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REVIEW

Hydrodynamic Modelling of Mangrove-Mediated Coastal Flood Protection: A Systematic Review and Bibliometric Analysis

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ABSTRACT

Mangroves are increasingly recognised as important nature-based systems for reducing coastal flood risk, yet research on their hydrodynamic performance remains dispersed across coastal engineering, eco-hydrology, restoration science, and environmental management. This study synthesises recent advances in mangrove-mediated coastal protection through a systematic review and bibliometric analysis of literature retrieved from the Scopus database. The search identified 404 publications published between 2021 and 2026, of which 185 articles met the inclusion criteria after screening and eligibility assessment. Publication output increased from 23 papers in 2021 to 58 papers in 2025, reflecting growing scientific interest in nature-based coastal adaptation and resilience. Five major research themes were identified: wave attenuation and hydrodynamic resistance, flood-depth reduction and storm-surge moderation, vegetation representation in numerical models, restoration and hybrid coastal protection strategies, and climate-related stressors affecting long-term ecosystem performance. The reviewed studies consistently demonstrated that mangrove ecosystems reduce wave energy, current velocity, and flood impacts, although protection effectiveness varies according to forest width, vegetation density, species composition, hydrodynamic conditions, and coastal morphology. Recent advances in LiDAR, remote sensing, terrestrial laser scanning, and coupled hydro-morphodynamic modelling have improved representation of vegetation–flow interactions within

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numerical simulations. Despite these developments, important challenges remain regarding vegetation flexibility, damage thresholds under extreme events, model validation, uncertainty assessment, and transferability across different coastal settings. The findings highlight the importance of viewing mangroves as dynamic coastal protection systems shaped by interacting ecological, geomorphological, and hydrodynamic processes. Future research should prioritise long-term monitoring, uncertainty analysis, and hybrid protection strategies that integrate ecosystem-based and engineered coastal infrastructure.

Keywords: Mangroves; Coastal Flooding; Hydrodynamic Modelling; Wave Attenuation; Nature-Based Solutions; Coastal Resilience; Bibliometric Analysis; Restoration

1. Introduction

Coastal flooding has become an increasingly critical global issue as sea-level rise, storm surges, extreme wave events, and rapid coastal development continue to intensify simultaneously. Recent global assessments indicate that economic losses associated with coastal flooding are expected to increase substantially throughout the twenty-first century if existing protection strategies remain unchanged [1, 2]. In response to these growing risks, attention has increasingly shifted toward ecosystem-based and nature-based coastal defence approaches, particularly in regions where conventional hard infrastructure is economically expensive, environmentally disruptive, or socially difficult to implement [3–5].

Among the available nature-based solutions, mangrove ecosystems have received considerable attention because of their ability to reduce wave energy, modify hydrodynamic flow, trap sediments, stabilize shorelines, sequester carbon, and support fisheries and coastal livelihoods [6–9].

However, recent studies suggest that the effectiveness of mangroves as coastal protection systems depends on multiple interacting factors rather than simply the presence of vegetation alone. Forest width, vegetation density, root and canopy structure are among the key determinants influencing wave attenuation and flood reduction [10–14]. In addition, tidal conditions, substrate characteristics, channel configuration, local topography, and the type of coastal hazard further influence the level of coastal protection provided by mangrove forests [15–17].

Beyond their hydrodynamic functions, mangrove ecosystems are increasingly being studied within broader environmental management and sustainability contexts. Recent reviews on mangrove ecosystem management in Indonesia, for example, highlight the need to integrate ecological, socioeconomic, and governance considerations into coastal management strategies [18]. Other studies have emphasized the multifunctional role of mangroves in environmental protection, including their contribution to phytoremediation and coastal water quality improvement [19]. These developments demonstrate that mangrove-mediated coastal protection should not be examined solely from an engineering perspective, but rather as part of a broader socio-ecological coastal system.

Investigating the interaction between mangrove ecosystems and coastal hydrodynamics requires integrated analytical approaches that combine ecological observations, field measurements, and numerical modelling techniques. Hydrodynamic models are now widely used to simulate wave propagation, water circulation, inundation processes, and sediment transport under different environmental and climate conditions. Recent studies have applied one-dimensional, two-dimensional, and coupled hydro-morphodynamic models to evaluate how mangrove vegetation influences coastal flooding and wave attenuation processes. At the same time, advances in remote sensing, Light Detection and Ranging (LiDAR), and terrestrial laser scanning technologies have significantly improved the representation of vegetation structure within numerical simulations, allowing more realistic modelling of vegetation-flow interactions.

Although research on mangrove-based coastal protection has expanded rapidly in recent years, the literature remains fragmented across several disciplines, including coastal engineering, hydrology, marine ecology, and environmental management. Many studies focus on site-specific applications or individual case studies, while comparatively fewer studies provide a comprehensive synthesis of recent advances in hydrodynamic modelling and mangrove-mediated flood protection mechanisms [9]. Consequently, important knowledge gaps remain regarding modelling approaches, vegetation parameterization, uncertainty assessment, restoration effectiveness, and long-term resilience under changing climate conditions.

The studies presented in **Table 1** demonstrate that previous publications have made important contributions to understanding mangrove ecosystem management, nature-based coastal protection, and flood-risk reduction. However, existing reviews have generally focused on ecological management, specific protection functions, or individual hazard scenarios. Comparatively limited attention has been given to synthesizing recent advances in hydrodynamic modelling, vegetation-flow interactions, modelling frameworks, uncertainty considerations, and emerging research trends within a single review. Furthermore, previous studies have rarely combined systematic review procedures with bibliometric analysis to examine how research themes, collaboration patterns, and modelling approaches have evolved over time. The present review addresses these limitations by integrating bibliometric mapping with a PRISMA-based systematic review to provide a comprehensive synthesis of hydrodynamic modelling applications, flood-protection mechanisms, research developments, and future research priorities related to mangrove-mediated coastal protection.

Table 1. Comparison of existing literature and the present review.

Reference	Primary Focus	Key Contribution	Limitations Relevant to the Present Study
Kurniawansyah et al. (2023) [18]	Mangrove ecosystem management	Discussed ecological management, governance, and sustainability issues affecting mangrove ecosystems	Limited discussion of hydrodynamic modelling, flood attenuation mechanisms, and numerical simulation approaches
van Hespen et al. (2023) [14]	Mangroves as nature-based solutions for coastal flood protection	Examined ecological and biophysical considerations influencing coastal protection performance	Did not provide a systematic synthesis of modelling approaches, bibliometric trends, or research evolution
Shokatian-Beiragh et al. (2024) [15]	Effectiveness of mangroves under extreme weather events	Evaluated mangrove performance during flood-related hazards	Focused on protection effectiveness rather than broader research development, modelling frameworks, and emerging research directions
Hu et al. (2025) [16]	Nature-based coastal protection under extreme waves	Advanced understanding of mangrove protection under severe hydrodynamic conditions	Concentrated on specific hydrodynamic processes rather than providing a comprehensive review of the field
Present Review	Hydrodynamic modelling of mangrove-mediated coastal flood protection	Integrates systematic review, bibliometric analysis, thematic synthesis, modelling approaches, research trends, and future research priorities	Provides a comprehensive assessment of recent developments and identifies remaining knowledge gaps across disciplines

A clearer synthesis of recent developments in hydrodynamic modelling, vegetation-flow interactions, and mangrove-based coastal protection is therefore needed to consolidate current knowledge and identify emerging research priorities. Combining bibliometric mapping with analytical synthesis also provides an opportunity to evaluate how research themes, modelling approaches, and interdisciplinary collaborations have evolved in recent years. Accordingly, this review presents a systematic review and bibliometric analysis of scientific literature related to hydrodynamic modelling of mangrove-mediated coastal flood protection. The review specifically aims to:

- Examine global research trends and collaboration networks related to mangrove-based coastal protection;
- Identify major research themes and modelling approaches applied in mangrove hydrodynamic studies;
- Synthesize current understanding of the hydrodynamic mechanisms through which mangrove ecosystems reduce coastal flood impacts;
- Identify key research gaps and future research

directions for improving mangrove-based coastal protection strategies.

Through this integrated review approach, the paper contributes to a broader understanding of the role of mangrove ecosystems in coastal flood risk reduction and supports the development of evidence-based nature-based solutions for climate adaptation and sustainable coastal management.

2. Methodology

2.1. Study Design

A systematic literature review combined with bibliometric analysis and analytical synthesis was employed to examine recent research developments related to hydrodynamic modelling of mangrove-mediated coastal flood protection. Systematic review approaches allow for structured identification, evaluation, and synthesis of scientific literature while minimizing potential selection bias during the review process. To enhance methodological transparency and reproducibility, the review procedure was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework.

The overall workflow consisted of four sequential stages. The first stage involved identifying potentially relevant publications through database searching. The second stage focused on preliminary screening based on titles and abstracts to remove clearly unrelated studies. During the third stage, full-text eligibility assessment was conducted to confirm the relevance of each publication to mangrove ecosystems, coastal flooding processes, and hydrodynamic or numerical modelling approaches. The final stage involved bibliometric mapping and qualitative analytical synthesis of the selected studies.

2.2. Literature Search Strategy

The literature search was conducted using the Scopus database on 15 March 2026. Scopus was selected because it provides extensive coverage of peer-reviewed journals across coastal engineering, marine science, environmental management, hydrology, and climate adaptation research. In addition, the database offers standardized bibliographic information that is compatible with bibliometric software such as VOSviewer, enabling consistent analysis of publication trends, collaboration networks, and thematic development.

The search strategy was designed to identify studies examining the role of mangrove ecosystems in coastal flood protection, wave attenuation, storm-surge reduction, and hydrodynamic modelling. Searches were performed within article titles, abstracts, and author keywords using the following query:

TITLE-ABS-KEY (mangrove* AND (flood* OR surge OR inundation OR coastal protection OR wave attenuation) AND (model* OR simulation OR hydrodynamic model* OR numerical model*))

The search covered publications from January 2021 to March 2026. This period was selected to capture the most recent developments in nature-based coastal protection, ecosystem-based adaptation, and advances in hydrodynamic modelling. It should be noted that publication records for 2026 represent a partial year because data collection was completed during the first quarter of 2026. Consequently, publication counts for 2026 should not be interpreted as directly comparable to those reported for previous full calendar years.

Only peer-reviewed journal articles and review papers published in English were included in the dataset. The decision to focus on English-language publications was made to ensure consistency during screening and analysis, as English remains the dominant language of international scientific communication within coastal and environmental research. Nevertheless, this criterion may have excluded relevant studies published in other languages and therefore represents a limitation of the review. Although restricting the review to English-language publications may have excluded some regional studies, English remains the dominant language of international scientific communication and accounts for the majority of publications indexed within Scopus. Consequently, the selected dataset is considered sufficiently representative for identifying global research trends, major modelling approaches, and thematic developments in mangrove-mediated coastal flood protection. Nevertheless, future reviews may benefit from incorporating non-English databases and regional literature sources to provide a more comprehensive understanding of local research perspectives.

2.3. Screening and Eligibility Assessment

The initial search retrieved 404 records from the Scopus database. All bibliographic information was exported in CSV format and screened manually to determine relevance to the objectives of the review.

The screening process was conducted in two stages. In the first stage, article titles and abstracts were examined to identify studies related to mangrove ecosystems, coastal flooding, wave attenuation, storm-surge mitigation, and hydrodynamic or numerical modelling. Publications that were clearly unrelated to these topics were removed.

In the second stage, the remaining articles were subjected to a full-text eligibility assessment. Studies were retained only when they provided direct relevance to mangrove-mediated coastal protection and included discussion of hydrodynamic processes, flood mitigation mechanisms, vegetation–flow interactions, or modelling approaches used to evaluate coastal protection performance.

Publications were excluded when they met one or more of the following criteria:

- The study did not focus on mangrove ecosystems;
- The study did not address coastal flooding, wave attenuation, storm-surge reduction, or coastal protection processes;
- The study did not involve hydrodynamic, numerical, or process-based modelling approaches;
- The publication focused primarily on ecological, biological, or environmental issues without direct relevance to coastal protection performance.

The screening and eligibility assessment were conducted by the authors through manual review of titles, abstracts, and full texts. Where uncertainty arose regarding article relevance, the publication was re-evaluated against the inclusion criteria before a final decision was made. This approach helped improve consistency during article selection and reduced the risk of excluding potentially relevant studies.

In addition to thematic relevance, journal quality was considered during the eligibility assessment. Journal quartile rankings obtained from the SCImago Journal Rank database were used as supplementary indicators of publication visibility and scientific influence. However, journal quartile alone was not used as an exclusion criterion. Relevant studies published in Q3 and Q4 journals were retained when they provided important methodological, thematic, or regional contributions to the review.

A formal quality-scoring framework was not applied because the review included a diverse body of literature encompassing numerical modelling studies, field investigations, laboratory experiments, and review articles. Instead, methodological robustness, relevance to the review objectives, and scientific contribution were considered during article evaluation and synthesis.

Following the screening and eligibility assessment process, 219 publications were excluded, resulting in a final dataset of 185 articles for bibliometric analysis and qualitative synthesis. The overall selection procedure is illustrated in the PRISMA diagram presented in **Figure 1**.

2.4. Bibliometric Analysis

Bibliometric analysis was conducted to examine research trends, thematic development, and the intellectual structure of studies related to mangrove-mediated coastal flood protection. This approach provides a quantitative overview of the scientific literature by identifying collaboration patterns, dominant research themes, and emerging areas of investigation within the field.

The analysis was performed using VOSviewer software, which is widely used for visualizing bibliographic and citation networks. A total of 185 selected publications were imported into the software to generate network maps based on co-authorship relationships, institutional collaboration, country-level research networks, and keyword co-occurrence patterns.

Keyword co-occurrence analysis was further applied to identify the major thematic clusters within the literature. To improve consistency and reduce the inclusion of infrequently used terms, a minimum threshold of five keyword occurrences was adopted during the mapping process.

The bibliometric outputs included network visualization, overlay visualization, and density visualization maps. Together, these visualizations provide insight into research concentration, thematic relationships, and the temporal evolution of scientific activity related to mangrove-based coastal protection.

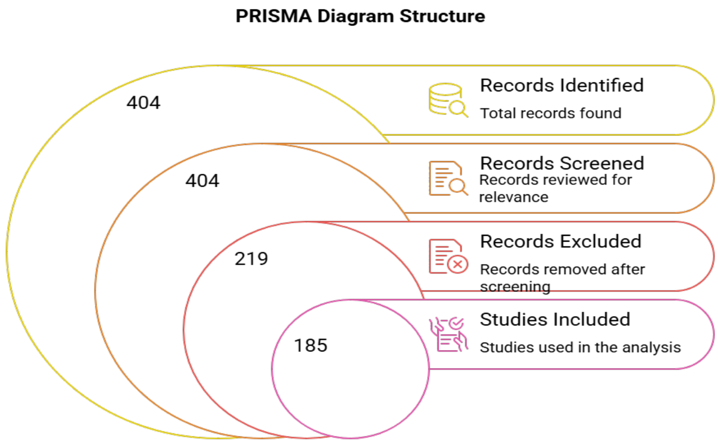

Figure 1. PRISMA diagram structure.

Source: Authors' work.

2.5. Analytical Synthesis

In addition to bibliometric mapping, the selected publications were examined through qualitative analytical synthesis. This approach enabled the integration and interpretation of findings from multiple studies to identify recurring patterns, methodological trends, and existing knowledge gaps related to mangrove-mediated coastal protection. Analytical synthesis is particularly useful in interdisciplinary reviews because it allows evidence from different research domains to be interpreted within a broader conceptual context.

Based on the thematic patterns identified through the bibliometric analysis, the literature was grouped into several major research themes. These included ecosystem services provided by mangrove ecosystems, hydrodynamic processes and wave attenuation, environmental factors influencing mangrove resilience, restoration and monitoring strategies, and threats affecting mangrove ecosystems. Organizing the literature into thematic categories allowed for clearer comparison of findings across different study settings and modelling approaches.

Combining bibliometric analysis with analytical synthesis provided both quantitative and qualitative perspectives on the current state of research. This integrated approach offers a more comprehensive understanding of how scientific interest, methodological development, and interdisciplinary collaboration have evolved within the field of mangrove-mediated coastal protection.

2.6. Conceptual Framework for Mangrove-Mediated Coastal Flood Protection

Figure 2 illustrates the relationships among ecological attributes, hydrodynamic behaviour, numerical simulation techniques, and coastal protection performance identified throughout the review. Characteristics such as forest width, vegetation density, root complexity, canopy configuration, and species composition influence the extent to which mangrove ecosystems modify wave energy, water movement, sediment dynamics, and flood propagation. Evaluation of these interactions commonly relies on numerical tools including Delft3D, SWAN, XBeach, HEC-RAS, and coupled hydro-morphodynamic models, which enable researchers to examine protective functions under different environmental conditions and hazard scenarios. Evidence reported in the literature consistently indicates that these ecological and physical interactions contribute to flood-risk reduction, shoreline stabilization, enhanced resilience, and broader climate adaptation objectives. Long-term effectiveness, however, is shaped by additional influences including sea-level rise, land subsidence, restoration success, climatic variability, and governance capacity. Viewed collectively, current knowledge suggests that coastal protection provided by mangroves emerges from a complex interplay between ecosystem characteristics, hydrodynamic responses, environmental change, and management interventions. This synthesis provides a structured basis for understanding the interconnected factors that determine protection performance across diverse coastal settings.

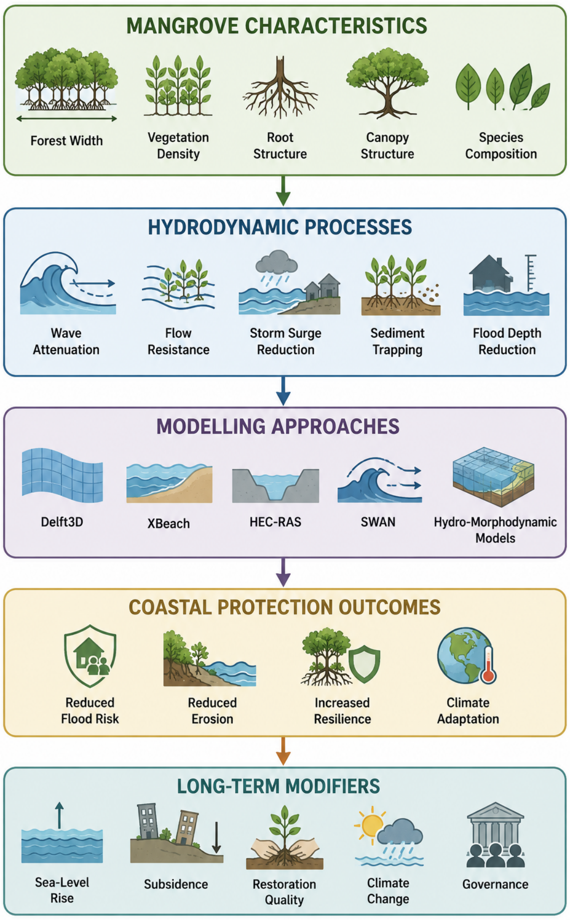

Figure 2. Conceptual framework for mangrove-mediated coastal flood protection.

Source: Authors' work.

3. Bibliometric Analysis Results

3.1. Publication Trends and Research Growth

Bibliometric analysis indicates a substantial increase in scientific interest in mangrove-mediated coastal protection in recent years. The final dataset consisted of 185 peer-reviewed publications published between 2021 and 2026, reflecting growing research attention toward nature-based approaches for coastal flood mitigation and climate adaptation.

Growing publication output appears closely linked to increasing global concern over climate change impacts, particularly sea-level rise, coastal flooding, and storm surge hazards affecting low-lying coastal regions. Mangrove ecosystems are increasingly recognized as natural coastal buffers capable of reducing hydrodynamic energy while simultaneously providing important ecological and socioeconomic benefits. This growing recognition has encouraged stronger interdisciplinary collaboration among researchers in coastal engineering, environmental science, marine ecology, hydrology, and climate adaptation.

Rapid progress in environmental monitoring technologies and numerical modelling capabilities has also contributed to the expansion of scientific literature within this field. Advances in high-resolution remote sensing, LiDAR-based vegetation mapping, and hydrodynamic simulation models have enabled more detailed investigation of mangrove ecosystem dynamics and vegetation-flow interactions. Consequently, recent research has gradually shifted from descriptive ecological assessments toward more quantitative modelling approaches and integrated coastal management applications.

Based on **Figure 3**, publication output increased steadily throughout the study period, indicating growing scientific interest in hydrodynamic modelling of mangrove-mediated coastal flood protection. The screened dataset contained 23 publications in both 2021 and 2022, followed by a moderate increase to 27 publications in 2023. Research activity expanded more substantially in 2024 with 39 publications and reached its highest level in 2025 with 58 publications. A total of 15 publications were identified for 2026 at the time of data collection, which most likely reflects partial database indexing rather than a decline in research activity. This publication trend reflects increasing research attention toward nature-based solutions, climate adaptation, and coastal resilience strategies in vulnerable coastal regions.

3.2. International Research Collaboration

Country-level collaboration analysis was carried out to evaluate international research partnerships related to mangrove-mediated coastal protection. VOSviewer software was used to generate collaboration networks using a minimum threshold of five publications per country. Network visualization revealed extensive collaboration among several major research hubs (**Figure 4**).

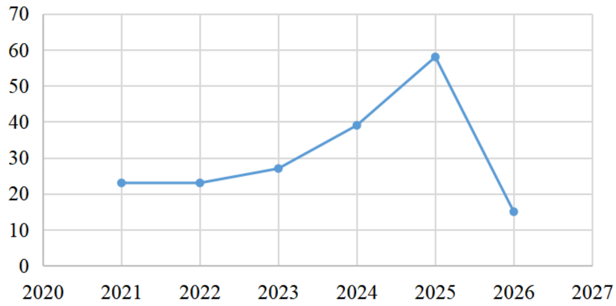

Figure 3. Publication trend analysis.
Source: Authors' work (from Scopus data).

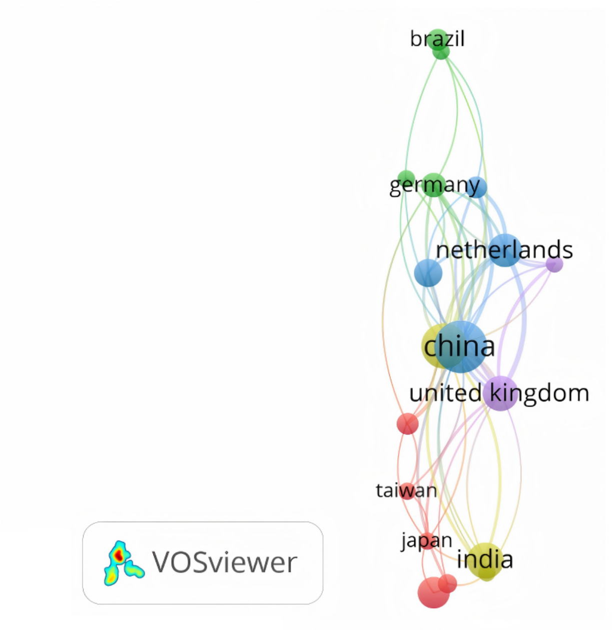

Figure 4. International collaboration network among countries in mangrove coastal protection research.
Source: Authors' work (visualized by VOSviewer).

China emerged as the most productive country within the dataset, contributing 46 publications, followed by the United States with 34 publications, India with 22 publications, the United Kingdom with 21 publications, and the Netherlands with 19 publications. These countries formed the principal nodes within the collaboration network and demonstrated substantial scientific influence in mangrove-related coastal protection research.

Evidence from the collaboration network also indicates strong interaction between European and Asian research institutions, particularly involving the Netherlands, the United Kingdom, and China. Much of this collaboration appears to be driven by interdisciplinary research associated with coastal engineering, hydrodynamic modelling, and ecosystem-based coastal protection strategies.

Additional contributions from countries such as Australia, Belgium, Germany, Indonesia, and Brazil further strengthen the international research landscape within this field. Participation from both developed and developing coastal nations highlights the broad global importance of mangrove ecosystems in addressing coastal hazards, sea-level rise, and climate-related flood risks.

Collectively, the collaboration patterns demonstrate that mangrove-based coastal protection research has evolved into a highly international and interdisciplinary field characterized by active knowledge exchange between regions vulnerable to coastal flooding and countries with advanced coastal engineering and environmental research capabilities.

While collaboration networks indicate increasing interaction among researchers from different disciplines and regions, co-authorship patterns alone do not necessarily demonstrate full integration of ecological, hydrodynamic, and engineering knowledge. Consequently, collaboration indicators should be interpreted as evidence of research connectivity and knowledge exchange rather than direct measures of interdisciplinary synthesis. Further integration of ecological observations, hydrodynamic modelling, and coastal management perspectives remains necessary to strengthen understanding of mangrove-mediated coastal protection processes.

3.3. Institutional Collaboration

Institutional collaboration analysis provides additional insight into the organizations contributing to research on mangrove hydrodynamics and coastal protection. **Figure 5** illustrates the institutional co-authorship network, showing several active collaborative relationships among universities and research institutes. The network indicates that Utrecht University occupies a central position, acting as the primary collaborative hub linking Deltares with the Guangdong Provincial Key Laboratory of Marine Resources and Coastal Engineering and other affiliated marine research institutions. The direct links among these organizations indicate active institutional collaboration in coastal engineering, hydrodynamics, and mangrove-based coastal resilience research.

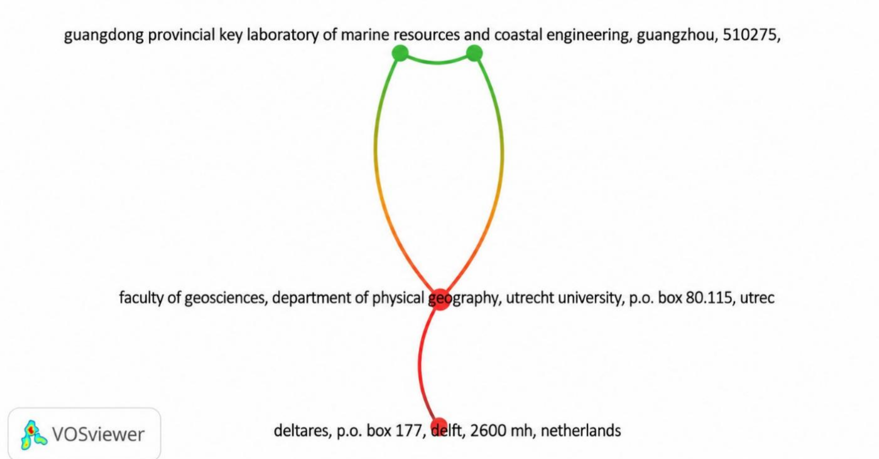

Figure 5. Institutional co-authorship network among organizations involved in mangrove-based coastal protection research generated using VOSviewer (minimum documents per organization = 2).
Source: Authors' work (visualized by VOSviewer).

A large proportion of the collaborating institutions are located in coastal regions where mangrove ecosystems are widely distributed, enabling researchers to conduct field investigations, long-term environmental monitoring, and hydrodynamic assessments. As depicted in **Figure 5**, collaboration occurs primarily between universities and specialized marine and coastal research institutes, reflecting the importance of interdisciplinary partnerships in addressing complex coastal protection challenges. Such collaborations also support large-scale research programmes on coastal resilience, ecosystem restoration, and climate change adaptation.

The institutional collaboration network presented in **Figure 5** further highlights the interdisciplinary nature of mangrove-based coastal protection research. Collaborative activities integrate expertise from coastal engineering, environmental science, marine ecology, hydrology, and geospatial analysis. The interaction among these disciplines facilitates a more comprehensive understanding of ecological processes and hydrodynamic behaviour, thereby supporting the development of effective nature-based solutions for sustainable coastal protection.

3.4. Keyword Co-Occurrence Network

Keyword co-occurrence analysis was carried out to identify the principal research themes and conceptual structure of studies related to mangrove-based coastal protection. Author keywords extracted from the Scopus dataset were analysed using VOSviewer with a minimum occurrence threshold of five keywords. Application of this threshold produced a network of frequently occurring terms representing the dominant research topics within the field (**Figure 6**).

Results indicate that "mangrove" was the most frequently occurring keyword, appearing in 100 publications. Other highly recurring terms included coastal protection (44 occurrences), wave attenuation (34 occurrences), climate change (34 occurrences), flooding (31 occurrences), and hydrodynamics (31 occurrences). Frequent appearance of these terms reflects the growing emphasis on mangrove ecosystems as nature-based coastal defence systems capable of reducing hydrodynamic energy and mitigating coastal flood impacts.

Several additional keywords also appeared prominently within the network, including nature-based solutions (20 occurrences), numerical model (21 occurrences), coastal zone (17 occurrences), mangrove forest (17 occurrences), and sea-level rise (12 occurrences). Increasing use of these terms suggests stronger integration between ecological approaches, hydrodynamic modelling, and climate adaptation strategies in recent coastal management research.

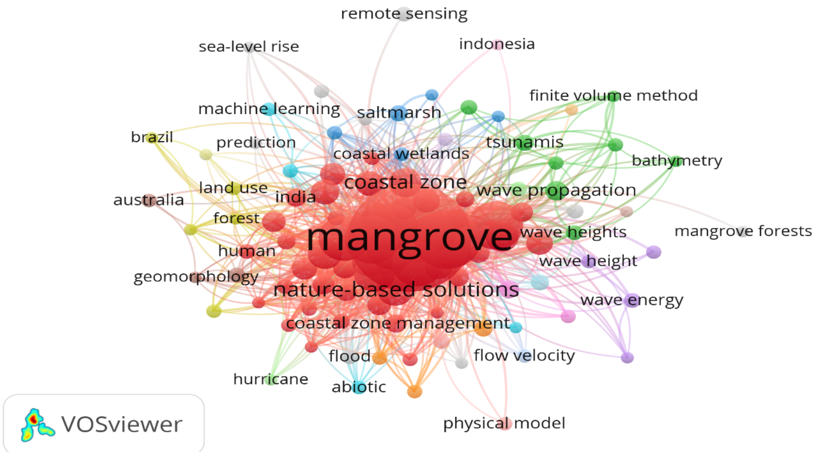

Figure 6. Keyword co-occurrence network showing major research themes within the literature on mangrove-mediated coastal flood protection.
Source: Authors' work (visualized by VOSviewer).

Network visualization further revealed several interconnected thematic clusters representing major research directions within the literature. One cluster concentrated on hydrodynamic and wave attenuation processes, incorporating terms such as wave propagation, wave height, wave energy, and sediment transport. Another cluster focused on coastal risk and climate-related hazards, represented by keywords including sea-level rise, storm surge, flooding, and vulnerability. A third cluster emphasized ecosystem-based coastal management, including nature-based solutions, ecosystem services, restoration, and coastal zone management.

Although sediment transport appeared within the hydrodynamic cluster, it did not emerge as one of the most dominant standalone keyword groups in bibliometric analysis. This does not imply that sediment processes are unimportant. Rather, sediment transport is often investigated as a component of broader themes such as wave attenuation, coastal morphology, shoreline stability, and ecosystem resilience. Given its critical role in vertical accretion, elevation maintenance, and adaptation to sea-level rise, sediment dynamics remain a fundamental process underpinning the long-term effectiveness of mangrove-mediated coastal protection.

Patterns observed within these thematic clusters illustrate the interdisciplinary character of mangrove-related research, bringing together coastal engineering, hydrodynamic modelling, ecological conservation, and climate adaptation perspectives. Increasing connectivity between these themes also reflects broader recognition of mangrove ecosystems as effective nature-based solutions for coastal flood mitigation and shoreline protection.

3.5. Temporal Evolution of Research Themes

Overlay visualization analysis provides insight into the temporal evolution of research themes within mangrove-mediated coastal protection studies. Earlier publications primarily concentrated on the ecological functions of mangrove ecosystems, particularly their contribution to shoreline stabilization and coastal ecosystem preservation. In more recent years, greater attention has been directed toward hydrodynamic modelling, climate adaptation strategies, and advanced environmental monitoring techniques.

Several emerging topics were identified from the overlay visualization map (**Figure 7**), including integration of remote sensing technologies with hydrodynamic simulation, machine learning-based ecosystem monitoring, and hybrid coastal protection approaches that combine mangrove restoration with engineered infrastructure. Growing interest in these themes reflects an ongoing transition toward more technologically advanced, data-driven, and interdisciplinary research approaches within the field.

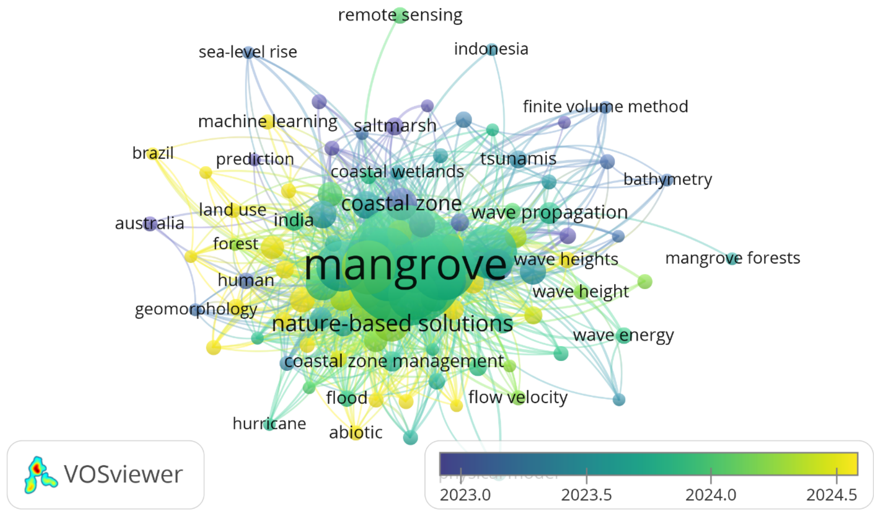

Figure 7. Overlay visualization of keyword co-occurrence illustrating the temporal evolution of research themes. Colors represent the average publication year associated with each keyword.
Source: Authors' work (visualized by VOSviewer).

3.6. Research Density and Thematic Concentration

Density visualization analysis in **Figure 8** highlights areas of high research concentration within the field of mangrove-mediated coastal protection. Regions with higher density are associated with frequently studied topics such as mangrove ecosystems, coastal protection, wave attenuation, and hydrodynamic modelling. Concentration of these themes indicates their central role within current scientific discussions and research activity.

Areas with lower density within the visualization map generally correspond to emerging or comparatively underexplored research topics. These areas may offer important opportunities for future investigation, particularly in subjects related to integrated coastal management, ecosystem-based climate adaptation, hybrid coastal defence strategies, and long-term evaluation of mangrove restoration effectiveness.

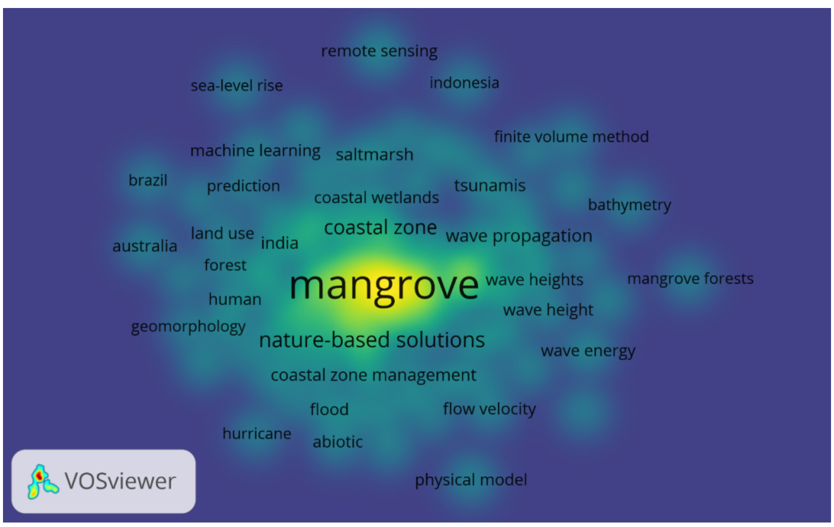

Figure 8. Density visualization of keyword co-occurrence highlighting areas of high research intensity within mangrove coastal protection studies.
Source: Authors' work (visualized by VOSviewer).

3.7. Highly Influential Publications and Citation Impact

Figure 9 highlights a group of publications that have played a significant role in shaping contemporary research on mangrove-mediated coastal protection. Several highly cited studies occupy central positions within the citation network, indicating their importance in advancing scientific understanding of the interactions between mangrove ecosystems and coastal hydrodynamic processes. The prominence of these publications reflects their contribution to the development of methodologies, conceptual understanding, and practical applications related to flood-risk reduction and climate adaptation.

A closer examination of the influential studies reveals a strong emphasis on quantifying the protective functions of mangrove ecosystems under varying environmental conditions. Particular attention has been given to wave attenuation, storm-surge mitigation, sediment dynamics, and the capacity of coastal vegetation to reduce flood impacts. Many of these investigations also contributed to the growing adoption of numerical modelling approaches, enabling researchers to evaluate protection performance across different coastal settings and hazard scenarios. As a result, research has gradually evolved from descriptive assessments of mangrove ecosystems toward more rigorous evaluations of their effectiveness as nature-based solutions.

The concentration of influential publications around themes such as ecosystem-based adaptation, resilience enhancement, and sustainable coastal management further illustrates the increasing integration of ecological and engineering perspectives within the field. This trend reflects a broader shift in coastal research, where mangroves are no longer viewed solely as ecological resources but are increasingly recognized as functional components of coastal defence systems. The citation patterns therefore suggest that future research is likely to focus on improving predictive modelling capabilities, evaluating long-term performance under changing climatic conditions, and supporting evidence-based decision-making for coastal adaptation and risk management.

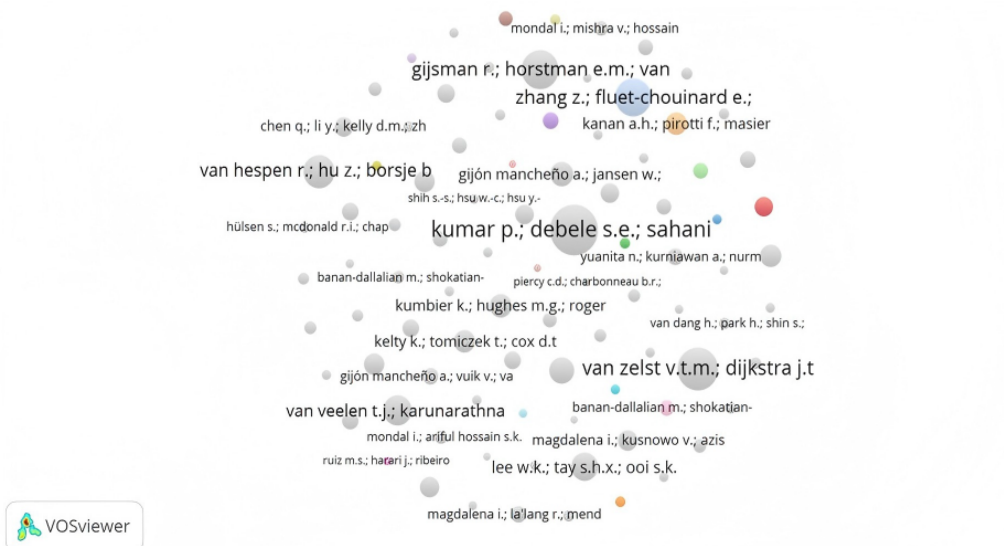

Figure 9. Citation network of influential publications in mangrove-mediated coastal flood protection research. Larger nodes represent publications with greater citation influence within the reviewed literature.
Source: Authors' work (visualized by VOSviewer).

3.8. Influential Sources and Publication Outlets

Figure 10 illustrates the citation network of publication sources contributing to mangrove-mediated coastal flood protection research. The network highlights several journals that have exerted substantial influence on the development of knowledge within the field. Among the most prominent outlets are *Estuarine, Coastal and Shelf Science*, *Ocean Engineering*, *Coastal En-*

gineering, *Science of the Total Environment*, and *Frontiers in Marine Science*. The larger node sizes associated with these journals indicate their strong citation influence and continued relevance to studies investigating coastal resilience, ecosystem-based adaptation, hydrodynamic processes, and nature-based solutions. Although the publication sources met the inclusion criteria for the citation analysis, no direct citation links were identified among the included journals under the selected analysis parameters, indicating that the journals contributed independently rather than forming an interconnected citation network.

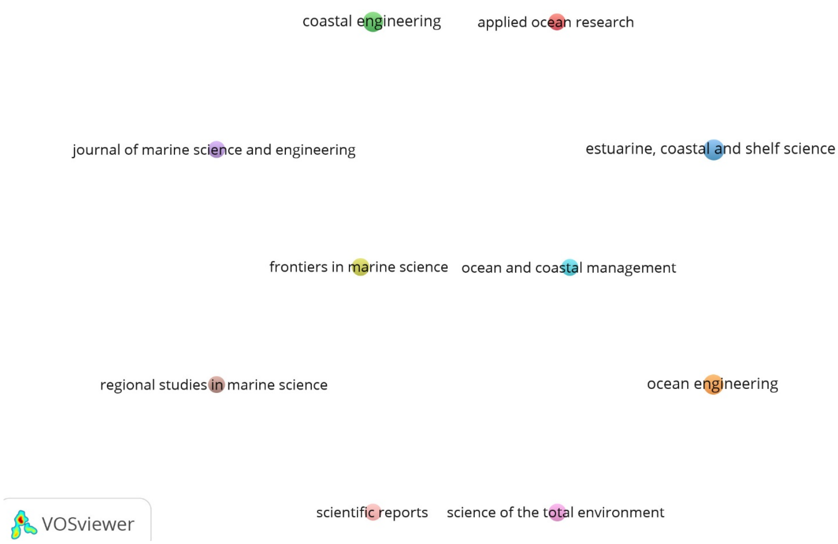

Figure 10. The citation network of publication sources.

Source: Authors' work (visualized by VOSviewer).

The composition of the network reveals the interdisciplinary character of the research area. Engineering-focused journals such as *Coastal Engineering* and *Ocean Engineering* have contributed significantly to advances in numerical modelling, wave attenuation assessment, and coastal hazard analysis. In contrast, journals including *Science of the Total Environment* and *Frontiers in Marine Science* have expanded understanding of ecological functions, environmental change, and ecosystem resilience. The presence of both engineering and environmental science outlets suggests that progress in mangrove-based coastal protection increasingly relies on the integration of ecological knowledge with quantitative modelling approaches.

The citation relationships presented in **Figure 10** further indicate a gradual transition from traditional ecological assessments toward application-oriented studies that support coastal planning and climate adaptation. Greater emphasis is now placed on evaluating protection performance, resilience enhancement, and long-term sustainability under changing environmental conditions. This publication pattern reflects the growing recognition of mangrove ecosystems as functional components of coastal defence strategies and highlights the importance of interdisciplinary collaboration in addressing future coastal challenges.

3.9. Intellectual Foundations of Mangrove-Mediated Coastal Protection

Figure 11 presents the co-citation network of highly influential references that have formed the intellectual foundation of mangrove-mediated coastal flood protection research. Co-citation analysis identifies studies that are frequently cited together, providing insight into the theoretical and methodological pillars that have guided subsequent investigations. The network reveals several interconnected clusters, indicating that the development of knowledge in this field has been shaped through contributions from coastal engineering, hydrodynamics, ecosystem-based adaptation, and nature-based solutions.

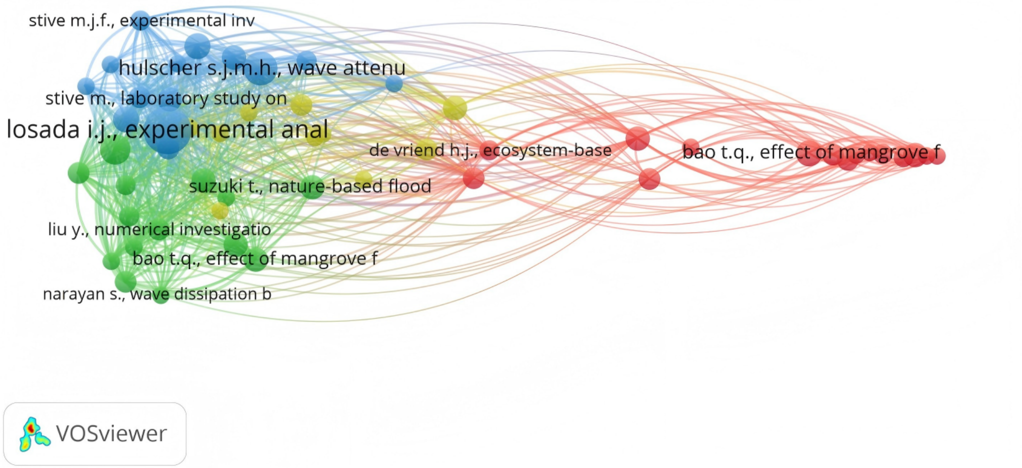

Figure 11. Co-citation network of foundational references underpinning mangrove-mediated coastal flood protection research. Larger nodes indicate references that have exerted greater influence on the development of the field.
Source: Authors' work (visualized by VOSviewer).

Prominent references within the network include studies by Losada et al., Narayan et al., Suzuki et al., Liu et al., De Vriend et al., and Bao et al. The central position and large node size of these references suggest that they have played a substantial role in advancing understanding of wave attenuation, vegetation–flow interactions, sediment dynamics, and the capacity of coastal ecosystems to reduce flood impacts. Many of these studies introduced experimental approaches, numerical modelling techniques, and conceptual perspectives that remain widely adopted in contemporary coastal protection research.

The clustering pattern observed in **Figure 11** also illustrates the gradual evolution of the field. Earlier investigations primarily focused on understanding physical hydrodynamic processes and the interaction between vegetation and water movement. More recent studies have expanded these foundations by incorporating ecosystem-based adaptation, resilience enhancement, and nature-based solutions into coastal management and climate adaptation strategies. Strong linkages among the cited references indicate that current research continues to build upon these foundational contributions rather than developing as isolated research streams.

Overall, the co-citation structure demonstrates that mangrove-mediated coastal protection research has evolved through the integration of ecological knowledge and engineering-based analysis. The enduring influence of these foundational studies highlights their continuing relevance for improving numerical modelling, evaluating protection performance, and supporting evidence-based decision-making in coastal adaptation planning.

3.10. Research Fronts and Emerging Directions

Figure 12 presents the bibliographic coupling network derived from the reviewed literature. Unlike co-citation analysis, which identifies foundational studies, bibliographic coupling highlights contemporary publications that share similar reference patterns and therefore reflect active research directions within the field. The presence of multiple interconnected clusters indicates that mangrove-mediated coastal protection research continues to expand across several complementary themes rather than following a single line of investigation.

Several clusters are associated with hydrodynamic modelling, wave attenuation assessment, vegetation–flow interactions, and flood-risk reduction. Other clusters demonstrate growing interest in ecosystem-based adaptation, climate resilience, nature-based solutions, and the integration of coastal ecosystems into adaptation planning. The coexistence of engineering-oriented and environmental management themes further reinforces the interdisciplinary character of the research area.

The coupling structure also suggests a gradual shift toward more applied and decision-oriented studies. Increasing attention is being directed toward evaluating protection performance under future climate scenarios, assessing long-term restoration outcomes, and improving the representation of ecological processes within numerical models. This trend reflects a broader effort to generate evidence that can support coastal planning, infrastructure resilience, and adaptation policy development.

Figure 12. Bibliographic coupling network illustrating contemporary research fronts in mangrove-mediated coastal flood protection studies. Different clusters represent groups of publications sharing common intellectual foundations and thematic orientations.

Source: Authors' work (visualized by VOSviewer).

Several emerging opportunities can also be identified from the network. Future investigations may benefit from greater integration of ecological monitoring, hydrodynamic simulation, socio-economic assessment, and climate projection modelling. Additional research is needed to evaluate long-term protection effectiveness under sea-level rise, changing storm characteristics, and land-use pressures. These directions are likely to play an important role in strengthening the scientific basis for mangrove-based coastal protection and enhancing the contribution of nature-based solutions to climate adaptation strategies.

Overall, the bibliometric findings indicate that research on mangrove-mediated coastal flood protection has expanded from descriptive ecological assessment toward more integrated, model-based, and application-oriented studies. The combined results from publication trends, keyword mapping, citation analysis, co-citation, and bibliographic coupling show that the field is increasingly shaped by collaboration between coastal engineering, marine ecology, hydrology, environmental management, and climate adaptation research. These patterns provide a useful basis for the thematic synthesis presented in the following sections, particularly in relation to vegetation–flow interactions, modelling limitations, restoration performance, and long-term coastal resilience.

4. Ecosystem Services of Mangrove Ecosystems

Mangrove ecosystems provide a wide range of ecological, environmental, and socioeconomic functions that contribute significantly to coastal resilience and environmental sustainability. These intertidal forests occur along tropical and subtropical coastlines where they regulate hydrodynamic processes, stabilize shorelines, and support diverse biological communities. Increasing recognition of these multifunctional roles has positioned mangroves as important components of nature-based solutions for climate adaptation and coastal disaster risk reduction. Recent studies have further emphasized their contribution to long-term environmental resilience and coastal community protection [20, 21].

Coastal protection remains one of the most widely studied ecosystem services provided by mangrove forests. Structural components such as aerial roots, trunks, and dense canopy layers interact with coastal hydrodynamics by increasing hydraulic resistance and dissipating wave energy. Field observations and experimental investigations have shown that waves travelling through mangrove forests experience noticeable reductions in wave height and energy due to frictional drag and turbulence generated by vegetation structures [22, 23]. This capacity for wave attenuation allows mangroves to function as natural buffers that reduce the impacts of storm surges and coastal flooding in adjacent inland areas. Growing interest in nature-based infrastructure has therefore strengthened the role of mangrove forests as complementary systems to conventional engineered coastal defences.

Effectiveness of mangroves in reducing coastal hazards depends on several ecological and physical characteristics of the forest. Vegetation density, forest width, tree height, and root architecture all influence the extent to which hydrodynamic energy is reduced within mangrove environments. Species with complex prop-root systems, particularly those within the genus Rhizophora, generally produce greater hydraulic resistance compared with species possessing simpler root structures. Variations in geometric characteristics among mangrove species therefore play an important role in shaping vegetation-flow interactions within coastal environments [21]. Such differences strongly influence the capacity of mangrove forests to function as natural barriers against waves, currents, and coastal flooding.

Sediment stabilization and land formation processes also contribute significantly to the protective function of mangrove ecosystems. Mangrove root systems reduce water velocity and trap suspended sediments transported by tidal currents and storm-driven flows. Accumulation of these sediments promotes vertical soil accretion and helps maintain mangrove surface elevation relative to rising sea levels. Over longer timescales, these geomorphological processes contribute to shoreline stabilization and reduce vulnerability to erosion and inundation. Continued sediment accumulation further strengthens the long-term adaptive capacity of mangrove ecosystems under changing coastal conditions.

Climate regulation through carbon sequestration represents another major ecosystem service associated with mangrove environments. Mangroves are widely recognized as highly efficient natural carbon sinks because of their ability to store substantial amounts of organic carbon within both vegetation biomass and waterlogged sediments. Organic matter accumulated in anoxic mangrove soils can remain preserved for extended periods, contributing to long-term climate change mitigation. Recent restoration studies have also demonstrated that rehabilitated mangrove forests can significantly increase carbon storage capacity in coastal regions [24]. These functions reinforce the importance of mangrove ecosystems within global climate regulation and sustainability initiatives.

Support for biodiversity and fisheries productivity further enhances the ecological significance of mangrove ecosystems. Complex habitat structures within mangrove forests provide shelter and nursery grounds for numerous aquatic organisms, including fish, crustaceans, and mollusks. Many commercially important fisheries species depend on mangrove habitats during critical stages of their life cycles. Contributions to fisheries productivity and food security therefore extend the importance of mangroves beyond environmental protection and into socioeconomic resilience for coastal communities.

Additional ecosystem functions include water quality regulation and nutrient cycling within coastal environments. Mangrove root systems trap sediments and filter nutrients transported from upstream terrestrial catchments. This filtration process improves water quality in adjacent marine environments and helps protect sensitive ecosystems such as coral reefs and seagrass beds from excessive sedimentation and nutrient enrichment. Through these processes, mangrove ecosystems help maintain ecological balance across interconnected coastal habitats.

Socioeconomic benefits provided by mangrove ecosystems also remain highly important for many coastal populations. Local communities frequently depend on mangrove resources for fisheries, fuelwood, timber, and other ecosystem goods. Ecotourism activities associated with mangrove environments can further generate economic opportunities while supporting environmental conservation efforts. Recognition of these combined ecological and socioeconomic benefits has increasingly positioned mangrove ecosystems as valuable forms of natural infrastructure that support sustainable coastal development.

Capacity of mangrove ecosystems to sustain these functions, however, remains strongly influenced by environmental conditions and ecosystem health. Land conversion, pollution, hydrological alteration, and coastal degradation can substantially reduce ecological functionality and protective performance. Effective conservation and restoration strategies are therefore essential for maintaining the long-term ecosystem services provided by mangrove forests and strengthening coastal resilience under future environmental change.

4.1. Vegetation Structure, Drag, and Wave Attenuation

One of the most consistent findings across the reviewed literature is that mangrove-based coastal protection is fundamentally governed by vegetation–flow interactions. Structural components such as roots, trunks, branches, and canopy layers increase hydraulic drag, generate turbulence, redistribute flow momentum, and reduce both wave height and current velocity. Laboratory experiments, prototype-scale investigations, field observations, and numerical modelling studies consistently demonstrate that wave attenuation generally increases with cross-shore distance through mangrove forests, although reported attenuation rates vary according to vegetation structure, water depth, and incoming wave conditions. However, attenuation behaviour is highly nonlinear and strongly influenced by vegetation density, stem diameter, root complexity, submergence ratio, and the frequency characteristics of incoming waves [10, 20, 22, 25–29].

Recent studies have also improved the representation of vegetation drag within hydrodynamic models. Integrated drag-coefficient formulations, local drag-force approaches, high-order phase-resolving simulations, and terrestrial laser scanning-based parameterisation methods have gradually replaced earlier assumptions that treated mangroves as uniform rigid cylinders [27, 30–32]. These developments are important because simplified parameterisation approaches often fail to capture variability among mangrove species, age classes, forest zones, and vegetation structures. Current evidence indicates that juvenile and mature forests, submerged and emergent canopies, and rigid and flexible vegetation elements produce substantially different attenuation responses [33–36].

An important development in recent years involves recognition that mangrove vegetation does not behave as a rigid structure under all hydrodynamic conditions. Flexibility within roots, stems, branches, and canopy elements can alter drag forces, turbulence generation, and energy dissipation characteristics. As a result, attenuation performance may differ substantially from predictions generated using simplified rigid-vegetation assumptions. Continued investigation of vegetation flexibility is therefore necessary to improve model realism and strengthen confidence in predictions of coastal protection performance under varying wave and inundation conditions.

Findings from recent studies also suggest that no universal attenuation coefficient can be reliably transferred across different coastal environments. Even when wave reduction is clearly observed, attenuation magnitude remains highly dependent on local hydrodynamic conditions and coastal morphology. Investigations involving storm-driven waves, solitary waves, regular waves, and tsunami-like conditions demonstrate that attenuation performance may weaken or change considerably under deeper water levels, increased vegetation submergence, or conditions approaching structural failure thresholds [37–40]. These observations highlight the importance of site-specific calibration when applying vegetation drag formulations in coastal protection planning. Distinguishing between routine attenuation performance and behaviour under extreme hydrodynamic conditions is therefore essential for improving the reliability of mangrove-based coastal defence strategies.

4.2. Flood-Depth Reduction and the Importance of Morphology

Protective functions provided by mangrove ecosystems rarely operate in isolation. Flood mitigation performance is strongly influenced by surrounding coastal morphology, including embayment configuration, intertidal elevation, tidal channels, and adjacent wetland systems. Recent studies demonstrate that drainage density can redistribute or even offset the protective benefits associated with dense vegetation, while variations in intertidal topography may either enhance or reduce flood attenuation performance [41–43]. These findings help explain why broad green-belt policies often produce inconsistent outcomes when local channel systems, tidal flats, and topographic connectivity are not adequately considered.

Evidence from coupled flood-risk modelling studies further illustrates the spatial complexity of mangrove-based flood protection. Although mangrove forests can reduce storm surge levels and inland flood damages, protective benefits are rarely distributed uniformly across coastal landscapes. Instead, attenuation effects vary considerably between neighbourhoods, land-use types, and hydrodynamic settings [12, 39, 44, 45]. In estuaries and river delta environments, compound flood behaviour is further influenced by upstream river discharge, tidal synchronization, and large-scale climatic anomalies such as ENSO and monsoon variability [46–48].

These observations suggest that management strategies based solely on generalized forest-width thresholds may oversimplify the behaviour of mangrove-mediated flood reduction. More reliable coastal planning approaches require integrated assessment of terrain characteristics, channel morphology, hydrodynamic forcing, and compound flood interactions within specific coastal settings.

Sediment transport processes represent another important component of mangrove-mediated coastal protection that remains comparatively underrepresented within many hydrodynamic investigations. Beyond reducing wave energy and current velocity, mangrove vegetation alters sediment pathways by promoting particle deposition, reducing resuspension, and enhancing vertical accretion within intertidal environments. These processes contribute directly to shoreline stability and may improve the capacity of coastal landscapes to adjust to gradual sea-level rise. However, sediment dynamics vary considerably among locations due to differences in sediment availability, tidal exchange, channel configuration, and vegetation characteristics. Greater integration of sediment transport processes within hydrodynamic modelling frameworks would therefore improve understanding of long-term coastal protection performance and ecosystem resilience.

4.3. Restoration is Not Automatically Equivalent to Protection

A recurring pattern identified across the reviewed literature is that restoration success does not necessarily translate directly into effective coastal protection performance. Restored or naturally regenerated mangrove systems may provide ecological, carbon sequestration, and social benefits long before they achieve hydrodynamic characteristics comparable to mature natural forests. In some environments, restored mangroves may never fully replicate the structural complexity, vegetation density, or geomorphological features of established natural stands [13, 49–51]. This distinction carries important implications for coastal management and policy because restoration programmes are frequently promoted as flood-protection measures even when their hydrodynamic performance has not been comprehensively evaluated.

Recent studies increasingly emphasize performance-based restoration approaches rather than relying solely on vegetation survival or planting success. Several investigations have examined mangrove establishment and survival across elevation gradients, linked restoration trajectories to flood reduction metrics, evaluated shoreline stabilization potential, and assessed wave attenuation performance under both laboratory and field conditions [23, 49, 51–53]. These approaches provide a more comprehensive understanding of how restored mangrove systems contribute to coastal protection over time.

An additional consideration concerns species composition within restored mangrove ecosystems. Restoration programmes frequently prioritise rapid establishment through single-species planting approaches, particularly involving Rhizophora species. While such initiatives may increase vegetation cover, monoculture plantations often exhibit lower structural complexity than naturally developed mixed-species forests. Recent restoration assessments further suggest that structural diversity and vegetation architecture may be equally important as restoration extent when evaluating long-term ecosystem functionality and resilience. Differences in root architecture, stem density, canopy structure, and ecological interactions may influence hydrodynamic performance and ecosystem resilience. Consequently, restoration success should not be evaluated solely on planting density or survival rates but should also consider species diversity, structural heterogeneity, and long-term ecosystem development when assessing coastal protection effectiveness.

Current evidence suggests that future restoration assessment should extend beyond conventional ecological indicators such as survival rates or canopy coverage alone. Greater attention should be given to biophysical conditions, vegetation structure, sediment dynamics, and hydrodynamic processes that influence long-term restoration success and coastal protection performance. Integrating these factors into restoration planning would improve the reliability of mangrove-based coastal defence strategies and strengthen long-term adaptation outcomes in vulnerable coastal regions

4.4. Comparative Synthesis of Hydrodynamic Protection Functions

Although the reviewed studies do not report hydrodynamic performance using fully comparable indicators, their findings can still be synthesized according to the primary protection function examined, modelling approach applied, and practical implications for coastal management. As previously presented in **Table 1**, several recurring patterns emerge across the literature regarding wave attenuation, flow resistance, storm-surge moderation, sediment trapping, and flood-risk reduction. Rather than presenting a pooled numerical estimate, the table provides a structured comparison of how mangrove characteristics, hydrodynamic processes, and modelling strategies contribute to coastal protection outcomes. This comparative synthesis helps identify areas of consensus within the literature while also highlighting factors that influence the effectiveness of mangrove-mediated coastal defence under different environmental conditions.

Table 2 indicates that mangrove-mediated coastal protection cannot be generalized using a single performance indicator. Protective capacity depends on the interaction between vegetation structure, hydrodynamic forcing, sediment availability, and coastal morphology. This finding supports the argument that future studies should move beyond broad claims of natural flood protection and instead report site-specific parameters, validation procedures, uncertainty ranges, and performance thresholds under different hazard conditions.

Table 2. Comparative synthesis of hydrodynamic protection functions and modelling approaches identified across reviewed mangrove coastal protection studies.

Protection Function	Main Controlling Factors	Common Modelling/Assessment Approach	General Findings from Reviewed Studies	Practical Implications
Wave attenuation	Forest width, vegetation density, root complexity, canopy submergence	Physical modelling, SWAN, XBeach, Delft3D, phase-resolving models	Denser and wider mangrove belts generally reduce wave height and wave energy more effectively	Mangrove width alone should not be used as the only design criterion
Flow resistance	Stem diameter, root structure, drag coefficient, vegetation flexibility	Drag-based formulations, local drag force models, 2D/3D hydrodynamic models	Vegetation increases hydraulic resistance, but simplified rigid-cylinder assumptions may overestimate or underestimate performance	Species-specific and structure-specific parameterisation is needed
Storm-surge moderation	Forest elevation, coastal slope, tidal channels, surge depth	Delft3D, ADCIRC, HEC-RAS, coupled flood models	Mangroves can reduce surge propagation, but performance varies strongly by local morphology	Site-specific validation is essential before using mangroves as flood-defence measures
Flood-depth reduction	Forest position, drainage density, land elevation, channel connectivity	Flood-risk modelling, inundation mapping, scenario simulation	Flood reduction is spatially uneven and may be weakened where channels bypass vegetation zones	Coastal planning must consider terrain and channel networks

Table 2. *Cont.*

Protection Function	Main Controlling Factors	Common Modelling/Assessment Approach	General Findings from Reviewed Studies	Practical Implications
Sediment trapping and elevation gain	Root density, tidal exchange, sediment supply, inundation frequency	Hydro-morphodynamic models, field monitoring, sediment budget analysis	Mangroves can promote sediment deposition and vertical accretion, supporting long-term resilience	Protection value depends on sediment availability and ability to keep pace with sea-level rise
Restoration-based protection	Species composition, planting density, survival rate, forest maturity	Restoration monitoring, scenario modelling, comparative site assessment	Replanted areas do not automatically provide the same protection as mature mixed-species stands	Restoration projects should include hydrodynamic performance indicators
Hybrid green-gray protection	Mangrove belt condition, breakwater/dike configuration, maintenance needs	Hybrid infrastructure modelling, overtopping analysis, cost-comparison studies	Hybrid systems can improve reliability where mangroves alone are insufficient under extreme events	Engineering design should evaluate ecological and structural components together

Although hybrid green-gray coastal protection systems are increasingly promoted as practical adaptation strategies, relatively few studies provide direct comparisons of long-term economic performance, maintenance requirements, and lifecycle costs between hybrid and conventional engineering approaches. Existing evidence generally suggests that hybrid systems may improve resilience and reduce dependence on hard infrastructure alone, while simultaneously reducing wave overtopping and enhancing protection performance under a wider range of hydrodynamic conditions. However, cost-effectiveness remains highly site-specific, although recent studies indicate that integrating vegetation into flood-defence systems may substantially reduce long-term protection costs under suitable environmental conditions. Future research should therefore integrate hydrodynamic performance assessments with economic evaluation and comparative assessment of green, gray, and hybrid protection strategies to support more informed coastal adaptation and investment decisions.

Beyond the individual protection functions presented in **Table 2**, several broader patterns emerge from the reviewed literature. Effective coastal protection depends on the interaction of ecological, hydrodynamic, and geomorphological factors rather than any single mangrove characteristic. Although wider and denser forests generally provide greater protection, their performance remains strongly influenced by local conditions, including sediment availability, tidal dynamics, vegetation composition, and coastal morphology. The synthesis also highlights growing interest in hybrid protection strategies that combine ecosystem-based approaches with conventional engineering measures to enhance reliability under extreme conditions [13, 49, 52]. These observations reinforce the need for site-specific assessments and caution against the direct transfer of findings between different geographical settings. Future evaluations should therefore prioritize integrated approaches that consider both short-term hazard reduction and long-term ecosystem resilience when assessing mangrove-based coastal protection measures.

5. Modelling Advances and Remaining Limitations

5.1. Progress in Numerical Representation

Recent literature demonstrates substantial progress in numerical modelling approaches used to investigate mangrove-mediated coastal protection. One-dimensional and porous-medium formulations continue to serve as useful tools for preliminary assessment and conceptual analysis, while newer local-drag and coupled hydro-morphodynamic models provide improved representation of spatial variability, wetting and drying processes, and interactions among vegetation, sediment transport, and channel systems [31, 54–57]. Increasing use of high-resolution modelling techniques, combined with remote sensing, Structure-from-Motion (SfM), unmanned aerial vehicle (UAV), and laser-scanning technologies, has also contributed to improved vegetation geometry representation and reduced parameter uncertainty within hydrodynamic simulations [58].

One of the most significant developments in recent years involves the transition from static vegetation representation toward more dynamic system-based modelling approaches. Processes such as mangrove growth, structural failure, survival, and long-term ecosystem evolution are increasingly being incorporated explicitly into modelling frameworks rather than being treated as fixed assumptions [36, 50, 52, 54, 59]. Incorporating these ecological dynamics is particularly important for long-term climate adaptation planning because the protective function of mangrove ecosystems changes over time. Forest expansion, thinning, migration, and degradation are all influenced by environmental drivers such as salinity, inundation frequency, sediment supply, and exposure to extreme hydrodynamic events.

A particularly important advancement concerns the growing recognition of vegetation flexibility within hydrodynamic modelling frameworks [56]. Earlier modelling approaches frequently represented mangrove vegetation as rigid cylindrical elements with fixed drag characteristics. Although computationally efficient, such simplifications may not adequately capture the deformation, reconfiguration, and energy-dissipation behaviour of vegetation under varying hydrodynamic conditions. More recent studies increasingly incorporate flexible vegetation formulations, dynamic drag representations, and vegetation-motion interactions, providing improved representation of flow resistance and wave attenuation processes. Nevertheless, flexible vegetation mechanics remain insufficiently implemented across many modelling applications, highlighting an important area for future methodological development.

The comparison presented in **Table 3** illustrates that no single modelling framework is universally suitable for all coastal protection applications. Model selection should be guided by the specific objectives of the study, spatial scale, data availability, and dominant hydrodynamic processes under investigation. Simpler models may provide efficient preliminary assessments, whereas coupled hydro-morphodynamic frameworks offer greater capability for evaluating long-term ecosystem evolution and climate adaptation outcomes. Consequently, future studies should place greater emphasis on selecting modelling approaches that align with the ecological and hydrodynamic complexity of the coastal systems being evaluated.

Table 3. Comparison of hydrodynamic modelling approaches used in mangrove coastal protection studies.

Model	Main Application	Strengths	Limitations	Typical Use in Mangrove Studies
Delft3D	Hydrodynamic and morphodynamic simulation	Simulates flow, sediment transport, erosion, and morphological change within a single framework	Requires extensive calibration and computational resources	Long-term coastal evolution, sediment dynamics, and restoration assessment
SWAN	Wave transformation and attenuation modelling	Well-established for wave propagation and coastal wave analysis	Limited representation of vegetation structure and morphological change	Wave attenuation and coastal wave climate assessment
XBeach	Storm-impact and extreme-event simulation	Effective for modelling storm surges, overwash processes, and coastal flooding during extreme events	Primarily event-based and less suitable for long-term simulations	Storm-surge, cyclone, and extreme-wave assessment
HEC-RAS	Flood inundation and hydraulic analysis	User-friendly and widely applied for flood mapping and water-level simulation	Simplified treatment of coastal vegetation and wave processes	Flood-depth estimation and inundation mapping
ADCIRC	Storm-surge and coastal circulation modelling	Strong capability for regional-scale surge simulation and coastal hazard assessment	Complex setup and high computational demand	Storm-surge prediction and coastal risk analysis
Coupled Hydro-Morphodynamic Models	Integrated simulation of ecological and physical processes	Captures interactions among vegetation, hydrodynamics, sediment transport, and morphology	High data requirements and model complexity	Long-term resilience assessment and ecosystem-based coastal protection planning

Although significant progress has been made in representing vegetation–flow interactions within numerical models, no modelling framework currently captures all ecological and hydrodynamic processes with equal accuracy. Simpler approaches often provide computational efficiency but may oversimplify vegetation structure and ecosystem dynamics. In contrast, coupled hydro-morphodynamic models offer greater realism by incorporating interactions among hydrodynamics, sediment transport, vegetation development, and morphological change, but they require extensive datasets, calibration effort, and computational resources. Consequently, the choice of modelling framework should be guided not only by technical capability but also by the specific objectives, spatial scale, temporal scale, and data availability of each study. Future advances will likely depend on improving the balance between model complexity, computational efficiency, and ecological realism.

5.2. Validation and Transferability Remain Weak Points

Despite considerable progress in numerical modelling, several important limitations remain within the current body of literature. One of the most persistent challenges involves the limited availability of validation data relative to the increasing complexity and ambition of modern modelling frameworks. Many studies continue to rely on short-duration field campaigns, simplified laboratory experiments, or restricted forcing conditions, reducing confidence when models are applied to different coastal settings or more extreme hydrodynamic scenarios [25, 28, 37, 60].

An additional concern relates to the temporal limitations of many validation datasets. A substantial proportion of field-based investigations are conducted over relatively short monitoring periods, often spanning only several days or weeks. While these studies provide valuable insights into vegetation–flow interactions, they may not adequately capture seasonal fluctuations in vegetation condition, sediment dynamics, hydrodynamic forcing, or long-term ecosystem responses to environmental change. Consequently, caution is required when extrapolating short-term observations to long-term assessments of mangrove-mediated coastal protection. Future research should place greater emphasis on multi-season and multi-year monitoring programmes capable of supporting more robust model validation and improving understanding of long-term ecosystem resilience.

Another important limitation concerns the representation of vegetation failure and structural damage under extreme conditions. Recent field observations and experimental investigations indicate that protective functions provided by mangroves cannot be assumed once wave forces exceed biomechanical resistance thresholds or when repeated storm exposure, sea-level rise, and climate-related ecosystem degradation alter vegetation structure and condition [36, 40, 56, 61]. Failure mechanisms associated with uprooting, stem breakage, and canopy damage remain insufficiently incorporated within many existing modelling approaches.

Understanding failure thresholds is particularly important because the protective function of mangrove ecosystems cannot be assumed under all hazard conditions. Extreme waves, prolonged inundation, storm surges, and repeated cyclone exposure may exceed the biomechanical resistance of vegetation, resulting in stem breakage, root failure, canopy loss, or large-scale forest degradation. Despite growing recognition of these processes, quantitative threshold values remain insufficiently documented across different species, age classes, and environmental settings. Future investigations should place greater emphasis on identifying critical failure conditions and incorporating vegetation damage mechanisms into predictive modelling frameworks used for coastal risk assessment [36, 40, 61].

Communication of uncertainty also remains relatively limited in many coastal protection studies. Only a comparatively small number of investigations explicitly quantify modelling uncertainty or present outputs in formats that can be directly interpreted by coastal managers and decision-makers [57, 62, 63]. Recent studies have also demonstrated the value of probabilistic approaches for representing uncertainty within vegetated hydrodynamic systems, enabling more robust assessment of flood-protection performance under varying environmental conditions. Insufficient uncertainty reporting may create unrealistic expectations regarding the reliability and transferability of mangrove-based coastal defence strategies, particularly when findings are translated into policy or large-scale implementation plans.

From a coastal management perspective, these limitations extend beyond technical modelling concerns alone. Poorly constrained uncertainty, incomplete validation, and simplified vegetation assumptions may reduce confidence in practical applications and increase implementation risks in real-world coastal adaptation projects. In addition, long-term coastal resilience may be influenced by environmental processes that are not always explicitly represented within hydrodynamic models, including groundwater salinization, changing freshwater availability, and sea-level-rise-induced ecosystem stressors that may affect vegetation health and ecosystem persistence over time. Future modelling studies would therefore benefit from more transparent reporting of calibration procedures, vegetation parameterisation, hazard scenarios, failure thresholds, and model sensitivity to morphological and boundary-condition variability [57].

Technological advancements are creating new possibilities for improving the accuracy and applicability of mangrove hydrodynamic modelling. Recent advances in remote sensing, unmanned aerial vehicles (UAVs), LiDAR surveys, machine learning, and real-time environmental monitoring have expanded the availability of high-resolution data for model development and validation [58]. These technologies can support more accurate representation of vegetation structure, topographic variability, and hydrodynamic processes across complex coastal environments. In addition, data-driven modelling approaches and real-time environmental monitoring may enable continuous updating of model predictions under changing environmental conditions [58]. Integrating these innovations with conventional hydrodynamic models could significantly enhance predictive capability and support more adaptive and evidence-based coastal management strategies.

6. Climate Stressors and Long-Term Viability

Protective functions provided by mangrove ecosystems can only be sustained if the forests themselves remain resilient under changing climatic and geomorphological conditions. Recent studies emphasize that sea-level rise, altered freshwater inflows, salinity variation, land subsidence, groundwater dynamics, and repeated storm exposure can all influence the long-term effectiveness of mangrove-based coastal protection [39, 48, 64–66]. In many deltaic environments, the central challenge is no longer limited to whether mangroves attenuate waves under present conditions, but whether sufficient sediment supply, accommodation space, and institutional support exist to maintain forest elevation and spatial extent over future decades.

Groundwater-related impacts represent an additional area that warrants greater attention within future coastal protection studies. Rising sea levels and prolonged saline inundation can contribute to groundwater salinization in low-lying coastal zones, potentially affecting vegetation health, freshwater availability, and ecosystem resilience. Although this issue has received increasing attention within climate adaptation research, its implications for long-term mangrove protection performance remain comparatively underexplored. Improved integration of groundwater processes into coastal resilience assessments may therefore provide a more comprehensive understanding of future environmental change [64–66].

An additional challenge involves the increasing occurrence of compound climate hazards, where multiple stressors interact simultaneously or sequentially to influence coastal vulnerability. In many coastal regions, mangrove ecosystems are exposed not only to sea-level rise but also to storm surges, extreme rainfall, river flooding, land subsidence, and salinity intrusion occurring within the same system. The combined effects of these hazards may amplify environmental stress, alter hydrodynamic behaviour, and reduce ecosystem resilience beyond what would be expected from individual stressors alone. Consequently, future research should place greater emphasis on integrated assessments that examine how interacting climate and environmental pressures influence the long-term effectiveness of mangrove-mediated coastal protection.

Integration between physical and ecological perspectives has therefore become increasingly important within recent research. Studies focusing on mangrove vulnerability, seedling establishment, lifecycle dynamics, and restoration suitability demonstrate that coastal protection performance cannot be separated from ecological processes such as recruitment, mortality, and landward migration potential [49, 59, 64]. These findings suggest that management strategies focusing solely on protecting existing mangrove belts may be insufficient. Integrating vegetation within broader flood-defence systems has also been shown to improve long-term coastal resilience and reduce protection costs under suitable environmental conditions [67].

Recent climate-risk studies additionally highlight the importance of compound flooding processes in coastal environments. Interactions among ENSO-related anomalies, storm surges, river discharge, groundwater fluctuations, and pluvial flooding can significantly alter inundation pathways and reduce the reliability of coastal protection strategies designed around single-hazard assumptions [39, 46, 47, 68]. More comprehensive coastal adaptation planning should therefore evaluate mangrove ecosystems within compound-risk frameworks that account for interacting hydrodynamic, climatic, and geomorphological drivers rather than relying solely on simplified wave attenuation concepts.

7. Hybrid Infrastructure, Decision Support, and Management Implications

Recent literature increasingly recognizes that mangrove ecosystems function most effectively when integrated within broader coastal protection systems rather than treated as standalone solutions. Hybrid approaches that combine mangroves with engineered structures such as dikes, breakwaters, reefs, or elevated coastal topography often provide more reliable protection than purely ecological or purely engineered interventions alone, particularly under extreme hydrodynamic conditions [69–71]. Comparative studies further demonstrate that mangroves frequently provide their greatest value by reducing wave loading, overtopping intensity, and long-term maintenance demands on conventional coastal infrastructure rather than fully replacing engineered defences [29, 70, 72, 73].

Economic considerations increasingly influence decisions regarding the adoption of mangrove-based and hybrid coastal protection strategies. While mangrove restoration may offer long-term environmental and social benefits, implementation costs, maintenance requirements, land availability, and time needed for ecosystem establishment vary considerably among locations. Hybrid approaches often require greater initial investment but may provide more reliable protection under extreme events while simultaneously reducing long-term maintenance demands on conventional infrastructure. Consequently, future evaluations should extend beyond hydrodynamic performance alone and incorporate economic, environmental, and social dimensions when assessing the suitability of alternative coastal protection options [69, 72, 73].

Management-focused studies also emphasize the growing importance of spatial planning and decision-support tools in coastal adaptation strategies. Opportunity mapping, geospatial analysis, and adaptation-planning frameworks are increasingly applied to identify locations where mangrove restoration is feasible, where hybrid infrastructure offers greater effectiveness, and where non-structural adaptation measures should complement physical protection systems [63, 74]. Such approaches are especially important in densely populated coastal regions where embankments, land scarcity, and channel modification limit ecological adaptation potential.

Several broader governance implications emerge consistently across the reviewed literature. One important shift involves moving from area-based restoration targets toward performance-based management objectives linked to measurable flood-reduction outcomes, ecological condition, and long-term maintenance requirements. Another critical priority involves strengthening monitoring programmes through integration of remote sensing technologies, field hydrodynamic measurements, and vegetation-structure datasets so that modelling frameworks can be updated continuously rather than treated as static project outputs [58, 75, 76]. Comparative evaluation of gray, green, and hybrid coastal protection alternatives should also be incorporated into future decision-support frameworks to support evidence-based coastal adaptation planning [77].

Growing evidence also suggests that coastal decision-making frameworks should evaluate co-benefits and trade-offs simultaneously rather than focusing exclusively on flood reduction performance. Biodiversity conservation, carbon sequestration, fisheries productivity, navigation requirements, land-use conflicts, and social acceptability all influence the long-term viability of mangrove-centred coastal protection strategies [6, 8, 14, 78]. Incorporating these interconnected factors into coastal planning processes is essential for developing adaptation strategies that remain both environmentally sustainable and socially practical over time.

8. Research Gaps, Agenda, and Future Directions

Growing scientific interest in mangrove-mediated coastal protection reflects increasing recognition of mangrove ecosystems as effective nature-based solutions for reducing coastal flood risks and strengthening climate resilience. Despite substantial progress in recent years, several important research gaps continue to limit both scientific understanding and practical implementation. Addressing these limitations will require a more integrated research agenda that connects hydrodynamic modelling, ecological processes, and coastal governance frameworks.

One of the most persistent challenges involves the representation of vegetation within hydrodynamic models. Many existing studies continue to simplify mangrove vegetation as rigid cylindrical elements to improve computational efficiency. Although this approach reduces modelling complexity, it often overlooks biological characteristics such as species composition, age structure, canopy submergence, and vegetation flexibility, all of which influence hydrodynamic behaviour and structural resistance. Recent empirical and modelling studies demonstrate that these factors significantly affect drag coefficients, energy dissipation, and vegetation failure thresholds [21, 27, 34–36]. Future modelling approaches should therefore prioritize biologically realistic parameterisation methods capable of representing species-specific morphology and vegetation damage states more accurately. Improving biological realism is essential for increasing model reliability and transferability across different coastal environments.

Limited availability of long-term and spatially diverse field observations also remains a major constraint. Although numerical modelling capabilities have advanced considerably, predictive reliability is still restricted by insufficient empirical validation. Many investigations rely on short-duration field campaigns or controlled laboratory conditions that may not adequately represent the variability of natural coastal systems. Expanded monitoring programmes across estuaries, deltas, open coastlines, and cyclone-prone regions are therefore needed to support more robust calibration and validation efforts [20, 32, 37]. Long-term datasets involving wave attenuation, sediment transport, and vegetation-flow interactions would substantially improve confidence in model outputs and reduce uncertainty within coastal risk assessments.

Another important limitation involves the tendency to represent mangrove ecosystems as static roughness elements rather than dynamic ecological systems. Mangrove environments continuously evolve through growth, mortality, regeneration, and sedimentary feedback processes that interact directly with hydrodynamic forcing. Insufficient integration between ecological and physical processes remains a major weakness within many current modelling frameworks. Continued development of eco-hydrodynamic and eco-morphodynamic modelling approaches is therefore essential for capturing these complex feedback mechanisms under changing environmental conditions [50, 55, 57, 59]. Such integration will become increasingly important for evaluating long-term ecosystem behaviour under sea-level rise and large-scale restoration scenarios.

Complexity associated with coastal flooding processes also remains underrepresented within many mangrove protection studies. Existing modelling efforts frequently focus on isolated drivers such as wave attenuation or storm surge while giving limited attention to compound flooding pathways involving river discharge, rainfall, groundwater fluctuations, and tidal interactions. This simplification reduces the applicability of findings for real-world coastal management, where flooding commonly results from multiple interacting processes. Future research should therefore incorporate compound flood dynamics more consistently within modelling frameworks [39, 47, 68]. More comprehensive representation of interacting flood mechanisms would improve risk assessments and strengthen coastal adaptation planning.

Representation of modelling uncertainty also requires considerable improvement. Many studies continue to report single deterministic estimates of wave attenuation or flood reduction despite substantial uncertainty associated with environmental variability, model assumptions, and parameter sensitivity. Coastal managers and decision-makers require outputs that communicate uncertainty more transparently through probabilistic analysis, sensitivity ranges, and scenario-based projections [62, 63, 79]. Greater integration of uncertainty analysis within hydrodynamic studies would improve the usefulness of modelling results for policy development and coastal planning applications.

Hydrodynamic performance of restored mangrove ecosystems also remains insufficiently quantified. Restoration programmes are widely implemented across many coastal regions, yet most evaluations continue to focus primarily on ecological indicators such as survival rates, stem density, above-ground biomass, structural diversity and spatial coverage [80]. These indicators do not necessarily correspond directly to flood protection performance. More research is therefore needed to assess the wave attenuation and sediment stabilization functions of restored mangrove systems and compare them with mature natural forests [13, 51, 53]. Long-term monitoring remains particularly important for evaluating whether restored ecosystems can eventually achieve comparable levels of hydrodynamic effectiveness.

Emerging technologies offer promising opportunities to address several of these research challenges. Advances in remote sensing, unmanned aerial vehicles, and terrestrial laser scanning now enable high-resolution mapping of vegetation structure and spatial distribution. When integrated with hydrodynamic simulations, these technologies can substantially improve vegetation representation and modelling accuracy. However, methodological application remains uneven across regions and would benefit from greater standardisation and data-sharing practices.

Attention toward governance and socioeconomic dimensions of coastal protection has also increased in recent years. Existing research remains heavily concentrated on engineering and ecological processes, while comparatively less attention has been given to institutional capacity, financing mechanisms, insurance frameworks, implementation barriers, and public acceptance of hybrid green–gray infrastructure systems. Strengthening connections between scientific modelling and governance research is therefore essential for translating theoretical benefits into effective coastal management practice [4, 63, 74].

Geographical concentration of current case studies presents an additional limitation to the broader applicability of existing findings. Many investigations remain site-specific and may not adequately represent the diversity of climatic, geomorphological, and hydrodynamic conditions observed across global coastlines. Comparative cross-regional studies would provide deeper understanding of the conditions under which mangrove ecosystems deliver the greatest protective benefits and would support development of more transferable coastal design and management frameworks.

Advancing research on mangrove-based coastal protection will therefore require a transition from simplified and discipline-specific approaches toward more integrated, data-rich, and application-oriented research frameworks. Improving biological realism within models, expanding empirical datasets, incorporating dynamic ecosystem interactions, addressing compound flooding, and integrating uncertainty analysis into decision-making processes should become central priorities for future investigations. Long-term progress will also depend on stronger integration among ecological science, coastal engineering, hydrodynamic modelling, and governance research to ensure that scientific advances can support practical and sustainable coastal adaptation strategies.

Despite substantial progress in understanding mangrove-mediated coastal protection, several important knowledge gaps remain. A large proportion of existing studies continue to focus on site-specific investigations, making it difficult to generalize findings across different environmental settings, species compositions, and hydrodynamic conditions. Variations in modelling assumptions, spatial resolution, vegetation parameterization, and validation procedures further complicate direct comparison among studies.

Another limitation concerns the representation of mangrove vegetation within numerical models. Many modelling approaches simplify vegetation characteristics using generalized drag coefficients or idealized structural parameters, which may not fully capture the complexity of natural mangrove ecosystems. Greater integration of field measurements and ecological monitoring data is therefore required to improve model realism and predictive accuracy.

The review also highlights a growing need for long-term assessments of protection performance under future climate conditions. Although sea-level rise, changing storm characteristics, and coastal development pressures are frequently acknowledged, relatively few studies have evaluated their combined influence on the long-term effectiveness of mangrove-based protection strategies, including mangrove dieback associated with climate extremes and the impacts of sea-level rise on coastal freshwater resources [81, 82]. Future research should therefore prioritize integrated assessments that combine hydrodynamic modelling, ecological processes, climate projections, and socio-economic considerations.

Further opportunities exist in the evaluation of hybrid coastal defence systems that combine mangrove ecosystems with conventional engineering structures. Comparative analyses of ecological, technical, and economic performance would provide valuable evidence for coastal adaptation planning. Addressing these research priorities will strengthen the scientific basis of mangrove-mediated coastal protection and support the development of more resilient and sustainable coastal management strategies.

9. Conclusion

Mangrove ecosystems play an increasingly important role in strengthening coastal resilience by reducing wave energy, moderating storm surge impacts, and supporting natural flood protection processes. This review synthesized recent scientific literature related to hydrodynamic modelling and mangrove-mediated coastal protection through systematic review, bibliometric analysis, and analytical synthesis of studies published between 2021 and 2026. Findings from the reviewed literature demonstrate rapidly growing scientific interest in mangrove-based coastal protection as coastal regions face increasing exposure to climate-related hazards and sea-level rise.

Bibliometric analysis revealed strong interdisciplinary collaboration among researchers working across coastal engineering, environmental science, marine ecology, hydrology, and climate adaptation. Keyword network analysis further identified several dominant research themes, including hydrodynamic modelling, wave attenuation, ecosystem services, coastal vulnerability, and nature-based solutions. Expansion of these themes reflects increasing recognition of mangrove ecosystems as multifunctional natural infrastructure capable of supporting both flood-risk reduction and broader environmental sustainability objectives.

Evidence synthesized from the reviewed studies indicates that mangrove forests influence coastal hydrodynamics through multiple interacting mechanisms. Vegetation structures such as aerial roots, trunks, and canopy layers increase hydraulic resistance, dissipate wave energy, reduce current velocity, and promote sediment deposition. These processes contribute directly to shoreline stabilization and reduction of coastal erosion and flood impacts. Existing modelling studies consistently demonstrate that vegetation density, forest width, and species-specific morphological characteristics strongly influence attenuation performance and flood reduction capacity.

Findings from the literature also emphasize that mangrove-based coastal protection is highly dependent on environmental and geomorphological conditions. Tidal inundation patterns, sediment supply, salinity gradients, coastal morphology, and sea-level rise all influence vegetation dynamics and hydrodynamic interactions. Mangrove ecosystems therefore function as dynamic systems shaped by continuous feedback among vegetation growth, sediment accumulation, hydrodynamic forcing, and environmental change.

Recent advances in remote sensing, LiDAR scanning, geospatial analysis, machine learning, and eco-hydrodynamic modelling have substantially improved the ability of researchers to evaluate vegetation–flow interactions and assess the protective functions of mangrove ecosystems under a wide range of environmental conditions. At the same time, growing interest in hybrid coastal protection strategies demonstrates an increasing recognition that effective adaptation may require integration of ecosystem-based approaches with conventional engineering measures. The comparative synthesis presented in this review further highlights that coastal protection performance cannot be explained by a single factor, but instead emerges from complex interactions among vegetation characteristics, hydrodynamic forcing, sediment dynamics, and coastal morphology.

Several important knowledge gaps nevertheless remain. Many existing modelling studies continue to rely on simplified vegetation parameterisation, limited validation datasets, and site-specific assumptions that restrict broader transferability. Additional challenges involve representation of compound climate hazards, vegetation failure thresholds under extreme events, long-term ecosystem dynamics, groundwater-related impacts, and uncertainty communication for practical coastal management applications. Addressing these limitations will require stronger integration between field observations, ecological monitoring, numerical modelling, and decision-support frameworks.

Future research should move beyond evaluating whether mangroves provide coastal protection and place greater emphasis on understanding when, where, and under what conditions protection functions remain effective. Priority research areas include improved representation of vegetation flexibility and vegetation failure thresholds under extreme hydrodynamic conditions, uncertainty quantification and sensitivity analysis, long-term ecosystem monitoring, eco-morphodynamic modelling, and restoration-performance assessment. Greater attention is also needed to evaluate the long-term effectiveness of hybrid green–gray coastal protection systems and to understand how climate change, sea-level rise, and groundwater-related stressors may influence future ecosystem performance and protection reliability. Addressing these challenges will require stronger integration of field observations, ecological monitoring, numerical modelling, and decision-support frameworks. Greater collaboration among coastal engineers, ecologists, hydrologists, climate scientists, and policy practitioners will be essential for developing adaptive and evidence-based management strategies. Overall, the findings of this review reinforce the importance of mangrove ecosystems as a key component of nature-based coastal protection while emphasizing that long-term resilience depends on integrated consideration of ecological processes, hydrodynamic behaviour, environmental change, and governance systems.

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Data Availability Statement

The data supporting the findings of this study were obtained from the Scopus database using the search strategy described in the Methodology section. The bibliographic records analyzed during the current study are available from the corresponding author upon reasonable request, subject to the licensing and access conditions of the Scopus database. No new experimental or observational datasets were generated during this study.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

AI Use Statement

During the preparation of this manuscript, the authors used generative artificial intelligence tools solely for language refinement, grammar checking, visualization support and editorial assistance. Specifically, Napkin AI was used to assist in the visual design of **Figure 1** (PRISMA workflow), while ChatGPT (OpenAI) was used to assist in the visualization and preparation of **Figure 2** (Conceptual Framework). No artificial intelligence tools were used for data collection, data analysis, interpretation of findings, bibliometric analysis, or generation of scientific conclusions. All content was critically reviewed, verified, and revised by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the manuscript.

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