investigations by Lucke and Nichols in Caloundra, Australia, revealed variable reductions in runoff volume and peak outflow [99]. They conducted four experiments on each of the three bioretention systems, and the results of the experiments showed that the percentage reduction in peak outflow after treatment with the three bioretention systems ranged from 79.5% to 93.6%. The role of infiltration and evapotranspiration is emphasized by Li et al. [100] of Maryland, who showed that approximately 20–50% more of the runoff entering bioretention was lost to infiltration and evapotranspiration. Winston et al. [101] reported runoff reductions in northeast Ohio in areas with low-permeability soil: runoff and peak flows were reduced by 36.00–59.00% and 24.00–96.00%, respectively. Hydraulic conductivity plays a pivotal role, with higher conductivity substrates facilitating extended interactions between the substrate and pollutants [102]. However, excessively high hydraulic conductivity could undermine the comprehensive treatment of contaminants [103]. The use of various substrates like biochar and zeolite has been explored to enhance specific characteristics such as hydraulic conductivity and plant growth [104]. Substrate depth also significantly influences hydrological performance, with deeper substrates yielding superior retention compared to shallower ones [100]. The role of flora in improving hydrological and hydraulic metrics is undeniable, with indigenous vegetation often preferred for its resilience [105].

Table 4. The application of bioretention systems for the reduction of runoff and peak flow.

Country	Bioretention System Information	Site Characteristics	Runoff/Outflow Reduction (%)	Peak Flow Reduction (%)	Other/Notes	Reference
China	A 10 cm aquifer layer, 5 cm mulch layer, 30 cm soil medium layer, 40 cm filler layer, and 15 cm gravel layer were set by geotextiles	The mean annual precipitation is 587 mm	14.00–78.00	9.00–91.00	In the 2-year, 30-year, and 100-year return period	Yang et al. [106]
USA	(250 ft) linear bioretention cell	Located in a highly impermeable area with a total area of 8494 square meters	80.10–98.20	N/A	45 storm events were observed, ranging from 1.8 to 49.5 mm	Mahmoud et al. [107]
USA	Referred to design guidance in the Ohio Rainwater and Land Development Manual	0.36 ha, 77.1% impervious catchment	36.00–59.00	24.00–96.00	1-year design rainfall intensities	Winston et al. [101]
Australia	Consisted of a filter medium (usually sandy), underlaid by a gravel drainage layer	The BRSs were located directly adjacent to the roadway	32.70–84.30	79.50–93.60	Natural rainfall events	Lucke and Nichols. [99]
Greece	Has a depth of 0.95 m, and media contained a 0.35 m depth of gravel and a 0.4 m depth of soil/planting soil.	Received stormwater runoff from a playground with an area of 7672 m^2	47.00–80.00	50.00–84.00	A total of 19 natural rainfall events were monitored	Jia et al. [108]
USA	The BRS employed two different media depths (0.6 and 0.9 m)	N/A	63.00–89.00	84.00–95.00	Rain depth (mm) between 8.80 and 99.6 mm	Brown and Hunt. [109]

4.3.2. Efficacy in Augmenting Stormwater Quality

Bioretention systems are highly effective in mitigating stormwater pollutants. Table 5 presents their capacity to attenuate TSS, COD, TN, and TP. Research by Shrestha et al. [110] demonstrated significant reductions in these pollutants, TSS, TN, and TP were reduced by 91.00–97.00%, 38.00–57.00%, and 86.00–94.00%, respectively. Jhonson et al. showed that bioretention removed 90.00%, 92.50%, 86.40%, and 93.50% for TSS, COD, TN, and TP, respectively. Substrate adsorption, filtration, and sedimentation play key roles in TSS removal, while the abatement of heavy metals depends on fillers and processes like precipitation and ion exchange [111,112]. Gülbaz et al. [113] showed varied metal removal rates due to different cation exchange capacities. The order of metal removal percentages was found to be Pb > Cu > Zn. Calculated delay factors ranged from 5 to 910 for Zn, 20 to 3600 for Cu, and 100 to 27,000 for Pb, with turf having the highest delay factor and gravel having the lowest. Substrate depth is a critical factor, affecting the interactions between the substrate, stormwater, and plants, thus enhancing contaminant removal [114].

Table 5. The attenuation of TSS, COD, TN, and TP in bioretention systems.

Country	Runoff Source	Scale	Filter Media	Pollutant Removal Efficiency (%)				Reference
				TSS	COD	TN	TP	
Malaysia	N/A	Laboratory	Sand, topsoil, and compost	90.00	92.50	86.40	93.50	Jhonson et al. [115]
China	Simulated rainfall events	Laboratory	Coal gangue (CG)	N/A	33.00–86.00	30.00–70.00	94.00–99.00	Zhang et al. [116]
China	Simulated rainfall events	Laboratory	Pyrite and zeolite	N/A	N/A	89.30	81.60	Chen et al. [117]
China	Simulated rainfall events	Laboratory	Traditional substrate: sand	N/A	86.00	71.80	68.00	Yang et al. [118]

Table 5. *Cont.*

Country	Runoff Source	Scale	Filter Media	Pollutant Removal Efficiency (%)				Reference
				TSS	COD	TN	TP	
USA	Natural rainfall events	Field	Compost	83.00–96.00	N/A	17.30–38.50	80.00–92.00	Shrestha et al. [119]
Japan	Simulated rainfall events	Laboratory	N/A	13.00–15.50	12.90–16.17	12.83–17.34	14.03–19.07	Zhang et al. [120]
China	Simulated rainfall events	Laboratory	Biochar	31.60	78.5–94.6	82.30–97.00	57.36–93.70	Xiong et al. [121]
China	Simulated rainfall events	Laboratory	Sandy loam	92.00–97.00	64.00–95.00	75.00	>99.00	Qiu et al. [122]
USA	Natural rainfall events	Field	Sandy	N/A	N/A	72.00	79.00	Johnson and Hunt [123]
USA	Natural rainfall events	Field	Sand, compost, and pure sand	91.00–97.00	N/A	38.00–57.00	86.00–94.00	Shrestha et al. [110]
USA	Natural rainfall events	Field	N/A	96.00	N/A	42.00	75.00	Braswell et al. [124]
Australia	Natural rainfall events	Field	N/A	83.00	N/A	23.00	11.00	Nichols et al. [125]

Traditional bioretention systems often show limited nitrogen removal efficiency due to aerobic conditions within substrates. Innovative approaches, such as creating anaerobic environments at the base, have significantly improved NO_3^- and TN removal [122]. The addition of carbon sources like wood chips to the submerged zone has proven effective in reducing nitrate leaching [31]. Plants play a crucial role in the removal of organic matter, nitrogen, and phosphorus, although their effectiveness varies with the type of pollutant [126]. Plants with longer roots are typically more efficient in nitrogen and phosphorus removal [127].

4.4. Constructed Wetlands (CWs)

Constructed Wetlands (CWs) are engineered ecosystems designed to mimic the functions and features of natural wetlands. They are proficient in eliminating a range of contaminants through the synergistic action of phytoremediation, facilitated by aquatic plants, and in bioremediation, conducted by microorganisms in the soil and rhizosphere, as illustrated in Figure 5 [128]. CWs are categorized based on their flow regimes into free water surface (FWS), subsurface flow (SSF)—which includes horizontal (HSSF) and vertical (VSSF) subsurface flow—and the emerging floating treatment wetlands (FTWs). FTWs are particularly adept at coping with the hydrological fluctuations of storm events, due to their unique floating vegetation matrices [129]. As a solution to the technical challenges of traditional stormwater management, especially in fluctuating hydrological conditions, FTWs can be seamlessly integrated into existing water bodies, negating the need for additional land use [130].

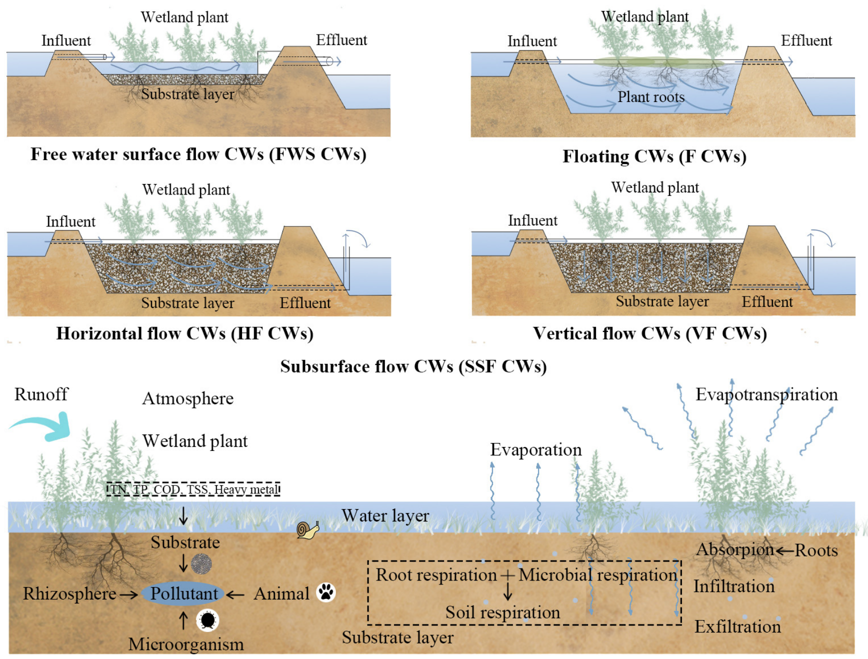

Figure 5. Mechanism diagram of Constructed Wetlands, providing regulation services for hydrological processes.

4.4.1. Efficacy in Stormwater Runoff Retention

While CWs are renowned for pollutant removal, their role in stormwater runoff attenuation is less emphasized due to their primary design focus on wastewater treatment [131]. Research into their potential as stormwater volume regulators is limited. Urban CWs face challenges such as land availability constraints and, in the case of FWS CWs, a minimal risk of pathogenic transmission. However, studies highlight their effectiveness in stormwater control. A North Carolina wetland demonstrated significant reductions in runoff volumes and peak flows by 54% and 80%, respectively [132]. Liu et al. [131] reported average reductions of 29.6% in runoff volume and 98.7% in peak flow across various rainfall events. Innovative approaches integrating CWs with urban drainage systems have also been explored. Rizzo et al. [133] developed a model evaluating the hydrological benefits of CWs in tandem with combined sewer overflow (CSO) systems, observing peak flow reductions up to 95.4%.

4.4.2. Efficacy in Augmenting Stormwater Quality

CWs harness a complex interplay of physical, chemical, and biological processes, including volatilization, mineralization, and biological degradation [128]. An investigation into a North Carolina stormwater wetland revealed substantial reductions of 42%, 36%, 47%, and 49% for NH_4^+-N, TN, TP, and TSS [132]. Chunbo et al. [134] found that optimizing the carbon-to-nitrogen ratio within CWs can significantly enhance NH_4^+-N, NO_3^--N, TN, and TP removal; removal rates were 19.0–75.3%, 63.6–96.1%, 61.94–74.4%, and 75.0–98.8%, respectively. FTWs, due to their increased biomass interaction interfaces, amplify pollutant removal efficacy by enhancing plant–microbe symbiosis and facilitating nutrient assimilation [135]. Studies in Singapore and New Zealand have demonstrated the potential of FTWs in removing TN and TP, as well as in assimilating heavy metals [136]. However, Maxwell et al. [137] caution that FTW enhancements in stormwater ponds may not always yield optimal water quality improvements.

4.5. Combination NbS Practices

In the evolving landscape of urban hydrology and water quality improvement, most evaluations of NbSs have traditionally focused on single-strategy implementations. However, recent research indicates a significant synergistic enhancement when multiple NbS approaches are integrated. This enhanced efficacy arises from the comprehensive application and mutual reinforcement provided by combined systems [138]. For instance, a singular NbS approach resulted in an 18.62% reduction in runoff and a 16.61% decrease in peak flow. Conversely, a composite Green Stormwater Infrastructure approach, incorporating infiltration trenches, rain barrels, and bioretention systems, led to a more substantial reduction of 42.95% in runoff and 31.17% in peak flow [138]. Echoing these findings, Liu et al. [22] demonstrated that integrated NbS solutions notably outperformed individual strategies in reducing runoff volume and pollutant load.

Delving into computational analysis, Luan et al. [139] explored the impact of a strategic combination of diverse NbS tools, including a concave greenbelt with a significant 50% concavity ratio, permeable pavements, bioretention cells, and vegetative swales. This comprehensive approach markedly surpassed the effectiveness of isolated methods, achieving an impressive peak discharge reduction of 55.7% across various rainfall events. However, it is crucial to recognize the variability and site-specific characteristics in NbS implementation. This necessitates the tailored customization of NbS combinations, ensuring that they are optimally aligned with the unique environmental contexts they are designed to enhance.

5. Barriers and Strategies for NbS Implementation

5.1. Barriers and Challenges

GSI has demonstrated great ecological benefits in urban hydrological management and has become an integral part of sustainable urban planning [140]. In the last two decades, there has been an upsurge in research on NbSs due to the increasing intensity and frequency of urban flooding events triggered by urbanization and climate change, which have caused substantial economic losses to human societies. These catastrophic experiences have prompted the public and stakeholders to explore NbSs as a sustainable solution. Despite the burgeoning recognition of NbSs in stormwater management, their adoption is often eclipsed by conventional Grey Infrastructure for Rainwater and Effluent (GREI) due to multifarious impediments. Variability in NbS applications and developmental paradigms across nations are significant, particularly in developing countries, where gaps exist in professional expertise, financial resources, and other essential areas. Additionally, varying climatic and pedological conditions impede the straightforward transplantation of NbS methodologies across regions. This discord between theoretical frameworks and practical application has notably hindered global NbS deployment. Predominant barriers to NbS implementation include financial constraints, technical and physical limitations, regulatory challenges, and public awareness issues.

5.1.1. Financial Constraints

While NbSs employ economically viable materials for micro-scale urban interventions, large-scale deployments demand substantial capital investments, constituting a significant economic hurdle [141]. Current research into cost–benefit analyses of NbSs suggests that although lifecycle costs are lower than traditional GREI, initial expenditures and ongoing maintenance costs are comparatively higher [89]. Presently, governmental funding is the primary financial source for NbS projects, with private investment remaining limited due to disproportionate returns. Moreover, ancillary benefits such as social welfare enhancement and land value appreciation are often underappreciated, thus deterring governmental financial backing.

5.1.2. Technical and Physical Limitations

The dearth of robust technical support impedes the widespread adoption of NbSs, leading to disparities in implementation success. Despite the availability of technical guidelines, a lack of expertise and skilled labor across design, construction, and maintenance phases poses significant challenges [142]. Data limitations in areas like hydrological characteristics and construction methodologies obstruct precise computational modeling, thereby undermining public confidence in NbSs [143]. Furthermore, diverse interpretations of NbSs, efficacy uncertainties, and the absence of localized benchmarks hinder progress [144].

5.1.3. Regulatory Barriers

While NbSs emerged in the 20th century, only a few countries have developed comprehensive legal frameworks and institutional mechanisms for their implementation. For example, Guangzhou, China, has integrated the 'sponge city' concept into urban planning, but such initiatives are not universally observed. Legislative restrictions and a lack of intersectoral collaboration further constrain NbS expansion. In addition, in places such as the USA, where conflicts between local ordinances and private property rights are clear, conflicts can also complicate the attribution of responsibility for maintenance when NBS areas are located on private property [19].

5.1.4. Public Awareness Challenges

Public unfamiliarity with NbSs' transformative potential in urban hydrological management and landscape enhancement remains a significant barrier [141]. For example, in American cities, the prevailing belief among residents is that the current price of municipal water is exceedingly low. Consequently, they view the adoption of new water harvesting techniques as lacking cost-effectiveness. This perception leads to reluctance in supporting new NbS practices [145]. Governmental entities play a critical role in advocating for NbSs, yet their efforts are often limited, underscoring the need for active public engagement and advocacy to foster broader acceptance and implementation.

5.2. Future Directions for Improving and Strategizing NbS Implementation

The advancement of NbSs is primarily driven by the urgent challenges faced by developing nations. Overcoming the barriers to NbS deployment necessitates the integrated efforts of various stakeholders, including government entities, the public, and the scientific community. A thorough assessment of NbSs, integrating social, economic, and environmental dimensions, is vital to highlight their benefits, particularly in the context of rapid urbanization and significant climatic shifts. The following strategies are proposed to address the previously identified challenges and offer guidance to urban planners and researchers.

5.2.1. Financial Strategy Enhancement

Governments should broaden and increase funding channels to support the ongoing operation and maintenance of NbSs. Collaborations between local authorities, the business sector, and private citizens are crucial for promoting NbS adoption (Shafique and Kim, 2017) [28]. Fiscal incentives and legislative support can help alleviate financial barriers, enhancing public–private partnerships. For example, China's Ministry of Finance issued a notification in 2014 to provide financial subsidies of RMB 80 per m^2 for three-star-level green buildings, while in Nanjing, Jiangsu Province, China, the design fee of the district is only RMB 20 per m^2 [146]. A financial subsidy can effectively stimulate the use of NbSs by enterprises. Furthermore, in-depth investigations into the economic feasibility of NbSs are essential to tap into their potential financial benefits.

5.2.2. Theoretical Framework Development

Educational institutions are key in advancing technical knowledge of NbSs and providing operational and maintenance guidance. Collaborative educational initiatives with the corporate sector can produce a workforce skilled in NbSs. The development of technical guides tailored to regional climatic and geological specifics, focusing on aspects like NbS design, material selection, and plant species, is necessary. Comprehensive maintenance plans are crucial for maintaining NbS effectiveness. Augmented research, including cost-efficiency analyses, can propel NbS advancements and enrich their ecological benefits. Cross-disciplinary collaborations can reveal innovative, cost-effective NbS approaches.

5.2.3. Legislative and Regulatory Advancements

Addressing regulatory barriers requires careful policy recalibration and the creation of appropriate legal frameworks. An equitable legislative structure or institution can promote inter-sectoral collaboration and NbS implementation. Authoritative bodies should develop and enforce NbS-specific regulations, integrating them into urban infrastructure planning. For example, Australia has established an intergovernmental committee to provide guidance on the implementation of WSUD [147]. Establishing minimum standards for post-development NbS management, stormwater discharge, groundwater protection, and nonpoint source pollution mitigation is crucial [143]. Oversight agencies or existing entities should monitor NbS development to ensure the sustainable integration into urban transformation.

5.2.4. Public Advocacy and Awareness

Enhancing the public awareness of NbSs can facilitate governmental support and mitigate economic challenges. Educating property owners about environmental and infrastructural aspects can encourage the adoption of NbS elements like green roofs and rainwater harvesting systems in existing buildings. The successful implementation of NbSs depends on diverse commitments, encompassing financial investments, coordinated efforts, and sustained dedication. Dedicated periods for specialized education, public awareness, and rigorous research are necessary. With prudent management and continuous refinement, these challenges—technical, legislative, financial, and socio-cultural—can be overcome, strengthening the resilience and efficacy of NbSs.

6. Conclusions

Emerging as a pivotal paradigm in urban development, NbS practices have witnessed escalating global commendation, anchoring extensive empirical research and pragmatic applications. Intrinsically designed as a sophisticated strategy for land utilization, NbSs exhibit an exceptional proficiency in orchestrating stormwater runoff management, enhancing aquatic quality, and fortifying environmental preservation. This proficiency is accentuated by their reliance on decentralized, micro-scale interventions, which draw inspiration from ecologically harmonious designs. Through the lens of the CIMO logical framework, this review endeavored to dissect an intricate question: "In the backdrop of urbanization and climatic shifts, how do the mechanisms underpinning NbS practices influence urban hydrological outcomes?"

A meticulous analysis of international research, emphasizing the mitigation of surface runoff and the elevation of water quality, demystified a discernible variability in the operational success of NbSs. This variability can be ascribed to a spectrum of localized environmental dynamics and distinct geographical contexts. The text delineates four salient impediments constraining the universal adoption of NbSs: fiscal limitations, intricate technical prerequisites, regulatory encumbrances, and perceptual voids in the public sphere. Concurrently, it accentuates strategies meticulously crafted to navigate these impediments, emphasizing the criticality of tailoring NbS design standards to resonate with indigenous environmental nuances and galvanizing comprehensive research endeavors in the NbS domain.

To actualize a resilient and efficacious urban stormwater management framework, intensified synergies among a diverse array of stakeholders—inclusive of academic researchers, urban planning mavens, and policy connoisseurs—are indispensable. Such a confluence of expertise and vision promises to curate and promulgate NbS strategies that are both innovative and apt for mitigating urban inundation challenges.

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