

# A Review on Assessing the Suitability of Various Ecological Flood Mitigation Methods in Multiple Climates

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## Abstract

*This review assesses the suitability of ecological flood mitigation approaches across tropical, temperate, and arid/semi-arid regions. While conventional engineered grey structures effectively reduce flood peaks, they often impose ecological degradation and high maintenance demands. Ecological strategies, including wetland restoration, riparian buffers, and green infrastructure, offer sustainable alternatives that integrate natural processes to manage runoff, enhance biodiversity, and improve water quality. However, most studies are location-specific, leaving a gap in understanding how these methods perform under differing climatic and governance contexts. This review therefore evaluates the comparative effectiveness of ecological flood mitigation methods to identify context-specific strengths, limitations, and policy implications. The objectives are: (i) to synthesise recent evidence on the performance of ecological approaches across tropical, temperate, and arid/semi-arid regions; (ii) to assess their ecological, hydrological, and adaptive functions in flood reduction; and (iii) to highlight key challenges and policy implications for enhancing flood resilience. Drawing from literature published between 2020 and 2024, findings reveal that tropical wetlands reduce runoff by ~30%, temperate levees offer up to 90% protection, and arid-region retention systems cut flood volume by ~40%. The review concludes that integrating hybrid solutions, strengthening governance, and promoting long-term comparative research are essential for advancing ecological flood resilience globally.*

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## Introduction

Flooding is a persistent and increasingly complex challenge exacerbated by rapid urbanisation and climate variability. Traditional structural flood management methods such as engineered flood barriers and dams, while effective in reducing flood peaks, have also been criticised for disrupting natural hydrological systems and ecosystems (Rambonilaza & Li, 2021). In contrast, ecological flood mitigation strategies, often referred to as nature-based approaches, have emerged as sustainable alternatives that integrate natural processes and systems to manage excess water while supporting biodiversity and improving urban resilience (Yang et al., 2020; He et al., 2023).

Examples of these strategies include wetland restoration, riparian buffer zones, and green infrastructure such as bioswales and rain gardens. These systems have shown potential for reducing flood intensity and runoff, enhancing groundwater recharge, and improving water quality (Yang et al., 2020; Zhao & He, 2023). However, the suitability and effectiveness of these methods vary significantly depending on the climatic region where they are applied. For instance, urban wetlands perform well in tropical climates but may struggle in arid or highly urbanised zones (Forster et al., 2023; Xiao et al., 2023). In the tropical context, Ali, Zakaria, and Hashim (2020) emphasize that eco-engineering practices in Southeast Asia, including mangrove rehabilitation and slope vegetation, are essential complements to flood mitigation, particularly in coastal and riverine communities.

Despite increasing research on ecological flood mitigation, most studies are location-specific, focusing on single sites or uniform climatic regions. Few have compared ecological approaches across differing climatic, hydrological, and governance contexts, limiting understanding of their transferability and adaptability. This review addresses that gap by evaluating the suitability and comparative effectiveness of ecological flood mitigation methods across tropical, temperate, and arid/semi-arid regions. It emphasises region-specific strategies, assesses their performance, and identifies key strengths, limitations, and policy implications for developing context-sensitive, globally applicable flood resilience solutions. The specific objectives are:

- i. To synthesise recent empirical evidence on the performance of ecological approaches in tropical, temperate, and arid/semi-arid regions;
- ii. To evaluate their ecological, hydrological, and adaptive functions in flood reduction; and
- iii. To highlight key challenges and policy implications for enhancing future flood resilience through ecological solutions.

The review identifies key strengths and challenges, providing recommendations to inform future research and strengthen policy integration for ecological flood resilience.

## Methodology

This study adopted a narrative review approach to evaluate ecological flood mitigation methods across multiple climatic regions. A narrative review was chosen over a systematic meta-analysis because the included studies encompass diverse methodologies, ranging from hydrological modelling and field assessments to socio-ecological evaluations, making it more suitable for integrating heterogeneous data and providing a comparative synthesis across climatic contexts.

## Data Sources and Search Strategy

Peer-reviewed journal articles were retrieved from Scopus and ScienceDirect, which were selected for their comprehensive coverage of environmental and engineering sciences. Searches were focusing on publications from 2020 to 2024 to ensure the inclusion of the most recent empirical findings. The following keywords and Boolean combinations were used:

“ecological flood mitigation” OR “nature-based solutions” AND “urban flooding” OR “green infrastructure” OR “wetlands” OR “riparian buffer” OR “water retention systems” AND (“tropical” OR “temperate” OR “arid”).

## Inclusion and Exclusion Criteria

Studies were included if they: Provided quantitative or qualitative evidence of flood mitigation effectiveness. Focused on ecological flood mitigation or nature-based solutions approaches (e.g., wetlands, levees integrated with green buffers,

retention systems). Represented tropical, temperate, or arid/semi-arid climates. Were peer-reviewed journal articles written in English. Studies were excluded if they: Discussed only conventional (grey) infrastructure without ecological components, Focused solely on theoretical or modelling frameworks with no empirical validation, or Lacked clear methodological or performance data.

## Screening and Selection Process

An initial search yielded 67 papers, which were screened based on titles and abstracts. After removing duplicates and non-relevant studies, 25 publications met all criteria and were included for full review. Each study was then categorized according to climatic zone and primary mitigation strategy.

## Data Extraction and Synthesis

Data from the selected studies were systematically coded and synthesized under three main thematic dimensions: Type of ecological strategy (e.g., wetland restoration, riparian buffer, levee, water retention system), Climatic and environmental context, and Effectiveness indicators (e.g., flood peak reduction, runoff control, ecological co-benefits). Comparative analysis was conducted across climatic regions to highlight similarities, differences, and contextual dependencies. Findings were synthesized narratively, supported by quantitative indicators where available, to identify performance patterns and policy implications.

## Summary of Reviewed Studies

A summary of representative studies is presented in Table 1, showing regional focus, mitigation type, effectiveness, strengths, and challenges.

Table 1: Data synthesized from selected peer-reviewed studies (2020–2024)

Climatic Region	Sources	Mitigation Strategy
Tropical (Malaysia)	Forster et al. (2023); Yang et al. (2020); Zhao & He (2023); Shen et al. (2021)	Urban wetlands
Temperate (Netherlands)	Jansen et al. (2023); Van der Meer & Van Oort (2021); Johnson & Davis (2023)	Levees and hybrid green buffers
Arid/Semi-Arid (Australia)	Brown & Reed (2022); Williams & Reed (2023); Brown & Wilson (2021)	Water retention systems

## Results

Figure 1 presents the geographical scope of the reviewed studies, encompassing tropical (Malaysia), temperate (The Netherlands), and arid/semi-arid (Australia) climates. These zones differ substantially in rainfall intensity, temperature, and hydrological dynamics, offering a broad basis for cross-climate analysis of ecological flood mitigation methods. The results are organized to highlight key strategies, their relative performance, and the environmental factors influencing their effectiveness.

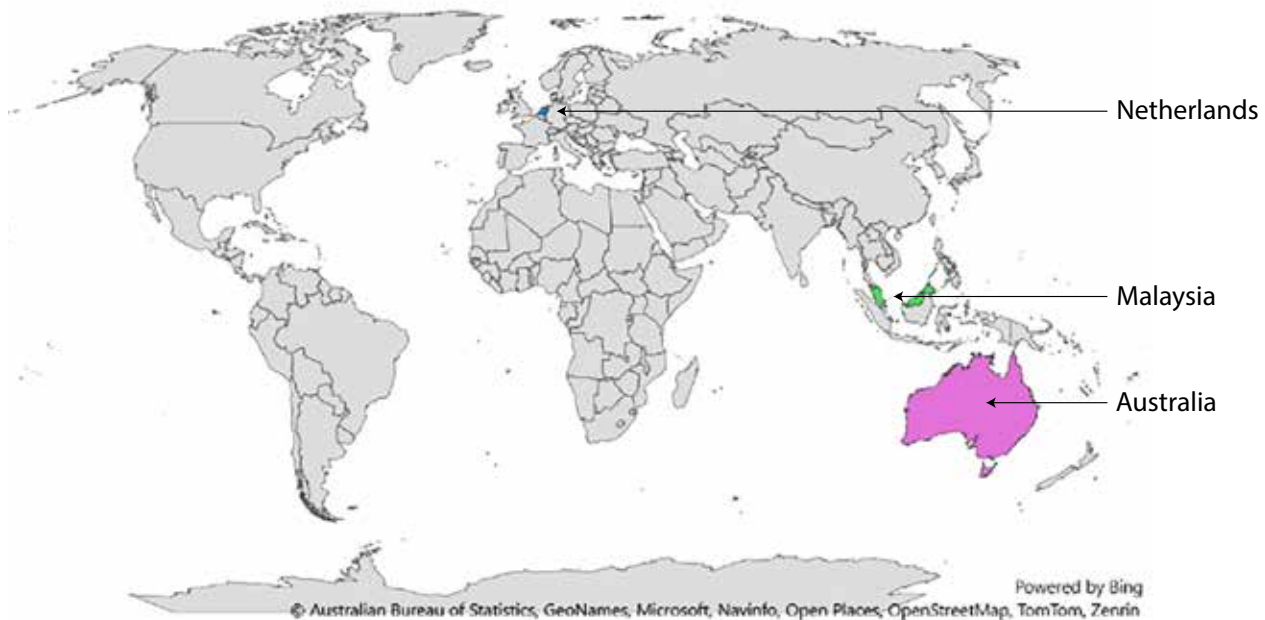


Figure 1: World map (Source: Australian Bureau of Statistics, GeoNames, Microsoft, Navi info, Open Places, Open StreetMap, Tom Tom, Zenrin Powered by Bing)

### Tropical Regions (e.g., Malaysia)

In tropical climates such as Malaysia, high rainfall intensity and humidity make urban wetlands and riparian restoration particularly effective. These systems reduce surface runoff and peak flow by up to 30% (Forster et al., 2023; Yang et al., 2020) by enhancing water infiltration and temporary storage capacity. The dense vegetation and high soil organic matter in tropical zones further improve absorption and evapotranspiration rates. However, the same climatic richness that supports vegetation also accelerates pollution accumulation and sedimentation, reducing long-term efficiency (Zhao & He, 2023; Shen et al., 2021). Studies by Khalid et al. (2022) and Aziz et al. (2021), highlight that integrating blue-green infrastructure systems, such as vegetated corridors and retention ponds, enhances both hydraulic performance and ecological co-benefits. Thus, hybrid systems that blend ecological and structural designs demonstrate the highest resilience in tropical environments.

### Temperate Regions (e.g., The Netherlands)

Temperate regions, such as the Netherlands, rely heavily on levees, dikes, and permeable pavements to manage water from both riverine and coastal sources (Jansen et al., 2023; Van der Meer & Van Oort, 2021). These grey-green hybrid systems achieve protection levels of up to 90% of flood-prone areas by stabilizing hydrological flows and preventing overtopping. The effectiveness of these measures is supported by moderate rainfall distribution, high soil permeability, and strong institutional management (Johnson & Davis, 2023). Vegetated levee buffers are increasingly integrated to improve adaptive capacity and biodiversity. Nonetheless, the high maintenance cost and potential for false security (Johnson & Davis, 2023) underline the need for diversified ecological measures that enhance flexibility under changing climate extremes.

### Arid and Semi-Arid Regions (e.g., Australia)

In arid and semi-arid climates, the scarcity of rainfall and high evaporation rates necessitate strategies that maximize water retention and minimize runoff losses.

Detention basins, infiltration ponds, and rainwater harvesting systems are the most effective, reducing flood volumes by up to 40% (Brown & Reed, 2022; Williams & Reed, 2023). These systems not only mitigate floods but also address water scarcity, a dual benefit unique to these environments. However, their success is highly dependent on rainfall frequency and soil permeability. Periodic droughts can limit infiltration efficiency, while construction and maintenance costs remain substantial. Integrating landscape-based recharge zones with engineered storage systems has been shown to optimize both hydrological regulation and urban water reuse.

### Cross-Comparative Synthesis

Across all climates, the performance of ecological flood mitigation methods depends largely on three environmental parameters, rainfall intensity, vegetation density, and soil permeability.

In tropical regions, high rainfall intensity and dense vegetation favour wetland and riparian systems with high storage and infiltration potential (Forster et al., 2023; Yang et al., 2020).

In temperate zones, moderate rainfall and well-managed soils support hybrid systems combining levees, permeable pavements, and green corridors (Jansen et al., 2023; Van der Meer & Van Oort, 2021).

In arid climates, low rainfall requires engineered–ecological hybrids such as infiltration basins that retain scarce water while providing ecological value (Brown & Reed, 2022; Williams & Reed, 2023).

Overall, wetlands and blue–green systems show high suitability in tropical zones; permeable pavements and levee–buffer combinations perform moderately to highly in temperate regions; and retention-based systems are moderately suitable but essential in arid zones. Therefore, Table 2 presents a comparative overview of the suitability of various ecological flood mitigation strategies across tropical, temperate, and arid/semi-arid climates.

Table 2: Comparative Suitability of Ecological Flood Mitigation Strategies Across Climate Types

Climate Region	Representative Methods	Effectiveness (%)	Qualitative Suitability	Key Strengths	Key Limitations
Tropical (Malaysia) (Forster et al., 2023; Yang et al., 2020; Zhao & He, 2023; Shen et al., 2021).	Urban wetlands, riparian buffers, blue–green corridors	Up to 30% reduction in peak flow	Moderate	Strong runoff absorption, biodiversity support	Pollution, sedimentation, urban encroachment
Temperate (Netherlands) (Jansen et al., 2023; Van der Meer & Van Oort, 2021; Brown & Reed, 2022; Williams & Reed, 2023)	Levees, dikes, permeable pavements.	Up to 90% flood protection	High	Reliable large-scale protection, strong governance	Expensive maintenance, risk complacency
Arid/Semi-Arid (Australia) (Brown & Reed, 2022; Williams & Reed, 2023)	Detention basins, infiltration ponds, rainwater harvesting	Up to 40% flood volume reduction	Moderate	Dual flood–water management benefit	High cost, climate variability

### Summary of Key Insights

The synthesis indicates that no single ecological strategy is universally optimal. Instead, context-specific hybridization that combines ecological, hydrological, and engineered elements offers the most resilient solutions. Methods with strong vegetative structures perform best under humid conditions, while those emphasizing infiltration and storage are better suited for arid zones. The comparative findings underscore the importance of climate-responsive design in developing integrated, ecological flood resilience frameworks adaptable across regions. The percentage effectiveness of these methods is illustrated in Figure 2.

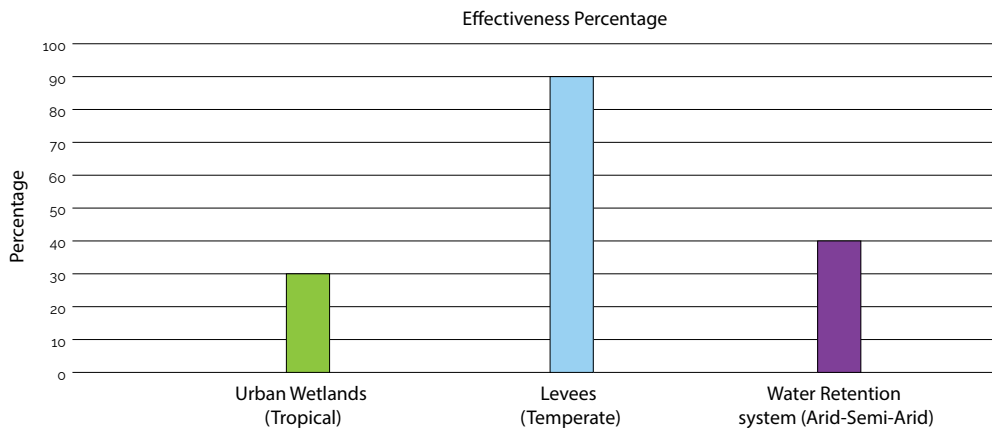


Figure 2: The Effectiveness of Flood Mitigation Strategies Across Climate Regions.

## Discussion

Ecological flood mitigation strategies differ in their hydrological and ecological performance according to climatic context. In tropical regions, wetlands, riparian buffers, and vegetated corridors exhibit strong flood attenuation capacity due to high rainfall and dense vegetation cover, which enhance infiltration and storage (Forster et al., 2023). However, their effectiveness is constrained by anthropogenic pressures such as urban encroachment and pollution, which disrupt their hydraulic capacity. The high rate of organic decomposition in humid climates can also reduce long-term water retention, necessitating continuous maintenance and integration with urban land use planning (Forster et al., 2023; Yeo et al., 2021).

As depicted in Figure 3, well-designed urban wetlands serve as multifunctional flood buffers that not only reduce surface runoff but also provide ecological and recreational value. In addition, green roofs in tropical cities mitigate urban heat and improve stormwater control by delaying runoff, demonstrating how temperature moderation can indirectly enhance system resilience.



Figure 3: Wetland Park, Putrajaya, Malaysia (Source: Visit Selangor, 2021)

As illustrated in Figure 4, in temperate regions, engineered systems such as vegetated levees and dikes remain central to flood management due to well-developed hydrological networks and stable rainfall patterns. Their reliability is well documented (Jansen et al., 2023; Van der Meer & Van Oort, 2021), yet they often provide limited ecological value. As illustrated in Figure 4, these structures demonstrate long-term effectiveness in containing sea water surges and protecting low-lying coastal zones. The success of hybrid systems that combine levees with green infrastructure lies in their capacity to absorb excess rainfall, reinforce riverbank and coastal embankments, as well as restore adjacent vegetation, thereby reducing system rigidity and enhancing ecological connectivity (Johnson & Davis, 2023; Wiering et al., 2023). Temperate soils generally exhibit moderate permeability, enabling the effective performance of permeable pavements and bioswales, which further support distributed stormwater management.



Figure 4: Levees in the Netherlands (Source: Waterisearth, 2016)

Figure 5 highlights, the stormwater retention system in Australia. In arid and semi-arid regions, rainfall scarcity and high evaporation rates reduce the efficiency of wetlands and vegetated systems, explaining their limited adoption. Instead, water retention basins, detention ponds, and rainwater harvesting structures are more suitable, as they capture runoff from short, intense rainfall events for gradual release or reuse (Brown & Wilson, 2021; He et al., 2023). The high infiltration capacity of sandy soils enhances groundwater recharge, although performance remains sensitive to climatic variability. Consequently, modular and low-cost designs that can flexibly operate under both drought and flash flood conditions are crucial for sustainable implementation (Brown & Reed, 2022; Williams & Reed, 2023).



Figure 5: Stormwater Retention System in Australia (Source: Enviropipes2024)

Across all climatic zones, three critical factors, vegetation density, soil permeability, and rainfall intensity, emerge as dominant determinants of ecological method performance. These parameters shape infiltration capacity, storage potential, and hydraulic response times. Regions with dense vegetation and high rainfall benefit more from ecological systems, while those with sparse vegetation and low rainfall depend on engineered–ecological hybrids. This explains the superior outcomes observed in tropical and temperate systems compared to arid ones.

When compared with earlier global reviews (e.g., Yang et al., 2020; Zhao & He, 2023), the present synthesis extends the discussion by providing a cross-climatic comparative framework rather than single-region evaluations. Previous studies tended to assess isolated interventions within local contexts, whereas this review highlights the contextual dependencies and trade-offs across climates. The findings reinforce that universal application of a single ecological technique is impractical, context-specific integration of hydrological and ecological functions is necessary for effective flood resilience planning.

Governance and institutional capacity also play pivotal roles. In Malaysia, for instance, fragmented responsibilities and limited inter-agency coordination constrain the effective scaling and implementation of ecological flood mitigation methods (Ismail, Abdullah, & Ramli, 2022). Similar institutional rigidity has been observed in European contexts where traditional engineering dominance limits the mainstreaming of green measures (Wiering et al., 2023). Thus, strengthening institutional frameworks and promoting co-management across agencies are essential for long-term resilience.

## Policy and Practical Implications

For tropical cities, integrating wetlands and vegetated corridors within urban planning frameworks is vital. Buffer zones should be legally protected to prevent encroachment and maintain hydrological function. Urban agriculture and green roof initiatives (Fadzil et al., 2023) can complement these systems by enhancing infiltration and delivering community co-benefits.

In temperate regions, hybrid levee–green infrastructure systems should be prioritised. Vegetated embankments, riparian corridors, and bioswales not only strengthen hydraulic redundancy but also improve ecological connectivity and community acceptance. Policy instruments encouraging multi-functional floodplain restoration can further enhance resilience.

For arid and semi-arid zones, modular retention systems such as infiltration galleries and rainwater harvesting units offer flexible solutions for managing unpredictable rainfall while addressing water scarcity. Governments should adopt incentive-based schemes and capacity-building programmes to support local implementation and maintenance.

Across all regions, urban planners should prioritise context-based combinations of ecological and engineered strategies according to rainfall variability, soil type, and available land. Effective governance, technical capacity, and long-term monitoring frameworks are key to ensuring the sustainability of these interventions.

## Future Research Recommendations

Future research should prioritize cross-regional and longitudinal analyses that quantitatively assess the hydrological and ecological performance of ecological flood mitigation measures. Comparative meta-analyses using standardized indicators, such as runoff reduction, infiltration capacity, and ecosystem resilience, would enable more robust benchmarking across climatic contexts. Further studies should also investigate the long-term maintenance, cost-effectiveness, and scalability of ecological and hybrid systems under changing climate conditions. Finally, collaborative research between scientists, policymakers, and local practitioners will be vital to bridge the gap between scientific innovation and on-ground implementation.

## Conclusion

This review is among the few that systematically compare the suitability and performance of ecological flood mitigation approaches across diverse climate zones. The findings reveal that while ecological strategies such as wetlands, riparian buffers, and green infrastructure demonstrate strong potential for reducing flood risks, their effectiveness is highly context-dependent, shaped by climatic, hydrological, and urban conditions. Hybrid systems that integrate ecological measures with engineered structures emerge as the most resilient and adaptable solutions. Future research should focus on developing standardized evaluation metrics for assessing the performance of nature-based flood mitigation and expanding empirical studies, particularly in underrepresented arid and tropical regions. Strengthening the integration of ecological planning into national flood policies will not only enhance local resilience but also contribute meaningfully to global climate adaptation goals and the United Nations Sustainable Development Goal 13 (Climate Action).

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