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Advances in Monitoring and Managing Aquatic Ecosystem Health: Integrating Technology and Policy

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Abstract The The health of aquatic ecosystems is crucial for ecological balance and human well-being. This study explores recent advances in monitoring and managing aquatic ecosystem health, focusing on technological innovation and policy integration. It evaluates various advanced monitoring technologies, including remote sensing, IoT devices, biological monitoring methods, and big data analysis, applied to different water bodies such as lakes, rivers, and wetlands. These technologies provide comprehensive and detailed water quality data, enabling real-time monitoring and trend prediction. Additionally, the study analyzes the advantages and limitations of these technologies, such as high data acquisition costs, technical maintenance complexity, and data analysis bottlenecks. To address these challenges, it proposes enhancing monitoring and management efficiency through interdisciplinary collaboration and public participation. On the policy front, it discusses how sustainable water resource management can be achieved through legal frameworks, government-community cooperation, and international technological exchange. The study emphasizes the importance of integrating technology and policy and suggests future directions, including the development of cost-effective monitoring technologies, improvement of data analysis capabilities, and strengthening multi-stakeholder cooperation. This research provides a comprehensive reference framework for researchers and policymakers, aiming to promote the continuous development of aquatic ecosystem health monitoring and management.

Keywords Aquatic ecosystems; Health monitoring; Management strategies; Remote sensing: IoT; Big data analysis; Policy integration; Sustainable development

1 Introduction

Aquatic ecosystems, encompassing freshwater bodies such as rivers, lakes, wetlands, and coastal areas, are among the most diverse and productive environments on Earth. However, they are also some of the most threatened due to anthropogenic pressures, including pollution, habitat destruction, and climate change. The health of these ecosystems is crucial not only for maintaining biodiversity but also for providing essential ecosystem services such as water purification, flood regulation, and recreational opportunities. Monitoring and managing the health of aquatic ecosystems have thus become imperative to ensure their sustainability and resilience (Schofield et al., 2018).

The importance of monitoring and management in aquatic ecosystems cannot be overstated. Effective monitoring provides critical insights into the long-term changes and current status of these ecosystems, enabling the identification of emerging threats and the assessment of conservation efforts. Various methods have been developed for the hydromorphological, physical-chemical, and biological monitoring of surface waters, which are essential for sustainable water management and the achievement of global sustainability goals such as the United Nations Sustainable Development Goals (SDGs) (Forio and Goethals, 2020). Ecosystem-based management (EBM) approaches have also been advocated to integrate biodiversity conservation with ecosystem service provision, emphasizing the need for a holistic, social-ecological perspective in environmental management (Langhans et al., 2019).

By synthesizing findings from multiple studies, this study highlights innovative monitoring techniques, such as the use of constructed treatment wetlands for enhancing biodiversity and ecosystem services, and the concept of freshwater ecosystem mosaics (FEMs) that emphasize the connectivity and dynamic nature of aquatic habitats.

Additionally, this study discusses the challenges and opportunities associated with implementing these advanced methods in the context of global environmental change, particularly in maintaining the biodiversity and ecosystem services of lakes and other freshwater bodies. Through this comprehensive analysis, the study seeks to provide actionable insights for policymakers, researchers, and practitioners dedicated to the sustainable management of aquatic ecosystems.

2 Technological Advances in Monitoring

2.1 Remote sensing technologies

Remote sensing technologies have significantly advanced the monitoring of aquatic ecosystems, providing critical data for managing water quality and ecosystem health. Hyperspectral sensors, such as PRISMA and DESIS, have been utilized to retrieve water quality parameters across various aquatic environments, including deep clear lakes and river dammed reservoirs. These sensors offer high spatial and spectral resolution, enabling detailed analysis of water bio-physical parameters and supporting management decision-making (Bresciani et al., 2022). Additionally, remote sensing has been applied to monitor submerged aquatic vegetation (SAV), which is crucial for ecosystem health but challenging to study due to water column effects. Techniques to correct for these effects have been developed, enhancing the accuracy of remote sensing in aquatic environments.

2.2 In-situ monitoring tools

In-situ monitoring tools have evolved to provide real-time data on water quality and ecosystem health. Biological early warning systems (BEWS) that monitor the behavior and physiological parameters of aquatic bioindicator species have been developed to detect sudden changes in water quality. These systems offer continuous monitoring and early warning capabilities, which are essential for timely management interventions (Bownik and Wlodkowic, 2021). Additionally, high-frequency environmental sensing tools have expanded the ability to measure aquatic ecosystem metabolism, providing insights into gross primary productivity and ecosystem respiration. These measurements are valuable for understanding ecosystem function and informing environmental management (Jankowski et al., 2021).

2.3 Molecular and genetic techniques

Molecular and genetic techniques, such as environmental DNA (eDNA) sequencing, have become integral to monitoring aquatic ecosystems. These techniques allow for the detection and monitoring of a wide range of organisms, including those that are difficult to observe using traditional methods. eDNA sequencing can trace the presence of various species, providing comprehensive data on biodiversity and ecosystem health. This approach is particularly useful in deep-sea ecosystems, where traditional monitoring methods are challenging and costly (Aguzzi et al., 2019).

2.4 Data analytics and artificial intelligence

The integration of data analytics and artificial intelligence (AI) has revolutionized the monitoring and management of aquatic ecosystems. AI and machine learning algorithms can process large datasets from remote sensing and in-situ monitoring tools, providing actionable insights for conservation and management. Automated monitoring systems facilitated by AI reduce data processing bottlenecks and long-term monitoring costs, enabling more effective and timely decision-making. Furthermore, advances in machine learning and cloud computing allow for the exploitation of the full electromagnetic spectrum, enhancing the ability to monitor and assess aquatic environments (Dierssen et al., 2021).

3 Policy Frameworks for Aquatic Ecosystem Management

3.1 International policies and agreements

International policies and agreements play a crucial role in the management and conservation of aquatic ecosystems. The United Nations' Sustainable Development Goals (SDGs), particularly SDG6 (clean water and sanitation) and SDG15 (life on land), provide a global framework for sustainable water management and the protection of terrestrial and freshwater ecosystems (Forio and Goethals, 2020). These goals emphasize the need for integrated monitoring and assessment methods to support sustainable development and ensure the health of aquatic ecosystems. Additionally, international agreements such as the Ramsar Convention on Wetlands and the Convention on Biological Diversity (CBD) set guidelines and targets for the conservation and sustainable use of aquatic resources, promoting international cooperation and the sharing of best practices.

3.2 National regulations and guidelines

National regulations and guidelines are essential for implementing international policies at the country level. In the United States, for example, the Clean Water Act provides a regulatory framework for maintaining and restoring the chemical, physical, and biological integrity of the nation's waters (Jankowski et al., 2021). This includes the use of high-frequency environmental sensing and statistical approaches to monitor aquatic ecosystem metabolism, which can inform environmental management practices. Similarly, European countries have adopted the Water Framework Directive, which aims to achieve good ecological status for all water bodies through comprehensive monitoring and management strategies (Jankowski et al., 2021). These national regulations often incorporate advanced technologies and methodologies, such as the Internet of Things (IoT) and smart monitoring systems, to enhance the accuracy and efficiency of aquatic ecosystem assessments (Glaviano et al., 2022).

3.3 Local management practices

Local management practices are critical for addressing specific environmental challenges and ensuring the effective implementation of national and international policies. Local initiatives often involve the use of integrated assessment frameworks that consider multiple indicator species and various biological communities to evaluate the health of aquatic ecosystems (Zhao et al., 2019). For instance, the use of smart buoy networks (SBNs), autonomous underwater vehicles (AUVs), and multi-sensor microsystems (MSMs) allows for real-time monitoring and adaptive management of coastal and marine environments (Glaviano et al., 2022). These technologies enable local managers to respond promptly to environmental changes and potential threats, thereby enhancing the resilience and sustainability of aquatic ecosystems.

3.4 Stakeholder involvement and community engagement

Stakeholder involvement and community engagement are fundamental components of effective aquatic ecosystem management. Engaging local communities, stakeholders, and indigenous groups in monitoring and conservation efforts can lead to more sustainable and inclusive management practices. For example, the use of IoT-based environmental assessment systems can facilitate community participation by providing accessible and transparent data on water quality and ecosystem health (Narmadha et al., 2023). Additionally, involving stakeholders in the development and implementation of management plans can help ensure that diverse perspectives and knowledge systems are considered, leading to more comprehensive and effective conservation strategies. Collaborative efforts between scientists, policymakers, and local communities are essential for achieving long-term sustainability and resilience of aquatic ecosystems (Zhao et al., 2019). By integrating international policies, national regulations, local management practices, and stakeholder involvement, we can develop a holistic approach to monitoring and managing aquatic ecosystem health. This integrated framework will support the sustainable use and conservation of aquatic resources, ensuring their continued provision of essential ecological services for human and environmental well-being.

4 Integration of Technology and Policy

4.1 Case studies of successful integration

The integration of technology and policy in monitoring and managing aquatic ecosystem health has shown promising results in various case studies. For instance, the H2020 project AQUACROSS has successfully unified policy strategies, knowledge, and management concepts of freshwater, coastal, and marine ecosystems to support the EU Biodiversity Strategy to 2020. This project embraced ecosystem-based management (EBM) to protect biodiversity and sustainably harvest ecosystem services, demonstrating the utility of EBM in safeguarding aquatic biodiversity (Langhans et al., 2019). Another example is the use of IoT technology for environmental assessment, where sensors and Arduino micro-controllers were employed to measure variables such as pH, Total Dissolved Solids, dissolved oxygen, and CO_2. This approach has proven effective in tracking the health of aquatic ecosystems and informing policy decisions for their protection. Additionally, the One Health approach, which integrates human, fish, and environmental health, has been applied to manage trace metal contamination in aquatic ecosystems. This approach uses statistical tools to identify contamination sources and pathways, assess health risks, and establish robust monitoring programs (Izah et al., 2023).

4.2 Challenges in integration

Despite the successes, several challenges hinder the effective integration of technology and policy in aquatic ecosystem management. One significant challenge is the need for frequent sensor calibration and ensuring data accuracy in IoT-based monitoring systems. Sensor malfunction and data loss can also pose risks to the reliability of the monitoring data (Narmadha et al., 2023). Another challenge is the limited application of advanced biomonitoring approaches, such as the SPEcies At Risk of pesticides (SPEAR) index, in tropical regions, which restricts the global applicability of these methods (Sumudumali and Jayawardana, 2021). Furthermore, the complexity of integrating multiple biological communities into a single assessment framework can lead to uncertainties in the results, as seen in the integrated assessment of ecosystem health using multiple indicator species. The need for high-frequency monitoring and the alignment of manual sampling with automatic and remote sensing methods also present logistical and technical difficulties.

4.3 Best practices for effective integration

To overcome these challenges and enhance the integration of technology and policy, several best practices can be adopted. First, incorporating redundancy in sensor systems and using machine learning algorithms for data analysis can improve the reliability and accuracy of IoT-based monitoring. Second, expanding the application of advanced biomonitoring approaches, such as the SPEAR index, to tropical regions can enhance the global applicability of these methods. Third, developing a comprehensive framework that integrates multiple biological communities and compensates for uncertainties in single-index assessments can provide a more holistic view of ecosystem health (Zhao et al., 2019). Additionally, adopting a holistic water monitoring approach that combines manual sampling, on-site automatic high-frequency monitoring, and remote sensing can facilitate more informed decision-making and adaptive water resource management (Yang and Zhang, 2019) (Figure 1). Finally, fostering collaboration between policymakers, scientists, and stakeholders is crucial for the successful implementation of integrated monitoring and management strategies. By addressing these challenges and adopting best practices, the integration of technology and policy can significantly improve the monitoring and management of aquatic ecosystem health, contributing to the sustainable development and conservation of these vital ecosystems.

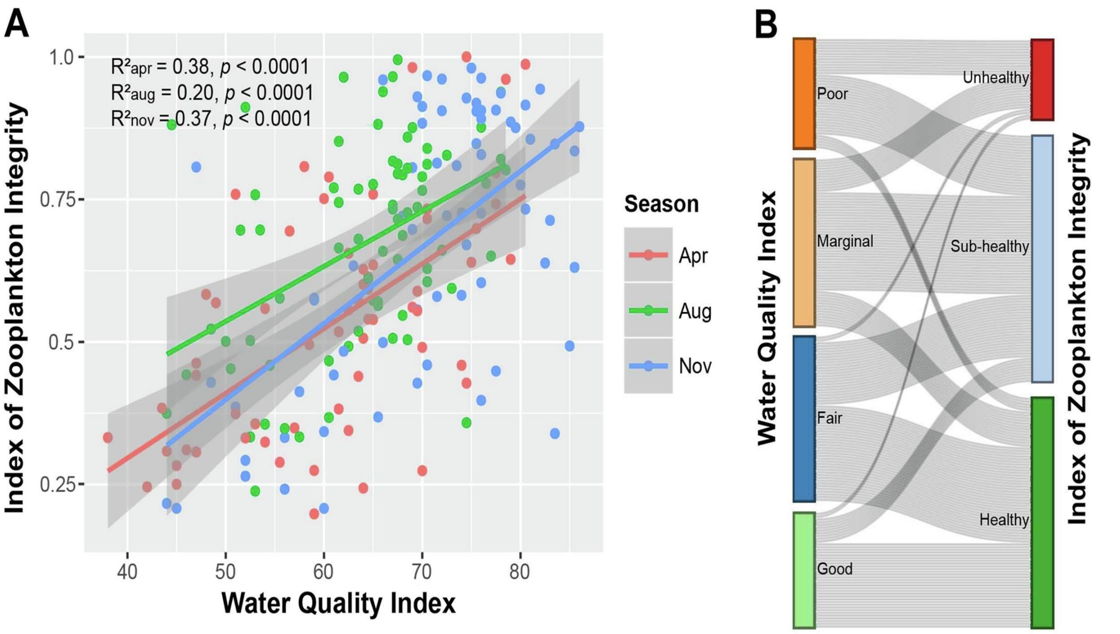

Figure 1 eDNA-based zooplankton integrity index and ecological status assessment (Adopted from Yang and Zhang et al., 2019)
Image capton: (A) Correlation between eDNA zooplankton integrity and water quality. (B) Ecological status classified according to the metabarcoding zooplankton integrity index and the water quality index (Adopted from Yang and Zhang et al., 2019)

Yang and Zhang (2019) found that the eDNA-based zooplankton integrity index demonstrates a significant correlation with water quality, with stronger correlations observed in April ($R^2 = 0.38$) and November ($R^2 = 0.37$) compared to August ($R^2 = 0.20$). These findings suggest that zooplankton integrity, as assessed through metabarcoding, is a reliable indicator of water quality. The ecological status, classified according to both the zooplankton integrity index and the water quality index, highlights a gradient from poor to healthy conditions. This classification can help in assessing and managing the ecological health of aquatic environments, showing that higher water quality typically corresponds with healthier zooplankton populations.

5 Case Studies in Monitoring and Management

5.1 Freshwater ecosystems

Freshwater ecosystems are critical for biodiversity and human well-being, yet they face significant threats from land-use changes, climate warming, and pollution. Recent advancements in monitoring technologies and methodologies have provided new insights and tools for managing these ecosystems. For instance, the use of stable isotope analysis and ecological modeling has enhanced our understanding of aquatic plant distribution and interactions within freshwater systems (Cherry and Pec, 2022). Additionally, integrated monitoring approaches that combine hydromorphological, physical-chemical, and biological assessments have been developed to support sustainable water management and the implementation of Sustainable Development Goals (SDGs). Biological monitoring, particularly using macroinvertebrates (Figure 2), has also proven effective in assessing the health of freshwater ecosystems and detecting pesticide pollution (Forio and Goethals, 2020).

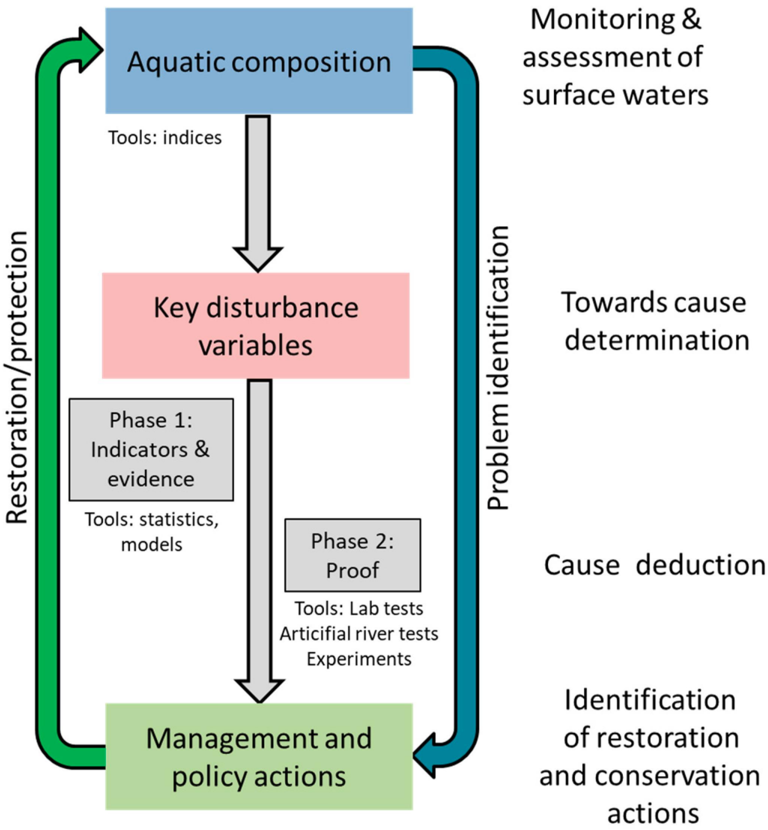

Figure 2 Diagram illustrating the cycles of monitoring and assessment programmes—management and policy action of water bodies towards sustainable development and the management of water resources (Adopted from Forio and Goethals, 2020)

Image capton: Water composition: Use tools such as indices to monitor and evaluate surface water, Key interference variables: Identify and demonstrate the factors that affect water quality through two stages, Stage one involves collecting indicators and evidence through statistical and modeling tools; Phase 2 is validated through laboratory testing and artificial river experiments, Management and policy actions: Based on the findings of the first two stages, develop and implement corresponding management and policy measures, Recovery/Protection: Feedback the results of management and policy actions into the monitoring and evaluation of water composition, forming a continuous improvement loop (Adopted from Forio and Goethals, 2020)

Forio and Goethals (2020) found that the process of sustainable water resource management involves a cyclic approach of monitoring, assessment, and management actions. This cycle begins with the assessment of aquatic composition using various indices. Identifying key disturbance variables is the next step, where indicators and evidence are gathered using statistical tools and models. This leads to problem identification and cause determination, which is further validated through lab tests, artificial river tests, and experiments. Management and policy actions are then implemented based on these findings. The final step in the cycle involves restoration and protection measures to maintain or improve water quality, thereby closing the loop and feeding back into continuous monitoring and assessment. This iterative approach ensures the effective management and sustainable development of water resources.

5.2 Marine ecosystems

Marine ecosystems are subject to various anthropogenic pressures, including pollution, overfishing, and climate change. The advent of smart monitoring technologies, such as smart buoy networks (SBNs), autonomous underwater vehicles (AUVs), and multi-sensor microsystems (MSMs), has revolutionized the monitoring and management of these ecosystems. These technologies enable real-time data collection and adaptive monitoring programs, which are crucial for responding to environmental changes and catastrophic events. The integration of Internet of Things (IoT) technology has further enhanced the ability to track and manage marine ecosystem health by providing accurate and precise measurements over large areas (Narmadha et al., 2023). Despite these advancements, the full potential of these tools in marine ecosystem management is yet to be realized and will likely become more evident in the coming decade (Glaviano et al., 2022).

5.3 Transitional and coastal ecosystems

Transitional and coastal ecosystems, such as estuaries and mangroves, are dynamic environments that provide essential services, including nutrient cycling, habitat provision, and coastal protection. These ecosystems are increasingly recognized for their role in supporting biodiversity and human livelihoods. The concept of ecosystem-based management (EBM) has been embraced to integrate biodiversity conservation and ecosystem service provision in these areas. EBM approaches environmental management from a social-ecological system perspective, aiming to protect biodiversity while sustainably harvesting ecosystem services. The AQUACROSS project, for example, has unified policy strategies and management concepts across freshwater, coastal, and marine ecosystems to support the EU Biodiversity Strategy targets (Langhans et al., 2019). This integrated approach is essential for addressing the complex challenges facing transitional and coastal ecosystems and ensuring their long-term sustainability.

6 Technological Innovations and Future Trends

6.1 Emerging monitoring technologies

Recent advancements in monitoring technologies have significantly enhanced our ability to assess and manage aquatic ecosystems. The integration of artificial intelligence (AI) and automated monitoring systems has emerged as a powerful tool for conservation managers, enabling the collection, transfer, and processing of data over large spatio-temporal scales. This approach reduces monitoring bottlenecks and long-term costs, facilitating timely and effective management decisions. Additionally, the Internet of Things (IoT) has revolutionized environmental assessment by providing accurate and precise measurements over larger areas through smart devices and increased networking capabilities (Glaviano et al., 2022). Smart buoy networks (SBNs), autonomous underwater vehicles (AUVs), and multi-sensor microsystems (MSMs) are examples of such technologies that can autonomously adapt their monitoring programs and send alarm messages to prompt human intervention (Glaviano et al., 2022).

6.2 Advances in data collection and analysis

The field of aquatic ecosystem monitoring has seen significant improvements in data collection and analysis methods. High-frequency environmental sensing and statistical approaches have expanded our understanding of aquatic ecosystem metabolism, allowing for the measurement and interpretation of gross primary productivity (GPP) and ecosystem respiration (ER) (Jankowski et al., 2021). The use of environmental DNA (eDNA) has also gained traction as a non-invasive method to gather relevant data on species presence and biodiversity, offering a cost-effective alternative to traditional sampling methods. Furthermore, the integration of IoT technology with machine learning algorithms has enhanced data accuracy and reliability, addressing challenges such as sensor calibration and data loss (Narmadha et al., 2023). These advancements enable the creation of comprehensive monitoring systems that can inform environmental management and policy decisions.

6.3 Future directions in technological development

Looking ahead, the future of aquatic ecosystem monitoring and management will likely be shaped by continued advancements in AI, IoT, and other emerging technologies. The development of integrated ecosystem assessments that synthesize physical, biological, and socioeconomic observations will provide a holistic understanding of ecosystem health and guide better management strategies. Additionally, the adoption of ecosystem-based fisheries management (EBFM) approaches, which consider changes in the physical environment and interactions between ecosystem elements, will further enhance our ability to manage marine resources sustainably (Schmidt et al., 2019) (Figure 3). The use of advanced diagnostic techniques, such as sequencing, biosensors, and CRISPR, will also play a crucial role in the early detection and monitoring of diseases in aquatic animals, improving aquaculture productivity and efficiency. As these technologies continue to evolve, their widespread adoption and integration into monitoring and management practices will be essential for the long-term conservation and sustainability of aquatic ecosystems.

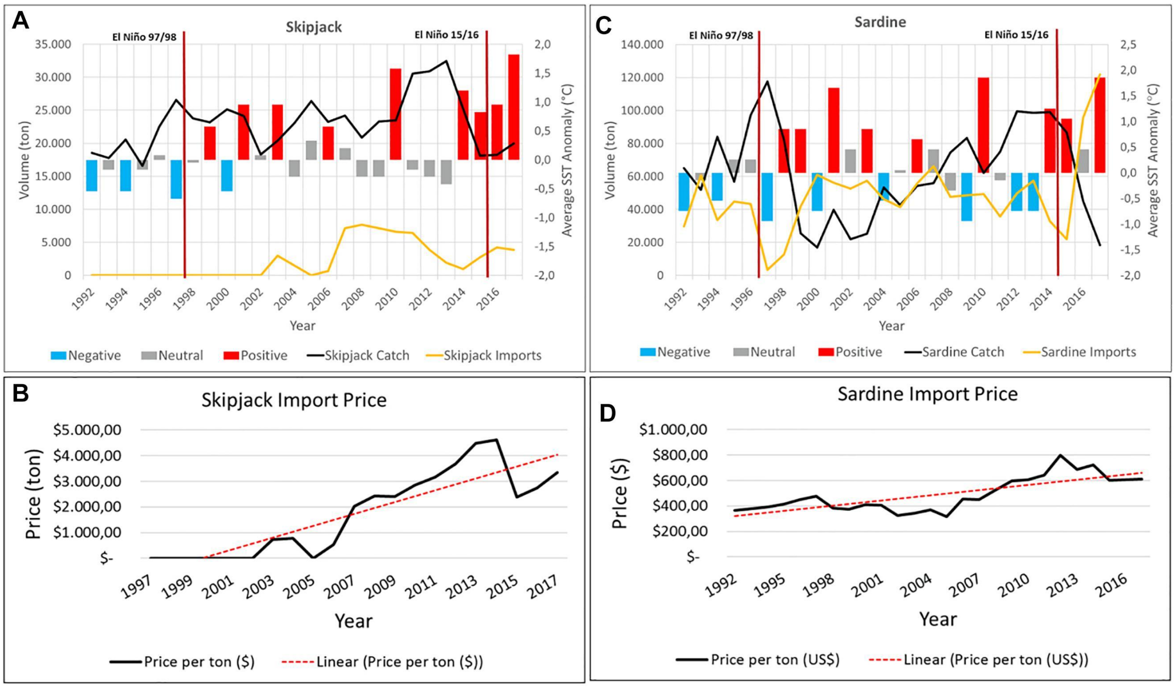

Figure 3 Impact of el niño events on skipjack and sardine catch volumes and import prices (Adopted from Schmidt et al., 2019)
Image capton: Skipjack (A) and sardine catches (C) from 1992 to 2017 along the south east and south Brazilian coasts associated to SST average annual anomalies from virtual stations over the 50 m and 1000 isobaths. Skipjack (B) and sardine (D) import volumes and prices over the study period (Adopted from Schmidt et al., 2019)

Schmidt et al. (2019) found that skipjack and sardine catches along the southeast and south Brazilian coasts are significantly influenced by sea surface temperature (SST) anomalies, particularly during El Niño events. The study observed notable variations in catch volumes corresponding to positive and negative SST anomalies. For skipjack, both catch volumes and import prices have shown an increasing trend over the study period, indicating a possible link between market demand and environmental conditions. Similarly, sardine catches and import prices exhibited fluctuations in response to SST anomalies, with a general upward trend in prices over time. These findings highlight the critical impact of climatic events on fish populations and market dynamics, underscoring the importance of monitoring SST anomalies to predict and manage fisheries' productivity and economic outcomes effectively.

7 Policy Developments and Future Directions

7.1 Recent policy innovations

Recent advancements in technology have significantly influenced policy innovations aimed at monitoring and managing aquatic ecosystems. The integration of smart devices and the Internet of Things (IoT) has enabled more precise and extensive monitoring capabilities, which are crucial for responding to environmental threats such as oil spills and other pollutants (Jankowski et al., 2021). The use of environmental DNA (eDNA) for non-invasive sampling has also been recognized for its potential to revolutionize data collection, providing policymakers with more accurate and comprehensive biodiversity assessments. Additionally, the development of real-time biological early warning systems (BEWS) that monitor behavioral and physiological parameters of aquatic species offers a proactive approach to water quality management, allowing for timely interventions (Yang and Zhang, 2019).

7.2 Trends in policy making

Current trends in policy making emphasize the importance of integrating technological advancements with traditional monitoring methods to enhance the management of aquatic ecosystems. Policies are increasingly focusing on the use of high-frequency environmental sensing and statistical approaches to measure ecosystem metabolism, which provides valuable insights into the health of aquatic environments4. There is also a growing trend towards the use of multi-community monitoring and assessment methods that support sustainable development goals (SDGs), particularly those related to clean water and sanitation (SDG6) and life below water (SDG14) (Forio and Goethals, 2020). The incorporation of IoT-based environmental assessment tools into policy frameworks is another emerging trend, as these tools offer continuous and accurate monitoring of water quality parameters.

7.3 Future directions in policy development

Future policy development should aim to further integrate advanced monitoring technologies with environmental management practices. The use of IoT and smart monitoring systems should be expanded to cover larger areas and more diverse ecosystems, providing real-time data that can inform policy decisions (Glaviano et al., 2022). Policies should also promote the use of eDNA metabarcoding for ecological status assessments, as this method has shown promise in improving the accuracy and efficiency of biodiversity monitoring. Additionally, there is a need for policies that support the development and implementation of automated calibration systems and machine learning algorithms to enhance the reliability and accuracy of monitoring data (Narmadha et al., 2023). Moreover, future policies should encourage the inclusion of microbial community dynamics in routine biomonitoring programs, as these communities play a crucial role in nutrient cycling and ecosystem functioning. Finally, there should be a focus on developing integrated socio-environmental models that link monitoring data to ecosystem interactions and functions, providing a holistic approach to managing aquatic ecosystems in the context of sustainable development. By embracing these technological advancements and integrating them into policy frameworks, we can improve the monitoring and management of aquatic ecosystems, ensuring their health and sustainability for future generations.

8 Challenges and Opportunities

8.1 Technical and methodological challenges

The integration of advanced technologies in monitoring aquatic ecosystems presents several technical and methodological challenges. One significant issue is the frequent need for sensor calibration to ensure data accuracy, as highlighted in the study using IoT technology for environmental assessment (Narmadha et al., 2023). Additionally, the risk of system failure due to sensor malfunction or data loss poses a considerable challenge. The complexity of modeling ecosystem metabolism, particularly in rivers and lakes, also remains a hurdle, despite advancements in high-frequency environmental sensing and statistical approaches (Jankowski et al., 2021). Furthermore, the vast amounts of data generated by modern sensor technologies and autonomous platforms can overwhelm current data analysis capacities, creating a bottleneck in effective data utilization (Malde et al., 2020).

8.2 Policy and regulatory challenges

Policy and regulatory frameworks must evolve to keep pace with technological advancements in ecosystem monitoring. The application of new technologies such as smart buoy networks, autonomous underwater vehicles, and multi-sensor microsystems necessitates updated regulations to ensure their effective and ethical use (Glaviano et al., 2022). Additionally, the integration of ecosystem metabolism data into regulatory settings requires overcoming historical logistical and conceptual limitations. There is also a need for policies that support the sustainable management of aquatic plants, which are threatened by land-use changes, modified water regimes, and climate warming (Cherry and Pec, 2022). Ensuring that monitoring and assessment methods align with the Sustainable Development Goals (SDGs) further complicates the regulatory landscape.

8.3 Opportunities for improvement and innovation

Despite these challenges, there are significant opportunities for improvement and innovation in monitoring and managing aquatic ecosystem health. The use of IoT technology, combined with machine learning algorithms, offers a promising approach to enhance data accuracy and system reliability. The development of smart monitoring devices, such as drones, can provide high-resolution data with minimal disturbance to wildlife, thereby improving the quality and frequency of ecosystem health assessments (McIntosh et al., 2018). Additionally, the integration of multi-community monitoring and assessment methods can support sustainable water management and contribute to the achievement of multiple SDGs (Glaviano et al., 2022). Advances in artificial intelligence and deep learning also present opportunities to address the data analysis bottleneck, enabling more effective use of the vast amounts of data collected. These innovations hold the potential to transform the monitoring and management of aquatic ecosystems, ensuring their long-term health and sustainability.

9 Concluding Remarks

The systematic review of recent advancements in monitoring and managing aquatic ecosystem health highlights several key findings. Firstly, the integration of multi-community monitoring and assessment methods has proven essential for sustainable water management and the achievement of various Sustainable Development Goals (SDGs)1. Biological monitoring, particularly using macroinvertebrates, has been effective in assessing ecosystem health and pesticide pollution. Advances in high-frequency environmental sensing and statistical approaches have expanded the application of aquatic ecosystem metabolism in environmental management. Technological innovations, such as the Internet of Things (IoT) and smart monitoring devices, have significantly enhanced the precision and scope of aquatic ecosystem monitoring. The One Health approach, combined with statistical analysis, offers a comprehensive framework for managing trace metal contamination and promoting sustainable interactions between human and environmental health. Additionally, environmental DNA (eDNA) has emerged as a powerful tool for biodiversity monitoring, enabling the detection and quantification of various species. Finally, integrated assessment frameworks using multiple indicator species provide a more holistic view of ecosystem health, reducing uncertainties associated with single-community assessments.

The importance of integrated approaches in monitoring and managing aquatic ecosystems cannot be overstated. By combining various monitoring methods, such as hydromorphological, physical-chemical, and biological assessments, researchers can gain a comprehensive understanding of ecosystem health and its relation to SDGs. The use of multiple biological indicators, including macroinvertebrates, fish, and plankton, allows for a more nuanced assessment of ecosystem changes and human impacts. Technological advancements, such as IoT and smart monitoring devices, facilitate real-time data collection and analysis, enabling more responsive and adaptive management strategies. The One Health approach underscores the interconnectedness of human, animal, and environmental health, promoting integrated management practices that address multiple facets of ecosystem health. Furthermore, the application of eDNA and integrated assessment frameworks using multiple indicator species enhances the accuracy and reliability of ecosystem health evaluations, supporting more effective conservation and management efforts.

Future research should focus on further developing and refining integrated monitoring and assessment methods to enhance their applicability and effectiveness in diverse aquatic ecosystems. This includes advancing the use of

IoT and smart monitoring technologies to improve data accuracy and reduce the need for manual sampling. Additionally, expanding the application of the One Health approach and statistical analysis can provide deeper insights into the complex interactions between human activities and ecosystem health, informing more sustainable management practices. Research should also explore the potential of eDNA in monitoring a broader range of species and environmental conditions, leveraging advances in sequencing technologies and computational tools. Policymakers should prioritize the implementation of integrated monitoring frameworks that utilize multiple indicator species to ensure comprehensive and reliable assessments of ecosystem health. Finally, there is a need for greater collaboration between scientists, policymakers, and stakeholders to develop adaptive management strategies that can effectively address the dynamic challenges facing aquatic ecosystems in the context of climate change and increasing anthropogenic pressures.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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