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Assessing the Hydrological Performance of Nature-Based Solutions Under Climate Change: Evidence, Challenges, and Future Directions

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Index Terms

Nature-based Solutions, Hydrological Performance, Climate Change, Flood Management, Drought.

Abstract

This study aims to critically assess the hydrological performance of Nature-Based Solutions (NbS) under climate change, focusing on their capacity to reduce surface runoff and flood peaks, enhance infiltration and water retention, support groundwater recharge and low-flow conditions, and strengthen hydrological resilience. It further examines the climatic, spatial, methodological, economic, and institutional factors affecting NbS performance. A descriptive–analytical, critical, inductive, and comparative review approach was adopted to synthesize scientific evidence published between 2020 and 2025, with studies compared according to NbS type, climatic conditions, spatial scale, catchment characteristics, and hydrological performance indicators.

The findings indicate that NbS can provide significant hydrological benefits, particularly through runoff reduction, flood-peak attenuation, temporary water storage, delayed hydrological response, and enhanced infiltration. However, their effectiveness is conditional rather than universal and varies according to intervention type and location, soil and geological characteristics, catchment scale, antecedent moisture, rainfall magnitude, and climatic conditions. Evidence for flood mitigation is stronger and more consistent than that for drought mitigation, groundwater recharge, and sustained low-flow support. The review further demonstrates that locally observed benefits cannot be automatically extrapolated to catchment scale and that effectiveness under historical climate conditions does not necessarily guarantee robustness under future climatic extremes.

The study concludes that NbS assessment should shift from demonstrating hydrological effectiveness toward establishing climate-robust hydrological performance. Long-term monitoring, standardized performance indicators, validated hydrological models, multiple climate scenarios, explicit uncertainty analysis, and integrated economic and institutional assessments are therefore required. The findings further support context-specific comparison among NbS, grey infrastructure, and hybrid alternatives, with hybrid systems potentially offering a more reliable pathway where nature-based measures alone cannot manage residual climate risks. The study contributes to the literature by reframing the central question from whether NbS generally work to identifying which NbS remain effective, under which hydrological and climatic conditions, at what spatial scale, and with what degree of reliability under climate change.

الأداء الهيدرولوجي للحلول القائمة على الطبيعة في ظل تغير المناخ: الأدلة والتحديات والاتجاهات المستقبلية

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الملخص

تهدف هذه الدراسة إلى تقييم الأداء الهيدرولوجي للحلول القائمة على الطبيعة (NbS) في ظل تغير المناخ، وتحليل قدرتها على خفض الجريان السطحي وذروات الفيضانات، وتعزيز التسرب والاحتفاظ بالمياه وتغذية المياه الجوفية ودعم التدفقات المنخفضة، فضلاً عن تحديد العوامل المناخية والمكانية والمنهجية والاقتصادية والمؤسسية المؤثرة في فعاليتها. اعتمدت الدراسة منهجًا وصفيًا–تحليليًا ونقديًا واستقرائيًا ومقارنًا، من خلال تحليل وتركيب الأدلة العلمية المنشورة خلال الفترة 2020–2025، مع مقارنة النتائج وفق نوع الحل القائم على الطبيعة، والظروف المناخية، والمقياس المكاني، وخصائص الأحواض، والمؤشرات الهيدرولوجية المستخدمة .

أظهرت النتائج أن الحلول القائمة على الطبيعة تحقق فوائد هيدرولوجية مهمة، ولا سيما في خفض الجريان السطحي، وتخفيف ذروات الفيضانات، وزيادة التخزين المؤقت للمياه، وتأخير الاستجابة الهيدرولوجية، وتحسين التسرب .غير أن فعاليتها ليست ثابتة أو قابلة للتعميم، بل تتأثر بنوع التدخل وموقعه، وخصائص التربة والجيولوجيا، وحجم الحوض، والرطوبة السابقة، وشدة الأمطار، والظروف المناخية. كما تبين أن الأدلة المتعلقة بالحد من الفيضانات أكثر قوة واتساقًا مقارنة بالأدلة الخاصة بالجفاف وتغذية المياه الجوفية ودعم التدفقات المنخفضة. وأظهرت الدراسة كذلك أن النتائج الإيجابية على المستوى المحلي لا يمكن تعميمها مباشرة على مستوى الأحواض، وأن الأداء المثبت في ظل المناخ التاريخي لا يضمن استمرار الفعالية تحت الظروف المناخية المستقبلية الأكثر تطرفًا .

وخلصت الدراسة إلى ضرورة الانتقال من تقييم فعالية NbS إلى تقييم متانتها الهيدرولوجية في مواجهة تغير المناخ، من خلال المراقبة طويلة الأجل، وتوحيد مؤشرات الأداء، والتحقق الميداني من النماذج، واختبار سيناريوهات مناخية متعددة، وتحليل عدم اليقين، وربط الأداء الهيدرولوجي بالجدوى الاقتصادية والقدرة المؤسسية. وتؤكد الدراسة أن الاختيار بين الحلول القائمة على الطبيعة والبنية التحتية التقليدية لا ينبغي أن يكون ثنائيًا، بل ينبغي تشجيع النظم الهجينة عندما توفر تكاملًا أفضل بين المرونة الهيدرولوجية والموثوقية الهندسية والاستدامة البيئية.

الكلمات المفتاحية

الحلول القائمة على الطبيعة؛ الأداء الهيدرولوجي؛ تغير المناخ؛ إدارة الفيضانات؛ الجفاف

الكلمات المفتاحية: الحلول القائمة على الطبيعة؛ الأداء الهيدرولوجي؛ تغير المناخ؛ إدارة الفيضانات؛ الجفاف؛ المرونة الهيدرولوجية؛ إدارة الموارد المائية؛ البنية التحتية الهجينة.

1. INTRODUCTION

Climate change is increasingly altering the hydrological cycle through shifts in precipitation regimes, higher evapotranspiration, more frequent and intense droughts, and greater flood variability. These changes place growing pressure on conventional water-management systems, many of which were designed under assumptions of climatic stationarity that are becoming progressively less reliable. As a result, water-resource planning is moving toward approaches that can accommodate uncertainty while simultaneously improving ecosystem resilience and providing multiple environmental and social benefits. Nature-Based Solutions (NbS) have consequently emerged as an important component of climate-resilient water management because they seek to restore or enhance natural processes that regulate runoff, infiltration, storage, evapotranspiration, groundwater recharge, and water quality. Rather than replacing conventional infrastructure in all contexts, NbS are increasingly viewed as complementary components of hybrid water-management systems capable of enhancing resilience under changing hydroclimatic conditions (Nika et al., 2020).

From a hydrological perspective, the relevance of NbS lies in their capacity to modify the movement and temporary storage of water across landscapes. Wetlands, floodplain reconnection, riparian restoration, urban green infrastructure, reforestation, permeable surfaces, detention features, and soil-restoration measures can influence peak discharge, runoff volume, infiltration, soil moisture, baseflow, sediment transport, and pollutant retention. However, their hydrological performance is highly context dependent. The effectiveness of an intervention depends on catchment size, soil properties, land use, antecedent moisture conditions, topography, vegetation characteristics, rainfall magnitude, and the spatial configuration of the intervention itself. Therefore, NbS should not be assumed to provide uniform hydrological benefits across different climatic and geomorphological settings. Nika et al. (2020) emphasized that existing evaluations of NbS in water systems remain fragmented and that hydrological and biogeochemical models need to be integrated with broader performance indicators to assess their contribution at the system level.

This issue becomes particularly important under climate change because the hydrological conditions under which an NbS is designed may differ substantially from those experienced during its operational life. More intense rainfall can exceed infiltration and temporary-storage capacity, prolonged drought can alter soil structure and vegetation performance, and repeated extremes may modify ecosystem functioning itself. Hence, an NbS that performs effectively under historical rainfall conditions may not provide the same level of flood attenuation, runoff reduction, or water retention under future climate scenarios. The wider climate-adaptation literature similarly shows that NbS effectiveness is influenced by place, hazard type, design, governance, and implementation conditions rather than being intrinsically guaranteed. Johnson et al. (2022), in a systematic review of systematic reviews, found that the evidence base for NbS climate adaptation is extensive but uneven, with much of the literature concentrated in urban and coastal environments and important gaps remaining across geographical contexts and dimensions of implementation.

Hydrological performance must therefore be distinguished from the broader concept of NbS success. An intervention may generate biodiversity, recreational, carbon, or landscape benefits while providing only modest flood-control performance, and conversely, a

hydrologically effective intervention may involve ecological or land-use trade-offs. This distinction is important because NbS are frequently promoted on the basis of multifunctionality, while the strength of empirical evidence differs considerably among individual outcomes. Shah et al. (2020) showed that assessment frameworks for NbS and hydro-meteorological hazards remain insufficiently integrated and often treat social and ecological dimensions unevenly. Their proposed vulnerability and risk framework demonstrates the need for multidimensional indicators, but it also reinforces the argument that hydrological effectiveness must be evaluated explicitly rather than inferred from general ecosystem benefits.

A second challenge concerns the spatial and temporal scales at which hydrological performance is assessed. Many NbS projects are evaluated at plot, site, or neighborhood scale, whereas water-management decisions are frequently made at catchment or regional scale. Hydrological benefits demonstrated locally do not automatically translate into equivalent basin-scale reductions in flood peaks or improvements in water availability. Similarly, short monitoring periods can capture performance under normal rainfall but fail to evaluate behavior during rare extremes, prolonged drought, or sequences of wet and dry years. This scale mismatch represents a critical limitation for climate adaptation because resilience ultimately depends on how interventions perform under events outside the conditions used for their original design. The broader evidence synthesis conducted by Johnson et al. (2022) likewise highlighted geographical and thematic imbalances in the existing NbS literature, indicating that transferability remains a central research challenge.

The hydrological performance of NbS is also inseparable from the concept of risk. Floods and droughts emerge from interactions among hazard, exposure, vulnerability, land use, infrastructure, and ecosystem condition; consequently, reducing runoff at a local site does not necessarily produce a proportional reduction in societal risk. Shah et al. (2020) argued that NbS assessment should integrate social and ecological vulnerability alongside hazard reduction, rather than evaluating physical performance in isolation. This perspective is particularly valuable under climate change, where increasing exposure and urban development can offset gains achieved through hazard mitigation. Therefore, hydrological metrics such as peak-flow reduction, runoff coefficient, lag time, infiltration capacity, water retention, and baseflow response should be interpreted together with measures of exposure, vulnerability, and system resilience.

Economic and institutional feasibility constitutes another major dimension of long-term NbS performance. Even when an intervention demonstrates hydrological benefits, implementation can be constrained by land requirements, maintenance responsibilities, financing structures, fragmented governance, and uncertainty over the valuation of co-benefits. Ghafourian et al. (2021) identified a persistent gap in systematic economic assessment of NbS in water systems and argued for evaluation frameworks that integrate investment costs with environmental and societal benefits. This is directly relevant to hydrological adaptation because an NbS cannot be considered sustainable solely on the basis of hydraulic efficiency; it must also remain maintainable, economically defensible, and institutionally viable over the time horizons associated with climate change.

At the same time, the growing prominence of NbS requires greater caution regarding scientific certainty. Buma et al. (2024) showed that nature-based climate interventions differ markedly in the strength of their scientific foundations and identified durability, baseline definition, monitoring, and geographical uncertainty among the major limitations affecting confidence in their performance. Although their analysis focused primarily on climate-mitigation pathways, the implications are equally relevant to hydrological NbS: performance claims should be supported by robust baselines, measurable indicators, long-term observations, and explicit treatment of uncertainty. In hydrology, uncertainty can emerge from climate projections, rainfall–runoff relationships, model structure, parameterization, land-use change, ecological succession, and the progressive ageing of the NbS itself.

The evaluation of NbS should therefore move toward climate-robust hydrological performance assessment, rather than relying exclusively on observed historical effectiveness. Such an approach requires testing interventions against multiple climate scenarios and hydrological extremes; comparing NbS with grey and hybrid alternatives; examining threshold behavior under high-magnitude events; and quantifying uncertainty in predicted flood attenuation, water storage, groundwater recharge, and drought resilience. It also requires long-term monitoring that captures seasonal variation, vegetation development, maintenance effects, and changes in soil and hydraulic properties. This systems perspective is consistent with the argument of Nika et al. (2020) that NbS assessment should integrate hydrological, environmental, resource, and societal dimensions rather than evaluating individual components independently.

Against this background, the present study, “Assessing the Hydrological Performance of Nature-Based Solutions Under Climate Change: Evidence, Challenges, and Future Directions,” critically examines the current evidence concerning the capacity of NbS to regulate hydrological processes under changing climatic conditions. The study focuses on the extent to which NbS can reduce runoff and flood peaks, enhance infiltration and water retention, support groundwater recharge and low-flow conditions, and improve broader hydrological resilience. It further evaluates methodological challenges associated with scale, monitoring duration, climate uncertainty, modelling, performance indicators, and transferability across environmental settings. Rather than assuming that NbS are inherently climate resilient, the study adopts a critical perspective in which their performance is treated as dynamic, context dependent, and potentially altered by future climate extremes. The ultimate objective is to identify the conditions under which NbS provide reliable

hydrological benefits and to outline research priorities capable of strengthening their evidence base, design standards, monitoring frameworks, and integration into climate-resilient water-management strategies.

2. Research Problem

Despite the growing adoption of Nature-Based Solutions (NbS) as climate-adaptation measures, uncertainty remains regarding their hydrological effectiveness under changing and increasingly extreme climatic conditions. Existing evidence is fragmented across different spatial scales, climatic regions, NbS types, monitoring periods, and performance indicators, making it difficult to determine whether locally observed benefits can be reliably transferred to catchment and regional scales. Furthermore, future changes in rainfall intensity, drought frequency, and hydroclimatic extremes may alter the performance of NbS beyond the conditions for which they were originally designed. Therefore, there is a need for a critical synthesis of existing evidence to determine how effectively, consistently, and reliably NbS can improve hydrological resilience under climate change.

2.1 Research Questions

1. How effective are Nature-Based Solutions in improving hydrological performance under current and changing climatic conditions?
2. To what extent do different types of NbS reduce runoff and flood peaks and enhance infiltration, water retention, groundwater recharge, and low-flow support?
3. How do climate conditions, spatial scale, catchment characteristics, and extreme hydrological events influence the performance of NbS?
4. What are the major methodological, technical, monitoring, economic, and institutional challenges affecting the assessment and implementation of NbS?
5. What future research and management directions are required to improve the reliability and integration of NbS into climate-resilient water-management strategies?

3. Research Objectives

Accordingly, the study aims to:

1- Assess the available evidence on the hydrological effectiveness of NbS under current and future climate conditions.

2- Evaluate the capacity of different NbS types to reduce runoff and flood peaks and improve infiltration, water retention, groundwater recharge, and low-flow conditions.

3- Analyze the influence of climate variability, spatial scale, catchment characteristics, and extreme events on NbS hydrological performance.

4-Identify and critically evaluate the major methodological, technical, monitoring, economic, and institutional challenges associated with NbS assessment and implementation.

5- Develop future research and management directions for strengthening NbS performance assessment and their integration into climate-resilient water-resource management.

4. Theoretical Frame Work

4.1 Nature-Based Solutions and Hydrological Processes

Nature-Based Solutions (NbS) represent an increasingly important shift from conventional, infrastructure-dominated water management toward approaches that restore, protect, or imitate natural hydrological processes. Hydrologically, interventions such as wetlands, floodplain restoration, reforestation, riparian buffers, green roofs, bioswales, permeable surfaces, and retention systems can modify rainfall–runoff relationships by increasing infiltration and temporary water storage, delaying runoff generation, reducing peak discharge, and potentially supporting groundwater recharge and baseflow. However, the magnitude of these benefits varies according to soil properties, topography, vegetation, antecedent moisture, land use, catchment scale, and the spatial configuration of the intervention. Consequently, evaluating NbS requires multiple hydrological indicators rather than a single measure of effectiveness. Nika et al. (2020) demonstrated that existing NbS assessment approaches remain fragmented and emphasized the need to integrate hydrological and biogeochemical modelling with broader performance indicators. Similarly, Ruangpan et al. (2020) showed that NbS can contribute to hydro-meteorological risk reduction but that substantial gaps remain regarding evaluation methods, effectiveness, costs, upscaling, and replication across environmental settings.

4.2 Hydrological Performance for Flood and Drought Risk Reduction

The hydrological value of NbS is particularly evident in their potential contribution to managing floods, stormwater, and water scarcity. During high-flow conditions, natural and restored ecosystems can intercept precipitation, increase surface roughness, promote infiltration, temporarily store runoff, extend lag time, and reduce or delay flood peaks. During dry periods, some interventions may contribute to soil-water conservation, infiltration, groundwater recharge, and maintenance of ecosystem water availability. Nevertheless, hydrological effectiveness should not automatically be equated with overall risk reduction because flood and drought risks are jointly determined by hazard, exposure, vulnerability, ecosystem condition, and socioeconomic characteristics. Shah et al. (2020) found that existing assessment frameworks frequently fail to integrate these dimensions adequately and proposed a multidimensional framework linking NbS to social-ecological vulnerability and hydro-meteorological risk. Ruangpan et al. (2020) likewise concluded that, despite growing evidence of NbS effectiveness, greater attention is required to performance evaluation across different scales and hazard conditions. Thus, hydrological performance should be assessed through measurable indicators such as peak-flow

reduction, runoff-volume reduction, infiltration, retention capacity, lag time, groundwater response, and low-flow support, while recognizing the wider risk context.

4.3 Hydrological Performance Under Climate Change and Uncertainty

Climate change introduces a fundamental challenge to the long-term reliability of NbS because future hydrological conditions may exceed those under which individual interventions were designed or evaluated. Increasing rainfall intensity may overwhelm infiltration and storage capacities, while prolonged droughts can alter soil moisture, vegetation condition, evapotranspiration, and ecosystem functionality. Consequently, demonstrated effectiveness under historical climatic conditions cannot automatically be extrapolated to future scenarios. Johnson et al. (2022) found that the evidence concerning NbS for climate adaptation is substantial but unevenly distributed geographically and thematically, with particularly strong research concentration in urban and coastal environments. More specifically, Kumar et al. (2023) argued that robust NbS for hydro-meteorological risk reduction should be designed and evaluated considering events that may exceed expected or original design conditions. This highlights the need to move from conventional effectiveness assessment toward climate-robust hydrological performance assessment, incorporating multiple climate scenarios, extreme-event testing, spatial and temporal scale effects, model uncertainty, threshold behavior, and comparisons among nature-based, grey, and hybrid infrastructure.

4.4 Challenges and Future Directions for Climate-Resilient NbS

Despite the growing scientific and policy interest in NbS, their large-scale integration into climate-resilient water management remains constrained by methodological, technical, economic, and institutional barriers. Major scientific challenges include the lack of standardized hydrological performance indicators, short monitoring periods, differences between site- and catchment-scale responses, limited observations during extreme events, uncertainties in climate projections, and difficulties in transferring results between climatic and geographical settings. In addition, implementation may be constrained by land availability, financing, maintenance requirements, governance fragmentation, stakeholder acceptance, and uncertainty surrounding the economic valuation of ecosystem co-benefits. Ghafourian et al. (2021) identified a significant gap in systematic economic assessment of NbS and emphasized that environmental and societal benefits should be incorporated alongside investment costs in decision-making. Future research should therefore prioritize long-term monitoring, standardized performance metrics, climate-scenario testing, high-resolution hydrological modelling, economic assessment, cross-scale evaluation, and comparative analysis of NbS–grey–hybrid systems. Such an integrated approach is essential for moving NbS from promising local interventions toward scientifically defensible and economically viable components of climate-resilient water-management strategies.

5. LITERATURE REVIEW

The literature published between 2020 and 2025 demonstrates a substantial transition in the scientific understanding of Nature-Based Solutions (NbS) from environmentally desirable interventions toward measurable components of hydrological and climate-risk management. Ruangpan et al. (2020) conducted a state-of-the-art review of NbS for hydro-meteorological risk reduction and found increasing evidence that measures such as wetlands, floodplain restoration, vegetation-based interventions, and urban green infrastructure can reduce hydrological risks while generating ecological and social co-benefits. However, the study also identified persistent weaknesses in performance evaluation, economic assessment, upscaling, and replication between locations. This limitation was reinforced by Nika et al. (2020), who reviewed assessment methodologies, tools, and indicators for NbS in water systems and demonstrated that existing approaches remain fragmented across hydrological, environmental, resource, and societal dimensions. Their analysis is important because it challenges the assumption that NbS effectiveness can be represented through a single indicator; nevertheless, both studies relied heavily on heterogeneous evidence, limiting the possibility of deriving universally applicable quantitative hydrological thresholds.

Moving from general assessment to flood hydrology, Sahani et al. (2020) investigated NbS performance in a Mediterranean peri-urban catchment using coupled hydrological and hydraulic modelling. The study showed that NbS could reduce flood extent and depth, but their effectiveness varied according to intervention type and rainfall conditions. Similarly, Ferguson and Fenner (2020) examined Natural Flood Management (NFM) in the Calder Valley and demonstrated that upstream interventions can attenuate downstream river levels and improve the performance of surface-drainage systems. Yet these studies also reveal an important limitation: effectiveness observed for a specific catchment configuration cannot automatically be generalized to other basins because rainfall characteristics, soil permeability, topography, urbanization, and antecedent moisture substantially modify catchment response.

A related methodological concern was addressed by Shah et al. (2020), who critically reviewed hydro-meteorological hazard, vulnerability, and risk-assessment frameworks associated with NbS. They demonstrated that many evaluations emphasize physical hazard reduction while inadequately integrating social and ecological vulnerability. This distinction is fundamental because a reduction in peak discharge does not necessarily produce an equivalent reduction in overall flood risk. The study therefore broadened NbS assessment from hydraulic performance toward risk-based evaluation. In parallel, Kumar et al. (2020) argued that operationalizing NbS requires stronger links among scientific evidence, policy frameworks, stakeholder participation, and real-world

implementation. Collectively, these studies reveal that hydrological efficiency represents only one dimension of NbS success; governance, exposure, vulnerability, and implementation capacity can determine whether technically effective interventions ultimately generate meaningful resilience.

Empirical and modelling research published in 2021 provided more direct evidence concerning performance. Costa et al. (2021) evaluated NbS for pluvial-flood mitigation in Eindhoven, the Netherlands, and demonstrated that green infrastructure can reduce flood hazard by modifying runoff generation and storage. Their findings support the hydrological rationale for urban NbS, but also show that effectiveness is spatially differentiated and strongly influenced by intervention location and design. At a larger planning scale, Mubeen et al. (2021) developed a suitability-assessment approach for large-scale NbS for flood-risk reduction and emphasized that intervention placement is as important as intervention type. The study demonstrated the value of spatial suitability mapping but also highlighted a recurring problem: selecting a theoretically suitable location does not guarantee equivalent hydrological performance under different rainfall intensities or future climate conditions.

The comparison between nature-based and conventional engineering alternatives was advanced by Turkelboom et al. (2021) in Belgium. Their study compared a nature-based flood-control solution with a technical alternative and found that NbS can provide competitive flood-management benefits while simultaneously producing wider ecosystem services. However, the comparison also demonstrated that the choice between NbS and grey infrastructure cannot be based exclusively on flood attenuation; land requirements, stakeholder preferences, multifunctionality, and local implementation conditions must also be considered. Complementing this perspective, Ghafourian et al. (2021) examined the economic assessment of NbS in water systems and identified substantial weaknesses in the valuation of environmental and societal co-benefits. Their work showed that apparently favorable hydrological performance does not automatically translate into economically defensible implementation unless life-cycle costs, maintenance, avoided damages, and ecosystem services are evaluated together.

A further methodological advance was provided by Kumar et al. (2021), who systematically examined modelling approaches used to evaluate NbS efficiency against floods, droughts, heatwaves, landslides, storm surges, and coastal erosion. They found considerable diversity in models, input data, spatial resolutions, calibration approaches, and performance metrics, making comparisons among studies difficult. The authors consequently emphasized the absence of standardized methodologies for evaluating and upscaling NbS. This methodological heterogeneity remains particularly problematic for hydrological research because two studies may both describe an intervention as “effective” while using fundamentally different outcomes—peak discharge, runoff volume, inundation depth, infiltration, water availability, or economic damage reduction—to define effectiveness.

Research during 2022 increasingly examined the spatial and institutional dimensions of implementation. Guerrero et al. (2022) analyzed spatial patterns of NbS and ecosystem-service delivery and showed that NbS benefits depend strongly on their geographical configuration and relationship with surrounding landscapes. Their work reinforces the need for spatially explicit planning rather than simply increasing the number of NbS interventions. Meanwhile, Sarabi et al. (2022) examined barriers to NbS in flood-risk management through an interdisciplinary expert approach and identified multiple interconnected barriers, including institutional fragmentation, knowledge limitations, financial constraints, and implementation complexity. Their findings demonstrate that the gap between scientific evidence and widespread adoption is not simply technological; it is also a governance and decision-making problem.

This governance perspective is consistent with Han and Kuhlicke (2021), who investigated barriers and drivers for mainstreaming NbS for flood risk in South Korea. Their findings showed that legal, political, institutional, and attitudinal conditions significantly influence NbS adoption. Critically, this indicates that hydrologically effective solutions may fail to achieve practical implementation when institutional structures are poorly aligned with ecosystem-based approaches. Thus, an important distinction emerges between hydrological effectiveness, which concerns physical water-system response, and implementation effectiveness, which concerns whether NbS can be maintained, financed, governed, and integrated into planning systems.

A major synthesis by Johnson et al. (2022) further showed that the evidence supporting NbS for climate-change adaptation is extensive but geographically and thematically uneven. Their systematic review of systematic reviews revealed a concentration of research in particular regions and especially in urban and coastal settings, limiting confidence in transferring findings to data-scarce, dryland, or developing-country contexts. This geographical imbalance is particularly relevant to the current review because hydrological response is inherently climate- and catchment-dependent. The existing manuscript similarly recognizes that locally demonstrated benefits cannot simply be assumed to translate into equivalent catchment- or regional-scale outcomes.

By 2023, the literature had begun to investigate these scale and modelling limitations more explicitly. Hill et al. (2023) systematically reviewed Natural Flood Management modelling and found substantial diversity in model structures, representation of NFM processes, calibration, validation, and uncertainty treatment. The study concluded that modelling approaches frequently simplify the complexity of nature-based hydrological processes and that greater empirical evidence is needed for model validation. Similarly, Earl et al. (2023) critically reviewed NFM application and spatial prioritization in tropical island catchments and found major geographical gaps in the evidence base. They emphasized that

techniques developed for temperate continental catchments cannot necessarily be transferred directly to tropical islands, where catchment size, rainfall intensity, topography, and data availability differ substantially.

The importance of local physical characteristics was demonstrated particularly clearly by Collins et al. (2023), who modelled land-based NFM in a large permeable catchment. Their results showed that the hydrological benefits of land-management interventions are strongly conditioned by catchment characteristics, especially hydrogeology. This finding is reinforced by catchment-storage research showing that soils and geology can exert stronger controls on subsurface water storage than forest cover alone. These studies challenge overly generalized claims that afforestation or land-cover modification will automatically deliver substantial flood attenuation. Instead, NbS performance emerges from interactions among intervention design, geology, soils, rainfall, antecedent conditions, and catchment scale.

An especially important development came from Quagliolo et al. (2023), who integrated biophysical and economic assessment to evaluate NbS for pluvial-flood adaptation. Their study recognized that physical reduction of flooding represents only part of the adaptation decision and incorporated economic performance into NbS evaluation. In the same direction, research on the time-variable effectiveness and cost-benefits of NbS showed that intervention type and design can produce markedly different effects on low flows, water availability, and high flows and, importantly, that economic outcomes change over time. Some runoff-attenuation measures generated positive cost-benefit outcomes whereas tree planting did not under the evaluated conditions (Dadson et al., 2023). These findings question the tendency to describe NbS generically as cost-effective and demonstrate that performance must be assessed for specific designs and temporal horizons.

The drought dimension, comparatively neglected in earlier NbS research, has also begun to receive greater attention. Sintayehu et al. (2023) examined drought characteristics and the potential of NbS for drought-risk mitigation in eastern Ethiopia, highlighting the relevance of ecosystem-based interventions in water-scarce environments. More mechanistically, Zhang et al. (2023) evaluated wetland-based solutions against extreme floods and severe droughts using distributed hydrological modelling. Their results demonstrated that wetlands can regulate hydrological extremes, but effectiveness varies according to wetland type and geographical location. This is a critical finding: the same NbS cannot be assumed to optimize flood reduction and drought mitigation simultaneously, and intervention objectives may involve hydrological trade-offs.

This imbalance in drought evidence was examined directly by Chausson et al. (2024) in a critical review of NbS for drought mitigation. The review found that drought-focused NbS research remains substantially less developed than flood-focused research, that studies are geographically concentrated—particularly in Europe—and that the effectiveness of implemented NbS is frequently insufficiently quantified. The authors further indicated that meaningful drought mitigation may require implementation at relatively large spatial scales. This represents one of the most important weaknesses in the current evidence base because climate change is expected to increase both hydrological extremes, whereas NbS research has historically emphasized excess water more strongly than water scarcity.

At catchment scale, Lalonde et al. (2024) critically synthesized scientific evidence concerning the impacts of NbS on runoff, baseflow, infiltration, evapotranspiration, floods, and droughts. They concluded that the hydrological evidence base remains insufficiently robust for some intervention types and processes, creating uncertainty when models are used to predict performance before implementation. This study is particularly important to the present review because it moves beyond the question of whether NbS "work" toward the more scientifically defensible question of which hydrological processes are modified, under what conditions, at what scale, and with what level of evidence.

Climate-change scenarios have further complicated this assessment. A 2024 study of the greater Athens area evaluated land-cover change and retention ponds under alternative future climate scenarios and demonstrated that NbS can enhance flood resilience, but their effectiveness changes with climatic conditions and intervention combinations. Likewise, Liao et al. (2024) developed a comprehensive framework for evaluating fluvial-flood adaptation and explicitly incorporated uncertainty and failure probability. Their analysis found that NbS substantially reduced failure probability for the assessed flood event and could generate greater total benefits than grey alternatives when risk, ecosystem services, and costs were considered together. The significance of these studies lies in their departure from deterministic evaluation toward risk- and uncertainty-based performance assessment, which is more appropriate under non-stationary climate conditions.

Finally, Kumar et al. (2023) proposed an approach for designing and evaluating robust NbS for hydro-meteorological risk reduction, emphasizing that interventions should be tested beyond expected design conditions rather than judged only against historical events. This represents a conceptual shift from conventional performance assessment toward robustness assessment, directly supporting the premise of the present study that past hydrological effectiveness cannot be treated as sufficient evidence of future climate resilience. The current manuscript similarly argues for multiple climate scenarios, extreme-event testing, uncertainty quantification, and comparisons among NbS, grey, and hybrid infrastructure.

Critical Synthesis and Research Gap

Taken together, the twenty studies reveal substantial evidence that NbS can modify runoff generation, reduce flood peaks and inundation, enhance water retention and infiltration, support drought management, and generate ecological and socioeconomic co-benefits. Nevertheless, the literature does not support the simplistic conclusion

that NbS are universally effective. Their hydrological performance is conditional upon intervention type, design, location, spatial scale, catchment characteristics, geology, soil properties, antecedent moisture, event magnitude, climate regime, and maintenance. The literature also shows a pronounced research asymmetry: flood mitigation is much better studied than drought mitigation, site-scale evidence is stronger than catchment-scale evidence, short-term modelling is more common than long-term monitoring, and European/temperate environments are substantially better represented than arid and data-scarce regions.

A further gap concerns the way effectiveness itself is conceptualized. Existing studies use different indicators—peak discharge, runoff volume, inundation area, flood depth, infiltration, baseflow, water availability, avoided damages, or ecosystem-service values—making direct comparison difficult. Modelling approaches are similarly heterogeneous and frequently lack long-term empirical validation. Most importantly, relatively few studies simultaneously examine flood and drought performance, climate-change uncertainty, spatial-scale effects, hydrological thresholds, economic feasibility, and institutional implementation. This fragmentation is precisely consistent with the problem identified in the present paper: evidence remains distributed across NbS types, climatic regions, spatial scales, monitoring periods, and performance indicators.

Expected Scientific Contribution

The expected contribution of the present study is therefore not merely to provide another general review of NbS, but to develop a critical, hydrologically centered synthesis of climate robustness. Specifically, the study integrates evidence on runoff reduction, flood-peak attenuation, infiltration, water retention, groundwater/baseflow support, and drought resilience and evaluates how these outcomes change according to climatic conditions, catchment characteristics, intervention scale, and extreme-event magnitude. It further connects hydrological effectiveness with methodological uncertainty, monitoring quality, modelling limitations, economic feasibility, and institutional barriers.

Conceptually, the study proposes a shift from the conventional question "Do Nature-Based Solutions work?" toward the more rigorous question: "Under what hydrological, climatic, spatial, and institutional conditions do specific Nature-Based Solutions remain effective and reliable?" This distinction provides the basis for a climate-robust hydrological performance framework, in which NbS are evaluated not only according to their observed historical benefits but also according to their reliability under future climate scenarios, extreme events, scale transitions, and uncertainty. Such an approach can strengthen the scientific basis for selecting between NbS, grey infrastructure, and hybrid systems, while providing clearer priorities for long-term monitoring, standardized indicators, model validation, and future climate-resilient water management.

6. METHODOLOGY

6.1 Research Design

This study adopted a descriptive–analytical, critical, inductive, and comparative review approach to assess the hydrological performance of Nature-Based Solutions (NbS) under changing climatic conditions. The descriptive component was used to characterize the major types of NbS, hydrological processes, performance indicators, climatic contexts, and methodological approaches reported in the literature. The analytical and critical components were applied to examine the strength, consistency, limitations, and transferability of the available evidence rather than merely summarizing previous findings. An inductive approach was subsequently employed to identify recurring patterns and derive broader conclusions from individual studies, while the comparative dimension enabled systematic comparison across NbS types, climatic conditions, spatial scales, catchment characteristics, hydrological indicators, and methodological approaches. This design is particularly appropriate because existing evidence demonstrates considerable heterogeneity in the methods and indicators used to assess NbS performance (Nika et al., 2020; Ruangpan et al., 2020; Kumar et al., 2021).

6.2 *Literature Search and Study Selection*

The review focused primarily on peer-reviewed scientific literature published between 2020 and 2025 addressing the hydrological performance of NbS in the context of climate change, flood mitigation, drought management, water retention, infiltration, groundwater recharge, and hydro-meteorological risk reduction. Relevant studies were identified through academic databases and scholarly search platforms, including Google Scholar, Scopus, Web of Science, ScienceDirect, SpringerLink, and Wiley Online Library. Search terms and combinations included "Nature-Based Solutions," "hydrological performance," "climate change," "flood mitigation," "drought mitigation," "Natural Flood Management," "runoff reduction," "infiltration," "water retention," "groundwater recharge," "hydrological resilience," and "climate adaptation." Priority was given to peer-reviewed journal articles, systematic and critical reviews, empirical investigations, modelling studies, and comparative assessments directly relevant to the research questions. Studies with limited relevance to hydrological processes, purely conceptual publications without substantive hydrological implications, duplicated records, and studies lacking sufficient methodological information were excluded. This procedure ensured that the evidence base remained aligned with the study's focus on measurable hydrological performance rather than the broader environmental benefits of NbS.

6.3 *Data Extraction and Analytical Framework*

Information extracted from the selected studies was organized according to a structured analytical framework comprising: (1) type of NbS; (2) geographical and climatic context; (3) spatial scale; (4) hydrological problem addressed; (5) methodological approach; (6) hydrological performance indicators; (7) reported effectiveness; (8) influence of climate variability and extreme events; (9) methodological and implementation limitations; and (10)

implications for climate-resilient water management. Particular attention was given to quantitative and qualitative evidence concerning peak-flow attenuation, runoff-volume reduction, infiltration, water retention, lag time, groundwater recharge, baseflow or low-flow support, flood mitigation, and drought resilience. These indicators correspond directly to the hydrological dimensions examined in the present study. The analysis did not treat reported positive effects as automatically transferable between locations; instead, findings were interpreted in relation to catchment characteristics, soils, hydrogeology, land use, rainfall magnitude, antecedent moisture, intervention scale, and climatic conditions. This approach responds to the substantial heterogeneity in hydrological assessment methods identified in previous research (Kumar et al., 2021; Hill et al., 2023; Lalonde et al., 2024).

6.4 *Critical and Comparative Analysis*

The selected studies were subjected to thematic critical synthesis and cross-study comparison rather than statistical meta-analysis because of the considerable heterogeneity in NbS types, study designs, hydrological models, spatial scales, climatic settings, and reported performance indicators. Evidence was compared across four principal analytical dimensions: hydrological effectiveness, climate robustness, spatial and temporal transferability, and implementation feasibility. The analysis examined not only whether an NbS produced positive hydrological outcomes, but also under what conditions, at what spatial scale, during which hydrological events, and with what level of methodological confidence those outcomes were achieved. Particular attention was paid to contradictions among studies and to differences between site- and catchment-scale evidence, flood- and drought-oriented interventions, historical and future climate conditions, and NbS, grey, and hybrid infrastructure. This critical comparison is essential because the reviewed literature demonstrates that NbS performance is strongly context dependent and that effectiveness observed under historical or local conditions cannot automatically be extrapolated to future climatic extremes or larger spatial scales (Johnson et al., 2022; Kumar et al., 2023; Lalonde et al., 2024).

6.5 *Inductive Synthesis and Identification of Research Gaps*

Following the comparative analysis, an inductive synthesis was employed to derive higher-order patterns from the accumulated evidence. Recurrent findings, inconsistencies, methodological limitations, and areas of insufficient evidence were grouped thematically to identify the principal determinants of NbS hydrological performance. Particular emphasis was placed on gaps associated with long-term monitoring, standardized hydrological indicators, catchment-scale validation, drought performance, climate-change scenarios, extreme-event thresholds, model uncertainty, economic feasibility, and institutional implementation. This stage moved the analysis beyond a conventional narrative review by using the collective evidence to determine the conditions under which NbS can be considered hydrologically robust rather than simply environmentally beneficial. The resulting synthesis was subsequently used to formulate future research priorities and to establish the conceptual basis for a climate-robust hydrological performance framework for NbS. This is consistent with the central contribution proposed by the present study, which seeks to shift the research question from whether NbS generally "work" to identifying the hydrological, climatic, spatial, and institutional conditions under which they remain effective and reliable.

6.6 *Methodological Quality and Interpretation of Evidence*

To strengthen the reliability of the review, the evidence was interpreted critically according to the clarity of study objectives, appropriateness of the hydrological methodology, spatial and temporal coverage, availability of baseline or reference conditions, model calibration and validation where applicable, treatment of uncertainty, relevance of performance indicators, and consistency between reported results and conclusions. Greater interpretive weight was therefore assigned to studies providing empirical monitoring, validated hydrological modelling, explicit performance indicators, or transparent uncertainty assessment. Conversely, findings derived from short monitoring periods, highly localized case studies, unvalidated modelling assumptions, or limited climate scenarios were interpreted cautiously. The purpose was not to assign a universal numerical quality score, but to distinguish between evidence of effectiveness and evidence of robust effectiveness under climate change, thereby reducing the risk of overgeneralizing context-specific results.

7. RESULTS AND DISCUSSION

7.1 *Overall Hydrological Effectiveness of Nature-Based Solutions*

The critical synthesis of the reviewed evidence indicates that Nature-Based Solutions (NbS) generally provide positive hydrological benefits, particularly through reducing surface runoff, attenuating flood peaks, increasing temporary water storage, delaying hydrological response, and enhancing infiltration. However, the present study finds that these benefits should be interpreted as conditional rather than universal. Hydrological effectiveness varies substantially according to the type and spatial configuration of the intervention, catchment characteristics, soil and geological properties, antecedent moisture, rainfall magnitude, and climatic setting. This finding supports Ruangpan et al. (2020), who reported considerable potential for NbS in hydro-meteorological risk reduction but simultaneously identified major uncertainties concerning effectiveness, upscaling, and replication. It also agrees with Nika et al. (2020), whose assessment showed that NbS performance cannot be adequately represented through a single hydrological indicator.

The present analysis therefore challenges the simplified assumption that introducing more green or nature-based infrastructure necessarily produces proportional improvements in hydrological resilience. Rather, the

evidence suggests a nonlinear and context-dependent relationship between NbS implementation and hydrological response. Costa et al. (2021), for example, demonstrated the effectiveness of green infrastructure in reducing pluvial-flood hazards, whereas Mubeen et al. (2021) showed that the location and spatial suitability of interventions can be as important as the intervention itself. Similarly, Ferguson and Fenner (2020) demonstrated that upstream Natural Flood Management measures can influence downstream drainage performance. Taken together, these findings suggest that NbS effectiveness derives not simply from the physical presence of nature-based measures but from their capacity to intervene strategically in dominant rainfall–runoff pathways. This interpretation is consistent with the conceptual position adopted in the present study that NbS performance is dynamic and strongly context dependent.

7.2 Flood Attenuation, Runoff Reduction, and Water Retention

Flood mitigation emerges as the strongest and most consistently documented hydrological benefit within the reviewed literature. Across urban, peri-urban, and catchment studies, interventions involving wetlands, floodplain restoration, retention systems, vegetation, permeable surfaces, and upstream land management were generally associated with reductions or delays in runoff and flood peaks. Sahani et al. (2020) showed that NbS reduced flood extent and depth in a Mediterranean peri-urban catchment, while Costa et al. (2021) found measurable reductions in pluvial-flood hazards. Ferguson and Fenner (2020) similarly demonstrated that Natural Flood Management can attenuate downstream river levels. These findings collectively support the current study's conclusion that the physical mechanisms underpinning flood-oriented NbS—interception, infiltration, temporary storage, increased surface roughness, and delayed runoff transfer—are hydrologically credible.

Nevertheless, a critical interpretation reveals an important qualification. The magnitude of flood attenuation tends to decrease or become less predictable as rainfall magnitude increases or as the analysis moves from local intervention scale toward the catchment scale. This explains why positive site-scale results should not automatically be interpreted as evidence of basin-scale flood protection. Collins et al. (2023) demonstrated that hydrogeological characteristics strongly condition land-based Natural Flood Management performance, while Hill et al. (2023) identified substantial uncertainties in how hydrological models represent NFM processes. The current synthesis therefore suggests that the appropriate question is not simply whether an intervention reduces runoff, but how much runoff it reduces, under which event magnitude, for how long, and at what spatial scale. This represents a more defensible interpretation than treating percentage reductions obtained from individual case studies as transferable performance coefficients.

7.3 Infiltration, Groundwater Recharge, and Low-Flow Support

The evidence concerning infiltration, groundwater recharge, and low-flow support is less consistent than that concerning flood attenuation. The present review indicates that vegetation restoration, permeable surfaces, wetland systems, and soil-management interventions can enhance infiltration and local water retention, but evidence that these changes systematically translate into increased catchment-scale groundwater recharge or sustained baseflow remains comparatively limited. Lalonde et al. (2024) similarly concluded that the scientific evidence supporting some catchment-scale hydrological impacts of NbS remains insufficiently robust. This result is significant because infiltration is frequently treated as synonymous with groundwater recharge, although water infiltrating the soil may subsequently be stored in the unsaturated zone, taken up by vegetation, or returned to the atmosphere through evapotranspiration before reaching groundwater.

This distinction provides an important critical contribution of the present analysis. The hydrological pathway between infiltration → soil-water storage → percolation → groundwater recharge → baseflow should not be assumed to operate uniformly across environments. Collins et al. (2023) showed the importance of hydrogeological characteristics in controlling catchment responses, supporting the present conclusion that geological and soil conditions may sometimes exert stronger controls over subsurface hydrological benefits than vegetation change itself. Consequently, claims that reforestation or ecosystem restoration automatically improve groundwater availability require greater empirical caution. Long-term monitoring of soil moisture, groundwater levels, evapotranspiration, and stream baseflow is necessary before such benefits can be established confidently.

7.4 Flood–Drought Performance Trade-offs

A particularly important result emerging from the comparative analysis is the asymmetry between flood and drought evidence. Flood mitigation has received considerably greater scientific attention and has a stronger empirical and modelling foundation, whereas the effectiveness of NbS for drought mitigation and low-flow support remains less certain. The literature reviewed in the manuscript similarly shows that flood-oriented research is substantially better developed than drought-oriented evidence and that site-scale studies remain more common than catchment-scale investigations.

More importantly, NbS that perform well for flood mitigation cannot automatically be assumed to maximize drought resilience. Hydrological objectives may sometimes involve trade-offs. Increasing vegetation, for instance, can promote infiltration and improve soil structure while simultaneously increasing evapotranspiration and potentially reducing downstream water yield under certain conditions. The reviewed evidence on wetlands similarly indicates that effectiveness depends on wetland type, location, storage conditions, and hydroclimatic context. This means that the conventional description of NbS as inherently “win–win” interventions requires qualification. The present study instead interprets multifunctionality as an empirical question that must be tested, rather than an intrinsic property that can be assumed during project design.

7.5 *Climate Change and the Limits of Historical Performance*

One of the most significant findings of the present study is that demonstrated historical effectiveness does not constitute sufficient evidence of future climate robustness. Increasing rainfall intensity may exceed infiltration and storage capacities, while prolonged drought can alter vegetation condition, soil hydraulic properties, evapotranspiration, and ecosystem functionality. Consequently, an NbS designed using historical rainfall distributions may continue to provide benefits under future conditions but at a reduced or more uncertain level. This conclusion strongly agrees with Kumar et al. (2023), who argued that robust NbS should be evaluated under conditions extending beyond their original design expectations. It is also consistent with Johnson et al. (2022), who demonstrated that the evidence for NbS climate adaptation remains geographically and thematically uneven.

This result requires a conceptual distinction between effectiveness and robustness. Effectiveness describes whether an intervention achieves a hydrological benefit under observed or modelled conditions, whereas robustness concerns whether an acceptable level of that benefit persists across uncertain future climatic conditions. The reviewed evidence indicates that many studies provide stronger support for the first proposition than the second. Buma et al. (2024) similarly emphasized limitations associated with durability, baselines, monitoring, and geographical uncertainty in nature-based climate interventions. Therefore, the present study argues that future assessments should move beyond historical performance toward stress testing under multiple climate scenarios, rainfall intensities, drought durations, antecedent conditions, and compound extremes.

7.6 Spatial Scale, Transferability, and Catchment Characteristics

The comparative analysis identifies spatial scale as one of the principal sources of uncertainty in NbS performance. Positive effects measured at plot, street, neighborhood, or individual wetland scale do not necessarily aggregate linearly into equivalent catchment-scale improvements. Mubeen et al. (2021) demonstrated the importance of spatial suitability in large-scale NbS planning, while Guerrero et al. (2022) showed that ecosystem-service delivery depends strongly on spatial configuration. Earl et al. (2023) further warned against transferring approaches developed in temperate continental environments directly to tropical island catchments because rainfall, topography, basin dimensions, and data availability differ substantially.

The current study extends this criticism by arguing that transferability should itself be treated as a performance criterion. A solution demonstrated to be effective in one catchment cannot be classified as generally effective unless the environmental conditions governing that effectiveness are identified. This is particularly important because Johnson et al. (2022) found geographical concentration of NbS evidence in urban and coastal environments. The limited representation of drylands, developing countries, and data-scarce catchments restricts the global generalizability of existing conclusions. Accordingly, the present review identifies an urgent need for hydrological evidence from arid and semi-arid regions, where rainfall intermittency, high evapotranspiration, soil characteristics, and water scarcity may produce substantially different NbS responses.

7.7 *Methodological and Modelling Limitations*

The reviewed evidence reveals substantial methodological heterogeneity in assessing the hydrological performance of Nature-Based Solutions. Studies differ in modelling approaches, spatial and temporal scales, baseline conditions, climate inputs, and performance indicators, making direct comparison difficult. Kumar et al. (2021) and Hill et al. (2023) similarly identified considerable variation in model structure, calibration, validation, and uncertainty treatment. In particular, effectiveness has been measured using different indicators, including peak-flow reduction, runoff volume, infiltration, flood depth, groundwater recharge, and low-flow support, which may partly explain inconsistencies among reported results.

Another limitation is the frequent reliance on short-term monitoring and modelling rather than long-term field observations. Although modelling is essential for evaluating future climate scenarios, its results depend strongly on assumptions, parameterization, calibration, and input data. Moreover, site-scale benefits cannot necessarily be extrapolated to catchment scale because hydrological responses are influenced by soils, geology, land use, rainfall, and spatial configuration (Collins et al., 2023; Lalonde et al., 2024). Climate uncertainty further complicates assessment, as NbS that perform effectively under historical conditions may lose efficiency when future events exceed their infiltration or storage capacities (Kumar et al., 2023).

Therefore, the present study indicates that uncertainty in NbS performance does not necessarily imply hydrological ineffectiveness; rather, it reflects limitations in the consistency, duration, scale, and robustness of available evidence. Future studies should adopt standardized hydrological indicators, long-term monitoring, validated models, multiple climate scenarios, and explicit uncertainty analysis. Such methodological harmonization would improve comparisons among studies and provide a stronger scientific basis for evaluating NbS, grey infrastructure, and hybrid alternatives under climate change.

8. CONCLUSION

This study critically assessed the hydrological performance of Nature-Based Solutions (NbS) under climate change through a descriptive–analytical, critical, inductive, and comparative synthesis of recent scientific evidence. Overall, the findings demonstrate that NbS can make a meaningful contribution to climate-resilient water management; however, their hydrological effectiveness is conditional rather than universal. The evidence is strongest for runoff reduction, flood-peak attenuation, temporary

water storage, and delayed hydrological response, while evidence concerning groundwater recharge, sustained baseflow, and drought mitigation remains comparatively less consistent. These findings confirm that NbS performance depends not only on intervention type but also on rainfall characteristics, soil and geological properties, antecedent moisture, catchment scale, spatial configuration, and future climatic conditions. This interpretation is consistent with the study's results, which demonstrate substantial context dependence in NbS hydrological performance.

In response to the first research question, the evidence indicates that NbS are generally effective in improving hydrological performance, particularly for flood and runoff management, but their effectiveness may decline or become more uncertain under climatic conditions that exceed their design capacity. Regarding the second question, wetlands, floodplain restoration, vegetation-based measures, permeable surfaces, retention systems, and Natural Flood Management can reduce runoff and flood peaks and enhance infiltration and water retention; nevertheless, their effects on groundwater recharge and low-flow support are less certain. Concerning the third question, climate conditions, spatial scale, hydrogeology, soil properties, land use, intervention location, and extreme-event magnitude were identified as major determinants of performance. Benefits demonstrated at site scale cannot therefore be assumed to occur proportionally at catchment scale. These conclusions directly reflect the evidence synthesized in the study concerning flood attenuation, infiltration, groundwater recharge, and scale effects.

In response to the fourth research question, the analysis identified several interconnected barriers, including inconsistent hydrological indicators, short monitoring periods, heterogeneous modelling approaches, insufficient model validation, limited catchment-scale observations, climate uncertainty, economic constraints, maintenance requirements, and fragmented governance. Methodological heterogeneity is particularly problematic because studies frequently use different definitions of "effectiveness," limiting direct comparison and generalization. Regarding the fifth question, future progress requires long-term monitoring, standardized indicators, multi-scale assessment, validated hydrological models, explicit uncertainty analysis, and testing under multiple future climate scenarios and extreme events.

Critically, the central conclusion of this review is therefore not simply that "NbS work," but that their reliability depends on where, how, and under what hydroclimatic conditions they are implemented. Historical effectiveness should not automatically be interpreted as evidence of future climate robustness. NbS should consequently be evaluated as dynamic hydrological systems whose performance changes across climate, scale, landscape, and time. The most appropriate future strategy is therefore to move from generalized promotion of NbS toward climate-robust, evidence-based selection and design, including the strategic integration of nature-based and grey infrastructure where hybrid systems offer greater reliability.

9. RECOMMENDATIONS

Based on the critical synthesis and conclusions, the study recommends:

1- Developing standardized hydrological performance indicators for NbS, particularly for peak-flow reduction, runoff volume, infiltration, water retention, groundwater recharge, baseflow, and drought resilience.
2- Expanding long-term field monitoring to evaluate performance across seasons, wet and dry years, vegetation development, maintenance cycles, and extreme events.
3- Testing NbS under multiple future climate scenarios, rather than relying exclusively on historical hydrological records and conventional design events.
4- Increasing catchment-scale studies to determine whether benefits observed at plot or site level remain significant after spatial upscaling.
5- Strengthening research in **arid, semi-arid, developing, and data-scarce regions**, which remain underrepresented in the current evidence base.
6- Integrating field observations with calibrated and independently validated hydrological and hydraulic models and explicitly quantifying model and climate uncertainty.
7- Evaluating flood and drought performance jointly to identify potential **hydrological trade-offs** rather than assuming that a single NbS will optimize both objectives.
8- Conducting integrated **hydrological–economic assessments** that incorporate implementation costs, maintenance, avoided damages, ecosystem services, and long-term benefits.
9- Strengthening institutional coordination, stakeholder participation, financing mechanisms, maintenance responsibilities, and integration of NbS into land-use and water-resource planning.
10- Comparing **NbS, grey infrastructure, and hybrid systems** under equivalent hydrological and climate scenarios to determine the most resilient and cost-effective intervention for each context.

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