Revista de Gestão Costeira Integrada

Journal of Integrated Coastal Zone Management

Volume 25(2): December 2025

ISSN 1646-8872



Editor-in-Chief Prof. Francisco Taveira Pinto

ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS

Revista de Gestão Costeira Integrada

Journal of Integrated Coastal Zone Management

Volume 25, Issue 2
December 2025

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Correspondence: aprh@aprh.pt

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Editorial consortium comprising:

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ISSN: 1646-8872

Revista de Gestão Costeira Integrada

Journal of Integrated Coastal Zone Management

25(2) – December 2025

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ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS

Journal of Integrated Coastal Zone Management (2025) 25(2): 75-80
© 2025 APRH
ISSN 1646-8872
DOI 10.5894/rgci-n824
url: https://www.aprh.pt/rgci/rgci-n824.html

Editorial note / *Nota editorial*

DA GESTÃO INTEGRADA À RESILIÊNCIA: REFLEXÕES SOBRE OS DESAFIOS CONTEMPORÂNEOS NA GESTÃO DA ZONA COSTEIRA

Luciana das Neves[@ 1], P. Rosa-Santos[1], T. Fazeres-Ferradosa[1], F. Taveira-Pinto[1]

É amplamente reconhecido que as zonas costeiras estão entre os sistemas socioambientais mais complexos e dinâmicos do planeta. Enquanto interfaces entre a terra e o mar, concentram ecossistemas de elevado valor ecológico, atividades económicas estratégicas, infraestruturas críticas e comunidades cujo património cultural e meios de subsistência estão intrinsecamente ligados aos ambientes costeiros e marinhos. Simultaneamente, estes territórios enfrentam pressões sem precedentes associadas à urbanização, ao crescimento demográfico, à intensificação económica, à degradação dos ecossistemas e aos impactos crescentes das alterações climáticas. Tais desafios destacam a necessidade de quadros de gestão das zonas costeiras que vão além das abordagens setoriais tradicionais, adotando estratégias integradas e adaptativas capazes de abordar as interdependências entre processos ambientais, exigências sociais e objetivos de desenvolvimento.

Os quatro artigos incluídos nesta edição apresentam perspetivas importantes sobre os desafios multifacetados que as regiões costeiras enfrentam em todo o mundo. Apesar dos seus contextos geográficos e focos de investigação distintos, refletem coletivamente as principais orientações na evolução contínua da investigação e da prática na gestão costeira. Surge um tema comum em todas estas contribuições: a sustentabilidade dos sistemas costeiros depende da integração de evidências científicas, processos ecológicos, mecanismos de governação e participação social em quadros de gestão coerentes e adaptativos. Ao fazê-lo, estes estudos sublinham a natureza cada vez mais interdisciplinar da gestão costeira e a importância crescente da resiliência, da adaptação e da governação colaborativa, na resposta aos desafios costeiros contemporâneos.

A reflexão proposta por Pawar e Nag (2026) sobre a evolução da Gestão Integrada da Zona Costeira (ICZM) proporciona um quadro particularmente oportuno para esta discussão. O seu trabalho revisita o desenvolvimento da ICZM, desde os seus primeiros esforços institucionais para coordenar setores, até à consolidação de um paradigma internacional assente na integração das dimensões ambientais, sociais, económicas e institucionais. Os autores defendem que a gestão da zona costeira surgiu, em grande parte, em resposta às limitações das abordagens setoriais, que, durante décadas, abordaram, de forma isolada, questões relacionadas com o desenvolvimento urbano, as pescas, o turismo, os transportes e a proteção ambiental. A experiência demonstrou que os desafios costeiros raramente se coadunam com as fronteiras administrativas ou disciplinares, tornando assim necessários mecanismos de coordenação capazes de lidar com sistemas socioambientais altamente interligados.

É importante reconhecer que esta observação continua a ser altamente relevante nos dias de hoje. Apesar do amplo consenso internacional sobre a necessidade de uma gestão integrada da zona costeira, persistem dificuldades significativas na implementação eficaz deste princípio. Em muitos contextos, a fragmentação institucional continua a limitar a eficácia das políticas públicas,

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Submission: 21 OCT 2026; Available on-line: 21 OCT 2026

enquanto que a ligação entre o conhecimento científico e a tomada de decisões permanece insuficiente. A gestão costeira enfrenta, portanto, um paradoxo recorrente: hoje em dia, há mais informação científica disponível do que nunca, mas os desafios de coordenação institucional continuam a impedir a tradução desse conhecimento em ações concretas.

Esta questão também surge nas outras contribuições deste volume. O estudo de Barros *et al*. (2026) sobre a vulnerabilidade dos sistemas dunares no sul do Brasil constitui um exemplo particularmente ilustrativo. Barros *et al*. (2026) documentam um aumento acentuado da vulnerabilidade das dunas ao longo da última década, apesar da existência prévia de instrumentos de planeamento e recomendações de gestão. As suas conclusões sugerem que esta deterioração não pode ser atribuída a uma compreensão insuficiente da dinâmica da erosão ou dos processos de degradação dos ecossistemas. Pelo contrário, reflete desafios persistentes na tradução do conhecimento disponível e dos quadros de planeamento em ações de gestão eficazes.

Esta conclusão merece especial atenção. Historicamente, têm sido dedicados esforços substanciais à melhoria da compreensão científica dos riscos costeiros, das vulnerabilidades e dos processos ambientais. Embora estes avanços tenham reforçado significativamente a base de evidências disponível para os gestores costeiros e os decisores políticos, nem sempre se traduziram em melhores resultados de gestão. Cada vez mais, o desafio fundamental reside, não na geração de novos conhecimentos, mas em garantir que o conhecimento existente informa o planeamento, a tomada de decisões e a implementação no âmbito de contextos institucionais e socioeconómicos, frequentemente complexos. A lacuna persistente entre o conhecimento e a ação continua, portanto, a ser um dos obstáculos mais significativos à eficaz governação costeira.

A contribuição de Barros *et al*. (2026) vai além da avaliação da vulnerabilidade das dunas em si, destacando uma mudança mais ampla na investigação costeira contemporânea no sentido de quadros de avaliação mais integrados. Enquanto as avaliações tradicionais se têm centrado principalmente nas características geomorfológicas e hidrodinâmicas, este estudo demonstra o valor de incorporar indicadores ecológicos nas análises de vulnerabilidade. A utilização de aves nidificantes como bioindicadores do estado das dunas reforça a noção de que a vulnerabilidade costeira não pode ser adequadamente compreendida apenas através de parâmetros físicos, mas deve também ter em conta a integridade do ecossistema, o funcionamento ecológico e a capacidade dos sistemas naturais para promover a resiliência e a adaptação.

Uma perspetiva semelhante é apresentada por Ma'rufatin *et al*. (2026) na sua revisão sistemática da resiliência dos mangais à variabilidade climática. O estudo vai além das interpretações ecológicas convencionais da resiliência, demonstrando que a capacidade dos ecossistemas de mangais de resistir, recuperar-se e adaptar-se a perturbações climáticas é moldada por uma combinação de fatores biofísicos, geomorfológicos, hidrológicos, ecológicos e institucionais. Ao fazê-lo, os autores reforçam um reconhecimento crescente na investigação sobre gestão costeira de que a resiliência emerge das interações entre processos ambientais e capacidades de governação, e não apenas das características ecológicas.

Ao destacar a governação, a participação comunitária e a qualidade institucional como componentes centrais da resiliência, o estudo reflete uma mudança mais ampla na investigação sobre gestão costeira. A resiliência é cada vez mais entendida não apenas como uma propriedade ecológica, mas também como uma característica emergente de sistemas acoplados humano-naturais, moldados pelas interações entre processos ambientais, sociais e institucionais. Esta mudança conceptual é particularmente relevante numa era de alterações climáticas aceleradas, em que os desafios de adaptação transcendem as fronteiras disciplinares tradicionais. Consequentemente, a adaptação costeira é cada vez mais enquadrada não apenas como uma preocupação ambiental ou de engenharia, mas como um processo abrangente que requer o alinhamento das capacidades ecológicas, sociais e de governação.

Vistos sob esta perspetiva, os sistemas de mangais e dunas discutidos nesta edição transcendem o seu papel tradicional como ecossistemas ecologicamente importantes. Surgem como ativos estratégicos para a adaptação climática, sustentando soluções baseadas na natureza que reforçam a proteção costeira, apoiam a dinâmica dos sedimentos e reduzem a vulnerabilidade aos riscos costeiros. O crescente reconhecimento destes ecossistemas como infraestruturas naturais sinaliza uma transformação mais ampla nas práticas de gestão costeira, passando de respostas predominantemente defensivas e baseadas na engenharia para abordagens que aproveitam os processos ecológicos para reforçar a resiliência e a sustentabilidade a longo prazo.

No entanto, reconhecer o valor dos ecossistemas como infraestruturas naturais não resolve os desafios de governação inerentes

à gestão costeira. A contribuição de Maia *et al*. (2026) demonstra que as questões costeiras não podem ser compreendidas adequadamente apenas através de processos físicos. Através do caso da erosão costeira na Praia de Peroba, no Brasil, Maia *et al*. (2026) mostram como as alterações ambientais podem cruzar-se com interesses sociais, valores e aspirações de desenvolvimento concorrentes. Consequentemente, as partes interessadas diferem, muitas vezes, não só nas respostas de gestão que preferem, mas também na interpretação dos próprios riscos, o que reforça a necessidade de processos de tomada de decisão participativos e inclusivos.

Talvez a contribuição mais importante deste estudo de caso seja a ilustração de um princípio mais amplo subjacente à governação costeira contemporânea: a Gestão Integrada da Zona Costeira vai além da mera coordenação entre instituições e setores. A sua eficácia depende igualmente da capacidade de criar espaços inclusivos para o diálogo, a negociação e a aprendizagem coletiva. No caso de Peroba, o conhecimento científico serviu como um «objeto-limite» crucial, proporcionando uma base de evidências partilhada para as partes interessadas cujos interesses eram inicialmente divergentes. No entanto, o conflito não foi resolvido apenas através da informação científica. Pelo contrário, resultou da combinação de evidências técnicas sólidas, mediação institucional e processos de governação participativa que promovem a confiança, a legitimidade e o consenso.

Esta conclusão tem implicações importantes para a gestão contemporânea da zona costeira. Os conflitos são frequentemente percebidos como barreiras à tomada de decisão e à implementação eficaz. No entanto, o caso aqui analisado sugere uma interpretação mais matizada, segundo a qual os conflitos podem servir de catalisadores para a inovação, a negociação e a aprendizagem institucional. Quando apoiados por mecanismos de governação adequados, podem criar oportunidades para desenvolver soluções de gestão mais legítimas, robustas e amplamente aceites. Concretizar este potencial requer instituições capazes de promover o diálogo, acomodar perspetivas diversas e facilitar processos de aprendizagem coletiva e de tomada de decisão adaptativa.

Em conjunto, os quatro artigos revelam uma clara evolução na forma como os desafios da gestão das zonas costeiras são conceptualizados e abordados. Os esforços iniciais centraram-se principalmente na integração entre instituições, setores administrativos e quadros políticos. Posteriormente, foi dedicada atenção crescente à compreensão das interações entre processos físicos e dinâmicas ecológicas. Mais recentemente, questões de governação, envolvimento das partes interessadas, resiliência e adaptação às alterações climáticas passaram para o primeiro plano, tanto das agendas de investigação como nas de gestão.

Em vez de sinalizar uma sucessão de paradigmas, esta evolução reflete um alargamento progressivo do próprio conceito de integração. A gestão contemporânea das zonas costeiras vai além da coordenação intersetorial, abrangendo as interdependências entre sistemas naturais e sociais, processos ecológicos e bem-estar humano, conhecimento científico e tomada de decisão, bem como a adaptação ambiental e o desenvolvimento territorial.

Esta compreensão alargada é particularmente relevante, dada a vasta gama de pressões que afetam as zonas costeiras. Embora tenha sido dedicada atenção considerável aos potenciais impactos das alterações climáticas, o estado e a resiliência dos sistemas costeiros são também fortemente influenciados pela alteração do uso do solo, pelos padrões de urbanização, pelo desenvolvimento socioeconómico, pela eficácia da governação e pelas decisões de gestão. Em muitos casos, estes fatores podem determinar a vulnerabilidade tanto quanto, ou mesmo mais do que, os fatores de stress climáticos mais amplos. Consequentemente, a vulnerabilidade e a resiliência são cada vez mais reconhecidas como resultados das interações complexas entre processos ambientais e ações humanas, o que realça a importância da governação e da capacidade de adaptação, a par das considerações biofísicas.

Os artigos apresentados nesta edição sugerem, coletivamente, que o reforço da resiliência costeira exigirá respostas multidimensionais e intersetoriais. O reforço da monitorização ambiental, a conservação e restauração dos ecossistemas costeiros, a adoção de soluções baseadas na natureza, o envolvimento significativo das partes interessadas e uma maior capacidade institucional não devem ser perseguidos como objetivos isolados. Pelo contrário, devem ser entendidos como componentes complementares de estratégias integradas de gestão da zona costeira que abordem os diversos desafios ambientais, sociais e de governação com que as regiões costeiras se deparam.

Em última análise, os artigos reunidos nesta edição apontam para uma conclusão comum: o futuro da gestão da zona costeira dependerá menos das tentativas de controlar os processos naturais e mais da capacidade de desenvolver sistemas de governação adaptativos e baseados no conhecimento, capazes de responder a condições em mudança e a exigências sociais em evolução. Numa era marcada por pressões múltiplas e interligadas sobre as zonas costeiras — incluindo alterações ambientais, crescimento demográfico, utilizações concorrentes dos recursos e pressões crescentes de desenvolvimento —, talvez a lição mais importante que emerge destas contribuições seja que a resiliência costeira não é nem puramente ecológica, nem exclusivamente institucional. Trata-se, antes, de um processo coletivo e adaptativo que surge da interação contínua entre ecossistemas, comunidades, conhecimento científico e mecanismos de governação.

FROM INTEGRATED MANAGEMENT TO RESILIENCE: REFLECTIONS ON CONTEMPORARY CHALLENGES IN COASTAL ZONE MANAGEMENT

Coastal zones are widely recognised as among the most complex and dynamic socio-environmental systems on Earth. As interfaces between land and sea, they concentrate ecosystems of high ecological value, strategic economic activities, critical infrastructure, and communities whose cultural heritage and livelihoods are intrinsically linked to coastal and marine environments. Simultaneously, these territories are experiencing unprecedented pressures associated with urbanisation, demographic growth, economic intensification, ecosystem degradation, and the increasing impacts of climate change. Such challenges highlight the need for coastal zone management frameworks that move beyond traditional sectoral approaches, embracing integrated and adaptive strategies capable of addressing the interdependencies between environmental processes, societal demands, and development objectives.

The four papers included in this issue provide meaningful perspectives on the multifaceted challenges facing coastal regions worldwide. Despite their differing geographical contexts and research focuses, they collectively reflect key directions in the ongoing evolution of research and practice in coastal management. A common theme emerges across these contributions: the sustainability of coastal systems depends on integrating scientific evidence, ecological processes, governance mechanisms, and societal participation into coherent, adaptive management frameworks. In doing so, these studies underscore the increasingly interdisciplinary nature of coastal management and the growing importance of resilience, adaptation, and collaborative governance in addressing contemporary coastal challenges.

The reflection proposed by Pawar and Nag (2026) on the evolution of Integrated Coastal Zone Management (ICZM) provides a particularly timely framework for this discussion. Their work revisits the development of ICZM, from its early institutional efforts to coordinate sectors to the consolidation of an international paradigm grounded in the integration of environmental, social, economic, and institutional dimensions. The authors argue that coastal zone management emerged largely in response to the limitations of sector-based approaches, which, for decades, addressed issues related to urban development, fisheries, tourism, transport, and environmental protection in isolation. Experience has demonstrated that coastal challenges rarely conform to administrative or disciplinary boundaries, thereby necessitating coordination mechanisms capable of addressing highly interconnected socio-environmental systems.

It is important to recognise that this observation remains highly relevant today. Despite broad international consensus on the need for integrated coastal zone management, significant difficulties persist in implementing this principle effectively. In many contexts, institutional fragmentation continues to limit the effectiveness of public policies, while the link between scientific knowledge and decision-making remains insufficient. Coastal management, therefore, faces a recurring paradox: more scientific information is available today than ever before, yet institutional coordination challenges continue to hinder the translation of that knowledge into concrete action.

This issue also emerges from the other contributions in this volume. The study by Barros et al. (2026) on the vulnerability of dune systems in southern Brazil provides a particularly illustrative example. Barros et al. (2026) document a marked increase in dune vulnerability over the past decade, despite the prior existence of planning instruments and management recommendations. Their findings suggest that this deterioration cannot be attributed to insufficient understanding of erosion dynamics or ecosystem degradation processes. Rather, it reflects persistent challenges in translating available knowledge and planning frameworks into effective management actions.

This finding warrants particular attention. Historically, substantial effort has been devoted to improving the scientific understanding of coastal risks, vulnerabilities, and environmental processes. Although these advances have significantly strengthened the evidence base available to coastal managers and policymakers, they have not always translated into improved management outcomes. Increasingly, the critical challenge lies not in generating new knowledge, but in ensuring that existing knowledge informs planning, decision-making, and implementation within often complex institutional and socio-economic contexts. The enduring gap between knowledge and action therefore remains one of the most significant obstacles to effective coastal governance.

The contribution of Barros et al. (2026) extends beyond the assessment of dune vulnerability itself, highlighting a broader shift in contemporary coastal research towards more integrated evaluation frameworks. Whereas traditional assessments have focused largely on geomorphological and hydrodynamic characteristics, this study demonstrates the value of incorporating ecological indicators into vulnerability analyses. The use of nesting birds as bioindicators of dune condition reinforces the notion that coastal vulnerability cannot be adequately understood through physical parameters alone, but must also account for ecosystem integrity, ecological functioning, and the capacity of natural systems to support resilience and adaptation.

A comparable perspective is advanced by Ma'rufatin et al. (2026) in their systematic review of mangrove resilience to climate variability. The study moves beyond conventional ecological interpretations of resilience, demonstrating that the ability of mangrove ecosystems to resist, recover from, and adapt to climatic disturbances is shaped by a combination of biophysical, geomorphological, hydrological, ecological, and institutional factors. In doing so, the authors reinforce a growing recognition within coastal management research that resilience emerges from the interactions between environmental processes and governance capacities, rather than from ecological characteristics alone.

By highlighting governance, community participation, and institutional quality as central components of resilience, the study reflects a broader shift within coastal management research. Resilience is increasingly understood not merely as an ecological property, but as an emergent characteristic of coupled human-natural systems shaped by interactions among environmental, social, and institutional processes. This conceptual shift is particularly relevant in an era of accelerating climate change, where adaptation challenges transcend traditional disciplinary boundaries. As a result, coastal adaptation is increasingly framed not only as an environmental or engineering concern, but as a comprehensive process requiring the alignment of ecological, social, and governance capacities.

Viewed through this lens, the mangrove and dune systems discussed in this issue transcend their traditional role as ecologically important ecosystems. They emerge as strategic assets for climate adaptation, underpinning nature-based solutions that enhance coastal protection, support sediment dynamics, and reduce vulnerability to coastal hazards. The growing recognition of these ecosystems as natural infrastructure signals a broader transformation in coastal management practice, shifting from predominantly defensive, engineering-based responses towards approaches that harness ecological processes to strengthen long-term resilience and sustainability.

Nevertheless, recognising the value of ecosystems as natural infrastructure does not resolve the governance challenges inherent in coastal management. The contribution by Maia et al. (2026) demonstrates that coastal issues cannot be adequately understood through physical processes alone. Through the case of coastal erosion at Peroba Beach, Brazil, Maia et al. (2026) show how environmental change can intersect with competing social interests, values, and development aspirations. Consequently, stakeholders often differ not only in their preferred management responses but also in their interpretation of the risks themselves, reinforcing the need for participatory and inclusive decision-making processes.

Perhaps the most important contribution of this case study is its illustration of a broader principle underpinning contemporary coastal governance: Integrated Coastal Zone Management extends beyond coordination across institutions and sectors. Its effectiveness depends equally on the ability to create inclusive arenas for dialogue, negotiation, and collective learning. In the Peroba case, scientific knowledge served as a crucial boundary object, providing a shared evidence base for stakeholders whose interests were initially divergent. Yet the conflict was not resolved through scientific information alone. Rather, it emerged from the combination of robust technical evidence, institutional mediation, and participatory governance processes that foster trust, legitimacy, and consensus.

This conclusion carries important implications for contemporary coastal zone management. Conflicts are frequently perceived as barriers to effective decision-making and implementation. However, the case examined here suggests a more nuanced interpretation, whereby conflicts may serve as catalysts for innovation, negotiation, and institutional learning. When supported by appropriate governance arrangements, they can create opportunities to develop more legitimate, robust, and broadly accepted management solutions. Realising this potential requires institutions capable of fostering dialogue, accommodating diverse perspectives, and facilitating processes of collective learning and adaptive decision-making.

Taken together, the four papers reveal a clear evolution in the way coastal zone management challenges are conceptualised and addressed. Early efforts focused primarily on integrating institutions, administrative sectors, and policy frameworks. Subsequently, increasing attention was devoted to understanding the interactions between physical processes and ecological dynamics. More recently, issues of governance, stakeholder engagement, resilience, and climate adaptation have moved to the forefront of both research and management agendas.

Rather than signalling a succession of paradigms, this evolution reflects a progressive broadening of the concept of integration itself. Contemporary coastal zone management extends beyond intersectoral coordination to encompass interdependencies among natural and social systems, ecological processes and human well-being, scientific knowledge and decision-making, and environmental adaptation and territorial development.

This expanded understanding is particularly relevant given the wide range of pressures affecting coastal zones. While considerable attention has been devoted to the potential impacts of climate change, the condition and resilience of coastal systems are also strongly influenced by land-use change, urbanisation patterns, socio-economic development, governance effectiveness, and management decisions. In many instances, these factors may shape vulnerability as much as, or even more than, broader climatic stressors. As a result, vulnerability and resilience are increasingly recognised as products of the complex interactions between environmental processes and human actions, highlighting the importance of governance and adaptive capacity alongside biophysical considerations.

The contributions featured in this issue collectively suggest that strengthening coastal resilience will require multidimensional and cross-sectoral responses. Enhanced environmental monitoring, the conservation and restoration of coastal ecosystems, the adoption of nature-based solutions, meaningful stakeholder engagement, and stronger institutional capacity should not be pursued as isolated objectives. Rather, they should be understood as complementary components of integrated coastal zone management strategies that address the diverse environmental, social, and governance challenges facing coastal regions.

Ultimately, the papers gathered in this issue point to a shared conclusion: the future of coastal zone management will depend less on attempts to control natural processes and more on the capacity to develop adaptive and knowledge-informed governance systems that can respond to changing conditions and evolving societal demands. In an era marked by multiple and interacting pressures on coastal areas, including environmental change, demographic growth, competing resource uses, and increasing development pressures, perhaps the most important lesson emerging from these contributions is that coastal resilience is neither purely ecological nor solely institutional. Rather, it is a collective and adaptive process that emerges from the continuous interaction between ecosystems, communities, scientific knowledge, and governance arrangements.

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ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS

Journal of Integrated Coastal Zone Management (2025) 25(2): 83-101
© 2025 APRH
ISSN 1646-8872
DOI 10.5894/rgci-n545
url: https://www.aprh.pt/rgci/rgci-n545.html

THE EVOLUTION OF INTEGRATED COASTAL ZONE MANAGEMENT (ICZM) IN INDIA: AN OVERALL REVIEW

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ABSTRACT: Coastal water systems are increasingly threatened by anthropogenic pressures, making natural recovery processes difficult and accelerating environmental degradation. Consequently, the urgent and strategic management of coastal and marine resources has become imperative to promote sustainability. Since the mid-19th century, various global and regional efforts have aimed to improve coastal conditions, among which Integrated Coastal Zone Management (ICZM) has emerged as a comprehensive and holistic framework. While a considerable body of literature exists on ICZM, a systematic review that synthesizes its historical evolution, conceptual foundation, policy frameworks, implementation models, and challenges remains lacking. This paper addresses this gap by providing an integrated, interdisciplinary overview of ICZM - tracing its development, highlighting significant governance approaches, assessing environmental, institutional, socio-economic, political, and scientific challenges, and identifying future directions. Special emphasis is placed on the Indian context, offering insights into national strategies, institutional mechanisms, and the application of remote sensing and spatial tools in coastal management. The paper also examines the contribution of ICZM toward achieving key Sustainable Development Goals (SDGs), reinforcing its role as a critical pathway to sustainable coastal governance.

Keywords: Integrated Coastal Zone Management (ICZM), Coastal Management, Coastal Governance, Sustainable Development, Policy Frameworks, Environmental Planning.

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Submission: 29 DEC 2022; Peer review: 7 MAY 2024; Revised: 11 FEB 2026; Accepted: 11 FEB 2026; Available on-line: -- 2026

1. INTRODUCTION

A large area of coastal waters and occasionally a short stretch of coastal lowlands make up the coastal zone. The coast is a location where the exosphere, ocean, biosphere, and atmosphere interact (Fig. 1). These parts are constantly exchanging mass and energy, and as a result of these interactions, a unique ecology is formed. Because of these interactions, coastal regions show remarkable biological production and variety, which has led to their transformation into the hub of human activity. Fish, shellfish, and seaweed are produced in coastal areas, where the ports serve as trade and commercial hubs. Many biotas are also suppliers of home goods, including detergent, fertilizer, and medicines. Additionally, coastal wetlands store nutrients, trap pollutants, and aid in the defense of the shoreline against erosion and storms. Because of their beauty, the coastlines draw visitors and encourage tourism. These goods and services help sustain human existence, which has an effect on a nation's economy and, in turn, its socioeconomic circumstances. To guarantee that coastal ecosystems are in excellent condition and continue to supply a range of goods and services for present and future generations, the practice of sustainable management must be actively implemented.

Around 37% of the global population lives within 100 km of the coastline, in areas where the population density is twice the global average (Cosby *et al*., 2024). The coastal region has emerged as the primary location for a wide range of commercial activity. Many coastal developing countries rely heavily on limited coastal resources for economic growth. In many nations across the world, rapid urbanization and economic growth give rise to a variety of complicated resource-use disputes and environmental degradation issues in the coastal zone. In many coastal developing countries plagued by hunger, unemployment, poverty, and fast population expansion, the problems have gotten worse.

However, these negative effects are not readily apparent in coastal countries with a small and sparsely populated population, an abundant natural resource base, and a rural economy. As the population grows and market forces are anticipated to have a greater impact on resource exploitation and usage patterns, the situation will progressively alter.



Figure 1. Coastal Zone as an Earth System Interface.

The complicated management problems in the coastal zone cannot be solved by conventional sectoral management. These problems are frequently cross-sectoral in character, whereby the operation of one sector negatively influences the growth of another (Fallon and Chua, 1990; Scura *et al*., 1992). The problems with coastal management have escalated usage disputes, sparked social unrest, and undermined the stability of the national economy, making them a serious danger to environmental sustainability and economic sustainability. There is a clear need for an efficient alternative management structure. There is growing and urgent demand from policymakers and resource managers worldwide across both developed and developing nations for a comprehensive and actionable roadmap to guide sustainable coastal development.

1.1 Historical Evolution

With exceptional economic and ecological significance, coastal regions are among the most inhabited and productive places on earth. Natural, social, and cultural resources deteriorate as a result of increased competition for marine and coastal areas and mounting resource pressures. The effects of climate change are anticipated to expose the shoreline even more. In the past, coastal planning initiatives or development choices were made on a sector-by-sector basis with little connection between them.

This fragmented approach to planning and management leads to inefficient use of resources, conflicting land-use interests, and missed opportunities for more sustainable coastal development. One of the earliest policy frameworks for integrated coastal zone planning and management was the United States Coastal Zone Management Program (CZMP), which was created under the Coastal Zone Management Act (CZMA) of 1972 (Knecht, 1993). As a concept, ICZM has evolved over the past 40 years from nonintegrated sectorial to integrated methods (Sorensen, 1997; Cicin-Sain and Knecht, 1998; Salomons, 1999). The environment was initially the focus of ICZM, but subsequently economic, social, and ethical considerations were included (Turner, 2000). Under the support of the United States Agency for International Development (USAID), the Association of Southeast Asian Nations (ASEAN) started a regional initiative in 1986 to address the concerns of natural resource depletion and coastal environmental degradation.

Integrated Coastal Zone Management (ICZM) emerged as a globally recognized framework following the 1992 United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil. Agenda 21, particularly Chapter 17.1, emphasized the need for 'new approaches to marine and coastal area management and development at the national, sub-regional, regional, and global levels', approaches that are integrated in content, and precautionary and anticipatory in nature. This marked a significant shift towards holistic and forward-thinking strategies for sustainable coastal governance.

1.2 Significance or need of Coastal Management

Conflicts exist between the need to utilize coastal resources for human benefit and the preservation and conservation of those resources for long-term usage, which has reached an extremely critical stage in many nations (figure 2). The states of the coastal region and its resources have irreversibly degraded (World Bank, 1993). Over the last 25 to 30 years, there has been significant population pressure on our beaches due to tourism, excessive and unplanned housing, industrial facilities, the use of coastal regions as dumping places, unrestricted sand extraction, the construction of ports, piers, seawalls, etc. without regard for aesthetics or ecological considerations, filling for land reclamations, excavations built for coastal recreation, and even the building of roadways as a coastal solution for traffic problems (Oylum and Osman, 2016). Due to their higher natural variability, coastal ecosystems are often more robust than open ocean ecosystems, but because of their close proximity to populated areas, they are also typically exposed to larger concentrations of a wide range of anthropogenic stressors (Shackeroff *et al*., 2009). Furthermore, it is widespread and well acknowledged that numerous stresses, including fishing, pollution, warming oceans, and ocean acidification, have a negative impact on coastal ecosystems (Craig, 2003; Craig, 2010). According to Guichard and Peterson (2009), "the intrinsic complexity of coastal ecosystems and their relationship with human activities can explain the typical failure of management strategies centered on addressing single components of coastal ecosystems independently of others."

The objectives of ICZM are to maintain vital ecological processes, life support systems, and biological diversity in coastal and marine areas as well as to achieve sustainable development of coastal and marine areas, reduce vulnerability of coastal areas and their inhabitants to natural hazards, and achieve sustainable development of coastal and marine ecosystems (Cicin-Sain and Belfiore, 2005). The objective of ICZM is to interlink all the aspects of the coastal zone and design management plans with a holistic approach (figure 3).

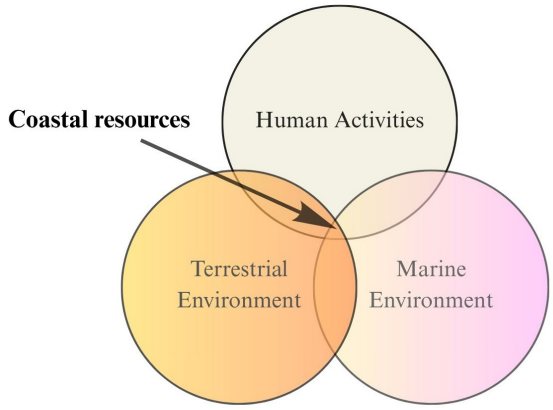


Figure 2. Conceptual Framework of the Coastal Resource System.

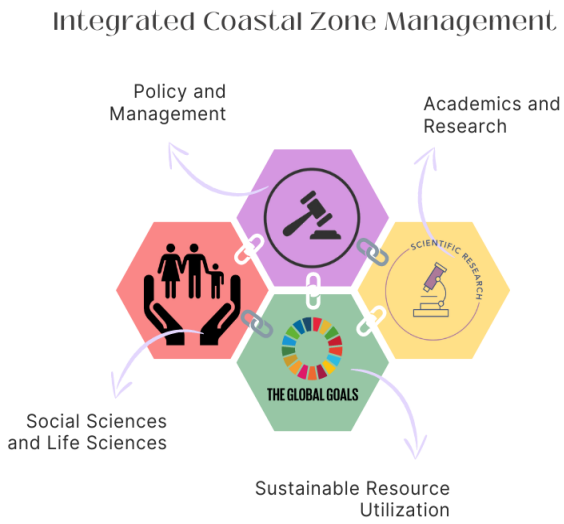


Figure 3. Interdisciplinary linkages supporting sustainable coastal resource management through policy, science, and society within the SDG framework.

The ocean is home to the biggest linked ecosystem in the world, which offers facilities and services vital to human survival. They control our environment and are anticipated to give communities all over the world a rising supply of energy, food, materials, leisure, and cultural services. As a result, environmental sustainability for the ocean is a common problem, necessitating the establishment of an appropriate global forum for the design of sustainable development goals backed by indices and ocean policies as well as the monitoring of their accomplishment. A specific Sustainable Development Goal (SDG) for the ocean and coasts that is developed and adhered to could spur greater international cooperation in order to achieve good environmental conditions for the ocean and coasts, secure blue wealth, ensure equitable access to ocean resources, and support the growth of resilient coastal communities. In addition to actively assisting in the achievement of 4 of the 17 SDGs, integrated coastal zone management is a powerful tool for ensuring a sustainable future. The integrated coastal zone management generally places the environment first, but occasionally it also emphasizes social and health considerations. Moreover, it also has influence on several other objectives of the SDGs besides those mentioned above.

2. COASTAL MANAGEMENT MODELS

Coastal management frameworks are broadly classified into two principal categories: the sustainability-oriented model and the conventional model. The sustainability model encompasses approaches such as ecosystem-based management (EBM), watershed-based management, and the establishment of protected marine areas (PMAs), all of which aim to maintain ecological integrity while supporting human needs. In contrast, the conventional model typically involves estuary-based management and integrated coastal zone management (ICZM), focusing more on administrative boundaries and sectoral planning rather than holistic ecosystem health (Kay and Alder, 2005; Cicin-Sain and Knecht, 1998).

2.1 Watershed management

Extending the scope of estuary-based management to encompass actual watershed-based management is a substantial change. The fact that circumstances in an inland watershed might differ from those in an estuary or coastal area makes in-land watersheds significant to those areas. Estuaries heavily rely on circumstances upriver and on the surrounding terrain that makes up their watershed (Costanza, 1998). It should be obvious that estuary-based management can only be increased in efficiency by extending management choices to the estuary's watershed.

2.2 Protected Areas

While climate change affects marine landscapes, a number of anthropogenic stressors are present in the background. Future projections indicate that the existing effects increasing warmth, acidification, oxygen depletion, and sea level rise will become more pronounced. Marine Protected Areas (MPAs) were created to

safeguard marine characteristics, typically with a goal of lowering fishing pressure and infrastructure installation. Since these MPAs are static in character and seldom take climate change into account, it is unclear how well they would be able to adapt as local adaptation strategies for conservation in response to climate change. When adaptive management practices and ecosystem-based techniques are applied, MPAs' resistance to climate change will be better supported (Hoppit *et al*., 2022).

2.3 Ecosystem management

Ecosystem-based management is a comprehensive management strategy that takes into account the entire ecosystem, including people. In order for an ecosystem to deliver the services that people desire and need, ecosystem-based management aims to keep it in a healthy, productive, and resilient state (Leslie, 2009). In contrast to existing approaches, which often concentrate on a particular species, sector, activity, or problem (McLeod *et al*., 2005; McLeod and Leslie, 2009), ecosystem-based management takes the cumulative consequences of several sectors into ecosystem-based management aims to keep it in a healthy, productive, and resilient state (Leslie, 2009). In contrast to existing approaches, which often concentrate on a particular species, sector, activity, or problem (McLeod *et al*., 2005; Leslie, 2009), ecosystem-based management takes the cumulative consequences of several sectors into account. MPAs are location-based marine management tools, roughly comparable to state and federal parks and wildlife refuges on land (Craig, 2003), both independently to safeguard specific ecosystems, such as kelp forests or coral reefs, or specific resources, such as fish species, and as a component of larger comprehensive maritime preservation plans, such as representative systems and EBM (Guichard and Peterson, 2009; Ruckelshaus, 2009; McLeod and Leslie, 2009). Any coastal or marine region that the appropriate government designates legally for some level of protection falls within the widest definition of an MPA.

2.4 Estuary

Estuaries are recognized as particularly important coastal ecosystems under estuary-based management, and efforts are made to avoid concentrating on the coastal zone, which is one of the main drawbacks of more extensive coastal zone management. Particularly, estuary-based management often develops in reaction to estuary deterioration brought on by upstream pollution, which motivates a watershed-based strategy for estuary management and restoration. Institutions created to control pollutants entering estuaries, however, can also develop into more thorough initiatives to conserve estuaries.

2.5 ICZM

Sorensen (1997), defined ICZM as "*the coordinated management and planning of coastal resources and habitats based on the physical, economic, and political linkages within and across dynamic coastal systems that collectively constitute the coastal zone.*" Effective ICZM necessitates the active coordination of stakeholders whose actions significantly influence the quantity and quality of coastal resources and ecosystems. According to Cicin-Sain and Knecht (1998), Coastal Zone Management (CZM) is defined as "*a dynamic and ongoing process for making informed decisions regarding the conservation, development, and protection of coastal and marine resources.*" This definition emphasizes the adaptive and continuous nature of CZM, highlighting its role in balancing ecological sustainability with socio-economic development objectives in coastal and marine environments.

The widely accepted and international definition of ICZM is given by the European Union, according to which ICZM is a dynamic, ongoing, and iterative process intended to advance sustainable management of coastal zones. The long-term goal of ICZM is to strike a balance between the benefits of economic growth and human uses of the coastal zone, the advantages of protecting, preserving, and restoring coastal zones, the advantages of minimizing the loss of human life and property, and the advantages of public access to and enjoyment of the coastal zone, all while staying within the bounds of natural dynamics and carrying capacity. The word 'integrated' in ICZM refers to both the integration of goals and the integration of the many tools used to achieve these goals. It entails integrating all pertinent policy domains, industry sectors, and administrative levels. It entails integrating the target territory's maritime and terrestrial components. ICZM is multidisciplinary by nature and integrated in both time and space. ICZM shouldn't merely be lumped in with 'environment', though despite the fact that ICZM refers to 'management', the ICZM process really encompasses the entire cycle of data gathering, planning, decision-making, management, and implementation monitoring. Thus, the term 'planning' is meant to refer to the creation of strategic policies as opposed to only land use planning or other sectoral planning in its broadest meaning. In order to assess the societal objectives in a particular coastal region at a particular time and to start taking the required steps to achieve these purposes, ICZM relies on the informed involvement and collaboration of all interested and affected parties (World Bank, 1993) (figure 4).

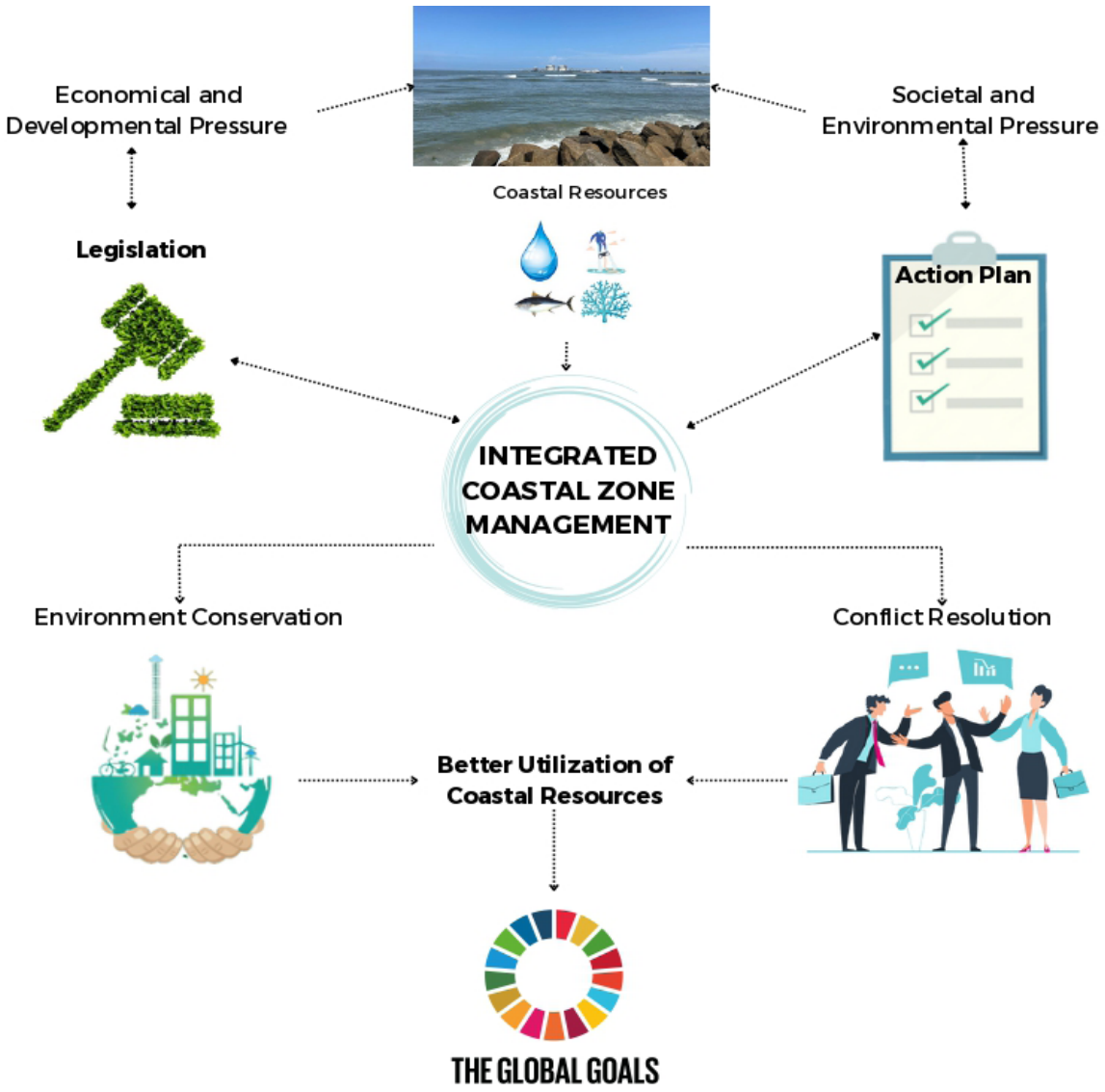


Figure 4. ICZM plan and guidelines.

3. ESSENTIAL ELEMENTS OF THE MANAGEMENT PROCESSES

3.1 Integrated Planning

Integrated resource management has gained widespread acceptance over the past 20 years as the key to attaining ecologically sustainable development. As a result, the Stockholm Declaration of the United Nations (1972), adopted one of its four guiding principles, which read in part: "*States should adopt an integrated and coordinated approach to their development planning so as to ensure that development is compatible with the need to protect and improve the human environment*". This principle laid the groundwork for future strategies, including the World Conservation Strategy (IUCN, 1980), which reinforced the concept of harmonizing development with environmental protection. Similarly, Principle 4 of the Rio Declaration on Environment and Development (UNCED, 1992) echoed this perspective, advocating for environmental protection to be an integral part of the development process. Lessons learned from prior planning for ICZM initiatives in Southeast Asia are included below.

In order to build the planning process, offer the framework for the management programme, and identify the important participating agencies, a multidisciplinary team should be formed during the first stages of programme creation. It's crucial to avoid focusing all of the resources under the control of one agency. The ASEAN/US Coastal Resources Management Projects (Chua, 1992) initially had a great deal of trouble keeping a comprehensive perspective on coastal concerns, especially in nations where a single line agency had been selected. The outcomes will be significantly impacted by this strategy. For instance, as the Fisheries Department is the primary coordinating and implementing agency for the ICZM initiatives for Lingayen Gulf and Segara Anakan, a greater focus is placed on fisheries. The planning team, according to (Scura *et al*., 1992) should consist of a core staff of six domains, including an expert in coastal management, a regional planner, a resource economist, ecology, a sociologist, and an environmental engineer. Depending on the available resources and how they will be used, specialists can be asked to join the planning team. Fisheries, aquaculture, coastal erosion, pollution, marine park administration, and environmental law are a few of the relevant fields (Scura, *et al*. 1992).

The model that has been suggested for Shanghai is a comprehensive coastal management model that uses a cross-sectoral approach and aims to take a number of difficulties into account. An ICZM plan should draw on Shanghai's current general development strategy (Shi *et al*., 2001), which has prioritized economic development while keeping environmental concerns in mind. Consequently, the following should be included in the ICZM plan: aims and goals, the legal system, institutional setting, a zonation system for coastal functions, management techniques and strategies, research in the sciences, training and education, system for monitoring and assessment, management of certain sensitive issues (such as biodiversity, aquaculture, nature reserves, and trash discharge regulation), particular action initiatives, funding strategy and the implementation framework. To guarantee that all needs are satisfied, the municipal government, local management organizations, economic sectors, scientific specialists, and locals should unquestionably be included in the planning process (Shi *et al*., 2001; Henocque, 2003). Figure 5 illustrates the decision-making framework employed in Integrated Coastal Zone Management (ICZM).

The collecting of information is crucial to the planning process. Unfortunately, a sizable portion of the information obtained could not be pertinent to the planning needs. On the other hand, crucial information for determining the management area's assimilative capability as well as for resource appraisal and regulation is typically overlooked. This is in part because they are hard to find, but more importantly because there isn't a multidisciplinary team to do effective programme design. It would be quite foolish to leave it up to the scientists to handle the initial phase of data collection and the subsequent design and planning of programmes. Clearly defining the sorts of data required for planning and programme design should occur early on. When implementing the strategic plans, research should only be done to offer definitive answers to the technical and management problems highlighted during the original phase.

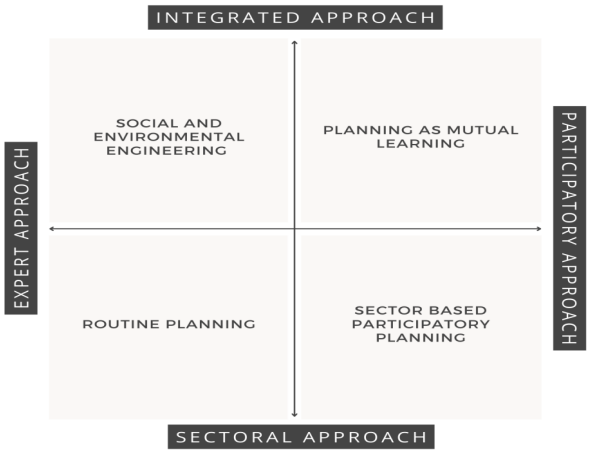


Figure 5. General framework of decision making (Welp, 2000).

Programs have frequently received revisions before the approval procedure was completed. Interests opposed to some aspects of the proposal may show up with novel and unexpected claims. Furthermore, a program's approval does not guarantee that it will receive sufficient funding (GESAMP, 1996). Scientists should examine original hypotheses before advising managers on whether the ICZM agenda needs to be revised or whether procedures need to be updated in order to take into account the most recent findings or to assimilate cutting-edge technological innovations that have practical applications (Forst, 2009). Appropriate consultation with the relevant resource management should be conducted and shall involve agencies of the federal and state governments, local government units, coastal communities, and other interested parties (Chua, 1993).

3.2 Implementation

Implementation involves employment of management practices that are eventually mutual and supportive. It requires a blend of sticks and carrots (OECD, 1993). Here, carrots refer to education, training, capital investments, participation in the formulation of policies, economic instruments (tradable permits, taxes, user charges), and decision-making procedures, while sticks refer to regulations (Sorensen, 1997). A lot of initiatives taken for ICZM did not move ahead of the planning phase. Programs developed for ICZM that do not involve concerned line agencies and government plans are commonly rejected by these organizations. If these planning and line agencies were involved before the start of ICZM programme development, it would have a tendency to become an integral part of the development plans of these agencies. Government funds and human resources play a major role in programme implementation, and these can be made useful only when policymakers are confident of the program's potential to create socio-economic benefits. Therefore, ICZM demands the implementation of programmes and projects. Implementation of these programmes and projects cannot happen all at once, and they are best implemented at the proposed time (Chua, 1993; Costanza, 2003).

The promotion and implementation of ICZM in the Mediterranean required a protocol to provide a framework to the Mediterranean states (21 in total) and the European Union, this came into force in March 2011. Acceptance of the protocol for implementation of ICZM policies and strategies in the Mediterranean countries provided a framework for managing the coast both in terms of information and boundaries. PEGASO stands for People for Ecosystem-Based Governance in Assessing Sustainable Ocean and Coast Development. It is a collaborative body of 25 Mediterranean and Black Sea institutions and organizations that assist the countries to follow the ICZM protocols in their respective areas. Its main objective is to utilize existing resources and develop a novel approach that can support policies for marine and coastal realms of the Mediterranean and accustom it to the requirements of the Black Sea (Santoro and Barbiere, 2013).

Spatial data infrastructure (SDI) is another asset for the implementation of ICZM and must include a government platform that connects scientists, administration, data providers, end-users, and other related official cartographic personnel (Strain *et al*. 2006). Initiatives that have the purpose of implementing data infrastructures on a large scale should be given importance. This can prove to be a major benefit for society, as technologies and the development of data sharing strategies are increasing. The necessity for a coordinated and effective management and administration plan for coastal zones is reinforced by the use of thematic SDIs, which can address coastal and marine infrastructures, land use changes, marine ecosystems, and biodiversity (Fowler, 2010). Because of its ability to combine existing but fragmented data and to improve users' access to source data, whether from the public, commercial, academic, government, or citizen sector, the deployment of adequate coastal and marine data and information infrastructures is becoming increasingly important (Strain *et al*., 2006; Binns, 2004). In addition, a robust and well-regulated framework needs to be established so that the governance mechanisms for the ICZM process are well in place (Malvárez *et al*., 2015).

However, even if these SDIs put forth endless efforts to validate the implementation and design, it is still difficult to have policy implementations that are fully integrated and operational (Cinnirella *et al*., 2012). The ICZM project was successfully implemented in Xiamen, in south eastern coast of China, in the mid 1990s. The ICZM of Xiamen has proven to have incorporated an ethical environmental management scheme. Success has also been duplicated in other countries, including southern coast of China. In 1994, Xiamen became one of the national demonstration sites for successful implementation of an ICZM programme and gained respect for achieving effective coastal and marine resources (Kazi *et al*., 2009; Hong and Xue, 2006).

This development leads to the establishment of cross-sectoral management. Implantation involved the planning and lively participation of stakeholders and scientists that eventually led to effective environmental protection and resource conservation. The implementation and management procedures of this ICZM also led to the prevention and mitigation of pollution of marine ecosystems, the protection of endangered species, lancelet (Branchiostoma), egret (*Egretta* spp.), Chinese white dolphin (*Sousa chinesis*) and mangroves, ocean use zoning, and the preservation of scenic spots (cultural sites, sandy beaches, and Maluan Bay on the east coast) (Peng *et al*., 2006). Most people agree that ICZM is a process that synchronizes a variety of policies and decision-making frameworks, enabling coordinated action to meet sustainable goals (Le Tissier and Hills, 2010). The rise in the number of projects at the European level that expressly include ICZM, such as those in Table 1, demonstrates the acknowledgement of its potential function.

Table 1. Different Projects addressing ICZM.

ICZM Measures	Year
Demonstration Programme	1996-1999
ICZM Strategies	1999
Communication on strategies	2000
ICZM recommendation	2002
Research into ICZM capacity requirements	2002
Evaluation of the extent of European Union ICZM implementation	2006
Green Paper of maritime policy	2006
Integrated Maritime Policy (Blue book)	2007
Maritime strategy framework directive	2008
ICZM protocol to the Barcelona Convention	2009
Review of the European Union ICZM recommendation	2011

European ICZM efforts over the past 15 years have primarily focused on investigating the needs for capacity building (Cicin-Sain *et al*., 2002), assessing the implementation of ICZM (Ballinger *et al*., 2006; Smith, 1997; Consult-Forschung and GmbH, 2006; European Commission, 1999) and developing policy frameworks, such as the ICZM strategy (European Commission, 1999), EU communication (European Commission, 2000), EU ICZM recommendation (European Parliament and Council, 2002), green paper (European Commission, 2006), blue book (European Commission, 2007), the marine strategy framework directive (Commission of the European Communities, 2008), ICZM protocol (Commission of the European Communities, 2009). According to the ICZM communication (2000), tool for implementing ICZM relates to the 8 principles that are listed in Table 2.

Table 2. Principles for ICZM (ICZM communication 2000)

Principle	Description of principle
1	Enable a holistic approach
2	Enable a participatory approach
3	Improve consideration of natural processes
4	Enable a locally specific approach
5	Support a long-term view
6	Involve relevant stakeholders
7	Introduce a combination of policy and technical instruments
8	Adaptive approaches

In Europe, the practical implementation of ICZM has been successful even with the support of a plethora of pan-European policy measures and legislative initiatives (Stojanovic *et al*., 2004). Some recurring challenges include the development of methods for implementing an interdisciplinary approach, such as overcoming problems associated with less interaction among policymakers, scientists, and practitioners (Fritz, 2010). It also includes uncertainty, data deficiency, indiscipline, difficult terminologies, and results from wide-ranging methodologies (Cooper, 2011; Olsen, 2002). The ICZM protocol for the Barcelona Convention is supposed to be the seventh protocol in the Framework. The existing set of protocols, including the Convention on Marine and Coastal Environments of the Mediterranean are complemented by this new reigning protocol and hold a significant place in the history of the Mediterranean Action Plan (MAP). This was signed in 2008 in Madrid and entered into force in 2011. The implementation of the ICZM programme along with the governance of the ecosystem put stress on the need to create initiatives on the basis of specific areas of interest (Olsen, 2002). In Greece, tourism turns out to be the main economic sector, especially in the Cyclades Islands. But the implementation of coastal policy in these regions is still fragile. There is no effective implementation of coastal environment management plans and no regulation of their respective planning systems. The sandy coast of North Lebanon, with a coastline of 100 km, has rocky terraces in order to protect the coast from erosion and storm surges. Despite the integration of national ICZM plans, it fails to incorporate an approach system to coherently use the plan for implementation of ICZM in the coastal zones. From the port side in the east to Alexandria in the west, the Nile delta area covers approximately 20,000 km2 and has a 240 km coastline. Because of water pollution, shoreline erosion, and urban sprawl, coastal resources are being degraded. This is negatively affecting the agricultural and allied sectors, especially fisheries and low-lying sectors. Due to a lack of institutional participation and coordination, many plans have not yet been implemented. Even though the national ICZM strategy was well explained in 2009, its approval is still pending (UNIVE, 2009).

3.3 Monitoring and evaluation

Monitoring and evaluation are important components of management processes, and these must be included in the planning and implementation phases of the ICZM programs (figure 6). The implementing agencies should actively monitor the progress made by the project along with the coordinating committee and evaluate the impact of the programme being implemented. The main purpose of these should be to measure the abilities of the ICZM program. They should see what can be done to achieve a good performance. They should have a tendency to seek opportunities for logistical and financial support in favour of the programme and make an assessment of the lessons learned from the impacts (Chua, 1993).

Monitoring on the coast gives a better understanding of the coastal zone and its environment, contributes to better decision-making on the coast by individuals (Williams, 1997), contributes to the well-being of the environment and its resources, and contributes to data sharing for the implementation and evaluation of management practices (Bayliss and Walker, 1996). When such monitoring practices are combined with evaluation, the scope of achieving benefits from work increases. These validate them and act as a feedback mechanism that shows the efficacy of plans and policies during their implementation. Monitoring and evaluation also deal with unexpected social, economic, and biophysical results that do occur as a result of management action (Scura *et al*., 1992). With respect to ICZM monitoring, it includes an intermittent surveillance that can discover the extent of conformity to an expected or unexpected norm (Hellawell, 1991). On the other hand, evaluation is the systematic use of social and scientific processes for assessing designs, concepts, value, and implementation of coastal zone plans and policy programmes (Rossi and Freeman, 1993). Evaluation should take into account the policies and programs' appropriate and effective procedures. It should aim to provide an appropriate data base that could be helpful for improving the program's performance. It should help with planning and improve decision-making. It should also provide better accountability for the policies and programmes of ICZM (Barrett, 1992; Sedgwick, 1993; Amies, 1994).

Coastal managers find it quite uneasy to evaluate the effective control of coastal programmes in terms of improving the condition and usefulness of the coast. The reason might be the low level of importance given to monitoring and evaluation procedures during and after implementation. This problem will continue until the present coastal monitoring systems are extended and integrated with a programme of evaluation. Monitoring and evaluation must, no doubt, be the focus of development and research so that coastal managers can see better management of coastal zones (Kay and Lester, 1997). Also, coastal managers within agencies should be provided a conceptual system or framework for proper management and decision-making that can be evaluated (Hildebrand and Norrena, 1992). Monitoring and evaluation clearly show whether the plan or programme is working or not. For better understanding, these should be isolated from other management activities and looked at separately in the planning and management system (Jacoby, 1994; CSIRO, 1994).

For adaptive management of the coastal zone, monitoring and evaluation is critical. These enable adjustment of management actions. However, the way in which monitoring and evaluation can support for adaptive management, is not often found considerable. To summarize, monitoring includes activities that estimates the effectiveness of actions and evaluation includes the interpretation of data (Jacobson, 2014).



Figure 6. Process flow of ICZM

4. ESSENTIAL ELEMENTS RELATED TO MANAGEMENT ISSUES

The ICZM development issues are related to a wide range of management problems and difficulties (Table 3). These issues can be due to environmental quality, resource utilization, institutional concerns and natural hazards (Chua, 1993).

Management issues are often linked with the quality of the environment and the utilization of resources. The historical, cultural, and archaeological resources need specific attention for protection. Institutional issues are linked to institutional power to implement programmes and influence legislation. Natural hazards such as tidal waves, storms, and typhoons can also cause issues with coastal management in the coastal zone. Sea level rise and sea temperature have a direct impact that can pose a set of new management issues and must be considered in the ICZM program. The identification of management issues requires a proper field survey and site inspection. These issues are frequently identified through consultative meetings with local government officials, communities, and members of other non-governmental organizations (NGOs) working in the field.

Table 3. Management issues identify in six of the pilot sites in ASEAN (Chua and Pauly, 1989).

Management Issues	Brunei Darussalam	Indonesia	Malaysia	Philippines	Singapore	Thailand
Resource utilization Sustainable fisheries development	Y	Y	Y	Y	N	Y
Sustainable aquaculture development	Y	N	Y	Y	Y	Y
Sustainable coastal forestry	Y	Y	Y	Y	N	Y
Land and water use conflicts	N	Y	Y	Y	Y	Y
Overfishing	Y	N	Y	Y	Y	Y
Open access	N	N	N	Y	N	N
Destructive fishing	N	N	N	Y	N	Y
Decreased tourism potential	N	N	N	Y	N	N
Destruction of habitats	Y	Y	Y	Y	N	Y
Undervaluation of resources and resource systems	Y	Y	Y	Y	Y	Y
Cultural/historical resources	N	N	Y	N	Y	N
Endangered wildlife	Y	Y	N	N	N	Y
Environmental quality Water quality	Y	Y	Y	Y	Y	Y
Siltation/sedimentation	Y	Y	Y	Y	N	Y
Solid/domestic waste	Y	Y	Y	Y	N	Y
Critical habitats	Y	Y	Y	Y	Y	Y
Oil spill	Y	N	Y	N	N	N
Coastal erosion	Y	Y	N	Y	N	Y
Pollution	Y	Y	Y	Y	Y	Y
Aesthetics	N	N	N	N	Y	Y
Floods	N	N	Y	Y	Y	N
Marine transportation	N	N	Y	N	Y	N
Dredging and filling	N	Y	N	N	Y	N
Coastal reclamation	N	N	N	N	Y	N
Waterfront development	N	N	N	N	Y	N
Agricultural waste	N	Y	Y	Y	N	Y
Conflicts in legislation	Y	Y	Y	Y	N	Y
Multi-sectoral integration/coordination	Y	Y	Y	Y	N	Y
Transnational cooperation	Y	N	Y	N	Y	N
Institutional capabilities	Y	Y	Y	Y	N	Y
Public awareness/involvement	Y	Y	Y	Y	N	Y
Legal framework	Y	Y	Y	Y	Y	Y
Ineffective law enforcement	N	Y	Y	Y	N	Y
Landownership	N	Y	N	N	N	N
Inadequate interdisciplinary planning capability	Y	Y	Y	Y	N	Y
Inter-sectoral conflicts	Y	Y	Y	Y	Y	Y
Lack of alternative livelihood	N	Y	N	Y	N	N
Equity	N	Y	N	Y	N	Y
Natural hazards red tide	N	N	N	Y	N	N
Flooding	N	N	Y	N	N	N
Typhoon/earthquake	N	N	N	Y	N	N

*("Y" for Yes and "N" for No)

Not every problem can be solved at once; in fact, it takes time. The ICZM assists in identifying priorities and characterizing management issues that must be addressed in order to implement long-term management strategies.

5. ESSENTIAL ELEMENTS RELATED TO MANAGEMENT ACTIONS

5.1 Institutional and organizational arrangements

A society creates institutional arrangements to divide finite resources among conflicting interests. Institutional arrangements are made up of laws, customs, and governing structures (stakeholders). A nation or sub-national entity has an institutional arrangement if it has set up a system to manage even one of its coastal resources (such as fisheries, beaches, sub-tidal lands, or port regions). The agreement could merely be on paper (such as laws that are ignored). The agreement does not have to be limited to the shore (as in a national fisheries law). The supporters of the ICM programme must be open and honest about the resources required at all phases of execution. Implementing institutional arrangements and regulations without the necessary funding would lead to countless expensive confrontations and gradually erode the initiative's credibility since it would be perceived as a hollow promise (Sorensen, 1997; Sorensen and McCreary, 1990).

For initiatives and programmes to be carried out, institutional and organizational frameworks are essential. Since ICZM is a government initiative, its execution must be legitimate. Without the support of the government, an ICZM initiative will frequently face significant challenges. The government must first transfer management responsibility to the affected local authorities or communities, even under the notion of "co-management" or "community management."

The government must nevertheless provide the essential oversight, technical support, and, in most cases, financial help. The management actions for an ICZM programme start with policy considerations. Regarding the promotion of sustainable development in inland, coastal, and marine regions, as well as the preservation of territorial use rights, biodiversity, coastal habitats, and environmental quality, government policies and regulations need to be developed or clarified. To solve organizational deficiencies, particularly with regard to law enforcement and the definition of roles and responsibilities, management measures are also necessary. The following are a few of the most frequent management actions that fall under this category: (a) defining and clarifying legal rights and obligations; (b) identifying organizational jurisdiction and responsibilities; (c) enhancing enforcement capacity; and (d) carrying out monitoring and evaluation. Since national, provincial, and local governments typically share jurisdiction over the coastal zone and ocean, it is generally recognized that ICM projects must operate from two perspectives: "top down" (involving the national government) and "bottom up" (involving the local community and provincial authorities) (Nayak, 2017).

5.2 Command and control

Many management practices fall into this category. To influence human behaviour in accordance with the aims of ICZM, both incentives and regulatory measures are required. Disincentives include high or new taxes, licenced fees, restricted seasons, and limiting access to certain resources, which are some of the strategies to encourage economic growth. Incentives include tax exemptions or reductions, government subsidies, and technical help to encourage environmental protection or forbid destructive or polluting behaviour (Chua, 1993).

Compulsory environmental licences, which are required for all types of potentially hazardous operations, significantly reduce the negative environmental effects. Other environmental laws have been passed to restrict the use of specific harmful substances, set emission caps, enforce specific technical requirements, hold producers accountable for the waste produced by their products, control land and coastal use planning, and prohibit the use of specific harmful substances. Another sort of legal document employed in CZM is a licensed for fishing or other coastal activity, which controls access. Protection zones, including national parks, conservation initiatives, etc., may be included in a simulation model that is built to provide the SAF-specified results. Legislations are the toughest sort of policy instrument, making them possibly the most foresighted instrument in a System Approach Framework (SAF) (Skorstad *et al*., 2020). The four types of command-and-control management actions that are most frequently used to reduce negative environmental effects are: (a) imposing new regulatory measures; (b) bolstering existing regulatory measures; (c) establishing and implementing standards, such as water quality and emission/discharge; and (d) offering incentives (Chua, 1993).

Direct public investment

This group of management practices entails a direct financial commitment from the government to raise public awareness, provide fundamental infrastructure, carry out research,

develop capabilities, or present opportunities that will result in the resolution of issues and problems related to coastal development. For instance, significant research funding is required to get a better knowledge of the elements that preserve the functional integrity of resource systems, the marine environment's capacity for assimilation, the societal costs of a poorly managed environment, waste management technology, etc. The managerial practices that most frequently fall under this category are (a) Public infrastructure, such as highways, embankments, and garbage collection and disposal systems or facilities, (b) Training and education, (c) Public awareness and information distribution, (d) Research and development and (e) Technical assistance (CRMP, 1992; NEDA, 1992).

6. COASTAL ZONE MANAGEMENT ACT (CZMA) AND POLICIES

In order to protect the marine and coastal environment for the current population as well as for future generations, ICZM is required, and ICZM regulations must be established. An ICZM policy is essential for preserving the biodiversity and productivity of coastal ecosystems, as well as improving the quality of life for human populations who rely on those ecosystems' resources (Bennett, 2001). A policy for ICZM also serves as a road map for future activities that must be undertaken to strike a balance between coastal development and conservation (Shi *et al*., 2001).

An ICZM policy offers definition and direction on resource utilization, enabling more coordinated decision-making. An ICZM policy provides a structure and procedure to connect various industries, fostering collaboration among users of coastal resources and their activities and choices. An ICZM policy has an impact on management by highlighting the relationships between users and the impact that each user has on one another, ensuring that logical decisions are made across sectors (Shi *et al*., 2001). The European Union has dealt with coastal zones through international accords governing its regional waters since the 1970s. Since 1996, the European Commission has been trying to find and promote solutions to the degradation of Europe's coastal zones and to improve the overall situation. The EU has only lately started to address issues, especially those connected to the condition of coastlines and the coast as a regional entity (EEA, 2006). The EU Demonstration Programme on Integrated Coastal Zone Management (ICZM), which was run by the Commission from 1996 to 1999, was built around a number of 35 demonstration projects and six topic studies (Reis, 2014). The objectives of this initiative were to: (1) disseminate technical knowledge on sustainable coastal zone management and (2) promote a robust discussion among the many parties engaged in the design, administration, or utilization of European coastal zones. The goal of the programme was to reach agreement on the steps that must be taken in order to promote ICZM in Europe.

In India, in order to prevent all development activities 500m or more from the High Tide Line, the initial policy framework for the protection of India's coastal zone was created in 1981. This was followed by the resolution of the Environmental Protection Act (1986) and a draught notification on the Coastal Regulation Zone (CRZ) in 1986. In 1991, CRZ notification was subsequently issued. In the meanwhile, in 1998, National and State Coastal Zone Management Authorities were established (Joseph and Balchand, 2000).

7. COASTAL ZONE MANAGEMENT IN INDIA

About 7500 km of the Indian coast are made up of diverse ecosystems and landforms. In India, a programme for integrated coastal zone management has been launched, and institutional frameworks at the national and state levels have been established to support it. The National Center for Sustainable Coastal Management (NCSCM), a Center of Excellence for Coastal Management, is built with cutting-edge research facilities as part of building knowledge and a planning basis. With seven significant coastal research subject areas, NCSCM is already supporting coastal management. Piloting ICZM approaches have been put into practice in some of the states of the country. Some of the planned activities for this component have also been completed, such as the completion of livelihood projects in 169 coastal villages and the enhancement of the Gujarat Pollution Control Board's capacity to monitor coastal and marine pollution. For the Odisha Pollution Control Board, 14 cyclone shelters were built, and the community helped with their operation and maintenance (World Bank, 2017).

The Indian government created an ICZM plan as a case study of the Andaman Islands that addresses, among other things, the creation of databases and knowledge bases, the use of framework methodologies, conflict detection, risk assessment, alternatives, cost-benefit analyses, strategic plans, action plans, and suggestions for institutional reforms (Devaraj and Arumugam, 2011). In order to encourage research on topics

linked to coastal processes, eco-systems, shoreline erosion, pollution, hazards, and coastal vulnerability, the Ministry of Earth Sciences launched the Integrated Coastal and Marine Area Management (ICMAM) programme in 1998. Incorporating environmental and social issues into all sectoral development operations by using techniques like geographic information systems (GIS), remote sensing, mathematical modeling, and environmental impact assessments (EIA) in coastal regions, this idea promotes sustainable management of the coastal zone and rational resource exploitation (NCCR, 2019).

India has a highly successful remote sensing programme, and during the past 40 years, changes in coastal ecosystems, landforms, shorelines, and other factors have been noted using the Indian Remote Sensing Satellite (IRS) series of satellites. The categorization and geometric accuracy of items, as well as the classification system for coastal ecosystems, are standardized. Coral reef characteristics and mangrove community details were created. Using satellite data, the high and low tide lines were precisely drawn over the whole coastline. The coastline database for the whole nation was generated once all of these data were grouped in a GIS (Gupta, 2001; Nayak, 2017).

On coastal ecosystems, the effects of several threats, including cyclones, tsunamis, and sea level fluctuations, were reported. Using elevation data acquired from satellite data, coastal multi-hazard vulnerability maps for the coastline of India were created based on topography, shoreline changes, and tides (Mahendra *et al*., 2011; Mahendra *et al*., 2010). The data on sea surface temperature and ocean colour were used to create prospective fishing advisories, which are sent out to fishermen every day. To pinpoint coastal control zones, marine protected areas, sensitive zones, etc., the coastal database was efficiently used. For the benefit of society, a number of services were developed for the tsunami, fishing, and coral reef bleaching. In order to foresee impending threats and expected changes in the coastal zone and take appropriate action, models for the coastal zone are designed. To comprehend the effects of anthropogenic activities and the changing climate on the coastal zone, socio-economic data must be integrated with the knowledge database of the coastal zone (Nayak *et al*., 1989; SAC, 2011).

A Society for Integrated Coastal Management (SICOM) was founded by the Ministry of Environment, Forests, and Climate Change with the goal of promoting the implementation of ICZM activities in India. SICOM stands for lively, marine, and resilient coastal and marine environments. In order to improve the protection, conservation, rehabilitation, management, and policy design of the coast, the SICOM developed and operationalized the National Centre for Sustainable Coastal Management (NCSCM) at Anna University in Chennai. The whole coast has also been cell mapped and ESA mapped as part of project phase 1 (ICZM, 2018), while phase 2 is focused on capacity development and implementing ICZM Plans, managing coastal pollution, and conserving coastal and marine natural resources (Telave and Chandankar, 2021).

8. CHALLENGES TO ICZM

8.1 Environmental challenges

Climate change is an important challenge for coastal management in terms of identifying future baselines and coastal setbacks. A coastal setback is simply a buffer zone just behind the shoreline. The European legal framework lacks particular provisions for accounting for coastal setbacks (Sanò, 2010). Along with coastal climate change, failures in management to protect coastal ecosystems and high development pressures resulting in environmental degradation tend to exacerbate conflicts over access to the integrated use of the coastal zone (Ahmed, 2010). In Algeria, a Mediterranean country, the growing population and their environmentally unfriendly activities present a challenge with respect to the implementation, monitoring, and evaluation of ICZM programs. This can heavily impact the coastal and marine environments of Algeria (Khelil *et al*., 2019). Other challenges, like natural disasters such as tsunamis and floods, could hinder the management activities.

8.2 Institutional challenges

Institutional setup, from planning to implementation and monitoring, is one of the key challenges imposed on ICZM. It requires political will, financial support, human resources, and cooperation among different stakeholders. When the institutional set-up is there, the legal and administrative framework can be formed just like in Mediterranean countries, and its heterogeneity in morphological aspects creates the implementation of the new ICZM provisions protocol. This may eventually result in the manifestation of prohibited buffer zone construction, approximately 100m from the coast. As a result, it proves to be a significant challenge for an early initiative to succeed (Sanò, 2010). In the North Adriatic case, it is interesting to note that international coordination and cooperation are put forward with the challenge of contributing to the management of biological resources and quality water in the coastal zone. It is challenging even for the Black Sea countries to adopt

an overarching legal framework for ICZM, just to adhere to a more coherent spatial scale for the management of coastal zones (Olsen, 2002). In Algeria, in total, 7 parameters have been evaluated in order to assess the institutional capacities for implementing the foundations of ICZM. These are the legal framework, financial resources, capacity building, participation, and awareness. The challenge is to create various legal and institutional reinforcements, like the creation of agencies dedicated to coastal management and the enactment of a coastal law with respect to ICZM (Kheli *et al*., 2019).

8.3 Socio-economic challenges

The coastal managers also face the most important challenge of designing an uncertain, complex socio-economic governance strategy involving the problem of fundamental scale definition. Hence, there is a challenging need to frame ICZM initiatives with strong regional and national strategies and a management framework (Olsen, 2002). The deteriorating environmental condition creates a highly acute situation and hinders social and economic development. This forces poverty, hunger, and disease, leading to a vicious cycle of environmental conflicts and the challenge of creating balance between short-term gains and long-term integrated resource management, prefigured as ICZM (Ahmed, 2010). Whereas economic sustainability in terms of public health risk requires a more complex understanding and determination of the role of environmental resources and conditions (Bowen and Riley, 2003). For example, the mainland of Ecuador and the Galapagos Islands face challenges in the face of constant changes in tourism and economic realities. Although Ecuador receives support for training for ICZM and has a few international financing heads for ICZM, it is obvious that this will not guarantee right management. This is due to changes in administrative, political, and, most importantly, economic factors. These have had a high impact on tourism and the dynamics of the economy in these coastal areas (Bowen and Riley, 2003).

8.4 Political challenges

Identifying the political issues seen along the coast and understanding their potential solutions continue to be the most difficult challenges for coastal managers and practitioners dealing with management. Not only this, but problems like lack of political and financial support in the medium and long terms, the difficulties faced by coastal managers in translating the principle of integration into daily management practices, and the unknown surety of the sustainability of ICZM initiatives and efforts the wide breach between science and political decision-making processes and the "dictatorship" of sectoral approaches can also represent important challenges. ICZM is a well-recognized principle for achieving sustainable development in coastal areas, but the theoretical framework for addressing the complexity of coastal governance is not an alternative; the main problem is translating the ICZM principle into daily management practices (Olsen, 2002).

8.5 Scientific challenges

Some scientific challenges include difficulties finding and collecting outcome data within the coastal management zone. The criteria for success are often unloaded by the fact that coastal legislation or programme plans are not always evident (Knecht *et al*., 1996). Countries need proper integration of scientific knowledge into coastal policies and ICZM programs. Even developed countries like Italy still face challenges regarding the proper coordination of science and policy, and there seems to be zero coordination between regional authorities and localities with national authorities (Cantasano, 2017).

To summarize, the multi-scale nature of coastal governance, the difficulties in promoting integration, the burdensome relationship between science and decision-making, the dictatorship of sectoral approaches, and the complexity in understanding the relationship between statutory frameworks and voluntary agreements have been identified as the primary factors impeding wider adoption of ICZM in the cases studied (Olsen, 2002).

9. FUTURE PERSPECTIVES

Over the past few decades, numerous local, regional, and national ICZM policies, programmes, initiatives, and activities have emerged. In ICZM, sharing experiences and learning from examples of effective practices are crucial. In light of this, the European Commission maintains the 'OurCoast' online database, which contains over 350 case studies on important subjects such as planning and land management tools, institutional coordination mechanisms, and information and communication. Despite all of its efforts, ICZM still has flaws, such as an inadequate political and legal standing or the absence of a standardized and relevant methodology for practitioners and policymakers. ICZM must be politically credible, legitimate, and consistent in its results, together with instructions on how to attain them. ICZM agreements have recently been created and approved for global and extensive regional marine regimes. For instance, the "Protocol on Integrated Coastal Zone Management in the Mediterranean," the first transnational, legally binding ICZM pact (21 nations in Europe, Africa, and Asia), came into effect in 2011. The European Union is

a party to the ratification, which is enforceable across all member states. Officially, it outlines the coastal zone, presents a vision of sustainable development, and responds to new ICZM needs. Coherence of governance and acts, legitimacy, and a hierarchy of tactics and plans. It is outcome-focused, offers step-by-step instructions for the process, is interactive, and can be expanded. If it can serve as a model for regional seas throughout the world, that will be evident in the future.

The integration of ICZM with maritime spatial planning, maritime policy, and marine environment protection, the integration of land and marine spatial planning, as well as the further development and implementation of tools such as systems approach frameworks (SAF) for coastal zones, are some of the significant issues that will need to be overcome in the future. To enhance the effectiveness of Integrated Coastal Zone Management (ICZM), several strategic steps can be considered, including: (1) determine and manage the consequences and implications that are caused by changes in the marine environment and how they relate to land and communities along the coast, (2) enable coastal communities to realize their legitimate ambitions in their adjacent coastal waters by ensuring complete synergy between the spatial planning and management of the marine and terrestrial environments, (3) establish a political agenda that is equitable and takes development, society, and the environment into consideration and (4) decision-making in coastal waters should be held to the same standards of consistency, openness, and democratic accountability as decisions made on land through long-term and, when necessary, legally formed partnerships for coastal and inshore waters, regional communities and stakeholders.

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ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS

Journal of Integrated Coastal Zone Management (2025) 25(2): 103-114
© 2025 APRH
ISSN 1646-8872
DOI 10.5894/rgci-n650
url: https://www.aprh.pt/rgci/rgci-n650.html

GESTÃO INTEGRADA DA ZONA COSTEIRA E A RESOLUÇÃO DE CONFLITOS: O CASO DA PRAIA DA PEROBA, ICAPUÍ – CE

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ABSTRACT: This study addresses the problem of coastal erosion on Peroba Beach, in Icapuí, Brazil, highlighting the socio-environmental conflicts resulting from territorial disputes and human interventions in the coastal zone. The erosion process is aggravated by natural and anthropogenic factors, such as disorderly occupation, climate change and alterations in sediment dynamics. The main conflict in Peroba involves two groups: the Peroba Residents Association (traditional fishermen), who advocated the construction of an adherent riprap, and the Preserve Peroba Association (new residents), who proposed a more ecological structure to restrain erosion. The dispute led to mediation by the Brazilian Federal Public Prosecutor's Office (MPF), which proposed an agreement between the parties. The solution adopted consisted of the construction of two permeable breakwaters and artificial beach nourishment, combining coastal engineering techniques and integrated coastal zone management. The study reinforces the importance of community participation, sustainable planning and the use of nature-based solutions to minimize environmental impacts and preserve local characteristics.

Keywords: Coastal erosion; Community participation; Socio-environmental conflicts.

RESUMO: *O estudo aborda a problemática da erosão costeira na Praia da Peroba, em Icapuí, Brasil, destacando os conflitos socioambientais resultantes da disputa territorial e das intervenções humanas na zona costeira. O processo de erosão é agravado por fatores naturais e antrópicos, como a ocupação desordenada, mudanças climáticas e alterações na dinâmica sedimentar. O conflito principal em Peroba envolve dois grupos: a Associação dos Moradores de Peroba (pescadores tradicionais), que defendiam a construção de um enrocamento aderente, e a Associação Preserve Peroba (novos moradores), que propunham uma estrutura mais ecológica para conter a erosão. A disputa judicializada levou à mediação do Ministério Públicos Federal (MPF), que intermediou um acordo entre as partes. A solução adotada consistiu na construção de dois espigões permeáveis e alimentação artificial da praia, combinando técnicas de engenharia costeira e gestão integrada da zona costeira. O estudo reforça a importância da participação comunitária, no planejamento sustentável e do uso de soluções baseadas na natureza para minimizar impactos ambientais e preservar as características locais.*

Palavras-chave: *Erosão costeira; Participação comunitária; Conflitos socioambientais.*

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Submission: 23 APR 2025; Peer review: 11 AUG 2025; Revised: 18 MAY 2026; Accepted: 18 MAY 2026; Available on-line: 25 MAY 2026

1. INTRODUÇÃO

As linhas de costa sofrem constantes mudanças à medida que as correntes costeiras, as ondas e os rios movimentam os sedimentos interagindo com a zona costeira. A evolução morfológica tende a acelerar sob a ação de eventos extremos, como tsunamis, tempestades e entrada de ondas do tipo Swell que provocam erosão intensa e podem levar a mudanças irreversíveis (Maia *et al*., 2025). A presença humana também tem uma influência importante, quer através da exploração dos recursos costeiros, quer como efeito colateral de atividades que resultam na deterioração desse ambiente (Vousdoukas *et al*., 2020; Pang *et al*., 2023). Além disso, a subida relativa do nível médio da água do mar contribui para a erosão costeira, especialmente em zonas baixas e planas, através de uma adaptação morfológica complexa, e aumentando a exposição a outros fatores morfodinâmicos (Filgueiras *et al*., 2023).

Os fatores antropogênicos são impulsionadores proeminentes das mudanças morfológicas costeiras, sendo necessário um planejamento costeiro integrado eficaz e estratégias de adaptação oportunas para travar esta tendência e reduzir os riscos costeiros (Carmo, 2018). É provável que a proteção costeira tenha impactos financeiros positivos em regiões muito povoadas e de rendimento elevado devido ao grande potencial da redução dos impactos, mas os investimentos econômicos necessários para medidas artificiais podem não ser possíveis em estados ou cidades de rendimento mais baixo (Silva *et al*., 2023).

No Brasil, o levantamento apresentado pelo Ministério do Meio Ambiente – MMA sobre o Panorama da Erosão Costeira no país, mostra que nas regiões Norte e parte do Nordeste, cerca de 60 a 65% da linha de costa está sob processo erosivo, ao passo que no Sudeste e Sul esse percentual é bastante inferior, cerca de 15%. A linha de costa do Nordeste, entre os estados do Maranhão e da Bahia, totaliza 3.317 km, apresentando um percentual médio de 28% das praias em erosão, ou seja, 939 km de praias sujeitas a este fenômeno. Os estados do Rio Grande do Norte e Ceará, apresentam as maiores porcentagens da linha de costa em erosão, respectivamente 60% e 47% (Muehe, 2018).

Na zona costeira do Ceará, além das altas taxas de erosão, os conflitos resultam principalmente da disputa por territórios entre comunidades tradicionais e o setor privado, muitas vezes apoiado pelo Estado. Esses conflitos têm origem na apropriação dos recursos naturais e na especulação imobiliária, impactando diretamente populações locais que vivem historicamente nessas áreas (Carvalho, 2023). Entre os principais conflitos, destacam-se:

- Disputa por posse de terras e expansão imobiliária e do turismo, devido à instalação de hotéis, resorts e condomínios de luxo que são construídos em áreas originalmente ocupadas por pescadores e agricultores tradicionais, gerando movimentos populacionais forçados e restrições ao acesso a áreas de uso comum (Lima, 2012);
- Implantação de parques de energia eólica em comunidades costeiras, que por vezes ocorre sem consulta prévia às populações afetadas, o que gera conflitos ambientais e sociais (Vidal, 2023);
- Implantação de fazendas de carcinicultura e destruição de manguezais, o que compromete ecossistemas locais e prejudica a pesca artesanal, afetando a segurança alimentar das comunidades (Pinto *et al*., 2014);
- Pesca predatória, cuja exploração descontrolada dos recursos marinhos por grandes empresas pesqueiras reduz a disponibilidade de pescado para comunidades que dependem dessa atividade para sobrevivência.

A Praia de Peroba, situada no Estado do Ceará, enfrenta desafios relacionados com a erosão, que podem ser agravados por fatores como mudanças climáticas, elevação do nível médio da água do mar, intervenções humanas e a dinâmica natural dos ecossistemas costeiros. A escolha do método para mitigar a erosão é crucial, pois intervenções inadequadas podem causar impactos negativos ao meio ambiente e à comunidade. Obras de engenharia costeira têm sido amplamente utilizadas para: a mitigação dos riscos de erosão; o restabelecimento de sistemas naturais (falésias, dunas, zonas úmidas e praias); a defesa contra possíveis inundações; e a proteção de obras civis (edifícios, infraestruturas, rodovias) na orla costeira (CIRM, 2018).

O conflito na Praia da Peroba perdura há vários anos, inicialmente devido à disputa de terrenos com a chegada de novos moradores, que mudaram os hábitos e a forma de ocupação dos terrenos adquiridos na comunidade, e posteriormente após a forte degradação da praia pela erosão costeira, à escolha da obra para combater este fenômeno. A disputa foi judicializada e as partes envolvidas constituíram associações para dispor de representantes legais, nomeadamente de: Associação dos Moradores de Peroba (pescadores nativos) e Associação

Preserve Peroba (novos moradores). Como partes adicionais no conflito estão a Prefeitura Municipal de Icapuí e a AQUASIS - Associação de Pesquisa e Preservação de Ecossistemas Aquáticos, que objetiva proteger espécies ameaçadas e habitats importantes para a conservação da biodiversidade no Ceará, e que instalou a primeira estrutura de quarentena para filhotes de peixes-boi (Trichechus manatus) na Praia da Peroba.

Nesse contexto de conflito, a escolha da obra para combater a erosão na Praia de Peroba deve considerar uma abordagem equilibrada, que leve em conta não apenas a eficácia técnica, mas também os impactos ambientais e sociais. Soluções baseadas na natureza podem oferecer alternativas mais sustentáveis e resilientes a longo prazo. Além disso, é fundamental envolver as comunidades locais e outros stakeholders no processo de decisão, garantindo transparência e participação. Entre as medidas que contemplam esses aspectos está a Gestão Integrada das Zonas Costeiras (GIZC), pois trata-se de uma abordagem abrangente e baseada no ecossistema para o desenvolvimento sustentável e a conservação ambiental. Essa intervenção se baseia num processo dinâmico de tomada de decisões para o desenvolvimento e implementação de estratégias. Requer um quadro político, disposições institucionais, capacidade de planejamento, uma base científica e tecnológica sólida e mecanismos de cooperação reforçados, e coloca a utilização dos oceanos e das zonas costeiras no âmbito mais amplo do desenvolvimento da Política Nacional, traduzindo decisões políticas amplas em atividades específicas do local (UM, 1996; Muehe, 2009).

No estado do Ceará, a GIZC vem sendo tratada no Projeto "Erosão Costeira: Causas, Mitigação e Adaptação às Mudanças Climáticas", no âmbito do Programa Cientista Chefe, instituído pela Lei Estadual Nº 17.378, de 4 de janeiro de 2021, da Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico – FUNCAP. Os principais objetivos são: identificar problemas da zona costeira que afetam a sociedade, como infraestruturas inadequadas e/ou degradação ambiental; compreender as relações entre diferentes processos que levam à erosão costeira, suas causas e impactos; e propor soluções técnicas de infraestruturas para combater os efeitos da erosão costeira.

Neste contexto, este artigo apresenta uma aplicação prática da GIZC na Praia da Peroba, com a perspectiva de resolução dos conflitos socioambientais resultantes da disputa territorial e das intervenções humanas na zona costeira local e proposta de solução técnica adequada para mitigação dos problemas associados à erosão da linha de costa.

2. ÁREA DE ESTUDO

A Praia da Peroba está localizada em Icapuí, um município do litoral leste do Ceará, na região Nordeste do Brasil, com 67 km de extensão. Localizado a 200 km de Fortaleza, capital do Estado (Figura 1), a região é caracterizada por uma vasta planície litorânea e possui uma população de pouco mais de 20.000 habitantes, de acordo com o censo nacional (IBGE, 2020).

Icapuí possui um litoral repleto de contrastes surpreendentes: coqueirais exuberantes, enseadas, recifes que formam piscinas naturais e imponentes falésias fazem parte de um panorama enriquecido por uma vegetação tipicamente sertaneja. Esta beleza singular tem contribuído para que, a cada ano, a cidade seja procurada para a construção de casas de veraneio, atraindo um número crescente de visitantes de diversas classes sociais em busca de tranquilidade e contato com a natureza.

3 MATERIAL E MÉTODOS

3.1 Caracterização do problema da erosão e quantificação da erosão

Este estudo insere-se no âmbito do Projeto "Erosão costeira: causas, mitigação e adaptação às mudanças climáticas", desenvolvido no contexto do Programa Cientista Chefe, instituído pela Lei Estadual nº 17.378, de 4 de janeiro de 2021, da Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico (FUNCAP). Trata-se de um projeto de pesquisa em andamento, cuja fase inicial correspondeu ao diagnóstico da situação ambiental, territorial e social da área de estudo. Nessa etapa, buscou-se identificar os principais vetores de degradação costeira, bem como os atores envolvidos e os conflitos territoriais associados. Nesse contexto, a erosão costeira no Ceará tem-se intensificado devido a pressões antrópicas diretas, como a urbanização e a expansão da infraestrutura portuária, e indiretas, associadas às mudanças climáticas (Pranzini *et al*., 2015). Esse processo compromete ecossistemas, infraestruturas e atividades econômicas, especialmente o turismo.

O estudo da erosão costeira na Praia da Peroba seguiu uma abordagem interdisciplinar, combinando análise territorial, levantamento de dados geoespaciais e modelagem numérica. Inicialmente, foram mapeados os conflitos territoriais e os interesses dos diferentes grupos envolvidos, incluindo a Associação dos Moradores de Peroba (composta por pescadores



Figura 1. Localização da Praia da Peroba no município de Icapuí, Ceará, Brasil. Fonte: Maia *et al.* (2024).

nativos), a Associação Preserve Peroba (formada por novos moradores), a Prefeitura de Icapuí e a AQUASIS, organização dedicada à preservação de espécies ameaçadas.

Para a caracterização da erosão e dos fatores que influenciam a dinâmica sedimentar da região, adotou-se uma abordagem quantitativa e qualitativa. Foram realizadas análises sobre o balanço sedimentar costeiro, considerando a interação entre processos naturais (ondas, marés, correntes e aporte fluvial) e fatores antrópicos (dragagens e construções costeiras). A deriva litorânea, um dos principais mecanismos responsáveis pelo transporte sedimentar ao longo da costa, foi avaliada por meio da interpretação de imagens de satélite e séries históricas de dados oceanográficos.

A metodologia incluiu a obtenção de dados primários e secundários. Foram realizados levantamentos batimétricos e sondagens para caracterizar a morfologia submarina e a

distribuição dos sedimentos. Além disso, foram analisadas bases de dados científicos existentes, permitindo a identificação de tendências erosivas e a sua relação com variáveis climáticas e antrópicas. A modelação hidrodinâmica e sedimentológica foi realizada utilizando a plataforma MIKE21, permitindo a simulação do transporte de sedimentos e a avaliação do impacto de diferentes cenários de intervenção costeira.

O estudo também considerou a influência das mudanças climáticas, como o aumento do nível médio da água do mar e a intensificação de ressacas, fatores que contribuem para acelerar o processo erosivo. A análise do uso e ocupação do solo permitiu identificar modificações no fluxo sedimentar associadas a atividades humanas e a obras costeiras em outras regiões que podem afetar o equilíbrio sedimentar em Peroba. Dessa forma, a metodologia adotada possibilitou uma avaliação integrada dos fatores que influenciam a erosão costeira na Praia da Peroba, fornecendo informação técnica para a escolha de estratégias de mitigação adequadas à realidade local.

A estabilidade das praias está diretamente relacionada com o balanço sedimentar, resultado da interação entre processos naturais, como ondas, marés, correntes e transporte fluvial, e intervenções humanas, incluindo dragagens e construções costeiras. Essa análise foi realizada por meio da quantificação da variação da linha de costa, utilizando técnicas de sensoriamento remoto.

A deriva litorânea foi considerada como um dos principais mecanismos de redistribuição sedimentar ao longo da costa, sendo avaliada a partir dos padrões espaciais e temporais de erosão e deposição identificados. Para quantificação dessas variações, foi aplicado o Digital Shoreline Analysis System (DSAS), por meio do cálculo dos parâmetros End Point Rate (EPR), expresso em $m \cdot ano^{-1}$, e Net Shoreline Movement (NSM), expresso em metros, os quais permitiram avaliar, respectivamente, as tendências temporais e a variação acumulada da linha de costa.

A metodologia proposta se baseou na identificação dos setores mais dinâmicos do litoral do município de Icapuí, onde se localiza a Praia da Peroba, através da utilização de produtos multitemporais de sensores remotos ópticos e técnicas de geoprocessamento que permitem determinar taxas de variação da linha de costa ao longo de uma série histórica de imagens orbitais.

A tendência erosiva ou deposicional ao longo da linha de costa da área de estudo foi, então, avaliada com a quantificação em área do balanço sedimentar para uma análise temporal de 35 anos (1988 a 2023), utilizando imagens orbitais do satélite Landsat com resolução espacial de 30 metros (órbita/ponto 216/063), compondo intervalos de cinco anos entre cada cena: 23/09/1988 (Landsat 5); 04/08/1993 (Landsat 5); 19/09/1998 (Landsat 5); 01/09/2003 (Landsat 5); 14/09/2008 (Landsat 5); 12/09/2013 (Landsat 8); 10/09/2018 (Landsat 8); e 01/12/2023 (Landsat 9). As imagens orbitais passaram por etapa de pré-processamento para correções atmosférica e geométrica. Então, técnicas de Processamento Digital de Imagens (PDI) e realces no histograma foram aplicadas a fim de ressaltar o contraste terra-água, facilitando a identificação da linha de costa e sua vetorização.

Tendo em vista que intervenções costeiras também podem alterar o transporte natural de sedimentos e agravar a vulnerabilidade de áreas como a região de Icapuí, foram considerados fatores climáticos e antrópicos de maneira integrada, avaliando-se sua influência potencial sobre os processos de transporte sedimentar e sobre os padrões de transporte sedimentar e sobre os padrões espaciais e temporais de variação da linha de costa.

3.2 Aspectos legais e jurídicos para mediação de conflitos na área

A escolha da melhor estratégia técnica para mitigar a erosão da Praia da Peroba gerou uma divergência entre os moradores e a administração pública. Existem classificações e diferenças entre os meios de solução de conflitos sob várias perspectivas, ressaltando-se a referência à jurisdição e ao poder decisório. A referência jurisdicional se divide em dois grupos: o judicial, também denominado modelo tradicional triádico, em que o conflito é dirimido por um juiz togado, que declara de quem é o Direito, e o extrajudicial, que pode ser subdividido em negociação, conciliação, mediação e arbitragem (Sales e Rabelo, 2009).

No processo judicial, o sistema triádico refere-se ao modelo clássico de resolução de conflitos baseado na presença de três partes principais: Demandante – A parte que apresenta a ação, alegando ter um direito violado e buscando uma solução judicial (nesse caso, as duas associações); Demandado – A parte contra quem a ação é movida, defendendo-se das alegações feitas pelo autor (Prefeitura de Icapuí); Juiz ou Árbitro – A autoridade imparcial responsável por analisar as provas, aplicar o direito e decidir o conflito de maneira justa. Esse modelo é fundamental para garantir um julgamento equilibrado e imparcial, pois o juiz age como um terceiro elemento neutro. O sistema triádico é a base dos sistemas judiciais modernos, pois busca assegurar

que a justiça seja feita de forma imparcial, com base nas leis e no devido processo legal (Kelsen, 1986).

Quando se trata de processos judiciais que envolvam questões técnicas complexas, como é o caso do conflito da Praia da Peroba, a nomeação de um perito desempenha um papel crucial na busca da verdade e na busca por uma resolução justa. Ou seja, os peritos são convocados até um processo, quando houver necessidade de um entendimento técnico ou científico, próprios de determinadas áreas do saber, no intuito de auxiliarem o magistrado em seu entendimento dos fatos e posterior julgamento da demanda. Segundo o artigo 156, §1º, do Código de Processo Civil (CPC): O juiz será assistido por perito quando a prova do fato depender de conhecimento técnico ou científico, os peritos serão nomeados entre os profissionais legalmente habilitados e os órgãos técnicos ou científicos devidamente inscritos em cadastro mantido pelo tribunal ao qual o juiz está vinculado.

Ao nomear o perito, o juiz fixa o prazo para a entrega do respectivo laudo, determinando a notificação do especialista e a intimação das partes. Intimadas da nomeação do perito, as partes podem, no prazo de 15 (quinze) dias, indicar assistente técnico, apresentar quesitos, e, se for o caso, arguir impedimento ou suspeição. O perito, por sua vez, ciente de sua nomeação, e entendendo não ser o caso de se escusar (arts. 157 e 467, CPC), deverá, no prazo de 05 (cinco) dias, apresentar: a) proposta de honorários; b) currículo, com comprovação de especialização; e, c) dados profissionais de contato, especialmente o e-mail para o qual serão endereçadas as intimações pessoais. Cumpridas estas exigências pelo perito, as partes serão devidamente intimadas a se manifestarem, oportunidade em que poderão solicitar a redução dos honorários periciais propostos quando se mostrarem excessivos, bem como, requerer a substituição do perito por falta de conhecimento técnico ou científico no objeto da perícia, o que só poderá ser constatado após tomarem conhecimento de seu currículo (art. 465, § 2º, II, CPC). Também nesta etapa, pessoas jurídicas podem se apresentar para participar das discussões técnicas como Amicus Curiae, uma expressão latina que significa “amigo da corte”, termo jurídico que se refere a um terceiro que pode ser convocado por um juiz para fornecer informações a um processo.

Na Gestão Integrada da Zona Costeira, que tem por princípio fundamental envolver todos os atores sociais no processo de ordenamento das regiões litorâneas, o perito nomeado cumpre um papel relevante ao contribuir com informações de natureza técnica. A participação das diversas comunidades que convivem no mesmo espaço é de extrema importância para o sucesso de empreendimentos que alteram a configuração e a paisagem costeira, desde a concepção do projeto nas discussões em audiências públicas, até ao acompanhamento da execução das intervenções.

O conflito pode ser compreendido como um processo dinâmico no qual dois ou mais indivíduos ou grupos manifestam divergências em função de metas, interesses ou objetivos percebidos como incompatíveis. Tradicionalmente, é tratado como um fenômeno negativo nas relações sociais, gerando prejuízos para pelo menos uma das partes envolvidas. Os conflitos tendem a intensificar-se progressivamente, configurando um ciclo de ação e reação no qual cada resposta se torna mais severa do que o estímulo precedente (Maia *et al*., 2014). Esse fenômeno, conhecido como espiral de conflito, evidencia que, à medida que a disputa se agrava, suas causas iniciais perdem relevância, uma vez que os envolvidos passam a priorizar respostas imediatas às ações adversárias recentes.

A Resolução Apropriada de Disputas inclui uma série de métodos capazes de solucionar conflitos, que oferecem, de acordo com suas respectivas peculiaridades, opções para se chegar a um consenso, a um entendimento provisório, à paz ou apenas a um acordo. No Brasil, o sistema público de resolução de conflitos que envolve o Poder Judiciário e outros órgãos de prevenção ou resolução de disputas (e.g. Defensoria Pública, Ministério Público, Secretarias de Justiça, entre outros), é composto, atualmente, por vários métodos ou processos distintos. Essa gama ou espectro de processos (e.g. processo judicial, arbitragem, conciliação, mediação, entre outros) forma um sistema pluriprocessual. Com esse sistema, busca-se um ordenamento jurídico, no qual as características intrínsecas de cada processo são observadas para proporcionar a melhor solução possível para uma disputa, de acordo com as particularidades analisadas do caso concreto (BRASIL, 2016).

Os conflitos socioambientais na zona costeira cearense resultam em múltiplas violações de direitos, incluindo relatos de intimidação, destruição de moradias e criminalização de lideranças comunitárias. Comunidades tradicionais perdem frequentemente o direito de uso de áreas costeiras essenciais para pesca e outras atividades tradicionais, enquanto ecossistemas como manguezais e campos dunares sofrem degradação, comprometendo a biodiversidade e a resiliência ambiental. Esses conflitos refletem a tensão entre diferentes modelos de desenvolvimento e o direito das comunidades tradicionais ao seu território. Nesse contexto, a resistência local tem sido fundamental para preservar modos

de vida sustentáveis e impedir a total privatização e degradação dessas áreas.

As alterações costeiras impactam significativamente os ecossistemas locais, uma vez que qualquer intervenção pode afetar manguezais, recifes de coral e fauna marinha, fundamentais para a biodiversidade e a subsistência das comunidades. No aspecto social, os interesses econômicos também são fortemente impactados, pois a erosão costeira compromete setores como turismo e pesca. Além disso, a escolha de determinadas obras de mitigação pode favorecer grupos específicos em detrimento de outros. Por fim, a ausência de consulta e participação das comunidades locais no processo decisório gera frequentemente conflitos e resistência às intervenções de proteção costeira (Silveira, 2025).

3.3 Soluções estruturais de mitigação de erosão costeira

As defesas costeiras podem ser projetadas usando técnicas de engenharia rígida ou flexível para minimizar ou mesmo "eliminar" riscos e, assim, proteger as populações locais, embora esteja claro que isso pode ser custoso e demorado (Sterr, 2008). As defesas rígidas ou flexíveis diferem em termos de dimensionamento, investimento e custos de manutenção, eficiência de curto prazo e consequências ambientais. O conceito básico da engenharia rígida, que se baseia em estruturas de enrocamento, é garantir a segurança a qualquer custo, fixando ou mesmo avançando a linha costeira e, assim, ignorando as funções naturais. Em contraste, a engenharia flexível, como zonas de amortecimento, praias e dunas artificiais, pode ser mais sustentável ambientalmente e pode fornecer proteção inicial e de longo prazo. No entanto, a alimentação com areia deve ser realizada regularmente para manter o litoral ou controlar seu recuo, bem como a utilização de espigões ao final do projeto de alimentação com areia para estabilizá-la (CIRM, 2018).

4 RESULTADOS

4.1 Quantificação da erosão da Praia da Peroba

O balanço sedimentar é negativo em uma parte significativa da região Nordeste do Brasil, sendo este o resultado da combinação de baixo relevo, pequenas bacias de drenagem e clima semiárido (Moreira *et al*., 2020). Segundo Barros (2024), o balanço negativo que afeta Icapuí, resulta em erosão parcial ou completa das praias do Rio Grande do Norte, porque os rios que drenam a região são de pequeno porte e com barragens à montante, reduzindo o aporte de sedimentos. Por outro lado, é o resultado da implementação de estruturas de proteção costeira e que retém os sedimentos impedindo a contribuição local como fonte para a deriva, nas praias de Barreira e Barreira da Sereia, a leste da área em estudo (nessa área foram colocados 3.900 m enrocamento). Além disso, as praias de perfil dissipativo em Icapuí, que são caracterizadas por possuírem uma inclinação suave e uma maior necessidade de sedimentos para garantir a estabilidade, apresentam maior risco de erosão em comparação com outros tipos de praias. Esses fatores tornam a região especialmente vulnerável, exigindo estratégias de monitoramento e mitigação contínuas.

Maia *et al*. (2024) efetuaram a análise da variação da linha de costa da Praia da Peroba ao longo de uma série temporal de 35 anos (1988 e 2023), por meio de imagens de satélites Landsat. Apesar do indicador de Taxa de Regressão Linear sugerir um equilíbrio ao longo de todo o período analisado, quando avaliados os intervalos de cinco anos percebe-se que este é um equilíbrio "dinâmico", sendo que a estabilidade da linha de costa varia bastante em cada intervalo temporal, alternando períodos de deposição e erosão (Figura 2).

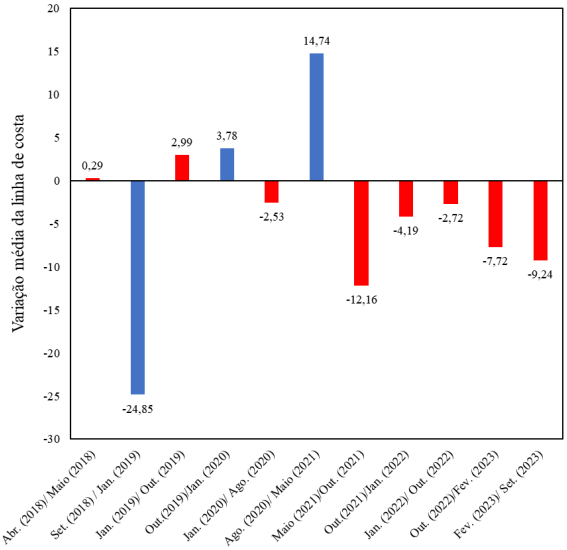


Figura 2. Evolução da variação média da linha de costa em metros para os intervalos temporais considerados na praia de Peroba entre 2018 e 2023, evidenciando a tendência erosiva ao longo dos últimos anos.

O parâmetro *Net Shoreline Moviment* – NSM utilizado para identificar a variação total da linha de costa, deixa ainda mais clara a gravidade do recuo da linha de costa na praia de Peroba entre 2018 e 2023. O setor mais afetado registou retração de mais de 5 m, chegando, em alguns pontos, a quase 15 m de erosão da faixa de praia (Figura 3).

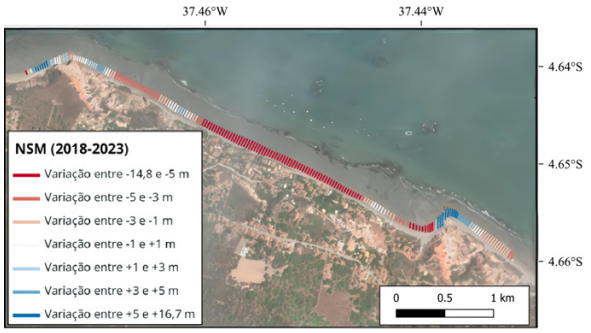


Figura 3. Variação acumulada da linha de costa na Praia da Peroba (2018 a 2023) com base no parâmetro *Net Shoreline Moviment* (NSM). Fonte: Maia *et al.* (2024).

Os processos erosivos parecem não predominar em toda extensão da Praia de Peroba. O setor mais afetado é o situado em sua parte mais central, expandindo-se em sentido leste, afetando diversas edificações já presentes no local. Este trecho apresenta setores com registo de erosão baixa, moderada e intensa.

4.2 Mediação de conflitos na Praia da Peroba

Na Praia da Peroba, a erosão costeira é um problema significativo, ameaçando não apenas as infraestruturas, mas também o meio ambiente e a comunidade local. Neste caso, a Gestão Integrada da Zona Costeira envolve a combinação de diferentes estratégias, considerando aspectos ambientais, sociais e econômicos, podendo equilibrar os interesses de diferentes stakeholders, requerendo coordenação entre múltiplos atores, o que pode ser complexo de implementar. O envolvimento das comunidades locais e outros stakeholders no processo de decisão, garantindo transparência e participação, pode contribuir no processo de decisão sobre as medidas a adotar.

O conflito da Praia da Peroba agravou-se nas discussões da escolha da obra para combater o fenômeno da erosão, pois as opções discutidas caracterizavam claramente o ponto de vista dos dois grupos de moradores representados legalmente pelas associações dos Moradores e Preserve Peroba. Os moradores tradicionais da comunidade pesqueira, que desejavam proteger as suas terras, decidiram pela colocação de um enrocamento aderente (muro de pedra) como os que foram implantados com grande sucesso nas praias adjacentes de Barreira da Sereia e Redonda em 2015, e que foi a opção inicial da prefeitura de Icapuí (Figura 4).

Por sua vez, a Associação Preserve Peroba desejava uma intervenção para combater a erosão costeira em consonância com a natureza do local e, neste sentido, contrataram um arquiteto para projetar uma obra de defesa costeira que não utilizasse enrocamento, em claro confronto com a opção dos pescadores. Tratava-se de uma estrutura de estacas intertravadas na forma de degraus, primeiro assente sobre um alicerce de bidim (manta geotêxtil) para evitar a erosão da base da estrutura, sendo o preenchimento final efetuado com sacos de areia (Figura 5). Estas intervenções foram custeadas pelos novos ocupantes, que passaram a contrastar com as casas mais simples dos pescadores que foram destruídas pelas ressacas do mar. Assim, teve início o conflito que evoluiu para um círculo vicioso de ação e reação.



Figura 4. Defesa costeira do tipo enrocamento aderente na praia de Redonda, também no município de Icapuí, Ceará. Fonte: Maia *et al.* (2024).



Figura 5. Estrutura projetada para defesa da erosão costeira sem a utilização de enrocamentos na Praia da Peroba. Fonte: Maia *et al.* (2024).

Nesse sentido, foi convocada pela Câmara de Vereadores de Icapuí a primeira audiência para discutir as possíveis soluções para a erosão, com a participação dos residentes das áreas afetadas, pescadores, comerciantes, lideranças comunitárias e gestores públicos.

4.3 Estrutura de mitigação da erosão na Praia da Peroba

O produto dos estudos foi entregue pelo perito (Luis Parente, um dos autores deste artigo) à 15ª Vara da Justiça Federal, relativo à perícia realizada na Praia da Peroba, Icapuí – CE, indicando as medidas mais adequadas de contenção da erosão costeira. A solução definida pela perícia técnica consistia na implantação de dois espigões permeáveis, para minorar os impactos ambientais, e o aumento da praia através da colocação de sedimentos visando recuperar parte dos terrenos perdidos para o mar (Figura 6).

A solução tecnológica proposta foi apresentada em audiência pública realizada na associação dos pescadores e na praia, para dirimir as dúvidas dos interessados. Após as apresentações iniciais, o perito respondeu às perguntas das partes presentes. Muitos participantes expressaram a urgência de agir, entre eles os representantes dos moradores locais, através da Associação de Moradores, que solicitaram ao poder público mais agilidade na solução diante da gravidade do problema, especialmente considerando as marés altas esperadas nos meses seguintes e o risco iminente aos imóveis, rede elétrica, estrada, coqueiros, entre outros. A maioria dos presentes expressou-se de forma educada e conciliadora e teve a oportunidade de manifestar suas opiniões e de colocar questões.

O perito convidou os presentes a visitar os locais onde os espigões deveriam ser construídos, fornecendo explicações adicionais e respondendo a todas as perguntas feitas pelos participantes. Durante essa visita, foram discutidos aspectos como o impacto ambiental previsto, acessos para pescadores e instalações para futuras manutenções de embarcações, possibilidade de melhor aproveitamento da praia para lazer e turismo, durabilidade e necessidade de futuras manutenções, e que o espigão é uma opção de médio porte, considerada tecnicamente uma obra permeável, que não intercepta toda a areia transportada e mantém o equilíbrio deste transporte de areia para outras praias a jusante (Figura 7).

A partir dos dados apresentados pelo perito e como resultado das discussões, ficou estabelecido o compromisso de todas as partes em trabalhar juntas para implementar a solução proposta o mais rapidamente possível, com a definição dos seguintes aspectos:

- O representante da Secretaria do Patrimônio da União - SPU, destacou que a SPU, responsável pela fiscalização e aprovação de quaisquer intervenções na faixa de praia, assume o compromisso de dar celeridade aos trâmites para aprovação da Cessão de Uso de Espaço Físico em Águas Públicas, exigido pelo órgão financiador do projeto.
- O representante da Prefeitura de Icapuí, Secretário de Governo, disse que “a Prefeitura se compromete a mobilizar todos os esforços para agilizar os prazos, para formatar os convênios com o Governo do Estado e União, além de lançar as licitações e contratações para a rápida execução das obras”;

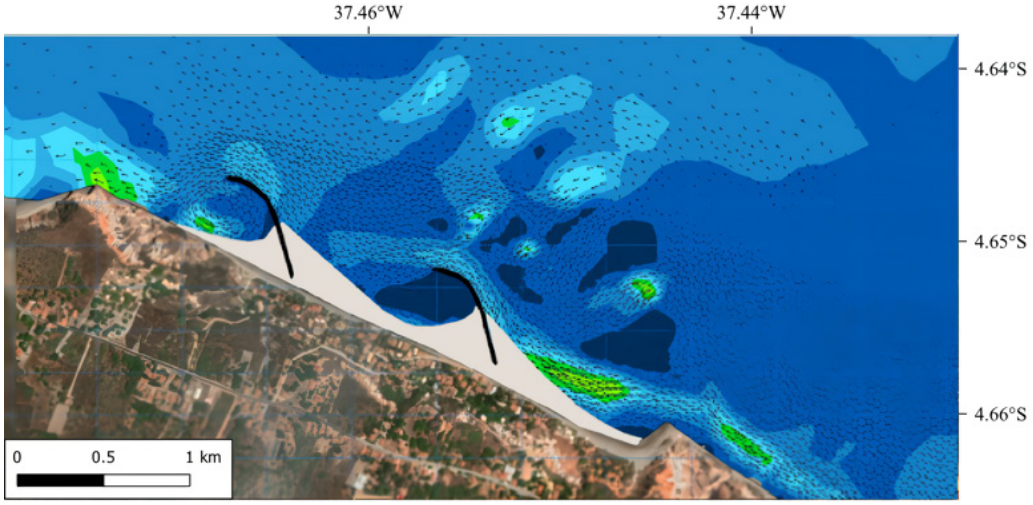


Figura 6. Modelo idealizado do efeito final da evolução da linha de costa decorrente da implantação de dois espigões na Praia da Peroba. Fonte: Maia *et al.* (2024).

- A Associação dos Moradores, por meio de seu presidente, ressaltou a necessidade de urgência na realização das obras, e afirmou que "compreendeu e concordou com os aspectos técnicos apresentados e que fará tudo o que estiver ao seu alcance para agilizar o processo".
- O representante da Associação Preserve Peroba, destacou "a relevância de seguir os caminhos apresentados pela ciência, de respeito pelo meio ambiente e que a solução apresentada vai promover a união de todos e renovar esperanças de solução para o grave problema";
- O vice-presidente da ONG AQUASIS, que desenvolve trabalho de preservação de espécies com riscos de extinção na Praia da Peroba, afirmou que como instituto de pesquisas, "apoiará as decisões com base científica de menor impacto para a vida das espécies alvo e que não fará oposição à solução que poderá trazer benefícios à comunidade";
- Ficou definido ainda, por sugestão do perito assistente, que concomitante à execução da obra, é necessário fazer um acompanhamento de assessoria técnica e de controle tecnológico e executar os programas ambientais previstos no projeto executivo, por técnicos com competência comprovada.



Figura 7. Audiência Pública convocada pela Justiça Federal para apresentar os resultados da perícia ambiental na Praia da Peroba. Fonte: Maia *et al.* (2024).

Em função do acordo geral das partes envolvidas no conflito da Praia da Peroba, foi realizado em 7 de junho de 2024 o arquivamento de procedimento preparatório cível instaurado para apurar as ações municipais na execução das obras para contenção de erosão marinha, na orla da Praia da Peroba, no Município de Icapuí/CE. A Ação Civil Pública, movida pela Associação dos Moradores de Peroba em face da União, em que o MPF foi integrado como interveniente e auxiliou a mediação de acordo entre as partes, o qual foi homologado por decisão judicial, proferida pelo Juízo da 15ª Vara Federal, da Seção Judiciária do Ceará.

Após o acordo entre as partes, a prefeitura de Icapuí realizou o processo de licitação, que definiu a empresa vencedora da contratação pública. Alguns fatores como a ocorrência de período eleitoral no município nos últimos meses de 2024, a conclusão do processo licitatório e feriados prolongados como o Carnaval atrasaram o início das obras, que ocorreu apenas em 23 de fevereiro de 2025. Na Figura 8, pode-se visualizar a construção em andamento da estrada de acesso para a implantação do primeiro dos dois espigões da Peroba, que é resultado de esforço coletivo da comunidade com participação do poder público.



Figura 8. Construção da estrada de acesso para a implantação do primeiro dos dois espigões da Praia da Peroba. Fonte: Maia *et al.* (2024).

5. CONSIDERAÇÕES FINAIS

A erosão costeira na Praia da Peroba representa um desafio complexo que exige uma abordagem equilibrada entre desenvolvimento urbano, preservação ambiental e interesses comunitários. A Gestão Integrada da Zona Costeira demonstrou ser a estratégia mais viável para mitigar os impactos da erosão, permitindo um modelo de governança participativa que conciliou diferentes interesses, mitigando conflitos, e evitou danos ambientais severos.

A atuação do MPF e a realização de perícias técnicas foram fundamentais para assegurar que a decisão judicial levasse

em conta não apenas a eficácia das obras, mas também a proteção dos ecossistemas locais e a minimização de impactos negativos para a comunidade. A solução final adotada reflete a importância da cooperação entre os stakeholders e reforça a necessidade de monitoramento contínuo para garantir a efetividade das medidas implementadas.

A experiência da Praia da Peroba demonstra que os conflitos ambientais podem ser resolvidos por meio de diálogo, transparência e adoção de medidas sustentáveis. No entanto, o sucesso dessas iniciativas depende do compromisso dos gestores públicos e das comunidades em seguir diretrizes técnicas e científicas, assegurando que a convivência entre desenvolvimento e preservação seja harmoniosa e duradoura.

Além disso, a atuação das associações foi essencial para garantir que as soluções considerassem tanto a preservação ambiental quanto os interesses da comunidade local. O Ministério Público Federal (MPF) foi crucial na mediação do diálogo entre as partes envolvidas, promovendo um equilíbrio entre a necessidade de conter a erosão costeira e a preservação ambiental da região.

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ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS

Journal of Integrated Coastal Zone Management (2025) 25(2): 115-133
© 2025 APRH
ISSN 1646-8872
DOI 10.5894/rgci-n708
url: https://www.aprh.pt/rgci/rgci-n708.html

INTEGRATING GEOMORPHOLOGICAL AND ECOLOGICAL INDICATORS TO ASSESS COASTAL DUNE VULNERABILITY IN SOUTHERN BRAZIL

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ABSTRACT: Coastal dunes play a vital role in protecting human communities and ecosystems by acting as natural barriers against erosion of urban infrastructure, storm surges, and sea-level rise. However, these systems are increasingly degraded by urban expansion and climate change. In this study, we reassessed coastal vulnerability to erosion in the municipality of Imbé, southern Brazil – one of the fastest-growing coastal areas in the state of Rio Grande do Sul – 12 years after the implementation of a local Dune Management Plan. A geomorphological checklist method across 44 coastal segments (each 250 m long) was applied, scoring 25 variables grouped into four parameters: dune morphology, beach condition, adjacent land use, and anthropogenic pressure. Relative Vulnerability Index (RVI) values ranged from 28.0 to 69.6%, with 36% of the segments experiencing an increase in vulnerability classification compared to the 2012 baseline. Cluster analyses revealed distinct spatial patterns between seasons, with winter clusters better reflecting structural vulnerability and summer clusters influenced by tourism-related pressures. Concurrently, 30 active nests from three bird species (i.e. *Athene cunicularia*, n = 15; *Vanellus chilensis*, n = 13; and *Haematopus palliatus*, n = 2) were recorded and georeferenced along 11 km of coastline. Nest abundance is negatively correlated with dune area and width (Pearson's r = -0.40 and -0.35, respectively), indicating that more degraded dune units supported fewer nesting birds. *A. cunicularia* emerged as a promising bioindicator due to its fidelity to nesting sites and preference for less fragmented dunes. These findings highlight the value of integrating physical and biological indicators to assess coastal vulnerability and suggest a cost-effective and ecologically informed framework for monitoring and managing sandy coasts under increasing environmental pressures.

Keywords: Avian reproduction; Bioindicators; Coastal erosion; Sandy beaches; Urbanization.

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Submission: 14 AGO 2025; Peer review: -; Revised: 18 MAY 2026; Accepted: -; Available on-line: 3 SEP 2026

1. INTRODUCTION

The coastline plays a critical role in protecting human communities, primarily through natural processes that mitigate the impacts of erosion and extreme weather events. Foredunes, for example, function as natural barriers against wind, tides, and flooding, thereby reducing damage to adjacent urban areas. However, the provision of these ecosystem services is increasingly jeopardized by climate change and unregulated coastal development. According to projections from the IPCC (2022), sea levels may rise between 0.29 and 1.1 m by 2100, depending on greenhouse gas emission scenarios, which would intensify erosion risks and threaten essential infrastructure and human settlements. In addition, extreme events such as storms and cyclones, becoming more frequent and intense, have already caused considerable destruction in coastal zones. Unplanned urbanization, often motivated by the economic value of beachfront property, further compounds these risks by replacing resilient natural ecosystems with more vulnerable artificial structures (You *et al*., 2018). Collectively, these factors underscore the urgent need for integrated coastal management strategies aimed at mitigating impacts and preserving the protective functions of these ecosystems (Claussen, 2013; Harris & Ellis, 2025).

The biota of foredunes plays a vital role in maintaining and stabilizing these coastal environments. Pioneer vegetation, such as grass species adapted to high salinity and strong winds, is essential for dune stabilization, as their root systems help retain sediments and form natural barriers against erosion (Tomazelli, 1994; Hesp, 2000; Sigren *et al*., 2014). The fauna associated with these ecosystems also depends directly on their stability, using dunes as habitats for feeding, breeding, and shelter. Among these organisms, birds stand out not only for their ecological associations with dune environments but also for their potential as bioindicators of dune geomorphology (Burger, 2023). The presence and behavior of birds provide valuable insights into dune configuration and dynamics, supporting the identification of appropriate management strategies to reduce coastal vulnerability. Their effectiveness as bioindicators stems from their sensitivity to changes in habitat structure and geomorphological processes, both of which reflect the overall stability and resilience of the system. Notably, the reproductive requirements of many bird species concerning dune morphology often align with the very conditions necessary to protect human communities from erosion and extreme events.

Coastal vulnerability assessment is a fundamental practice for the sustainable planning and management of coastal zones, particularly in light of increasing urbanization pressures and the impacts of climate change. A variety of methodologies have been developed to identify and quantify the factors that render these areas more susceptible to erosion and other environmental hazards. Among these, beach cross-shore profiles are commonly used to monitor morphological and sedimentological variations, while evolutionary models, such as that of Hesp (1988), describe the stages of dune stabilization and degradation. Additionally, integrated vulnerability analyses (e.g., Williams *et al*., 1993) offer a systematic framework to assess parameters related to dune morphology, beach conditions, adjacent land characteristics, and anthropogenic pressures. A notable practical application of this approach is the method adapted by Tabajara *et al*. (2013), which used the municipality of Imbé, on the southern coast of Brazil, as a case study. Based on a structured checklist, the method evaluates 25 variables grouped into four categories: dune morphology; beach conditions; characteristics of the 200 m adjacent to the shoreline; and usage pressure. Each variable is scored from 0 to 4, and these scores are then used to calculate a Relative Vulnerability Index (RVI), expressed as a percentage of the maximum possible score. The results revealed significant variation in RVI, ranging from 24 to 67%, with the northern coastal sectors exhibiting the highest vulnerability due to urban encroachment, reduced dune width, and sand loss. This approach effectively identified priority coastal sectors for intervention, particularly areas where urban expansion has encroached upon dune systems or where environmental degradation is most severe.

In Brazil, approximately 26% of the population (around 50 million people) live in the coastal region, spread across 280 municipalities along more than 7,000 km of coastline (IBGE, 2011; MMA, 2021). These figures underscore the strategic importance of coastal zones and the urgent need to monitor the consequences of human occupation and ecosystem alterations in order to prevent climate- and environment-related disasters. The southern coast of Brazil is characterized by an extensive, straight stretch of dissipative sandy beaches with medium-grain sediments. This region experiences low tidal amplitude and a high frequency of meteorological tides, making it particularly dynamic and sensitive to climatic and oceanographic influences. Population growth along this coast has shown heterogeneous patterns across its southern, central, and northern segments. According to 2022 census data from the Brazilian Institute of Geography and Statistics (IBGE, 2023), the northern coastal region of Rio Grande do Sul, which is the southernmost state in Brazil, recorded the highest annual population growth rates between 2010 and 2022, reaching nearly 2% per year, with some municipalities growing by as much as 4.79% annually. This

contrasts sharply with the state's average growth rate of only 0.15% over the same period. Of the ten municipalities with the highest population growth in the state, seven are located along the coast, and several have seen growth rates exceeding 50%, including the municipality of Imbé (51.81%). These demographic trends clearly illustrate the increasing anthropogenic pressure on coastal ecosystems, reinforcing the need for comprehensive assessments of coastline vulnerability and adjacent habitats in the context of ongoing climate change.

In southern Brazil, the coastal region provides critical habitat for both migratory and resident bird species that depend on its unique ecosystems for survival. These environments, defined by stabilizing vegetation and dynamic geomorphological features, offer essential shelter and food resources, particularly for species such as burrowing owls, American oystercatchers, and southern lapwings, which rely on nearby intertidal zones rich in benthic invertebrates. Given the close ecological association between these bird species and foredune habitats, alterations in these environments can have direct impacts on their populations. Monitoring avian use of foredunes, especially breeding activity, can therefore offer valuable insights into the stability and resilience of coastal ecosystems under increasing anthropogenic pressure and climate change. This is particularly relevant considering the potential use of these species, especially *Athene cunicularia*, as cost-effective bioindicators for the long-term monitoring of coastal vulnerability.

Therefore, this study aimed to assess foredune vulnerability to erosion in southern Brazil, using as a case study a municipality with one of the highest population growth rates in the region. In parallel, all bird nests located on foredunes were mapped and evaluated as potential bioindicators of coastal vulnerability. The findings have direct practical implications for the management of foredune systems, not only within the study area but also across other municipalities situated along the extensive, straight sandy coastline that characterizes southern Brazil. Moreover, the study provides novel insights into the use of avian reproductive activity as a cost-effective and ecologically relevant indicator of coastal vulnerability, particularly in the context of climate change adaptation and integrated coastal zone management.

1.1 Study area geological context and delimitation

The coastal plain of southern Brazil constitutes the emerged portion of the Pelotas Basin, an open marginal sedimentary basin (Barboza *et al*., 2021). Late Quaternary sea-level variations were the primary drivers for the formation of the current lagoon-barrier depositional systems (Villwock *et al*., 1986; Tomazelli & Dillenburg, 2007). In this region the interplay between high sediment supply and wind conditions favorable to onshore accumulation has facilitated the development of dune fields and transgressive dune ridges on the Holocene Barrier System IV over millennial timescales (Barboza & Rosa, 2014). Currently, different sectors of this Holocene barrier exhibit progradational, retrogradational or aggradational behaviors, leading to varied small-scale morphologies (Dillenburg *et al*., 2009; Watanabe *et al*., 2023). Ultimately, negative sediment budget balances across both short and long temporal scales remain the primary cause of erosion along this coastline (Dillenburg *et al*., 2004).

Within this morphological context, the present study was carried out in the municipality of Imbé, located on the northern coast of Rio Grande do Sul, southern Brazil. Bordered by the Atlantic Ocean, the area features open beaches that range from intermediate to dissipative, primarily shaped by wave action under a semidiurnal microtidal regime, with an average tidal amplitude of 0.30 m (Toldo *et al*., 1993). During winter, meteorological tides can cause more pronounced variations, reaching up to 1.2 m (Almeida *et al*., 1997). Owing to the homogeneous granulometric characteristics of the coastline, beach morphology in the region is largely governed by hydrodynamic energy, which influences the seasonal dynamics of the backshore extension (Weschenfelder & Zouain, 2002).

The area examined in this study corresponds to the same 11 km stretch of coastline analyzed in the dune vulnerability assessment by Tabajara *et al*. (2013). Its width extends from the swash zone (defined as the beach area between the minimum and maximum water run-up after wave breaking) to 200 m inland from the shoreline (Figure 1).

2. METHODS

2.1 Assessment of vulnerability levels to erosion in foredunes

The vulnerability of dunes is defined as a set of conditions that induce dune erosion and ecosystem manipulation (Davies *et al*., 1995). To evaluate dune vulnerability to erosion along the coastline of the municipality of Imbé, the checklist method proposed by Williams *et al*. (1993, 2001) and adapted by Tabajara *et al*. (2013) was applied during two field campaigns: one in July 2022 (winter) and another in January 2023 (summer) (Figure S1). This method characterizes and delineates dune areas according to their degree of vulnerability. It also helps identify specific weaknesses in the system by assigning scores from 0 to 4 to each variable across 50,000 m^2 per sampling unit.



Figure 1. Location of the study area, showing neighborhood boundaries, delineation of landscape units, and their respective winter Vulnerability Index (RVI) classifications. Base map: World Imagery (ArcGIS Map Service, 2024); municipal boundary data: IBGE (2020).

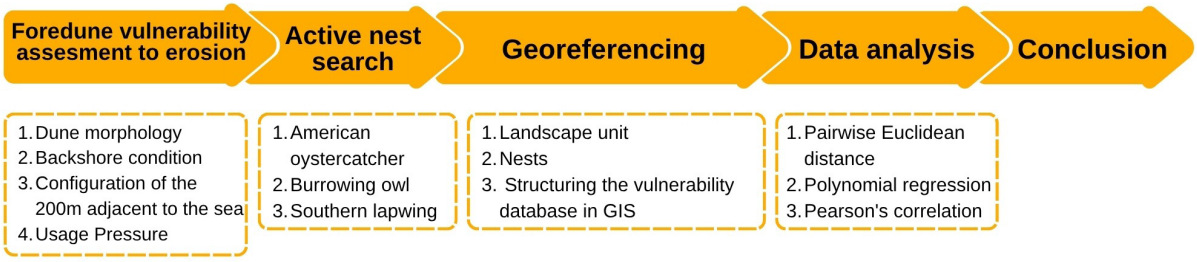


Figure 2: Methodological workflow applied in the assessment of coastal vulnerability and bioindicator analysis.

Table 1. Parameters used in the checklist. Source: Franchini (2010).

Parameter	Importance	Variables
Dune Morphology	Geomorphological condition (extent and sediment volume) determines the resilience of foredunes.	Surface area (m^2); dune width (m); height of the tallest dune (m); scarp and slope on the marine-facing side.
Backshore Condition	The backshore condition is related to the sand supply for foredunes (development of the dune's marine-facing slope).	Backshore width (m); sand supply; breaches in the beach face; width of breaches in the beach face; presence of embryonic dunes.
Characteristics of the 200 m Adjacent to the Sea	Synthesizes the biophysical characteristics and processes that interfere with local sediment dynamics (such as fragmentation of the system by blowouts).	Percentage of blowout areas, sand loss from the system to the continent; percentage of breaches in the dune system; percentage of vegetation on the seaward side of the dune; recent sand deposition; percentage of impermeable coverage; presence of exotic vegetation; and number of drainage/runoff outlets.
Usage Pressure	Evaluates anthropogenic interference in the balance of foredunes.	Number of vehicle access points; pedestrian path density; percentage and stage of urbanization; urbanization position; number of kiosks; and number of property owners.

The four parameters and their associated variables are presented in Table 1. For the checklist application, the coastline of Imbé was divided into 44 segments (Figure 1), each with a latitudinal length of 250 m, referred to as sampling units. These units were numbered and surveyed from south to north, beginning at the city center and ending in the Balneário Imara area, during both the winter and summer assessments (Figure 2). Although the segmentation approach followed the method used by Tabajara *et al*. (2013), one additional sampling unit was included in the present study due to a 250 m northward shift in the municipal boundary marker. Subsequently, each sampling unit was assigned a vulnerability index from 1 (very low) to 5 (very high), following classification criteria adapted from Laranjeira (1997).

2.2 Active nest search

The census of nests for three bird species that nest directly on the substrate was conducted through active visual searches, carried out biweekly between October and December 2022 (spring in the southern hemisphere). Both direct evidence (e.g., observation of nests and chicks) and indirect evidence (e.g., pairs exhibiting territorial defense behaviors such as vocalizations and low flights) were used to identify active nests of *Athene cunicularia* (burrowing owl), *Haematopus palliatus* (American oystercatcher), and *Vanellus chilensis* (southern lapwing) during the four sampling efforts. During this phase, the entire 11 km coastline of the municipality was surveyed on foot using a zigzag search pattern, the most effective method for ensuring complete visual coverage of the area, even in the presence of blind spots caused by substrate irregularities (Bibby *et al*., 1992). All active nests were georeferenced for subsequent spatial analysis and mapping.

2.3 Data analysis and georeferencing

Using a Geographic Information System (GIS) environment, the 44 landscape sampling units were georeferenced along with the coordinates of the identified nests (Table S1). To avoid double-counting, only the highest number of nests observed per species within each sampling unit across the four campaigns was recorded. Checklist variables requiring an overhead perspective - such as dune surface area and system width - were analyzed using orbital

imagery from the Wide Field Multispectral and Panchromatic Camera (WPM) aboard the CBERS-4A satellite (image acquisition date: July 2nd, 2022). These data were processed with ArcGIS Pro 10.3 (ESRI®). Calculations of dune area and width were conducted within the UTM planar coordinate system, referenced to the SIRGAS2000 datum, zone 22S. Checklist data collected during field assessments were organized in Microsoft Excel 2007®, where Relative Vulnerability Indices (RVI) were calculated. All datasets and outputs were subsequently georeferenced and converted into shapefile vector formats. Classification values of each checklist variable were plotted using local polynomial regression (loess), implemented via the *ggplot2* package in R (Cleveland *et al*., 1992; Wickham, 2016; R Core Team, 2022). Additionally, a Pearson correlation matrix was constructed, and correlograms were generated using the *corrplot* package (Wei & Simko, 2021). Finally, pairwise Euclidean distances were calculated between sampling units based on checklist variables, and a dendrogram was created using the *tidyverse* package (Wickham *et al*., 2019).

3. RESULTS

3.1 Classification of the coastline by vulnerability index

Winter results showed that, of the 44 coastal segments evaluated, two were classified as vulnerability level 2, 29 as level 3, and 13 as level 4. No segments received the minimum (1) or maximum (5) classification. Only 4.5% of the coastline fell into level 2, indicating segments with less pronounced erosive changes. The remaining 95% were classified as levels 3 or 4, reflecting more evident signs of degradation. Of these, 30.95% corresponded to landscape units where dunes lacked mechanisms of resistance to erosion, while 69.05% showed intermediate conditions.

Cluster analysis based on winter data resulted in six distinct groups of landscape units (Figure 3). In summer, three clusters were identified (Figure 4). The units classified with the lowest vulnerability levels were not grouped together but rather distributed across different clusters in both seasons. In both seasonal assessments, the first cluster included units where dunes were absent, either due to replacement by built structures such as a boardwalk (units P1–P4) or road infrastructure (units P42–P44). Between winter and summer, changes in vulnerability classification were limited. In summer, only unit P17 remained at level 2. Units P7 and P29, previously level 4, shifted to level 3. While small variations were noted across parameters, most units retained their original classification. The observed variations affected cluster composition.

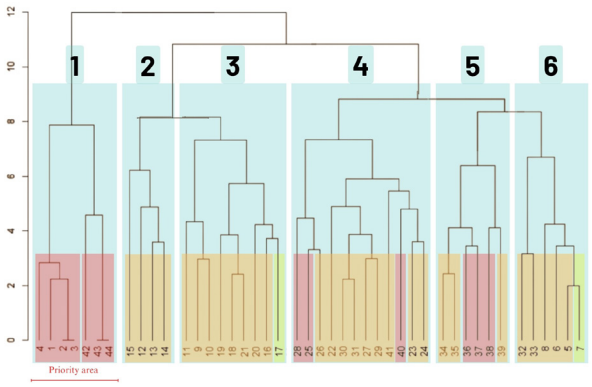


Figure 3: Euclidean distance dendrogram of the variables analyzed in the dune erosion vulnerability checklist applied in winter 2022. Aquamarine rectangles indicate clusters of landscape units based on similarity of vulnerability profiles. Red, orange, and yellow rectangles denote landscape units classified with Relative Vulnerability Index (RVI) levels 4, 3, and 2, respectively.

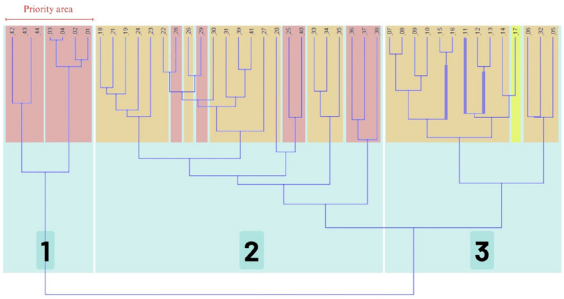


Figure 4: Euclidean distance dendrogram based on the variables analyzed in the dune erosion vulnerability checklist applied during the summer of 2023. Aquamarine rectangles delineate clusters of landscape units. Color-coded rectangles represent the vulnerability classification of each unit: red for level 4, orange for level 3, and yellow for level 2.

Among the remaining segments, two main clusters were identified. One encompassed units P18 to P41 (excluding P32), which shared characteristics of narrow and fragmented dunes. The other included units P05 to P17 and unit P32, which had wider dune areas (Figure 4).

(Figure 3) comprised only level 3 units. These segments were characterized by high erosive scarps and steep slopes, with low coverage of impermeable surfaces within the 200 m buffer (Figure 6A–C). Cluster 3 contained mostly level 3 units and one at level 2. These areas also had high scarps but greater impermeable surface coverage (Figure 6D–E). Cluster 5 included an equal number of level 3 and 4 units, with a mean RVI of 60.17% (SD: 3.11%). These segments had highly fragmented foredunes with narrow dune widths (Figure 7A). Cluster 6 was composed mainly of level 3 units and one at level 2, with relatively wide dune areas. The mean RVI for this group was 44.33% (SD: 3.14%). Cluster 4 included mostly level 3 units, and three classified as level 4. These segments had small remaining dune fragments and a mean RVI of 57.25% (SD: 3.94%).



Figure 5: Sampling units grouped within the area identified as a priority for coastal management interventions. A–D: dune absence due to replacement by a boardwalk in the southern sector. E–H: dune loss caused by erosion and the encroachment of the Interpraias Road in the northern sector.

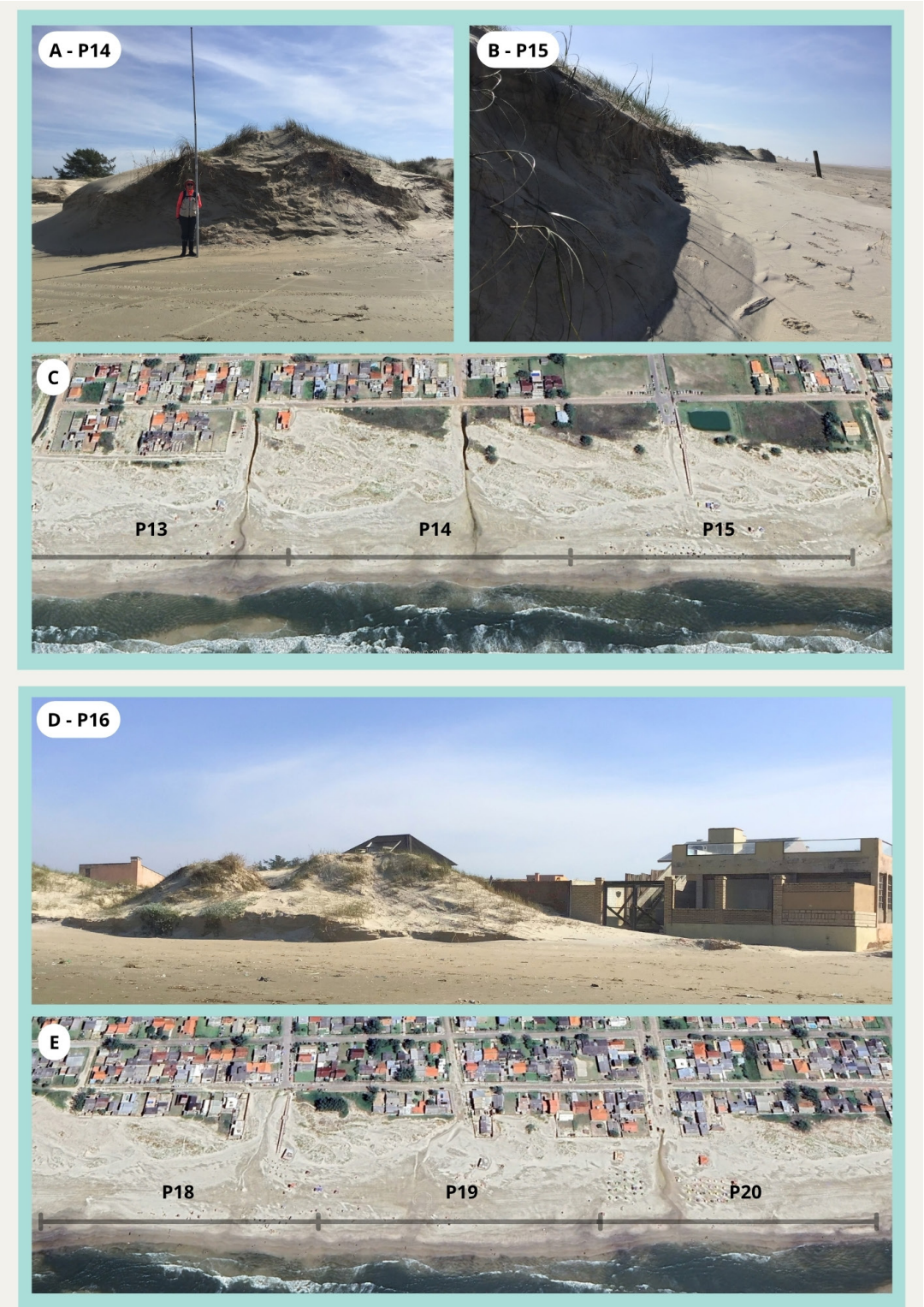


Figure 6: Records of sampling units with dunes characterized by steep slopes and erosional scarps. A–C: units from Cluster 2, highlighting the low percentage of impermeable surface within 200 meters inland from the shoreline. D–E: units from Cluster 3, characterized by a higher percentage of impermeable coverage in the same adjacent area. E - Google Earth Pro Satellite image (June 2023) of sampling unit P18-P20 from Cluster 3.

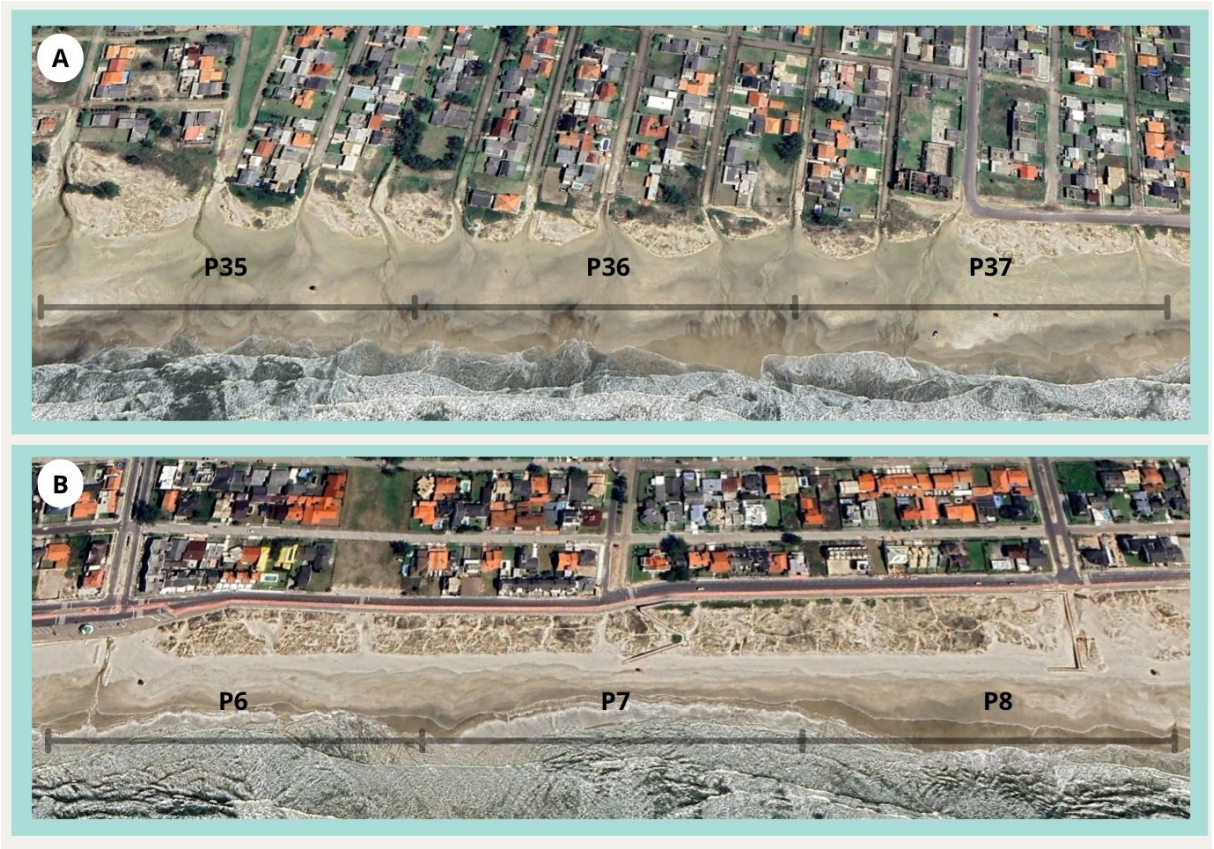


Figure 7: Google Earth Pro Satellite images (June 2023) of sampling unit clusters 5 and 6. A: sampling units belonging to similarity Cluster 5. B: sampling units comprising Cluster 6, as identified by the Euclidean distance analysis.

3.2 Relationship between the checklist and bird nest abundance

To examine the relationship between predictor variables of dune erosion vulnerability and the number of bird nests per landscape unit, data from the winter vulnerability assessment were used. A total of 30 nest sites or territorial pairs exhibiting nest defense behavior were georeferenced, including 2 nests of *Haematopus palliatus* (American oystercatcher), 13 of *Vanellus chilensis* (southern lapwing), and 15 of *Athene cunicularia* (burrowing owl) (Figure 8, Table S2). Of these, 86.67% were located in the southern half of the municipality. Nest distribution across coastal sectors varied by species. Most *A. cunicularia* nests (11) were found in the foredune, along with one *H. palliatus* and one *V. chilensis* nest. In the dune field, a total of six nests were recorded: three of *V. chilensis*, two of *A. cunicularia*, and one of *H. palliatus*. In the urban portion of the coast, 11 nests were observed, including 9 of *V. chilensis* and 2 of *A. cunicularia*.

Among the checklist parameters, dune morphology (IVA) exhibited the highest positive correlation with the overall vulnerability classification of the sampling units (Figure 9A). Within this parameter, the variables with the strongest correlations to vulnerability levels were dune area and dune width (Figure 9B). When the relationship between the number of nests and dune morphology variables was evaluated, negative correlations were observed for dune area ($r = -0.40$) and dune width ($r = -0.35$). These results indicate that units with smaller dune areas and widths tended to contain fewer nests (Figure 10B).

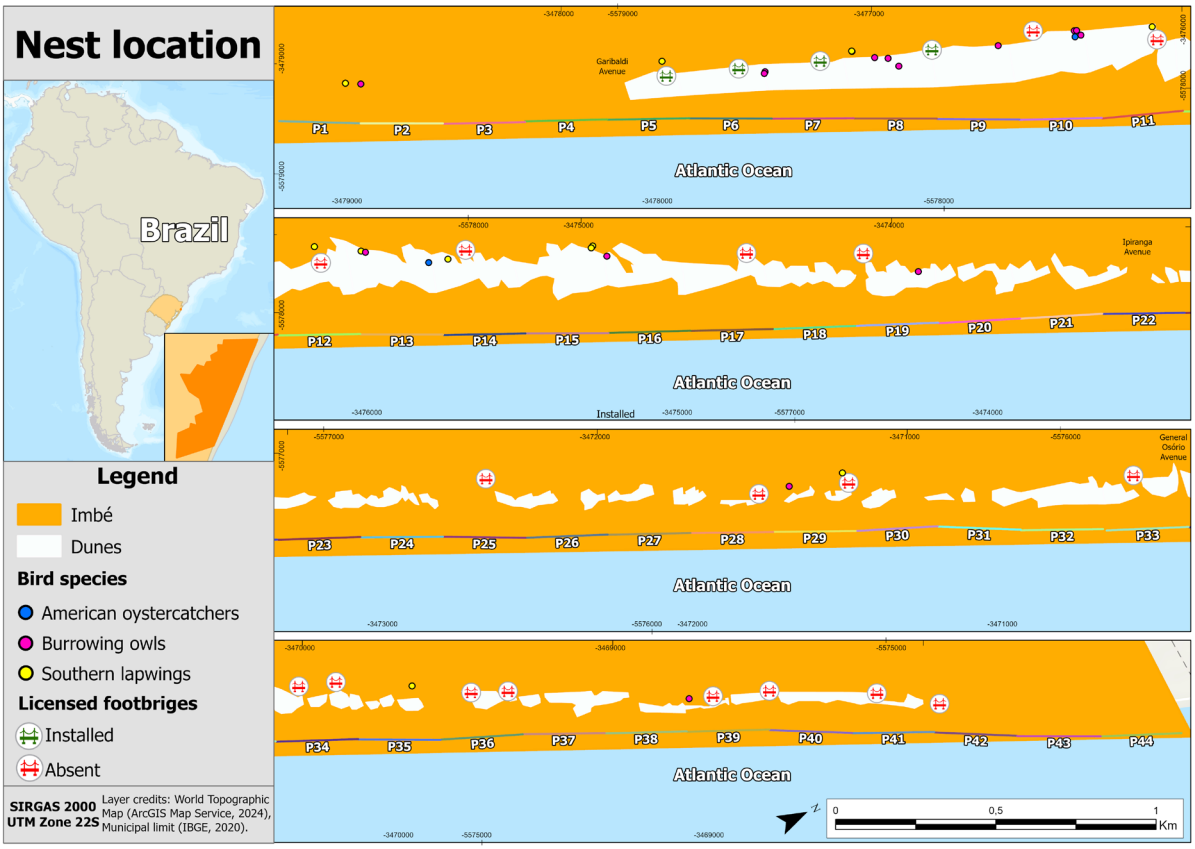


Figure 8: Spatial distribution of bird nests recorded between October and December 2022 in Imbé (RS), Brazil.

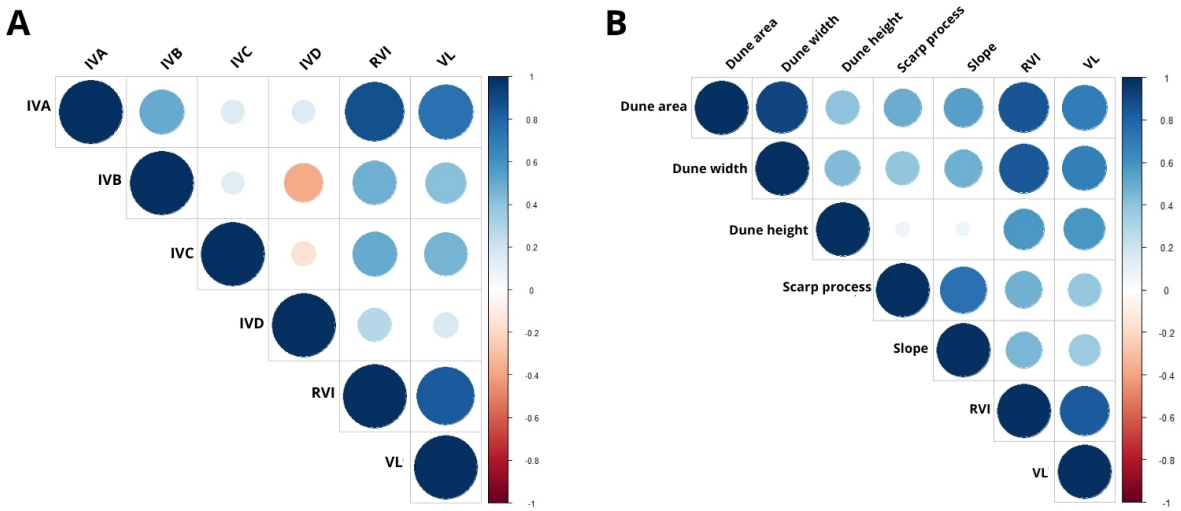


Figure 9: Pearson correlation matrix. A: correlogram showing relationships between the checklist parameters, Relative Vulnerability Index (RVI), and Vulnerability Levels (VL) along the coastline of Imbé, RS. B: Correlogram showing correlations between the individual variables of the dune morphology parameter and both RVI and VL. Checklist parameter acronyms: IVA = dune morphology; IVB = beach conditions; IVC = characteristics of the 200 m adjacent to the sea; IVD = usage pressure.

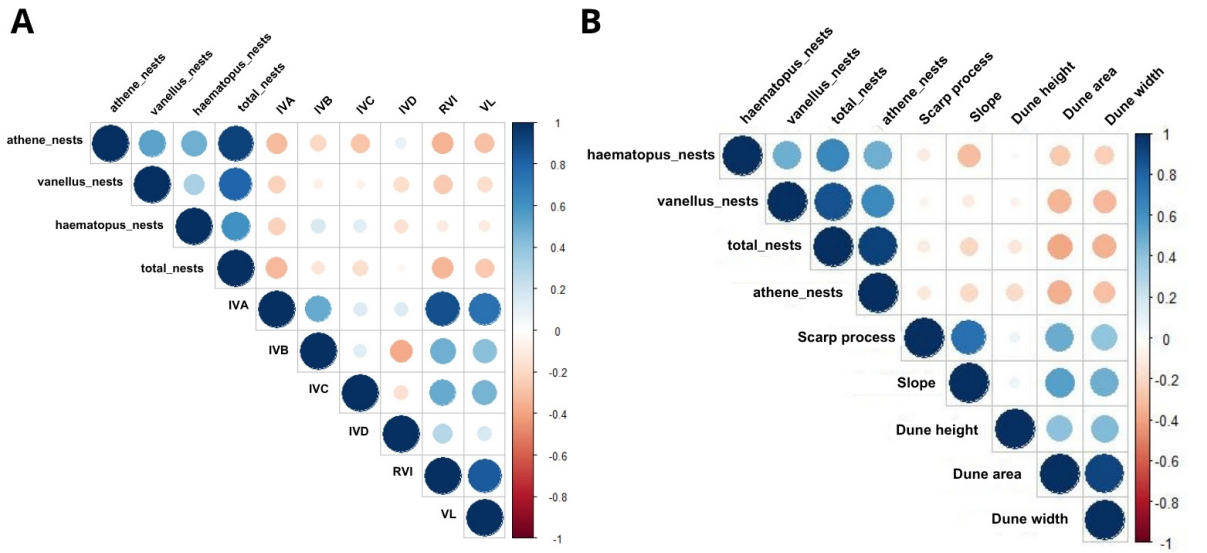


Figure 10: Pearson correlogram showing the relationships between the checklist parameters assessed in winter 2022 and the total number of bird nests, as well as nests of each species observed during spring and early summer 2022 in Imbé (RS), Brazil. B: Pearson correlogram between the individual variables of the dune morphology parameter (IVA), assessed in winter 2022, and the total and species-specific nest counts. Circle size indicates the strength of the correlation; color denotes direction, blue for positive and red for negative correlations.

4. DISCUSSION

This study provides an updated and spatially explicit diagnosis of coastal dune vulnerability in the municipality of Imbé, 12 years after the implementation of the local Dune Management Plan. The results indicate that 36% of the coastline has experienced an increase in vulnerability classification since the previous assessment, accompanied by significant changes in dune morphology and a reduction in natural buffering capacity. These findings underscore the need for periodic reassessment and offer clear evidence of ongoing degradation in dune systems. At the local scale, this research directly informs the refinement of coastal management strategies by identifying the most erosion-prone sectors and the specific vulnerability drivers in each landscape unit. More broadly, the study contributes to conceptual and methodological advancements by integrating a standardized geomorphological checklist with data on avian reproductive activity, presenting a dual-assessment approach that is both ecologically grounded and operationally feasible. Compared to widely adopted approaches such as the Coastal Vulnerability Index (Thieler & Hammar-Klose, 1999), the integrated checklist used here adds a biological dimension that captures ecosystem functionality and resilience, not just geomorphological exposure.

The importance of foredunes as natural barriers against sea level rise and storm surges is further emphasized in regional flood modeling studies for Imbé and Tramandaí. According to Silva *et al*. (2020), projected sea level rise scenarios could inundate up to 60% of the urbanized areas in these municipalities by 2100 under extreme emission trajectories. The presence and integrity of dune systems are thus crucial not only for biodiversity and sediment retention but also for reducing flood risks to coastal infrastructure and populations at different temporal scales.

The most erosion-prone coastal dune segments were concentrated at the southern and northern extremes of the municipality, where dunes had either been replaced or lost their capacity for inland migration due to public infrastructure such as boardwalks and roads (Pedroza *et al*., 2013). In these priority areas, storm-induced erosion has already damaged access ramps, recreational decks, and roadways. In other highly vulnerable zones, such as the neighborhoods of Harmonia (P28), Mariluz Plano B (P25), and Santa Terezinha (P35–P38), the primary driver of vulnerability was dune morphology, particularly the fragmentation caused by pedestrian paths, vehicle tracks, and drainage channels. These segments also exhibited the narrowest dunes, directly related to unregulated urban encroachment (FEPAM, 2000; FEPAM, 2022; Quiroz-Villanueva *et al*., 2022; FEPAM, 2024).

In the central part of the coastline, specifically segments P34 to P39 (Cluster 5), management interventions such as the implementation of macro-drainage studies and the fencing of pedestrian accesses are needed to support sediment retention and lateral dune recovery. In these locations, seasonal stormwater runoff intensifies lateral erosion, exacerbating the vulnerability of the dune system (Ferreira *et al*., 2021). Elevate walkways represents a strategic tool for minimizing fragmentation while maintaining beach accessibility (Tabajara *et al*., 2013). Until 2024, only five of twenty-two licensed and planned elevated walkways were constructed.

While Cluster 3 contains wide dunes, it is under intense human pressure due to its central location in the city. Although some elevated walkways have been installed, informal trails continue to undermine vegetation cover, especially on the seaward dune face. Nonetheless, this segment maintained a medium vulnerability classification (level 3), suggesting that moderate intervention measures such as fencing and environmental education could be sufficient to prevent further degradation. Many of the segments identified in this study as highly vulnerable had already been flagged in the 2012 Dune Management Plan (Tabajara *et al*., 2013), which proposed, for example, sediment removal and urban cleaning instead of dune restoration. As a result, prior actions may have inadvertently reduced sediment stocks and intensified dune erosion (Seagrass, 2012). In Imara (P42–P44), no mitigation measures were implemented in the past decade, despite prior recommendations to relocate the Interpraias Road and restore the dune system. This lack of action has led to progressive erosion and infrastructure damage.

This pattern of inadequate planning aligns with findings from other studies. Pedroza *et al*. (2013) and Quiroz-Villanueva *et al*. (2022) documented similar processes on the Mexican Pacific coast, where anthropogenic infrastructure near dunes increased erosion by disrupting sediment dynamics and fragmenting vegetation. These parallels reinforce the conclusion that ineffective coastal management can directly exacerbate natural vulnerability, leading to irreversible ecosystem degradation.

Although the classification of most units did not change significantly between seasons, cluster composition varied, particularly in response to the "use pressure" parameter (D), which is influenced by seasonal population growth due to tourism. Parameters related to dune morphology and beach conditions (A and B) remained relatively stable, likely due to sediment accretion during summer months (Weschenfelder & Zouain, 2002; Martinho *et al*., 2010). However, the distribution of beach kiosks and pedestrian access varied considerably between seasons, altering the clustering of units. Summer clusters revealed spatial standardization in use profiles of contiguous units, while winter data provided a clearer picture of structural vulnerability in the absence of high tourist pressure. This highlights the robustness of the checklist as a tool that incorporates both environmental and cultural seasonality, while also indicating the importance of incorporating additional variables, such as tourism intensity, to capture finer seasonal dynamics (Ciccarelli *et al*., 2017; Barros & Baldraia, 2023).

One of the key innovations of this study was integrating ecological indicators into vulnerability assessment. The correlation between dune morphology and nesting distribution supports the interpretation that dune area and width are limiting factors for avian reproductive success, as narrower and more fragmented dunes hosted fewer nests. Most nests were concentrated in the southern half of the study area, which had the broadest and least disturbed dunes. Among the species observed, *Athene cunicularia* (burrowing owl) emerged as the most promising bioindicator, given its nesting fidelity, preference for nest building in dunes, and tolerance to moderate human disturbance (Orsi *et al*., 2021; CEMAVE, 2025a). In contrast, *Vanellus chilensis* (southern lapwing) nested opportunistically in more urbanized areas, and *Haematopus palliatus* (American oystercatcher) was observed in insufficient numbers to support firm conclusions (McGowan & Simons, 2006; Nol & Humphrey, 2012; Delfino & Carlos, 2020; CEMAVE, 2025b; CEMAVE, 2025c).

These findings are consistent with the broader literature on habitat compression and reproductive avoidance by sensitive coastal bird species (Gjerdrum *et al*., 2005; Defeo *et al*., 2009; Canabarro & Fedrizzi, 2010). Therefore, it is proposed that long-term monitoring of *A. cunicularia* nesting activity could serve as a proxy for assessing the evolution of dune vulnerability. Since these birds often reuse nesting burrows across reproductive cycles, mapping and revisiting these sites offer a cost-effective alternative to repeated application of the full checklist method. Additionally, targeted studies in areas with higher densities of *H. palliatus* could clarify its utility as a complementary indicator species (Nol & Humphrey, 1994; Sanders *et al*., 2004).

Despite its utility, the proposed method may have limited applicability in coastal systems with high tidal amplitude or sediment dynamics strongly influenced by estuarine inputs. In such contexts, tidal variation can significantly alter dune-beach interactions, influencing sediment supply and wave energy, and should be considered in future adaptations of the checklist

(Williams *et al*., 1993; Fairley *et al*., 2020). Likewise, future refinements could benefit from incorporating more precise proxies for human pressure, such as visitation frequency, spatial intensity of foot traffic, or metrics of tourist infrastructure density (Ciccarelli *et al*., 2017).

Finally, this study highlights the importance of coastal governance and the effectiveness of simple structural interventions. The installation of walkways not only reduces dune fragmentation but also enhances habitat availability for nesting birds. Conversely, unmanaged pedestrian access contributes to erosion through the formation of stormwater runoff paths. These findings suggest that relatively low-cost interventions, when strategically implemented, can yield significant conservation benefits. As sea level rise and coastal urbanization intensify globally, integrating biotic indicators into standard vulnerability assessments may enhance our ability to monitor and manage the resilience of sandy beach ecosystems (IBGE, 2023; IPCC, 2022; Silva *et al*., 2023; Cosby *et al*., 2024).

5. CONCLUSIONS

This study demonstrates that the municipality of Imbé is undergoing a progressive degradation of its coastal dune systems, with 36% of the evaluated segments showing increased vulnerability over the past decade. The combination of a standardized geomorphological checklist and avian nesting data enabled the identification of both structural and ecological indicators of vulnerability, with particular emphasis on dune width, fragmentation, and the spatial distribution of nests by species with different sensitivities to human presence. Among them, *Athene cunicularia* proved to be a reliable and low-cost bioindicator for long-term monitoring.

The findings reinforce the relevance of dune systems not only as ecological assets but also as critical infrastructure for climate adaptation, especially in light of projected sea level rise and flood risk scenarios for the region. The integration of biotic and abiotic metrics within vulnerability assessments is shown to be a valuable approach for improving coastal zone planning and prioritizing management interventions.

In practical terms, this study provides updated spatial information that can support the revision of the local Dune Management Plan and the implementation of targeted measures such as the installation of elevated walkways, restriction of informal access paths, and restoration of fragmented dune stretches. As coastal pressures intensify across the globe, the methodology and insights presented here may serve as a replicable model for other sandy beach environments facing similar socio-environmental challenges.

ACKNOWLEDGMENTS

NFB thanks the fieldwork colleagues, Gabriela Menegolla, Giovanna Löffler, Kristina Leão, Leonardo Nunes, Luísa Bertoloni, Luiza Ferreira, Sara Fumagalli, and Thaísa Deichel, whose dedication and collaboration were essential for the data collection process. The authors also thank UFRGS/CECLIMAR for providing logistical support during both the field and laboratory phases of this project, and Dra. Samanta Cristiano and Dr. Felipe Caron, for their valuable and constructive review of this manuscript, which greatly contributed to the improvement of this work.

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SUPPLEMENTARY MATERIAL

Table S1. Code and UTM coordinates of the evaluated landscape sampling units (from P01 to P44).

Landscape sampling unit code	Start coordinates	End coordinates	Landmark
P01	22J 584950 6683627	22J 585089 6683755	Beira Mar Ave. - Bent Gonçalves St.
P02	22J 585089 6683755	22J 585198 6684001	Bent Gonçalves St. - Castelo Branco St.
P03	22J 585198 6684001	22J 585281 6684246	Castelo Branco St. - Santa Rosa Ave.
P04	22J 585281 6684246	22J 585363 6684461	Santa Rosa Ave. - Garibaldi Ave.
P05	22J 585363 6684461	22J 585445 6684707	Garibaldi Ave. - between the first and second elevated walkways
P06	22J 585445 6684707	22J 585527 6684953	Between the first and second elevated walkways - Between the second and third elevated walkways
P07	22J 585527 6684953	22J 585609 6685167	Between the second and third elevated walkways - Secret kiosk
P08	22J 585609 6685167	22J 585718 6685413	Secret kiosk - Carazinho Ave.
P09	22J 585718 6685413	22J 585801 6685658	Carazinho Ave. - near Não-Me-Toque Ave.
P10	22J 585801 6685658	22J 585883 6685873	Near Não-Me-Toque Ave. - the end of the Las Olas apartment complex
P11	22J 585883 6685873	22J 585992 6686150	The end of the Las Olas apartment complex - near Tancredo Neves Ave.
P12	22J 585992 6686150	22J 586074 6686334	Atlântida Ave.
P13	22J 586074 6686334	22J 586156 6686518	Presidente district
P14	22J 586156 6686518	22J 586265 6686794	Presidente district
P15	22J 586265 6686794	22J 586348 6687039	Presidente district
P16	22J 586348 6687039	22J 586430 6687254	Rivera district
P17	22J 586430 6687254	22J 586539 6687500	Ipiranga district
P18	22J 586539 6687500	22J 586621 6687715	Ipiranga District
P19	22J 586621 6687715	22J 586757 6687960	Ipiranga Ave. - near Nordeste Ave.
P20	22J 586757 6687960	22J 586839 6688175	Mariluz District
P21	22J 586839 6688175	22J 586948 6688389	Salvador do Sul St. - Alegrete St.
P22	22J 586948 6688389	22J 587057 6688635	Monteiro Lobato St.
P23	22J 587057 6688635	22J 587140 6688880	Mariluz Ave.
P24	22J 587140 6688880	22J 587249 6689095	Campo Bom St.
P25	22J 587249 6689095	22J 587331 6689341	Estrela St.
P26	22J 587331 6689341	22J 587440 6689524	Mariluz Plano B district
P27	22J 587440 6689524	22J 587549 6689801	Mariluz Plano C district
P28	22J 587549 6689801	22J 587631 6690015	Harmonia district
P29	22J 587631 6690015	22J 587713 6690230	Mariluz Norte district
P30	22J 587713 6690230	22J 587823 6690476	Harmonia Ave. - Mariluz Norte Ave.
P31	22J 587823 6690476	22J 587932 6690690	Albatroz district
P32	22J 587932 6690690	22J 588041 6690905	Albatroz district
P33	22J 588041 6690905	22J 588123 6691181	Marisul district
P34	22J 588123 6691181	22J 588205 6691396	Travessa 1 St. - General Osório Ave.
P35	22J 588205 6691396	22J 588314 6691611	General Osório Ave. - Pedro Alves St.
P36	22J 588314 6691611	22J 588397 6691856	Pedro Alves St. - Camargo St.
P37	22J 588397 6691856	22J 588479 6692102	Camargo St. - Capitão Manna St.
P38	22J 588479 6692102	22J 588615 6692316	Capitão Manna St. - Farroupilha St.
P39	22J 588615 6692316	22J 588697 6692562	Farroupilha St. - Piscinas's Bar
P40	22J 588697 6692562	22J 588780 6692777	Piscinas's Bar - near Parque Pajé
P41	22J 588780 6692777	22J 588889 6693022	Near Parque Pajé - Tapuia Ave.
P42	22J 588889 6693022	22J 588998 6693237	Tapuia Ave. - near Padre Cacique St.
P43	22J 588998 6693237	22J 589107 6693451	Estrada Interpraias
P44	22J 589107 6693451	22J 589161 6693508	Estrada Interpraias - municipal boundary sign

Table S2. Code and UTM coordinates of the nesting sites.

UTM E (m)	UTM N (m)	Species	Landscape sampling unit code
585524	6685001	*Athene cunicularia*	P07
585527	6684997	*Athene cunicularia*	P07
585622	6685326	*Athene cunicularia*	P08
585640	6685362	*Athene cunicularia*	P08
585672	6685381	*Athene cunicularia*	P08
585800	6685921	*Vanellus chilensis*	P10
585798	6685919	*Athene cunicularia*	P10
585800	6685925	*Athene cunicularia*	P10
585817	6685931	*Athene cunicularia*	P10
586022	6686458	*Vanellus +chilensis*	P13
586030	6686468	*Athene cunicularia*	P13
586131	6686630	*Haematopus palliatus*	P13
586146	6686689	*Vanellus chilensis*	P14
586289	6687110	*Vanellus chilensis*	P15
586331	6687135	*Athene cunicularia*	P16
587651	6690166	*Athene cunicularia*	P29
588625	6692434	*Athene cunicularia*	P39
585580	6685271	*Vanellus chilensis*	P08
585578	6685271	*Vanellus chilensis*	P08
585742	6685686	*Athene cunicularia*	P09
586745	6687981	*Athene cunicularia*	P19
585045	6683817	*Vanellus chilensis*	P01
588259	6691681	*Vanellus chilensis*	P35
585955	6686334	*Vanellus chilensis*	P12
585883	6686141	*Vanellus chilensis*	P11
586292	6687103	*Vanellus chilensis*	P15
585065	6683859	*Athene cunicularia*	P01
585374	6684729	*Vanellus chilensis*	P05
587682	6690333	*Vanellus chilensis*	P29
585814	6685912	*Haematopus palliatus*	P10

Landscape unit:

Reference point and/or coordinates

Section A - Dune Morphology

		0	1	2	3	4
1	Dune surface area (m²)	>10000 [ ]	> 7500 [ ]	> 5000 [ ]	> 2500[ ]	< 2500[ ]
2	Dune width (m)	> 50 [ ]	> 40 [ ]	> 30 [ ]	> 20 [ ]	> 10 [ ]
3	Height of the tallest dune (m)	> 5[ ]	> 4 [ ]	> 3[ ]	> 2 [ ]	< 1[ ]
4	Scarp process	low [ ]		moderate [ ]		high [ ]
5	Slope on the marine-facing side	smooth [ ]		moderate [ ]		marked [ ]
	TOTAL SCORE:					

Section B - Backshore Condition

		0	1	2	3	4
1	Backshore width (m)	>100 [ ]	> 80 [ ]	> 60 [ ]	> 40 [ ]	<40 [ ]
2	Sand supply	alto [ ]		moderate [ ]		low[ ]
3	Breaches in the beach face	none [ ]		some [ ]		many [ ]
4	Width of breaches	< 2 [ ]		2 - 10 [ ]		>10 [ ]
5	Embryonic dunes	many[ ]		some[ ]		few [ ]
	TOTAL SCORE:					

Section C - Characteristics of the 200 m adjacent to the sea

		0	1	2	3	4
1	Blowout areas (%)	< 5 [ ]	> 5 [ ]	> 10 [ ]	> 20 [ ]	>40 [ ]
2	Sand loss to the continent	little [ ]		some [ ]		much [ ]
3	Breaches in the dune system (%)	>0 [ ]	> 5 [ ]	> 25 [ ]	>50 [ ]	> 70 [ ]
4	Vegetation on the seaward side (%)	>90 [ ]	>60 [ ]	> 30 [ ]	>10 [ ]	<10 [ ]
5	Recent sand deposition	much [ ]		some [ ]		none [ ]
6	Impermeable coverage (%)	little [ ]		some [ ]		a lot [ ]
7	Presence of exotic vegetation	none [ ]		some [ ]		many[ ]
8	Number of runoff outlets	0[ ]		1 [ ]		2 or + [ ]
	TOTAL SCORE:					

Section D - Usage Pressure

		0	1	2	3	4
1	Number of vehicle access points	0 [ ]	1 [ ]	2 [ ]	3 [ ]	4 [ ]
2	Pedestrian path density	low [ ]		medium [ ]		high[ ]
3	Stage of urbanization	none [ ]	rustic [ ]	horizontal [ ]	mixed [ ]	vertical [ ]
4	Percentage of urbanization	<10 [ ]	>10 [ ]	30 - 50 [ ]	>50 [ ]	>70 [ ]
5	Urbanization position	without [ ]	final third [ ]	post dune [ ]	foredune [ ]	backshore[ ]
6	Number of kiosks	0[ ]	1 - 2 [ ]	3 - 5 [ ]	6 - 8 [ ]	9 - 10 [ ]
7	Number of property owners	one [ ]		some [ ]		many [ ]
	TOTAL SCORE:					

Figure S1. Checklist method proposed by Williams et al. (1993) and adapted by Tabajara et al. (2013).

ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS

Journal of Integrated Coastal Zone Management (2025) 25(2): 135-150
© 2025 APRH
ISSN 1646-8872
DOI 10.5894/rgci-n711
url: https://www.aprh.pt/rgci/rgci-n711.html

A SYSTEMATIC REVIEW OF MANGROVE RESILIENCE TO CLIMATE VARIABILITY

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ABSTRACT: This systematic literature review synthesizes recent research on the resilience of mangroves in response to climate variability. Mangroves play a crucial role in coastal protection, carbon sequestration, and biodiversity conservation. However, climate variability, including extreme weather events, sea level rise, and changing precipitation patterns, poses significant challenges to mangrove ecosystems. Using Covidence for article selection and analysis, this study investigates the relationship between climate variability and mangrove resilience. This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological accuracy and transparency. A search of the Scopus database (2014–2024) identified n = 223 records, which after screening and eligibility assessment, resulted in n = 44 studies included in the final synthesis. The review identified sea level rise, extreme weather events, and altered sediment dynamics as the primary climate-related stressors affecting mangrove resilience, while vegetation structure, species composition, and recovery capacity emerged as the most frequently used resilience indicators. This review concludes that strengthening mangrove resilience requires integrated socio-ecological strategies that combine ecological processes with adaptive governance, sediment management, and community-based adaptation. Addressing research gaps through geographically and interdisciplinary approaches will be crucial for enhancing the role of mangroves in climate adaptation and sustainable coastal management. The findings underscore the importance of mangroves in relation to the global Sustainable Development Goals (SDGs), particularly SDGs 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land).

Keywords: Mangrove resilience, climate variability, coastal ecosystems, socio-ecological adaptation, systematic review

RESUMO: *Esta revisão sistemática da literatura sintetiza pesquisas recentes sobre a resiliência dos manguezais em resposta à variabilidade climática. Os manguezais desempenham um papel crucial na proteção costeira, no sequestro de carbono e na conservação da biodiversidade. No entanto, a variabilidade climática, incluindo eventos climáticos extremos, elevação do nível do mar e mudanças nos padrões de precipitação, impõe desafios significativos aos ecossistemas de manguezais. Utilizando o Covidence para a seleção e análise dos artigos, este estudo investiga a relação entre variabilidade climática e resiliência dos manguezais. O estudo empregou as diretrizes Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) para garantir rigor metodológico e transparência. A busca na base de dados Scopus (2014–2024) identificou n = 223 registros, dos quais, após as etapas de triagem e avaliação de elegibilidade, resultaram em n = 44 estudos incluídos na síntese final. A revisão identificou a elevação do nível do mar, os eventos climáticos extremos e a alteração da dinâmica sedimentar como os principais fatores de estresse relacionados ao clima que afetam a resiliência dos manguezais, enquanto a estrutura da vegetação, a composição de espécies e a capacidade de recuperação emergiram como os indicadores de resiliência mais frequentemente utilizados. Esta revisão conclui que o fortalecimento da resiliência dos manguezais requer estratégias socioecológicas integradas que combinem processos ecológicos com governança adaptativa, manejo sedimentar e adaptação baseada na comunidade. A superação das lacunas de pesquisa por meio de abordagens geográficas e interdisciplinares será crucial para ampliar o papel dos manguezais na adaptação climática e na gestão costeira sustentável. Os resultados destacam a importância dos manguezais em relação aos Objetivos de Desenvolvimento Sustentável (ODS) globais, particularmente os ODS 13 (Ação Climática), 14 (Vida na Água) e 15 (Vida Terrestre).*

Palavras-chave: *Resiliência de manguezais, variabilidade climática, ecossistemas costeiros, adaptação socioecológica, revisão sistemática*

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Submission: 3 SEP 2025; Peer review: 27 SEP 2025; Revised: 19 MAY 2026; Accepted: 21 MAY 2026; Available on-line: 26 MAY 2026

1. INTRODUCTION

Mangroves are intertidal forest ecosystems distributed across tropical and subtropical coastlines, occupying approximately 140,260 km² globally (Bunting *et al*., 2022) and providing critical ecological and socio-economic services. They are widely recognized for their multifunctionality in preserving coastal ecosystems and significantly contributing to protection from natural hazards by dissipating wave energy, stabilizing sediments, and buffering storm surges (Menéndez *et al*., 2020; Zhang *et al*., 2022). Despite their global importance, mangroves are experiencing significant decline due to both anthropogenic pressures and climate-related stressors (Friess *et al*., 2019; Goldberg *et al*., 2020). Their capacity to mitigate climate variability, such as sea-level rise, tropical storms, and tidal anomalies, depends strongly on ecological processes, including sediment accretion and hydrodynamic interactions (Gijsman *et al*., 2021; Menéndez *et al*., 2020; Zhang *et al*., 2022). However, when sea level rise surpasses natural sedimentation rates, mangroves face ecological collapse (Lovelock *et al*., 2015). In addition, climatic variables such as temperature and precipitation significantly influence mangrove growth and health, while extreme events, including cyclones and droughts, often trigger large-scale dieback (Allen *et al*., 2021; Silva *et al*., 2022). Therefore, the resilience of mangroves to such disturbances is critical, as these ecosystems function as natural barriers that reduce coastal erosion and flooding risks, thereby protecting coastal communities (Mugilan *et al*., 2024).

The presence of mangroves is integral to achieving several of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). These ecosystems provide numerous benefits that enhance climate resilience and promote biodiversity conservation, which are crucial in the face of ongoing environmental challenges (Gijsman *et al*., 2021). Sustainable coastal management frameworks are increasingly recognizing the value of preserving mangroves and other critical habitats as natural defenses, while supporting biodiversity and mitigating climate change (Rumondang *et al*., 2024; Xavier *et al*., 2022). Integrating ecological considerations into coastal development and urban planning is crucial to maintain these ecosystem services (Martínez *et al*., 2025). Collaborative management approaches, particularly those engaging local stakeholders in restoration efforts, have been shown to enhance both ecological recovery and community resilience (Hasan *et al*., 2022). Sustainable coastal management relies on striking a balance between ecological integrity and the socio-economic realities of the communities that depend on these ecosystems.

The concept of mangrove resilience provides a fundamental framework for analyzing the effects of climate variability. It is defined as the capacity of an ecosystem to resist, recover from, and adapt to climate-induced disturbances while preserving its essential functions and services, including increased sea levels, a higher probability of catastrophic storms, and shifts in salinity levels (Alongi, 2015; Friess *et al*., 2019; Portela, 2025; Ward *et al*., 2016). Resilience is influenced by multiple factors, such as biodiversity, ecological interactions, and local environmental conditions (Dong *et al*., 2023; Smith *et al*., 2022). In this study, resilience encompasses the ecological aspects of mangroves' responses to climate variability and the climate indicators that drive mangrove resilience. Diverse species responses to climate variability, referred to as response diversity, may improve ecosystem resilience, encouraging functional continuity even during stress (Feit *et al*., 2021). Studies demonstrate that terrain attributes, including bedrock and soil composition, have a substantial influence on ecosystem reactions to climatic variability (Dong *et al*., 2023).

Mangroves demonstrate resilience through mechanisms such as sediment trapping, land-building processes, and rapid recolonization following disturbance, allowing them to maintain ecosystem functions despite stress (Alongi, 2015). Their resilience is strengthened by the preservation of ecological connectivity, genetic diversity, and local community management, reducing vulnerability to climatic extremes (Dahdouh-Guebas *et al*., 2005). However, human-induced pressures, including deforestation and coastal development, reduce mangrove resilience, making them more vulnerable to climate-related degradation (Friess *et al*., 2019). Environmental stressors, such as significant rainfall-induced flooding, can reduce groundwater salinity, which has been demonstrated to enhance the growth of particular mangrove species (Li *et al*., 2022). This explains the ever-changing relationship between mangrove health and local hydrological conditions, indicating that changes in freshwater supply can enhance the ecosystem's resilience. Freshwater ecosystems are vulnerable to fluctuations in temperature and precipitation, requiring management solutions customized to local ecological contexts to enhance resilience (Portela, 2025; Rivers-Moore & Dallas, 2022). Studies showing increased resilience in mangrove ecosystems subjected to such fluctuations highlight the importance of understanding local environmental conditions to improve conservation methods (Li *et al*., 2022). A comprehensive framework is necessary

to integrate ecological processes with adaptive governance, restoration strategies, and climate adaptation policies, thereby ensuring the ongoing provision of essential services, including coastal protection, carbon sequestration, and biodiversity conservation, in the face of climate variability (Lee *et al*., 2014; Ward *et al*., 2016).

Recent studies have increasingly explored mangrove ecosystems through review and synthesis approaches, addressing topics such as ecosystem services, carbon dynamics, vulnerability to sea-level rise, and restoration strategies (Alongi, 2008; Friess *et al*., 2019; Sasmito *et al*., 2020). However, these studies often focus on specific dimensions of mangrove systems, particularly biophysical processes or localized case studies, without explicitly integrating climate variability as a central driver of resilience. As a result, existing syntheses remain fragmented and lack a comprehensive framework that connects climatic drivers, ecological responses, and socio-institutional mechanisms. This limitation constrains a holistic understanding of mangrove resilience and its variability across regions. Therefore, a more integrative and systematic synthesis is needed to bridge these gaps and advance the understanding of mangrove resilience within a coupled socio-ecological context.

This study aims to establish a fundamental basis for investigating the relationship between climate variability and mangrove resilience. It synthesizes and critically evaluates recent research examining how mangrove ecosystems respond to climatic variability and related stressors. To guide this synthesis, the review is structured around the following research questions: (1) What are the drivers of mangrove resilience? (2) What methods have been employed to assess mangrove resilience under climatic variability? (3) How do mangroves respond to climate variability? (4) What research gaps remain concerning the interactions between climate variability and mangrove ecosystems? Together, these questions provide a structured framework for synthesizing existing knowledge and identifying opportunities for future research. This study contributes by systematically identifying and classifying the factors influencing mangrove resilience across both biophysical and socio-institutional dimensions, while proposing an empirically grounded typology of response pathways, including resistance, recovery, and dieback. This approach advances current understanding from a predominantly biophysical perspective toward a more integrated socio-ecological framework, supporting more effective and sustainable coastal management strategies.

2. METHODS

2.1 Search Strategy

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a structured and transparent framework to enhance reproducibility and methodological rigor (Rethlefsen *et al*., 2021). The literature search was conducted using the Scopus database (accessed on November 28, 2024), as it offers comprehensive coverage of peer-reviewed environmental and interdisciplinary journals. The search was limited to articles published between 2014 and 2024. This time frame was chosen to reflect the most recent advances in mangrove resilience research, particularly the growing emphasis on climate variability, extreme events, and integrated socio-ecological methods. It also indicates a movement in the literature from primarily biophysical viewpoints to more interdisciplinary and policy-relevant frameworks.

To capture the relevant scope, the following Boolean string was applied: mangrove AND climat* AND resilience AND NOT carbon. This formulation was designed to focus on the relationship between mangrove resilience and climate variability, while excluding studies that primarily addressed carbon dynamics, thereby avoiding bias toward mitigation research and maintaining an emphasis on adaptation and ecological resilience. The literature search initially identified a total of n = 223 records from the Scopus database. After the removal of duplicates and limitation of document type and language, n = 181 unique records remained for the screening stage. During title and abstract screening, n = 121 records were excluded for not meeting the predefined inclusion criteria. Subsequently, n = 60 full-text articles were assessed for eligibility, of which n = 16 were excluded due to reasons such as lack of direct relevance to mangrove resilience, methodological limitations, or insufficient focus on climate variability. Finally, n = 44 studies met all criteria and were included in the qualitative synthesis, forming the basis for this systematic literature review. The detailed process is summarized in the PRISMA flow diagram (Figure 1).

2.2 Screening and Eligibility

All search results were imported into Covidence software to facilitate screening and overall reference management. Covidence has become one of the most widely used platforms for conducting systematic literature reviews, particularly in health sciences, environmental studies, and social sciences, because it streamlines study selection, data extraction, and quality assessment (Babineau, 2014; Haby *et al*., 2024; Harrison *et al*.,

2020). Its increasing adoption across disciplines demonstrates its reliability and efficiency in supporting transparent and reproducible review processes. Duplicate records were removed, and a two-stage screening process was performed: (1) title and abstract screening, followed by (2) full-text screening. Studies were included if they explicitly addressed research examining mangrove ecosystems, concentrating on coastal regions in tropical and subtropical climates, and research examining mangroves impacted by climate variability, including sea level rise. Exclusion criteria encompassed articles focusing exclusively on blue carbon storage and stressors unrelated to climate, such as pollution, that do not pertain to sea level rise and mangrove resilience, studies not peer-reviewed, and non-English publications. Table 1 outlines the detailed inclusion and exclusion criteria.

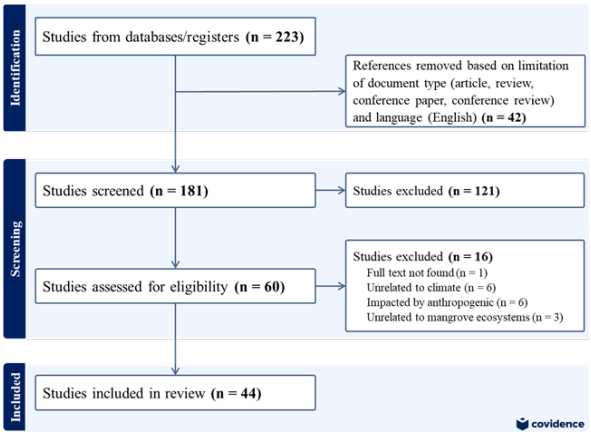


Figure 1. PRISMA flow diagram.

Table 1. Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Publication years	2014–November 2024	Any study outside these dates
Language	English	Other language
Type of article	Journal article, journal review, conference paper, conference review	Book chapter, unpublished research, PhD theses, reports
Study focus	Article mentioned about mangrove resilience and climate variability	Article focused on blue carbon storage in mangroves and stressors unrelated to climate
Geographical area of interest	Research in tropical and subtropical coastal areas affected by climate variability	Research conducted beyond coastal regions

2.3 Data Extraction

Data extraction was carried out systematically using a standardized coding sheet developed in Covidence. In the data extraction phase, a structured framework was applied to ensure the systematic collection of relevant variables from each included study. The extracted information encompassed bibliographic details such as year of publication, name of journal, and DOI, as well as the aim of the study and the research type. Contextual variables were also documented, including country or location, climate regions, and the type of climate variability examined. Ecological dimensions were captured by identifying mangrove species, ecological indicators measured, and mangrove responses to climate variability, while methodological aspects included the research methodology, climate indicators measured, and data processing tools utilized. Furthermore, the analysis considered key findings, and underlying drivers of mangrove resilience. The extraction component enabled the identification of cross-cutting patterns and established a foundation for synthesizing knowledge on mangrove resilience to climate variability.

2.4 Data Synthesis

The extracted data were synthesized through qualitative content analysis to identify recurring themes, knowledge gaps, and emerging trends. Findings were then interpreted within the broader framework of sustainability and coastal management, highlighting the adaptive capacity of mangrove ecosystems in mitigating climate-induced risks. The synthesis aimed to establish an integrative understanding of how mangrove resilience contributes to disaster risk reduction and supports sustainable development pathways in coastal zones.

3. RESULTS AND DISCUSSION

3.1 Patterns and Characteristics of the Reviewed Literature

The literature review identified 44 papers for the final analysis. These articles encompass studies concerning mangrove resilience related to climatic variability conducted during the past decade. The selected studies cover diverse geographical regions, employ various research approaches, and address multiple dimensions of mangrove resilience, providing a broad basis for subsequent analysis. Figure 2 illustrates the historical trends in publications addressing mangrove resilience under climate variability between 2014 and 2024. The figure demonstrates a relatively modest level of research activity during

the early years (2014–2017), with annual outputs ranging from one to three publications. A slight increase is observed in 2018, followed by a temporary decline in 2019. Research productivity intensified again in 2020, reaching five publications, and remained relatively stable through 2021–2023, with four to five publications per year. By 2024, research on mangrove resilience to climate variability has seen a significant increase in publication production, indicating increased attention and research engagement with this field of study. This underscores the heightened focus on the topic within coastal management, which integrates nature-based solution (NBS) considerations and, in this case, is viewed through a climatic perspective.

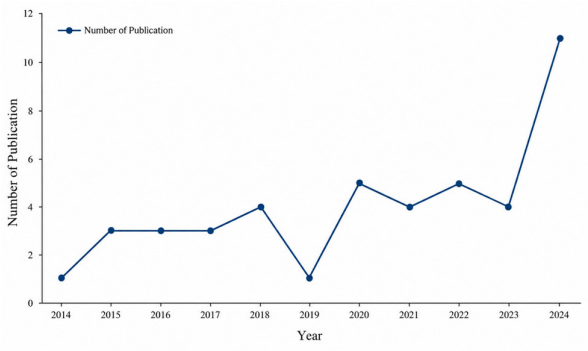


Figure 2. Recent publication trends on mangrove resilience under climate variability (2014–2024).

Further research on the multifaceted benefits of NBS remains critical, particularly as coastal regions are increasingly affected by the compounded effects of climate change and urbanization (Kindeberg *et al*., 2023; Wu & Barrett, 2022). Policymakers and coastal managers are encouraged to embrace NBS not only as standalone solutions but as integral parts of comprehensive coastal management frameworks that prioritize sustainability and community engagement (van der Meulen *et al*., 2023; Yahia *et al*., 2024). This approach aligns with global trends that advocate for holistic and adaptive management practices, leveraging natural processes for long-term viability (Knight, 2024; Sutton *et al*., 2023). The integration of NBS in coastal management demonstrates significant potential for enhancing environmental resilience and is increasingly recognized as a necessary adaptation to the vulnerabilities posed by climate change.

To further understand the spatial emphasis of existing research, the reviewed articles were categorized based on their regional and climatic focus. Figure 3 shows the geographical distribution of the 44 reviewed studies across different regions and climate zones. The United States (US) accounts for the largest share (8 studies), followed by Colombia and the Caribbean Sea, as well as global-scale studies (6 each). Southeast and East Asia represent another key focus (5 studies). The distribution highlights a predominant emphasis on tropical regions, with fewer contributions addressing subtropical areas. This pattern may be partially influenced by using English-language publications as a selection criterion, which could contribute to the overrepresentation of English-speaking countries in the dataset.

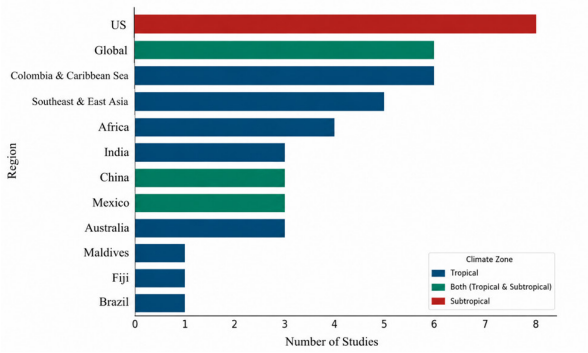


Figure 3. Geographical distribution of reviewed studies on mangrove resilience to climate variability by climate zone.

When this distribution is further considered in relation to the global extent of mangrove forests, a notable imbalance becomes evident. The United States, despite having a relatively smaller share of global mangrove coverage, shows the highest research output, whereas regions with extensive mangrove ecosystems, such as Southeast Asia, are comparatively underrepresented. This indicates a spatial mismatch between ecological importance and research effort, suggesting that scientific output is influenced more by research capacity, funding availability, and institutional infrastructure than by the actual distribution of mangrove ecosystems (Bunting *et al*., 2022; Friess *et al*., 2019).

Although mangrove ecosystems have been widely studied, the relatively limited number of selected studies in this review reflects the specificity of the search criteria, which focused exclusively on research explicitly addressing mangrove resilience in relation to climate variability. As a result, a substantial body of literature addressing other aspects, such as blue carbon, biodiversity, or general ecosystem services, was excluded. At the same time, this outcome also points to a gap in the literature, particularly in studies that explicitly integrate climate variability within resilience frameworks. Therefore, the limited number of studies should be interpreted not only as a methodological constraint but also as an indication of emerging research needs in this field. Such variations further highlight the need for more

geographically balanced and thematically integrated research efforts to ensure that assessments of mangrove resilience accurately represent global diversity. In addition to spatial disparities, it is also important to examine how research themes and methodological approaches have evolved over time.

Table 2 further illustrates the temporal evolution of research types and aims in mangrove resilience studies under climate variability. Early studies (2014–2016) primarily focused on fundamental resilience mechanisms and sea-level rise, often employing review articles, global syntheses, and paleo-based reconstructions to establish a baseline understanding. This focus gradually shifted during the mid-phase (2017–2020) toward disturbance ecology and regional-scale impacts, with increased use of longitudinal analyses, genetic diversity studies, and ecosystem modeling. These approaches reflect a growing emphasis on understanding ecosystem responses to climate extremes and environmental variability at finer spatial and temporal scales. In the most recent period (2021–2024), research has expanded into more integrative and applied domains, including socio-ecological adaptation and predictive risk modeling. Studies in this phase increasingly incorporate adaptive management, vulnerability assessment, disaster resilience, and policy-oriented strategies. This progression indicates a clear transition from predominantly biophysical and descriptive approaches toward more interdisciplinary and solution-oriented frameworks. It highlights the growing need to bridge ecological science with governance and policy to effectively address accelerating climate risks in coastal environments.

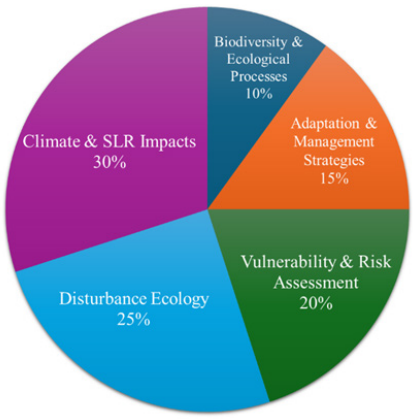


Figure 4. Distribution of research aims of reviewed studies.

A synthesis of research aims and types was conducted across the 44 articles reviewed in this study. Figure 4 shows the distribution of research aims. Overall, most studies focus on the impacts of climate change and sea-level rise, with an emphasis on resilience mechanisms and accretion processes (Alongi, 2015; Friess *et al*., 2019). Many articles examine disturbance ecology, particularly ecological responses of mangroves to cyclones, hurricanes, and other extreme events (Sasmito *et al*., 2020; Ward *et al*., 2016). Additional studies address vulnerability and risk assessment by integrating ecological, spatial, and socio-ecological perspectives, reflecting the complexity of climate impacts. These patterns indicate a growing research emphasis on understanding not only the ecological sensitivity of mangroves to climate-related disturbances, but also their adaptive capacity

Table 2. Temporal shifts in research types and aims on mangrove resilience to climate variability

Year	Number of Studies	Representative Research Types	Representative Research Aims
2014	1	Review article	Resilience & sea-level rise (SLR) mechanisms
2015	3	Empirical paleo-reconstruction, remote sensing	Climate change impact assessment, proxy-based SLR estimation
2016	3	Global synthesis, indicator-based quantitative assessment	Cyclone disturbance recovery, regional vulnerability & resilience
2017	3	Longitudinal ecological study, remote sensing	Climate extremes & range dynamics, SLR & climate change simulation
2018	4	Genetic diversity analysis, Longitudinal field study	Disturbance ecology, Historical SLR & resilience limits
2019	1	Paleoecological reconstruction	Historical drought resilience
2020	5	Field experiment & modeling, field-based survey	Ecosystem connectivity & resilience, sedimentation & vegetation influence
2021	4	Case study, quantitative palaeoclimate analysis	Adaptive management, ecological impact of extremes
2022	4	Global remote sensing and statistics, predictive modeling	Cyclone impact quantification, Sediment accretion resilience
2023	4	Field study, geospatial modeling	Future vulnerability hotspots, long-term vulnerability assessment
2024	12	Empirical observation, field experimentation, remote sensing, mixed methods	Climate resilience strategies, cyclone/tsunami resistance, policy-oriented risk

and contribution to long-term coastal resilience. Recent research increasingly emphasizes the management and policy relevance of adaptive strategies, highlighting the implementation of nature-based solutions to enhance coastal resilience.

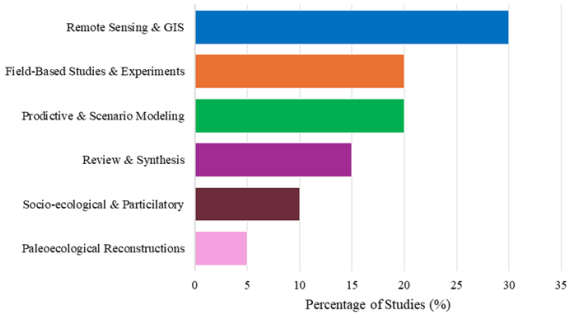


Figure 5. Distribution of research types based on methodological approaches across reviewed studies.

The distribution of methodologies, as illustrated in Figure 5, demonstrates the diversification of approaches in mangrove and coastal resilience research and the growing integration of ecological, spatial, and socio-political dimensions. The research types are classified based on the primary methodological approach employed in each study, rather than the research objectives, to ensure consistency across diverse study designs. The results indicate a clear dominance of empirical approaches, with remote sensing and GIS-based analyses, predictive and scenario modeling, and field-based experiments representing the core of the field.

Remote sensing, in particular, emerges as the most widely employed technique, reflecting its capacity to provide long-term, large-scale insights into mangrove and coastal dynamics. Predictive ecological modeling and scenario-based approaches further highlight the field's forward-looking orientation, allowing researchers to assess potential futures under varying climate and sea-level rise trajectories. Field-based studies and controlled experiments complement these remote analyses by generating site-specific evidence on ecological mechanisms and resilience processes. Parallel to these empirical approaches, a considerable share of the literature draws on review and synthesis methods, which play a pivotal role in consolidating dispersed findings into integrative knowledge frameworks. Moreover, socio-ecological and participatory approaches, though less frequent, signal an increasing awareness of the necessity to link ecological science with community-based adaptation and governance strategies. Paleoecological reconstructions, however, being a minor percentage, yield essential long-term insights into mangrove responses to historical climate variability, thereby providing significant baselines for understanding current and future changes.

3.2 Drivers of Mangrove Resilience

A multi-dimensional approach is essential for accurately evaluating and improving mangrove resilience in considering projected climate variability and change. In this study, mangrove resilience is determined by four primary dimensions: biophysical, geomorphological-hydrological, climatic, and socio-institutional. The interaction among biophysical and species-level traits, geomorphological and hydrological settings, climatic and environmental variability, and socio-institutional and governance dimensions, as summarized in Table 3, collectively shapes resilience outcomes.

As outlined in Table 3, sediment dynamics and hydrological connectivity (geomorphological-hydrological dimension) play a

Table 3. Categories of drivers influencing mangrove resilience. Note: ENSO = El Niño–Southern Oscillation; IOD = Indian Ocean Dipole; PDO = Pacific Decadal Oscillation; AMO = Atlantic Multidecadal Oscillation.

Category	Key Drivers Identified
Biophysical and species-level traits	Root productivity and morphology; species-specific physiological adaptations (*e.g.*, salinity tolerance, redox adjustment, salt excretion in *Avicennia germinans*); canopy structure; tree size and wood traits; regeneration dynamics (propagule dispersal, epicormic resprouting); structural redundancy; prior exposure and life stage
Geomorphological and hydrological settings	Sediment supply and accretion; tidal flushing; elevation capital; geomorphic context; hydrological buffering (lagoons); freshwater inflow and connectivity; storm-driven deposition; migration space availability
Climatic and environmental variability	Sea-level rise; drought severity; storm frequency and intensity; freeze thresholds; temperature anomalies; historical climate patterns; ENSO, IOD, PDO, AMO oscillations; regional climate stability; ocean–land buffering (*e.g.*, nocturnal canopy warming)
Socio-institutional and governance dimensions	Anthropogenic pressures (urbanization, land use change, population density, encroachment); adaptive governance; policy support; protected area coverage; spatial connectivity; monitoring and enforcement; community engagement; knowledge integration; sustainable livelihoods

key role in facilitating adaptation to sea-level rise, while species-specific traits and canopy structure (biophysical dimension) influence tolerance to climatic extremes. In addition, climatic variability, including sea-level rise and extreme events, acts as a key external driver, while the effectiveness and inclusivity of governance and management practices (socio-institutional dimension) critically determine whether resilience is strengthened or weakened.

This review conceptualizes the drivers of mangrove resilience as stemming from climate variability. Table 4 organizes these drivers into major themes, including gradual processes such as sea-level rise and temperature anomalies, as well as episodic disturbances, including tropical cyclones, hurricanes, and compound extreme events. This structure clarifies the synthesis and highlights the primary climatic drivers influencing mangrove dynamics. It also demonstrates the range of stressors addressed in the literature, supporting a comprehensive understanding of the interactions between climate variability and mangrove resilience.

Analysis of 44 studies indicates that sea-level rise, examined in 21 studies, and tropical cyclones or hurricanes, examined in 17 studies, are the most frequently investigated climate drivers affecting mangrove ecosystems. Researchers often assess these drivers both independently and in conjunction with additional stressors, such as storm surge, salinity intrusion, and precipitation variability. Temperature-related factors, including warming anomalies and extreme cold events, were linked to physiological thresholds and changes in mangrove distribution in 12 studies. Precipitation and hydrological changes, addressed in 14 studies, were also identified as critical, particularly in relation to flooding, salinity balance, and freshwater availability. Large-scale climatic oscillations, such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), were identified in 9 studies as key modulators of multiple hazards, influencing droughts, storms, and rainfall extremes. Only four studies examined compound extreme events, such as tsunamis and wind-wave energy events, which, despite their rarity, pose significant risks to mangrove resilience. Overall, the literature addresses gradual drivers, such as sea-level rise, temperature warming, and rainfall variability, as well as episodic high-intensity hazards, including cyclones and hurricanes. In contrast, compound and cascading extreme events remain insufficiently explored.

Table 4. Climate variability category addressed in mangrove resilience studies.

Climate Variability Category	Examples	Number of Articles (n=44)	Source
Sea-level rise (SLR)	Historical SLR, projected SLR (Representative Concentration Pathways (RCP)/ Shared Socioeconomic Pathways (SSP), subsidence, sediment supply, salinity intrusion	21	Agraz-Hernández *et al*., 2022; Allen *et al*., 2021; Cinco-Castro and Herrera-Silveira, 2020; Ding *et al*., 2024; Duncan *et al*., 2018; Dutta Roy *et al*., 2024; Ellison and Strickland, 2015; Gijsman *et al*., 2021; Guo *et al*., 2018; Hens *et al*., 2018; Huang *et al*., 2020; Krauss *et al*., 2014; Li *et al*., 2022; Liang *et al*., 2023; Maina *et al*., 2021; McKee *et al*., 2020; Parkinson and Wdowinski, 2022; Sardar and Samadder, 2023; Srivastava *et al*., 2015; Urrego *et al*., 2019; Ward *et al*., 2023
Temperature variability	Warming trends (+1.5–2°C), long-term anomalies, extreme cold/ freezing events	12	Bonilla-Roman & Acuña-Guzman, 2024; Cinco-Castro & Herrera-Silveira, 2020; Feehan *et al*., 2024; Flower *et al*., 2017; Huang *et al*., 2020; Li *et al*., 2022; Liang *et al*., 2023; Mo *et al*., 2023; Osland *et al*., 2015, 2017; Urrego *et al*., 2019; Xu *et al*., 2016
Precipitation & Hydrological variation	Rainfall variability, drought cycles, runoff patterns, flooding (freshwater & seawater)	14	Agraz-Hernández *et al*., 2022; Andrieu *et al*., 2020; Cinco-Castro & Herrera-Silveira, 2020; Flower *et al*., 2017; Galeano *et al*., 2017; Hens *et al*., 2018; Li *et al*., 2022; Maina *et al*., 2021; Sewilam *et al*., 2024; Srivastava *et al*., 2015; Sunkur *et al*., 2024; Touza *et al*., 2021; Urrego *et al*., 2019; Ward *et al*., 2016
Tropical cyclones & Hurricanes	Cyclone Eline (2000), Hurricanes Hugo, Irma, Maria, North Atlantic TCs, storm surges, wind intensity	17	Allen *et al*., 2021; Andrieu *et al*., 2020; Bennion *et al*., 2024; Bonilla-Roman & Acuña-Guzman, 2024; Carruthers *et al*., 2024; Cohen *et al*., 2024; Hens *et al*., 2018; Hill *et al*., 2024; Imbert, 2018; Li *et al*., 2022; Liang *et al*., 2023; Macamo *et al*., 2016; McKee *et al*., 2020; Mo *et al*., 2023; Odériz *et al*., 2020; Peereman *et al*., 2022; Ward *et al*., 2023
Large-scale climatic oscillations	ENSO, IOD, PDO, AMO, Indian Ocean Dipole, El Niño & La Niña	9	Agraz-Hernández *et al*., 2022; Allen *et al*., 2021; Galeano *et al*., 2017; Gijsman *et al*., 2021; Kathirvelpandian *et al*., 2024; Maina *et al*., 2021; Srivastava *et al*., 2015; Touza *et al*., 2021; Urrego *et al*., 2019
Compound extreme events	Tsunamis, extreme tides, wind-wave energy events, multi-hazard combinations	4	Crameri & Ellison, 2022; Ding *et al*., 2024; Dutta Roy *et al*., 2024; Peereman *et al*., 2022

3.3 Mangrove Responses to Climate Variability

A review of 44 studies identifies five primary mangrove response pathways, as summarized in Table 5. The pathways are: (1) resistance to disturbance through structural and physiological buffering; (2) recovery through regrowth, resprouting, and increased sediment or elevation; (3) reorganization through species turnover and altered stand structure; (4) range shifts, including landward migration or retreat, determined by elevation and available space; and (5) threshold responses that result in partial or widespread dieback under compound or persistent stress.

Mangrove resilience pathways are diverse, but the combined effects of climatic, geomorphic, ecological, and anthropogenic drivers fundamentally determine their trajectories. Resistance is supported by ecological factors, such as species-specific physiological traits and wood structure, as well as by geomorphic factors, including elevation and buffered microclimates. These drivers enable mangroves to withstand stress with minimal canopy loss. For example, species-specific resistance has been observed in multiple contexts: *Avicennia germinans* demonstrated higher adult survival and resprouting capacity compared to juveniles under extreme cold stress (Osland *et al*., 2015), while *Avicennia marina* and *Rhizophora mucronata* exhibited differential recovery following cyclone Eline, with sheltered sites showing greater resilience (Macamo *et al*., 2016). Similarly, root productivity and soil elevation feedback contribute to buffering effects against sea-level rise and storm surges (Krauss *et al*., 2014). Complementing these empirical findings, previous study highlights that wood density and root architecture in species such as *Rhizophora mangle* and *Avicennia germinans* play a decisive role in minimizing uprooting and canopy damage during storms (Alongi, 2015).

Recovery processes, such as resprouting, canopy infill, and sediment-driven elevation gain, are closely linked to geomorphic and hydrological drivers, including sediment supply, connectivity, and storm deposition. For instance, *Avicennia germinans* adults exhibited resprouting capacity following extreme cold stress in the Gulf of Mexico (Osland *et al*., 2015), while root productivity and storm-induced sedimentation enhanced vertical accretion in several regions (Galeano *et al*., 2017; Gijsman *et al*., 2021; Imbert, 2018; Krauss *et al*., 2014; Li *et al*., 2022; McKee *et al*., 2020; Parkinson & Wdowinski, 2022; Urrego *et al*., 2019; Ward *et al*., 2016). However, recovery potential is often contingent on hydrological connectivity, as illustrated by differences in recovery between sheltered and exposed sites after cyclone Eline in Mozambique (Macamo *et al*., 2016). This pattern aligns with broader evidence showing that fragmented or embanked mangrove areas tend to display delayed or incomplete regrowth (Cinco-Castro & Herrera-Silveira, 2020; Parkinson & Wdowinski, 2022; Sewilam *et al*., 2024; Ward *et al*., 2016).

Reorganization reflects adaptive restructuring, where ecological drivers such as species turnover and regeneration dynamics interact with climatic disturbances, including hurricanes, droughts, and sea-level rise. This process often manifests as shifts in species dominance, altered recruitment patterns, and modified structural configurations. For example, life stage–dependent responses in *Avicennia germinans* revealed that adult trees resprouted more effectively than juveniles after extreme cold stress, reshaping population structure (Osland *et al*., 2015). Similarly, post-cyclone assessments in Mozambique

Table 5. Concise typology of mangrove response pathways to climate variability.

Response pathway	Typical field/ remote sensing indicators	When it occurs	Typical outcomes
Resistance	Minimal canopy loss; stable normalized difference vegetation index (NDVI)/evapotranspiration (ET); low uprooting	Steep/elevated, buffered microclimates; mature stands	Short-term persistence with limited functional loss
Recovery	Resprouting, lateral infill, gradual NDVI/ET rebound; storm-delivered sediments	Moderate events; adequate sediment supply/ connectivity	Structural rebuild; elevation maintained
Reorganization	Species turnover; altered canopy height/ biomass; changed litterfall/propagules	Post-hurricane/drought sequences; heterogeneous settings	New dominant species; modified ecosystem functions
Range shift	Inland edge advance; retreat at seaward edge; marsh–mangrove ecotone movement	SLR with available upland space; warming at cold margins	Landward migration; fragmentation where constrained
Threshold/dieback	Large NDVI drop; stable carbon isotope ($\delta^{13}C$) and intrinsic water-use efficiency (iWUE) changes; elevation loss; mass mortality	Compound extremes; accelerating SLR; chronic human pressure	Dieback, functional collapse, slow/failed recovery

documented differential recovery among *Avicennia marina*, *Rhizophora mucronata*, and *Bruguiera gymnorrhiza*, leading to altered species composition across sheltered and exposed sites (Macamo *et al*., 2016). In Fiji, mangrove zonation reorganized through landward migration of *Rhizophora stylosa* in response to relative sea-level rise (Ellison & Strickland, 2015). Over longer timescales, interactions between sediment supply, soil elevation change, and regeneration processes drive shifts in ecosystem functioning and resilience (Krauss *et al*., 2014). Such reorganizations suggest resilience at the ecosystem level, buffering against total collapse, but they also entail trade-offs, including reductions in biodiversity and altered provisioning services (Galeano *et al*., 2017; Imbert, 2018; Urrego *et al*., 2019).

Range shifts are primarily driven by climatic forces, particularly sea-level rise and temperature increases, but they are critically moderated by geomorphic settings and constrained by anthropogenic pressures. Landward migration of mangroves has been widely documented in multiple regions. For instance, in Fiji, relative sea-level rise has triggered landward retreat of species such as *Rhizophora stylosa* (Ellison & Strickland, 2015), while in the Gulf of Mexico, warming winters reduced freeze frequency, enabling *Avicennia germinans* to expand poleward into salt marsh zones (Osland *et al*., 2015). A similar poleward expansion has also been observed at marsh-mangrove ecotones in Australia, consistent with broader climate warming trends (Alongi, 2015). Geomorphic feedback, including sediment supply and elevation gain, strongly influences whether mangroves can track sea-level rise through vertical or lateral shifts (Krauss *et al*., 2014). Conversely, in arid and densely populated coasts such as western India, rising temperatures interact with land-use change to alter mangrove distribution and constrain potential migration pathways (Srivastava *et al*., 2015). In urbanized Southeast Asia, hard infrastructure such as seawalls has blocked natural landward migration, leading instead to coastal squeeze, fragmentation, and heightened vulnerability (Lovelock *et al*., 2015).

Threshold responses occur when climatic extremes interact with persistent anthropogenic stress, driving ecosystems beyond resilience limits. Large-scale dieback has been reported in northern Australia, where extreme drought, coupled with heatwaves, led to the mortality of over 7,000 hectares of mangroves (Duke *et al*., 2017). In Mozambique, Cyclone Eline caused severe structural damage and incomplete recovery in exposed stands, highlighting how extreme storms can push mangrove ecosystems beyond recovery thresholds (Macamo *et al*., 2016). In subtropical USA, juvenile *Avicennia germinans* experienced widespread mortality following freeze events, contrasting with the survival of adults, which suggests life-stage-specific thresholds (Osland *et al*., 2015). In India, interacting pressures from sea-level change and land-use modification have exacerbated declines in mangrove density (Srivastava *et al*., 2015), while in Fiji, relative sea-level rise combined with limited sediment supply has led to persistent elevation deficits and landward retreat (Ellison & Strickland, 2015). More broadly, global syntheses show that threshold responses are rarely the result of climate drivers alone, but are compounded by geomorphic constraints, governance gaps, altered hydrology, and land-use pressures (Alongi, 2015; Krauss *et al*., 2014).

Mangroves rely on both natural geomorphic settings and human management for effective resilience. Adaptive governance, sediment management, and conserving landward migration corridors are crucial for supporting resilience as climate variability intensifies. Evidence from the reviewed studies indicates that ecological processes, such as resprouting, species turnover, and vertical accretion, are fundamentally influenced by geomorphic factors, including elevation, sediment supply, and hydrological connectivity (Ellison & Strickland, 2015; Krauss *et al*., 2014; Osland *et al*., 2015). However, the persistence of these natural buffering mechanisms is increasingly dependent on anthropogenic interventions. Cases from India and Mozambique illustrate how land-use change, embankments, and exposure to extreme storms constrain recovery and accelerate vulnerability (Macamo *et al*., 2016; Srivastava *et al*., 2015). This underscores that resilience is not only an ecological attribute but also a socio-ecological outcome shaped by management and policy. Strengthening resilience, therefore, requires integrating climate-adaptive governance, proactive sediment and hydrological management, and the protection of landward migration corridors to prevent coastal squeeze (Alongi, 2015; Lovelock *et al*., 2015). Together, these measures ensure that mangrove ecosystems can reorganize, recover, and persist under intensifying climate variability while continuing to provide critical biodiversity and ecosystem services.

3.4 Research gap

This synthesis identifies several critical gaps in the current understanding of the interactions between climate variability and mangrove ecosystems. Geographically, research is unevenly distributed, with concentrations in the United States, Southeast and East Asia, Colombia, the Caribbean, and parts of Africa,

while evidence from Australia, South America, and small Pacific islands remains limited, constraining the global generalizability of findings. A clear zonal disparity is also evident between tropical and subtropical regions. Tropical mangrove systems, particularly in Southeast Asia and the Caribbean, dominate the literature, reflecting their high biomass, biodiversity, and vulnerability to sea-level rise. By contrast, subtropical ecosystems represent a much smaller proportion of studies, leaving major gaps in understanding how mangroves at climatic margins respond to variability and extremes, such as resilience thresholds, poleward range expansion, and sensitivity to cold events. This scarcity of evidence in transitional zones weakens the ability to capture cross-latitudinal dynamics of resilience.

Our findings further show that sea-level rise and storms are the most frequently studied climatic drivers (Table 4). Correspondingly, the most commonly reported response pathways include range shifts in response to sea-level rise and recovery or dieback in response to storms (Table 5). This indicates that the research community has primarily focused on responses to gradual long-term changes and large-scale episodic disturbances. While such focus has generated important insights, it leaves other critical drivers, such as droughts, heat stress, and compound or cascading events, comparatively underexplored.

Thematically, most studies emphasize biophysical and climatic processes, while socio-institutional dimensions, including governance, community-based adaptation, and policy integration, remain insufficiently addressed. Another important gap lies in the integration of multi-scalar perspectives: paleoecological records, contemporary monitoring, and predictive modeling are seldom combined, yet such integration is essential for projecting future resilience trajectories. Moreover, limited research addresses the interactions between climatic variability and anthropogenic pressures, such as land-use change, aquaculture expansion, or coastal infrastructure development, which may amplify vulnerability and constrain natural adaptive capacities. Addressing these research gaps requires more geographically inclusive, interdisciplinary, and socio-ecological approaches to comprehensively capture how mangrove ecosystems respond and adapt to intensifying climate variability.

3.5 Limitations of the study

Despite its contributions, this review has several limitations. The spatial and temporal distribution of studies is uneven, with underrepresentation in regions such as Australia, South America, and small Pacific islands, limiting global generalizability. Methodological heterogeneity and the predominance of descriptive approaches restrict opportunities for meta-analysis and quantitative synthesis. In addition, the graphical representations presented in this study are primarily descriptive and may not fully capture complex relationships between variables, such as interactions between biophysical, climatic, and socio-institutional drivers.

The reliance on English-language, peer-reviewed literature and the exclusive use of the Scopus database may also have led to the omission of relevant local or regionally indexed studies. In addition, the exclusion of the keyword carbon, although intended to avoid bias toward mitigation studies, may have overlooked research that frames resilience through carbon-related indicators, despite the inherent link between resilience and carbon dynamics. Finally, most studies emphasize biophysical drivers, while governance, policy, and community-based adaptation remain comparatively neglected.

Despite these limitations, this review provides an integrative synthesis that highlights key gaps in the understanding of mangrove resilience under climate variability, particularly the limited integration of climatic, ecological, and socio-institutional dimensions. This contribution is essential for supporting more comprehensive and policy-relevant resilience frameworks. Overall, the findings should be interpreted as indicative rather than universal, while underscoring the need for more inclusive, interdisciplinary, and socio-ecological research on mangrove resilience in support of global sustainability agendas, particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

4. CONCLUSIONS

This systematic review demonstrates that mangrove resilience to climate variability is shaped by interconnected biophysical, geomorphological, climatic, and socio-institutional drivers, with sea-level rise, tropical cyclones, precipitation anomalies, and large-scale oscillations such as ENSO emerging as the most influential stressors. Mangroves respond through pathways of resistance, recovery, reorganization, range shifts, and threshold dynamics, yet these adaptive capacities are increasingly constrained by anthropogenic pressures, including land-use change, fragmentation, and coastal infrastructure. Across the reviewed studies, a consistent pattern emerges in which resilience is governed by the interaction between environmental stressors and ecosystem adaptive capacity, highlighting the

importance of integrated system-level understanding. The findings highlight that resilience is not solely an ecological attribute, but a socio-ecological outcome that requires integrated strategies to safeguard sediment and hydrological processes, protect migration corridors, and strengthen adaptive governance. However, significant gaps remain, particularly in the limited integration of climatic drivers with socio-institutional processes and the underrepresentation of certain geographical regions. Addressing geographic and disciplinary gaps through interdisciplinary and inclusive research will be essential to enhance the role of mangroves as natural buffers against climate extremes, thereby supporting biodiversity, ecosystem services, and the achievement of global sustainability goals, particularly SDGs 13, 14, and 15. These insights underline the need for more application-oriented and policy-relevant research to support effective climate adaptation and coastal management strategies.

AUTHOR'S CONTRIBUTION

Anies Ma'rufatin: Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, and Writing - Review & Editing. Novian Andri Akhirianto: Writing - Review & Editing, Data Curation, and Validation. Khusnul Setia Wardani: Supervision and Data Curation. Amalia Nurwijayanti: Software, Methodology, and Validation. Farikhotul Chusnayah: Investigation, Resources, and Methodology. Favian Mavazi Giska Putra: Methodology and Visualization.

ACKNOWLEDGMENT

This study is a part of the research activities conducted by the Coastal Resilience & Extreme-wave Solution Research Group at the Technology Research Center for Hydrodynamics Technology, BRIN. The authors gratefully acknowledge their colleagues for the support and valuable advice provided during this research.

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