

Emerging Digital Technologies for Aquatic Biodiversity Monitoring: Integrating Blockchain, Remote Sensing, and Citizen Science in Freshwater and Marine Conservation

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Abstract— Despite extensive conservation efforts, the integrity of freshwater and marine ecosystems is in decline, highlighting a critical need for more effective and transparent monitoring frameworks. This paper addresses a significant knowledge gap by providing a comprehensive synthesis of the integration of blockchain, remote sensing, and citizen science for aquatic biodiversity monitoring. We explore how remote sensing and Geographic Information Systems provide high-resolution data on habitats and water quality, while citizen science mobilizes public engagement to expand monitoring coverage and validate ground-truth data. We then demonstrate how blockchain technology serves as a secure and immutable ledger, providing a backbone for data traceability and stakeholder trust. The review further examines how the synergy of these tools, enhanced by machine learning can overcome longstanding challenges related to data quality, interoperability, and the lack of equitable participation. We conclude by outlining a vision for integrated, interdisciplinary approaches that can sustain aquatic biodiversity and meet global conservation goals.

Index Terms—Aquatic Conservation, Biodiversity, Blockchain, Remote Sensing and Citizen Science.

I. INTRODUCTION

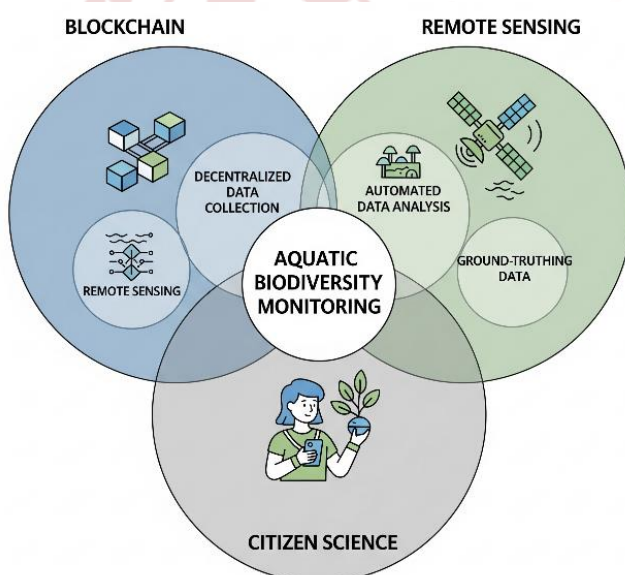


Figure 1. Integration of Citizen science, remote sensing and blockchain for biodiversity conservation

Despite extensive conservation efforts, the integrity of freshwater and marine ecosystems is in decline, highlighting a critical need for more effective and transparent monitoring frameworks. In response, emerging digital technologies are fundamentally altering the landscape of aquatic biodiversity monitoring, offering new avenues for data collection, analysis, and public participation. The integration of tools such as blockchain, remote sensing, and citizen science platforms is enabling more precise, transparent, and inclusive approaches to understanding and managing these vital ecosystems.

Remote sensing and Geographic Information Systems (GIS) have become indispensable, providing high-resolution spatial and temporal data that facilitate the monitoring of aquatic environments like lakes, rivers, and coastal zones (Akindele, 2024). The ability to repeatedly acquire spectral information allows for quantitative and qualitative assessments of phenomena such as coral bleaching, algal

blooms, and habitat degradation (Khanal et al., 2020). Paired with software like ArcGIS and QGIS, these tools streamline the interpretation of complex environmental datasets for researchers and decision-makers (Ali et al., 2024; Christie, 2022).

Concurrently, citizen science initiatives are recognized as valuable contributors, engaging the public to expand the spatial and temporal coverage of monitoring efforts while enhancing community stewardship of aquatic resources (Lameira et al., 2025; Della Rocca et al., 2024). This involvement, when combined with digital platforms and open science practices, improves the transparency and reproducibility of biodiversity assessments (Maedche et al., 2024). However, the success of citizen science requires sustained capacity-building and quality assurance to ensure data reliability (Moussa & Mohan, 2024).

The potential of this digital transformation is further amplified by the integration of big data analytics, the Internet of Things (IoT), and blockchain technologies, which enable

the secure aggregation and sharing of vast datasets to support real-time adaptive management (Tong et al., 2025). While traditional methods like in-situ sampling remain crucial for validation, challenges persist in protecting freshwater biodiversity networks, as terrestrial protected areas often provide only incidental protection (Ban et al., 2023). The convergence of these cutting-edge digital tools with traditional monitoring is driving a paradigm shift, enabling more responsive and adaptive management of freshwater and marine ecosystems (Ahmed et al., 2022).

This paper provides a comprehensive synthesis of how blockchain, remote sensing, and citizen science can be integrated to create a synergistic and robust framework for aquatic biodiversity monitoring. We will explore the conceptual foundations of each tool, analyze their individual and combined applications in addressing key conservation challenges, and conclude by outlining a vision for an integrated, interdisciplinary approach to help meet global conservation goals.

Table 1. Probs and Cons of Traditional and Modern Technologies in Biodiversity Conservation

Method	Scale	Cost	Data Integrity	Key Limitations
Traditional: In-situ Sampling, Lab Analysis	Localized, site-specific	High (lab & manpower)	Accurate but limited coverage	Time-consuming, delayed results
Traditional: Field Surveys & Visual Observation	Small-scale	Moderate	Subjective, prone to error	Low reproducibility, limited scalability
Digital: Remote Sensing (Satellite/Drone)	Large-scale, regional/global	Moderate–High	Consistent, lower precision for water quality	Cloud cover & limited subsurface detection
Digital: IoT Sensors, Smart Probes, Buoys	Local to basin-scale	Moderate–High (setup & maintenance)	Very high (automated, standardized)	Needs infrastructure, power, data systems
Digital: eDNA & AI-driven Analytics	Local–Regional	High	High sensitivity/specificity	Expensive, requires expertise, not fully standardized

Importance of Freshwater and Marine Ecosystems

Freshwater and marine ecosystems are fundamental to the stability and functioning of the biosphere, supporting a remarkable diversity of life and providing essential services to human societies. Freshwater systems, though they contain only about 0.01% of the planet's water, are home to approximately 9.5% of all known animal species, highlighting their extraordinary biodiversity relative to their spatial extent (Ahmed et al., 2022). These ecosystems, which include rivers, lakes, wetlands, and streams, are not only reservoirs of biodiversity but also play a crucial role in regulating hydrological cycles, purifying water, and supporting agricultural and industrial activities (Author, n.d.). The health of freshwater environments is intimately linked to human well-being, as they supply drinking water, food resources, and recreational opportunities, while also acting as

buffers against floods and droughts (Ahmed et al., 2022). Marine ecosystems, encompassing oceans, coastal zones, and estuaries, are equally significant. They regulate global climate by absorbing carbon dioxide and distributing heat, and they sustain major fisheries that are vital for food security worldwide. The productivity of marine environments underpins complex food webs, from microscopic phytoplankton to large marine mammals, and supports the livelihoods of millions of people. These systems also provide raw materials, genetic resources, and cultural value, making their conservation a matter of both ecological and socioeconomic importance (Author, n.d.). The integrity of both freshwater and marine ecosystems is increasingly threatened by anthropogenic pressures such as pollution, habitat destruction, overexploitation, and climate change. Rapid population growth and intensified human activities have led to habitat fragmentation, water quality degradation,

and a heightened risk of species extinction, particularly in freshwater environments. The loss of biodiversity in these systems can disrupt ecosystem processes, reduce resilience to environmental change, and compromise the delivery of ecosystem services that are critical for sustainable development (Ahmed et al., 2022). Monitoring the status and trends of aquatic ecosystems is therefore essential for informed management and conservation. Because loss or degradation of these systems can have cascading effects on ecosystem services, threatening both environmental and human health. The importance of freshwater and marine ecosystems thus extends beyond their intrinsic ecological value, encompassing their role in supporting sustainable development, cultural heritage, and global environmental stability (McGlone et al., 2020).

Key Challenges in Aquatic Conservation

Aquatic conservation is challenged by ongoing biodiversity loss in freshwater systems, where protected areas and current strategies may be insufficient, often focusing on single species rather than ecosystem integrity (Gann et al., 2019). Limitations in data availability and quality, including reliance on coarse surrogates and a lack of comprehensive species data, hinder effective planning and action (Longo et al., 2024). Furthermore, biases in scientific literature, such as the predominance of English and exclusion of non-peer-reviewed outputs from NGOs and local communities, can omit crucial insights into participatory methods and operational issues. Technological advancements like remote sensing and GIS aid ecosystem assessment but require integration with conventional data, facing technical, logistical, and financial barriers (Munawar et al., 2020).

New digital tools like blockchain and AI introduce complexities in standardization and data governance, while citizen science faces hurdles from language barriers, limited access to literature, and underrepresentation of local knowledge, with many project outputs not reaching peer-reviewed publication. Management must address threats such as pollution, habitat degradation, climate change, and contaminants like plastics, necessitating continuous monitoring. Implementing monitoring programs is constrained by resources, capacity, and the need for interdisciplinary collaboration (Gürsu, 2024). Ultimately, enhancing aquatic biodiversity conservation requires a holistic approach that integrates advanced digital tools with traditional knowledge, promotes data sharing, and actively involves local communities and stakeholders through integrated and adaptive strategies.

Blockchain Technology Overview

Blockchain technology is fundamentally characterized by its distributed ledger structure, which ensures that information, once recorded, is highly resistant to modification. This immutability is achieved through a consensus mechanism that validates and secures each

transaction across a decentralized network of nodes, making unauthorized alterations practically infeasible (Sriyono, 2020). Blockchain enhances data integrity and provides traceability for digital and physical assets, especially in aquatic biodiversity monitoring. Its core principle is tokenization, where unique tokens are assigned to entities via smart contracts, automating transactions and reducing human error. This ensures the authenticity and lineage of data. The transparency inherent in blockchain systems allows all participants to access and verify historical records, supporting open data policies and enhancing trust among stakeholders (Vladucu et al., 2024). Blockchain ledgers offer transparency and security through open, auditable access for verification and compliance. Cryptographic techniques protect data from tampering and unauthorized access. Each block contains a cryptographic hash, preventing retroactive alterations and requiring consensus for modification. Distributed ledger technology offers secure data management across sectors like environmental monitoring. Consensus protocols, like Proof of Work or Proof of Stake, balance security, scalability, and energy efficiency. The choice of consensus protocol can significantly influence the environmental impact and operational sustainability of blockchain applications, especially in conservation and resource management contexts. Customizing digital technologies like blockchain for ecological and socio-economic needs is crucial for their effectiveness and high-trust, decentralized data management capabilities (Akindele, 2024). In aquatic biodiversity monitoring, these principles enable the reliable recording and sharing of ecological data, support collaborative management efforts, and facilitate the verification of conservation outcomes (Vladucu et al., 2024) (Akindele, 2024) (Sriyono, 2020). By integrating blockchain with other digital tools, such as remote sensing and citizen science platforms, stakeholders can enhance the accuracy, accessibility, and credibility of environmental data, ultimately advancing the effectiveness of ecosystem management.

Types of Blockchain Architectures

Blockchain architectures can be classified by accessibility, governance, and consensus mechanisms, each with unique benefits and drawbacks for aquatic biodiversity monitoring and water resource management. The main types include public, private, and consortium (or federated) blockchains, with hybrid models emerging to meet specific needs (Cong et al., 2025) (Satilmisoglu et al., 2024a) (Satilmisoglu et al., 2024b). Public blockchains provide high transparency and decentralization, making them suitable for monitoring aquatic ecosystems, allowing open verification and data sharing among stakeholders, which mitigates trust issues. However, their open nature can lead to lower transaction throughput and higher energy consumption due to consensus mechanisms like proof-of-work (Cong et al., 2025). Private blockchains limit participation to a single organization, offering better control over data access and transaction

validation, and utilizing efficient consensus protocols for quicker transactions and reduced computational costs. They can enhance data integrity and compliance in water governance applications (Satilmisoglu et al., 2024a) (Satilmisoglu et al., 2024b). Consortium blockchains serve as a compromise, allowing a group of selected organizations to manage the network collectively, combining the transparency of public blockchains with the efficiency of private systems. This model fosters collaboration among governmental agencies, research institutions, and NGOs in aquatic biodiversity monitoring, ensuring trustworthy data management and enabling smart contracts for conservation incentives (Satilmisoglu et al., 2024). Hybrid architectures are being explored to merge the strengths of various models, such as using a public blockchain for immutable audit trails while managing sensitive data on a private or consortium chain, optimizing transparency and operational efficiency for large-scale water management (Cong et al., 2025). The choice of blockchain architecture significantly impacts financial transparency, trust, and scalability of conservation initiatives.

The development of cryptocurrencies and smart contracts can incentivize water conservation and enhance governance. Moreover, blockchain adoption in aquatic monitoring is likely to reduce pollution and improve sustainability when implemented in a full-adoption equilibrium (Cong et al., 2025). The design of blockchain systems must align with water management requirements, including data privacy, interoperability, and stakeholder engagement (Satilmisoglu et al., 2024).

Advantages and Limitations of Blockchain

Blockchain technology presents significant advantages for aquatic biodiversity monitoring, such as its decentralized architecture, which enhances data security and integrity by requiring consensus for any alterations (Cong et al., 2025) (Zhong et al., 2022). This feature is crucial for maintaining the authenticity and traceability of data in environmental monitoring. Additionally, blockchain facilitates shared access among stakeholders through consortium networks, allowing for efficient collaboration among various organizations (Satilmisoglu et al., 2024). Smart contracts can automate processes and improve operational efficiency, while the immutability of blockchain records supports long-term ecological studies by providing a verifiable history of data (Cong et al., 2025). Despite these strengths, challenges such as implementation complexity, regulatory hurdles, scalability, and data privacy issues must be addressed (Miller et al., 2025). The need for interdisciplinary collaboration and the integration of blockchain with other digital tools also pose significant barriers (Miller et al., 2025). Overall, while blockchain offers substantial benefits for aquatic biodiversity monitoring, its limitations require careful consideration for effective adoption (Zhong et al., 2022).

Table 2. Advantages and Disadvantages of Blockchain

Advantages	Limitations
Immutability: Data records cannot be altered once entered	Scalability Issues: Network performance may slow with large datasets
Transparency: Ensures open and verifiable environmental data sharing	High Energy Consumption (for some consensus mechanisms like Proof-of-Work)
Security: Strong cryptographic protection against tampering	Implementation Complexity: Requires technical expertise and infrastructure
Traceability: Enables tracking of pollution sources, resource use, or monitoring devices	Cost: Initial setup and maintenance can be expensive
Decentralization: Reduces reliance on a single authority, preventing data manipulation	Regulatory Uncertainty: Lack of clear legal and institutional frameworks

Blockchain for Data Traceability

Blockchain technology is increasingly seen as a transformative tool for improving data traceability in freshwater biodiversity monitoring, especially for invasive species detection and management. Its key advantage is a decentralized and immutable ledger that ensures secure, transparent, and tamper-evident recording of transactions and data entries, which is crucial for tracking invasive species and maintaining the integrity of ecological data (Vladucu et al., 2024). By integrating various data sources, blockchain enhances data integrity and security, essential for reconstructing invasive species introduction pathways and verifying reported sightings or management actions (Allena, 2020).

The application of blockchain in emission trading and supply chain transparency has shown its ability to build trust among stakeholders through verifiable records of transactions and environmental performance. In aquatic biodiversity, similar frameworks can be adapted to trace the origin and movement of invasive species and assess the effectiveness of control measures by various actors, including governmental agencies and local communities (Vladucu et al., 2024) (Allena, 2020). Proposed blockchain-based systems for marine and coastal ecosystems highlight their versatility and potential for data sharing and invasive species monitoring.

Integrating smart contracts can reward participants for high-quality data contributions, while automated validation protocols can identify inconsistencies, thereby enhancing data quality (Vladucu et al., 2024). This not only improves the reliability of invasive species records but also fosters

community engagement, which is crucial for early detection and rapid response. Blockchain's secure architecture also helps combat illegal activities related to unauthorized species introductions, providing an auditable trail for regulatory compliance (Akindele, 2024).

Moreover, businesses and organizations are incentivized to maintain robust internal controls and transparent reporting practices when blockchain is utilized, given the high likelihood of detection (Allena, 2020). However, challenges such as interoperability with existing data systems, scalability, and the need for standardized data formats must be addressed for widespread adoption in invasive species management (Vladucu et al., 2024) (Akindele, 2024). Nonetheless, blockchain's integration with IoT devices and QR codes can automate data collection and verification, streamlining the monitoring and management of invasive species in freshwater ecosystems. Its ability to provide secure, transparent, and verifiable records supports scientific research, regulatory enforcement, and community participation, ultimately enhancing aquatic biodiversity conservation efforts (Vladucu et al., 2024) (Akindele, 2024).

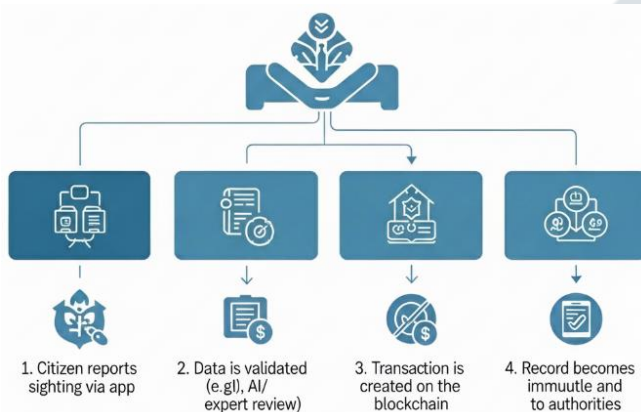


Figure 2. Workflow for Traceable Invasive Species Reporting using Blockchain

Blockchain for Distributed Data Collection

Blockchain technology is increasingly recognized as a transformative tool for distributed data collection in large-scale marine biodiversity monitoring. Its core attributes, decentralization, immutability, and transparency, address several persistent challenges in aquatic data management, particularly those related to data integrity, provenance, and trust among diverse stakeholders. In distributed marine observation networks, data are often generated by a wide array of sources, including autonomous sensors, research vessels, and citizen scientists. Ensuring the reliability and traceability of these heterogeneous data streams is essential for robust ecological assessments and policy interventions (Liu et al., 2019). The integration of blockchain with supporting technologies such as edge computing and IoT sensors enables the secure collection, transmission, and storage of environmental data. Blockchain technology, when

combined with other technologies, can create tamper-proof records, enhancing data security and real-time information sharing in urban water management scenarios. This approach also incentivizes data contribution and quality assurance. (cite) By embedding incentive mechanisms within smart contracts, participants, ranging from automated sensors to citizen scientists, can be rewarded for providing high-quality, timely data. An incentive-based architecture that leverages blockchain and edge computing to promote efficient water distribution and conservation, a model that can be extended to marine biodiversity monitoring by rewarding accurate species observations or environmental measurements. (cite). Despite these opportunities, there are notable challenges. Many blockchain-based environmental solutions developed by private entities remain proprietary, limiting transparency and public access to data and technical details (Vladucu et al., 2024). This lack of openness hinders the evaluation of environmental impact and the reproducibility of scientific findings. For distributed marine observations, open and interoperable blockchain systems are essential to maximize the benefits of collaborative data collection and to ensure that data can be integrated across platforms and jurisdictions (Liu et al., 2019) (Vladucu et al., 2024). Blockchain's potential extends beyond technical data management, fostering trust and cooperation among scientists, policymakers, and local communities, especially in marine environments for effective conservation action. The digital ecosystem envisioned by Liu et al. (Liu et al., 2019) relies on the active participation of citizens, governments, and organizations in collecting, sharing, and analyzing data, with blockchain serving as a backbone for secure and transparent information exchange. Furthermore, the combination of blockchain with big data analytics and artificial intelligence can enhance the value of distributed marine observations. By ensuring the authenticity and provenance of input data, blockchain supports advanced analytics that can reveal patterns in species distribution, ecosystem dynamics, and environmental change (Akindele, 2024). This synergy enables more targeted and adaptive management strategies for marine biodiversity conservation.

Blockchain for Conservation Incentives

Blockchain technology is being used to incentivize marine conservation, particularly in coral reef monitoring and protection. It provides transparent, immutable records of transactions, fostering trust and accountability among stakeholders. Blockchain facilitates the creation and management of digital assets. These tokens can be traded or redeemed, providing direct financial or reputational rewards to individuals, communities, or organizations that contribute to conservation goals (Vladucu et al., 2024) (Satilmisoglu et al., 2024). Blockchain systems offer transparency for stakeholders, reducing disputes and enhancing credibility. However, concerns about data privacy arise when sensitive information is involved. Careful design is needed to balance openness with data protection. Smart contracts automate

conservation incentive schemes, releasing payments or issuing certificates only when ecological indicators are verified. This automation reduces administrative overhead and minimizes opportunities for fraud or manipulation, which have historically undermined the effectiveness of incentive-based conservation programs (Vladucu et al., 2024) (Satilmisoglu et al., 2024a). Vladucu et al. state that while blockchain can mitigate some risks of data manipulation, challenges remain in ensuring the integrity of raw ecological data, especially when it is collected by distributed sensor networks or citizen scientists. The application of blockchain in water trading markets provides a useful parallel for conservation incentives. In these markets, blockchain has been used to increase transparency, streamline financial settlements, and manage water rights through smart contracts (Vladucu et al., 2024). These same mechanisms can be adapted to conservation contexts, where the "commodity" being traded is not water but verified conservation outcomes. The digitalization of traditional markets through blockchain has demonstrated benefits such as lower transaction fees, real-time access to market information, and enhanced accountability, all of which are directly relevant to the design of effective conservation incentive systems (Satilmisoglu et al., 2024a) (Satilmisoglu et al., 2024b). Despite these advantages, scalability remains a significant challenge. Blockchain-based conservation platforms face scalability issues due to increased computational and energy demands. Addressing these is crucial for widespread adoption in marine biodiversity monitoring. Blockchain offers a promising framework for transparent, tamper-proof records, automated incentive distribution, and stakeholder engagement. However, realizing its full potential will require ongoing innovation to address challenges related to data privacy, scalability, and the verification of ecological outcomes (Vladucu et al., 2024) (Satilmisoglu et al., 2024a) (Satilmisoglu et al., 2024b).

Blockchain-Based Reputation Systems

Blockchain-based reputation systems are increasingly utilized in citizen science, particularly for aquatic biodiversity monitoring, as they tackle data governance and participant motivation challenges. By recording actions and data submissions as immutable transactions on a distributed ledger, these systems ensure transparency and stakeholder auditability. The inherent transparency and traceability of blockchain facilitate the creation of tamper-proof histories of contributions, which can be used to calculate reputation scores (Vladucu et al., 2024). Smart contracts automate reputation management and reward distribution, linking scores to recognition or rewards, while tokenization fosters gamified environments for competition and collaboration (Vladucu et al., 2024) (Satilmisoglu et al., n.d.).

In aquatic ecosystem monitoring, blockchain's secure, decentralized data management is vital for maintaining data

integrity and provenance, helping to prevent manipulation, duplication, or loss of data (Moussa & Mohan, 2024). This is particularly important when integrating various data sources, ensuring proper attribution and traceability. The synergy of blockchain with emerging technologies like artificial intelligence can enhance citizen science initiatives by improving data accuracy and participant engagement (Miller et al., 2025).

Moreover, blockchain-based reputation systems can promote collective action through group-based rewards, fostering collaboration and knowledge sharing among participants. The public display of leaderboards can stimulate competition and increase participation rates (Arts et al., 2015). However, challenges remain, including ensuring accessibility for participants with varying technical expertise and addressing ethical concerns regarding data permanence and privacy (Moussa & Mohan, 2024). Collaboration among technologists, ecologists, and community stakeholders is essential for developing effective and equitable systems in citizen science, ultimately enhancing data integration, sharing, and quality control in aquatic biodiversity monitoring (Arts et al., 2015).

Remote Sensing for Habitat Mapping

Remote sensing is essential for habitat mapping in freshwater biodiversity monitoring, allowing for the visualization and quantification of aquatic environments. Technologies such as sidescan sonar and multibeam reflection sounders map both surface and subsurface features, revealing habitat heterogeneity and species distribution. Ground-penetrating seismic techniques enhance the visualization of subsurface structures, providing insights into habitat complexity that traditional field surveys cannot access (Finkl & Makowski, n.d.). The use of aircraft and satellite-assisted remote sensing has broadened the spatial coverage of habitat mapping, enabling efficient assessment of large, often inaccessible areas. These platforms collect high-resolution imagery and spectral data, which can be processed to delineate habitat types, monitor changes over time, and detect anthropogenic impacts. However, the application of remote sensing in field studies is often limited to small spatial scales, typically less than a few kilometers, highlighting the need for broader implementation in fragmented landscapes under environmental pressure (Suter, 2024).

The potential for scaling up remote sensing applications within systematic habitat mapping frameworks is significant, especially as sensor technologies and data processing algorithms improve. Remote sensing data is crucial not only for mapping physical habitat features but also for supporting legislative and conservation objectives. Monitoring programs addressing specific pressures, such as pollution and habitat loss, rely on remote sensing for time series data and updates on habitat status, which are vital for tracking conservation effectiveness and meeting biodiversity directives (Patrício et al., 2016). Additionally, remote sensing supports

comprehensive environmental assessments required by large-scale policies like the EU Marine Strategy and the United Nations Convention on Biological Diversity, providing consistent measurements necessary for informed management decisions (Teixeira et al., 2016). Integrating remote sensing data with in situ observations and citizen science enhances the resolution and reliability of habitat maps, improving the monitoring of species distribution and abundance in dynamic aquatic systems. Continuous advancements in remote sensing methodologies, including spectral indices and machine learning for image classification, are expected to increase the accuracy and utility of habitat mapping. As these technologies become more accessible and cost-effective, their use in freshwater biodiversity monitoring is likely to grow, aiding in effective conservation planning and adaptive management strategies (Suter, 2024) (Patrício et al., 2016).

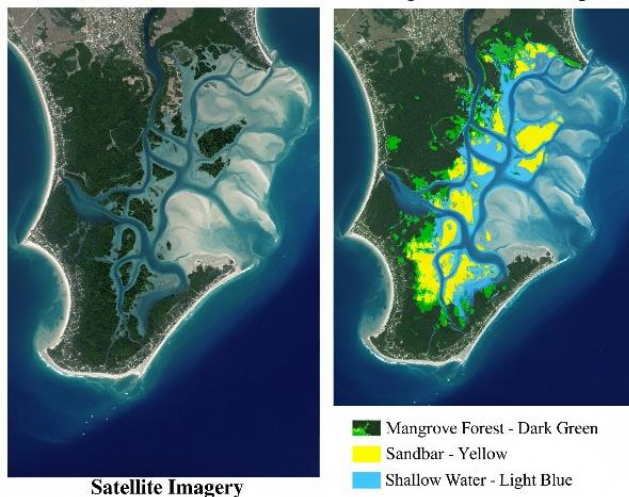


Figure 3. Satellite (Left and Corresponding Classified Habitat Map Right) of a Coastal Area Right) & Habitat Map

Remote Sensing Indicators of Water Quality

Remote sensing is an essential tool for evaluating water quality in freshwater ecosystems, offering extensive and frequent data that can enhance traditional sampling methods. It enables the detection and quantification of water quality parameters such as turbidity, chlorophyll-a concentration, and aquatic vegetation, making it particularly valuable for monitoring large or inaccessible water bodies where ground-based sampling is limited. The integration of remote sensing data with digital tools like machine learning algorithms and citizen science observations improves the accuracy and interpretability of water quality assessments (Suter, 2024). Machine learning can analyze large datasets to identify subtle changes in water quality, while crowdsourced data helps validate remote sensing predictions. Additionally, combining locality data with remote sensing outputs aids in continuously assessing biodiversity and validating models of species distribution changes influenced by water quality fluctuations (Pimm et al., 2015). Remote sensing also monitors

anthropogenic impacts on aquatic environments, such as nutrient loading and land use changes, with automated detection of these changes linked to shifts in water quality (Liu et al., 2019). This capability is vital for early warning systems and adaptive management, facilitating the rapid identification of threats to freshwater biodiversity. Moreover, remote sensing can monitor biological components like phytoplankton, macroalgae, and angiosperms, which are crucial for water quality assessments (Patrício et al., 2016). However, challenges remain in data governance, standardization, and integrating diverse data sources (Liu et al., 2019). Ensuring the reliability of remotely sensed water quality indicators necessitates robust calibration and validation protocols, often involving ground-truthing with in situ measurements or citizen science data. Fraisl et al. (2020) emphasize the importance of understanding metadata and existing data sources for effective use of citizen science and remote sensing data in indicator development. The collaboration between remote sensing, digital data ecosystems, and participatory monitoring is reshaping aquatic biodiversity assessment, leading to more accurate and timely insights into water quality dynamics and supporting better conservation and management of freshwater resources (Patrício et al., 2016).

Remote Sensing for Habitat Health

Remote sensing (RS) is crucial for evaluating habitat health in coral reefs and sensitive marine environments due to its capability for large-scale, non-invasive observations. It enables the detection of changes in ecosystem structure, function, and stressors, which are essential for conservation and management. A significant benefit of RS is its cost-effectiveness compared to traditional field surveys, allowing for extensive monitoring of coral reefs, including bleaching events and human impacts. The combination of RS data with GIS enhances its effectiveness in quantifying biomass and identifying vulnerable areas, aiding in prioritizing management actions and understanding habitat conditions over time. Recent advancements in sensor technology have expanded RS applications, with autonomous underwater vehicles (AUVs) now utilized for benthic habitat mapping, marine geology, and fisheries assessment, providing high-resolution imagery and environmental data in difficult environments. However, accurate interpretation of RS data requires thorough ground-truthing and calibration, emphasizing the importance of integrating field observations and other monitoring methods. RS is also increasingly used in freshwater systems for mapping aquatic vegetation, water quality, and habitat structure (Finkl & Makowski, n.d.). Challenges such as sensor penetration in shallow waters and the need for high-quality reference data necessitate the development of new algorithms and machine learning techniques. The integration of RS technologies with digital tools enhances data collection and interpretation, with citizen scientists providing ground-truth data to improve RS model

calibration, while AI algorithms automate the processing of large datasets for faster and more accurate habitat health assessments (McClure et al., 2020). Overall, technological innovation and community engagement are propelling the use of RS in conservation science, particularly for monitoring coral reefs and sensitive habitats.

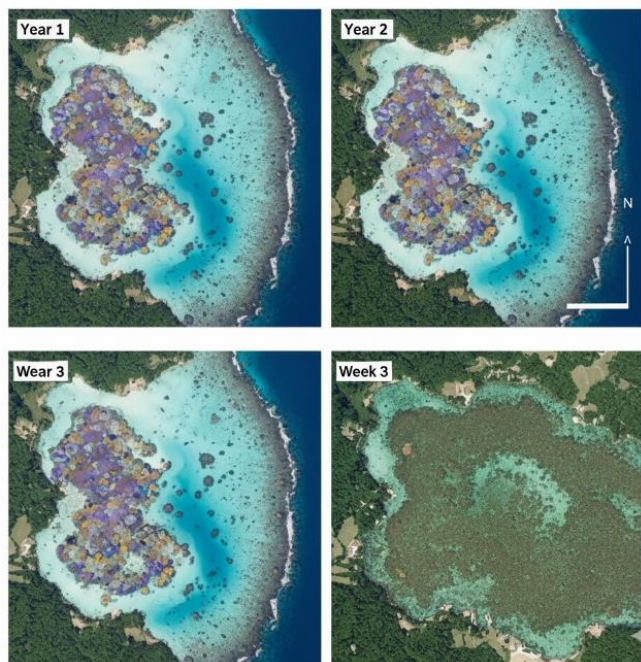


Figure 4. Time-series Satellite Data Showing Coral Reef Health Progression in

Citizen Science in Environmental Monitoring

Citizen science involves non-professional individuals actively participating in scientific research, contributing intellectual effort, local knowledge, and tools to advance scientific understanding, including hypothesis generation, data analysis, and results dissemination. The European Commission defines citizen science as public engagement in scientific research activities, highlighting contributions that extend beyond traditional academic boundaries (Njue et al., 2019). This definition underscores the democratization of science, promoting inclusive knowledge production that addresses local and global needs, provides tangible benefits to participants and communities, and generates valuable data for scientific and policy objectives. This dual focus ensures that citizen science initiatives create reciprocal value, enhancing both scientific outcomes and community engagement. It is particularly vital for integrating into biodiversity monitoring frameworks (Pocock et al., 2018), involving systematic volunteer engagement in activities like species identification and environmental monitoring, often facilitated by digital platforms for large-scale participation and data sharing. The integration of technology, such as mobile applications and online databases, has expanded the reach and efficiency of citizen science (Miller et al., 2025). The social dimension is also significant, with initiatives

encouraging community interaction and knowledge exchange, which enhances data quality and fosters environmental stewardship and scientific literacy (Dionisio et al., 2022). Strong ecological policies and community engagement programs bolster citizen science efforts, especially in regions with established aquatic research traditions (Lameira et al., 2025). The sustainability of citizen science relies on its adaptability to evolving scientific and societal needs, with trends like open data principles and artificial intelligence for real-time data validation promising to enhance data reliability (Miller et al., 2025). By adhering to standards that ensure data are findable, accessible, interoperable, and reusable, citizen science projects can maximize their impact on environmental monitoring and policy development (van Rees et al., 2020).

Citizen Science for Species Observation

Citizen science plays a vital role in monitoring species in freshwater ecosystems by providing essential data on their distribution and abundance. This approach involves non-professional volunteers, which broadens biodiversity monitoring efforts and emphasizes species identification and population counts. Such initiatives yield insights into species presence, density, and patterns within aquatic habitats (Moussa & Mohan, 2024). By engaging local communities, citizen science projects enhance tracking of species distribution and can identify rare or transient species often missed by traditional monitoring methods. The systematic consolidation and analysis of citizen science data in aquatic ecology have led to improved methodologies that ensure data quality and reliability. Participatory monitoring, a key aspect of citizen science, primarily targets species ecology and conservation goals, gathering crucial information on ecological requirements to inform conservation strategies aimed at preserving biodiversity. This approach not only generates extensive datasets but also fosters public awareness and stewardship of freshwater resources, aligning with broader sustainability objectives (Lameira et al., 2025).

Advancements in digital technologies facilitate the integration of citizen science data into scientific research and policy-making, enhancing data collection, transmission, and analysis. Tools such as mobile applications and cloud-based databases enable real-time reporting and validation of species observations, improving the accuracy and accessibility of biodiversity data. These innovations support the creation of evidence-based conservation policies and bolster adaptive management of freshwater ecosystems (Liu et al., 2019) (Moussa & Mohan, 2024). However, citizen science also encounters challenges, including data standardization, observer bias, and the necessity for effective training and communication strategies. Addressing these challenges is crucial for maximizing the scientific value of citizen-generated data and ensuring its integration with professional monitoring efforts (Lameira et al., 2025). Continuous refinement of protocols and quality control measures is

essential to uphold the credibility and utility of citizen science in species observation. Overall, citizen science is a transformative tool for monitoring species distribution and abundance in freshwater systems, leveraging the involvement of numerous observers and digital innovations to reshape aquatic biodiversity monitoring and enhance conservation practices (Moussa & Mohan, 2024).

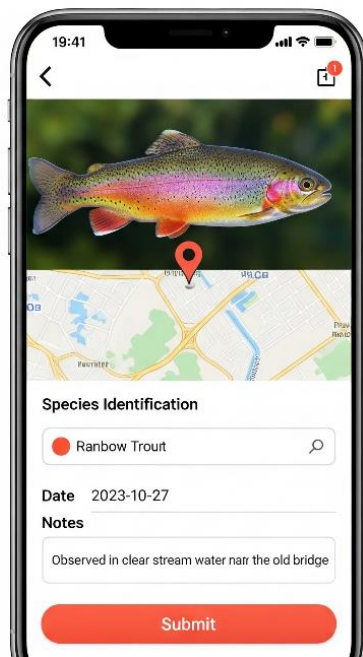


Figure 5. Example of a Mobile Citizen Science Application Interface for Reporting Species

Citizen Science for Coastal and Offshore Monitoring

Citizen science plays a vital role in large-scale coastal and offshore monitoring, facilitating the collection of extensive datasets that traditional scientific teams often find challenging due to logistical and financial constraints. The environmental sector has benefited significantly from citizen science, with projects focusing on sustainable development goals such as clean water, healthy marine life, and resilient coastal communities (Fraisl et al., 2020). The public's accessibility to coastal zones and heightened awareness of marine conservation issues drive this focus. Activities in citizen science include recording marine species sightings, monitoring water quality, and documenting invasive organisms, which not only yield valuable data but also enhance public awareness and stewardship of marine resources (Callaghan et al., 2021).

Technological advancements have further improved coastal and offshore monitoring by enabling real-time georeferenced observations and enhancing data accuracy. This creates a feedback loop where data collected by citizen scientists refine future data collection protocols and boost participant motivation, leading to improved data quality and engagement (Pocock et al., 2018) (Callaghan et al., 2021). The integration of citizen science with remote sensing and

digital tools has broadened marine monitoring capabilities, allowing citizen-generated data to calibrate satellite-derived products, thus enhancing the reliability of large-scale environmental assessments. This synergy is crucial in coastal and offshore areas, where satellite data may be limited by factors like cloud cover and water turbidity (Fraisl et al., 2020).

However, challenges persist in sustaining citizen science initiatives, such as ensuring long-term volunteer participation, which requires innovative funding and consideration of incentives and barriers. The enabling environment must also address data quality assurance, participant training, and the integration of citizen-generated data into official monitoring frameworks (Fraisl et al., 2020) (Callaghan et al., 2021). Additionally, the sharing of biodiversity information collected through citizen science is often limited by the lack of open science practices, which restricts the broader use and impact of these datasets (Suter, 2024). Overall, citizen science is increasingly recognized for its potential in supporting large-scale marine observations, informing policy responses, and aiding conservation strategies, as emphasized by organizations like the Intergovernmental Science-Policy Platform on Biodiversity. By synthesizing data from various sources and encouraging government action based on monitoring results, citizen science fosters a more responsive and adaptive approach to marine biodiversity management (Tickner et al., 2020).

Synergies Between Blockchain and Remote Sensing

The integration of blockchain technology with remote sensing offers a promising avenue for enhancing the monitoring and management of aquatic ecosystems. Remote sensing, through satellite and aerial imagery, provides large-scale, real-time data on aquatic environments, enabling the detection of pollution events, habitat changes, and other ecological dynamics with high spatial and temporal resolution (Miller et al., 2025). However, the reliability and transparency of such data streams can be challenged by issues of data manipulation, loss, or lack of verifiable provenance, especially when multiple stakeholders are involved in data collection and interpretation (Zhong et al., 2022). Blockchain technology addresses these challenges by introducing a decentralized, immutable ledger for recording and sharing environmental data. When remote sensing data are logged onto a blockchain, each entry is time-stamped and cryptographically secured, ensuring that the information remains tamper-proof and accessible to all authorized participants (Vladucu et al., 2024). Blockchain technology offers immutability, crucial for data integrity in regulatory compliance, scientific research, and stakeholder dispute resolution. It automatically uploads pollutant data for monitoring environmental standards (Zhong et al., 2022). The synergy between these technologies extends to the automation of monitoring and reporting processes. Smart contracts on blockchain platforms can be programmed to

analyze incoming remote sensing data streams, execute predefined actions, and facilitate transparent, auditable decision-making without human intervention (Vladucu et al., 2024). Blockchain technology automates environmental incidents, accelerates response times, and fosters trust among diverse actors. It supports joint management of water resources and promotes equitable participation in conservation initiatives. The traceability enabled by blockchain also supports long-term ecological studies, as historical remote sensing data can be reliably archived and retrieved for trend analysis and impact assessment (Vladucu et al., 2024) (Zhong et al., 2022). Despite these advantages, the integration of blockchain and remote sensing is not without challenges. Issues such as data privacy, scalability, and the energy consumption of blockchain networks must be carefully managed to ensure that the environmental benefits outweigh the technological costs (Vladucu et al., 2024). Nevertheless, the combination of these digital tools holds significant potential for advancing the accuracy, transparency, and accountability of aquatic biodiversity monitoring, ultimately supporting more effective and inclusive ecosystem management (Miller et al., 2025).

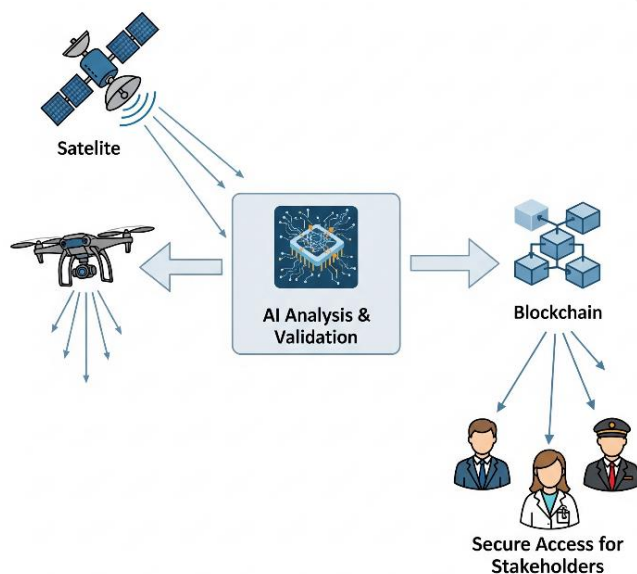


Figure 6. Integrated Framework for Secure Environmental Monitoring

Citizen Science and Blockchain Interoperability

Citizen science, when combined with blockchain technology for monitoring aquatic biodiversity, addresses challenges related to data transparency, traceability, and trustworthiness. Blockchain's decentralized and immutable ledger system allows for real-time recording, verification, and sharing of citizen-contributed data, ensuring the integrity and provenance of environmental observations (Allena, 2020) (Vladucu et al., 2024). This integration enhances the reliability of biodiversity datasets by securely recording data points such as species sightings and water quality

measurements, preventing unauthorized alterations and providing a transparent audit trail essential for scientific reproducibility and regulatory compliance (Allena, 2020). The transparency facilitated by blockchain supports informed decision-making and collaboration among stakeholders in aquatic monitoring projects. Additionally, blockchain aligns with the distributed nature of citizen science, improving environmental reporting and enabling conservation mechanisms (Allena, 2020).

In the European context, initiatives like the Digital Single Market for Water services and ICT4Water have promoted the integration of digital applications, including blockchain, to enhance environmental governance and data management (Liu et al., 2019). Citizen science projects often involve diverse participants and data types, making confidentiality and ethical data use critical. Blockchain can facilitate these needs through permissioned access and smart contracts, which automate data sharing agreements and protect sensitive information. Maintaining confidentiality and minimizing biases are vital for the credibility of citizen science initiatives (Moussa & Mohan, 2024). Furthermore, the synergy between citizen science and blockchain has significant implications for policy and conservation outcomes, as citizen-generated data increasingly inform biodiversity policy and support international frameworks aimed at reversing nature loss (Della Rocca et al., 2024). Overall, integrating these tools will enhance aquatic biodiversity conservation through ongoing digital infrastructure development (Allena, 2020).

Combining Remote Sensing with Community Observations

The integration of remote sensing and community observations in aquatic biodiversity monitoring represents a significant methodological advancement, allowing for the assessment of parameters such as chlorophyll concentration, water temperature, and habitat distribution (Author, n.d.). Remote sensing provides extensive spatial coverage and temporal resolution, enabling the mapping of surface and subsurface features, which helps visualize topographic and ecological patterns that traditional fieldwork cannot access (Finkl & Makowski, n.d.). However, remote sensing alone may not suffice in areas with persistent cloud cover or water turbidity, necessitating community observations through citizen science initiatives. Citizen scientists can gather in situ data on water quality, species presence, and habitat conditions, addressing critical gaps left by remote sensing and providing ground-truthing for its data (Callaghan et al., 2021). The integration of these data streams enhances the accuracy and reliability of aquatic monitoring, as community observations can validate remote sensing outputs, while remote sensing can optimize community-based sampling efforts (Njuea et al., 2019). Digital platforms further amplify the synergy between these approaches, facilitating data sharing and collaborative analysis. For instance, mobile applications and web-based portals allow citizen scientists to

upload georeferenced observations in real time, which can be cross-referenced with satellite or drone imagery (Dionisio et al., 2022). eBird's Human/Computer Learning Network exemplifies this integration by combining human observers and machine learning algorithms for rapid ecological event detection, thereby enhancing data quality (McClure et al., 2020). In Europe, the Copernicus Earth Observation Programme and the INSPIRE Directive have established frameworks for systematic data collection and integration, including contributions from community observers (Liu et al., 2019). These initiatives highlight the need for harmonizing data standards and ensuring interoperability between remote sensing products and citizen science datasets. This combined approach not only expands the spatial and temporal scope of monitoring but also democratizes data collection, engaging local communities in aquatic resource stewardship (Callaghan et al., 2021). Despite these advancements, challenges remain in data quality, managing diverse sources, and sustaining community engagement in marine and coastal citizen science programs.

Engagement Strategies for Diverse Communities

Aquatic biodiversity monitoring strategies for diverse communities use gamification and incentivization, using digital tools like mobile applications and online platforms to motivate participation, sustain engagement, and ensure inclusivity (Pocock et al., 2018). Citizen science platforms use gamification elements like achievement badges and leaderboards to foster accomplishment and competition, enhancing ecotourism participation and community connection with nature. However, technical issues, such as application crashes, can undermine motivation by causing loss of data and missed opportunities for recognition, highlighting the importance of robust and user-friendly design (Dionisio et al., 2022). Incentivization projects empower rural and marginalized communities by enabling them to contribute to scientific research through meaningful local contexts, such as reporting wildlife sightings or environmental incidents. The accessibility of basic digital devices ensures that engagement is not limited to technologically advanced regions, broadening the reach of citizen science (Pimm et al., 2015). Community engagement is further enhanced by tailoring projects to local interests and needs. The eBird initiative, for instance, demonstrates how global biodiversity monitoring can remain relevant to local participants by valuing their observations and integrating them into a larger scientific framework (Pocock et al., 2018). This dual focus on local relevance and global impact encourages sustained participation and a sense of ownership among contributors. Digital applications also facilitate inclusive and participatory governance by enabling citizens to actively shape conservation policies and practices (Liu et al., 2019). By providing platforms for dialogue and collaboration among citizens, scientists, and policymakers, these tools help bridge gaps between different stakeholders

and ensure that diverse perspectives are represented in decision-making processes (Schulz et al., 2023) (Liu et al., 2019). Effective communication, interdisciplinary collaboration, and community-based rewards are crucial for successful conservation initiatives, aligning technological innovation with community goals and values (Schulz et al., 2023). The PlantWatch program in Canada exemplifies how community-driven data collection can inform rapid responses to environmental threats and optimize conservation strategies, reinforcing the value of collective action (Moussa & Mohan, 2024). The integration of gamification and incentivization in citizen science is not without challenges. Ensuring data quality and scientific rigor requires standardized protocols, participant training, and validation methods to maintain the credibility of community-generated data (Njue et al., 2019). Nonetheless, when thoughtfully implemented, these strategies can transform passive observers into active contributors, enhance the accuracy and scope of biodiversity monitoring, and build lasting partnerships between scientists and the public (Lameira et al., 2025).

International Collaboration and Data Sharing

International collaboration and data sharing are essential for enhancing aquatic biodiversity monitoring, with digital tools such as blockchain, remote sensing, and citizen science platforms playing a significant role in research practices. These technologies facilitate data exchange, allowing for more accurate assessments of aquatic ecosystems across geopolitical boundaries. Customized digital applications enhance accessibility and accuracy, enabling participants from various countries to contribute standardized observations (Lameira et al., 2025). Moussa & Mohan (2024) highlight that citizen science data can inform evidence-based conservation initiatives amid global biodiversity threats. Interdisciplinary approaches, including remote sensing technologies, foster trust and knowledge sharing, aiding in the development of robust habitat classification models critical for international data comparability.

The integration of remote sensing, machine learning, and citizen science can also enhance archaeological prospection, with similar methodologies applicable to aquatic biodiversity monitoring (Suter et al., 2024). Blockchain technology offers a secure and transparent framework for data sharing across international networks, addressing concerns about data integrity and access control, particularly in managing virtual water trade and water footprint data (Satilmisoglu et al., 2024). However, challenges such as legislative, social, and administrative barriers must be overcome to fully leverage blockchain's potential in the water sector (Satilmisoglu et al., 2024a).

Despite the promise of these digital tools, issues related to data quality and bias persist, especially when aggregating information from diverse sources and jurisdictions. Developing comprehensive datasets and improved data-

sharing frameworks is crucial for ensuring models are reliable across contexts (Miller et al., 2025). Standardization of protocols is vital for interoperability, allowing meaningful data comparisons from different regions. Long-term engagement and sustained funding are key to the success of international data-sharing initiatives, as financial constraints can limit collaborative project sustainability (Moussa & Mohan, 2024).

Mobile applications have proven effective in engaging international communities in aquatic biodiversity monitoring, exemplified by platforms like Whale Report, which allows thousands of observers to report marine species sightings, contributing to a shared conservation database (Dionisio et al., 2022). Digital tools facilitate real-time data sharing and collective action, necessitating the development of interoperable standards, transparent governance structures, and ethical frameworks for successful international collaboration. Stakeholder engagement is critical for equitable knowledge exchange, and integration into international monitoring networks faces various technical, social, and policy challenges.

Supporting Open Science Through Policy

Supporting open science through policy is increasingly recognized as a strategic approach to enhance the effectiveness, transparency, and inclusivity of aquatic biodiversity monitoring. Open science aims to make scientific research, data, and dissemination accessible to all levels of society, thereby amplifying the collective capacity to tackle complex environmental challenges. Integrating open science principles into policy frameworks is particularly relevant for aquatic ecosystems, where persistent issues include data gaps, limited resources, and the urgent need to respond to biodiversity loss (Suter, 2024).

The European Union's legislative landscape features a complex interplay of directives and regulations aimed at protecting aquatic biodiversity, such as the Birds and Habitats Directives, the Water Framework Directive, and the Marine Strategic Framework Directive. However, despite these efforts, the loss of aquatic biodiversity continues, indicating that traditional regulatory instruments are insufficient (Rouillard et al., 2018). Open science policies can enhance research by promoting data sharing, collaborative research, and public engagement, allowing diverse stakeholders to participate in data collection, analysis, and interpretation (Pimm et al., 2015).

Open science tools, including open-access databases and collaborative platforms, can improve biodiversity assessments and enhance the legitimacy of conservation actions, although they face challenges such as data quality, intellectual property rights, and the need for standardized protocols (Suter, 2024). Policies that encourage or mandate open data sharing among private enterprises and public institutions can unlock new opportunities for environmental innovation and more effective enforcement of environmental

standards. Liu et al. (2019) highlight the significant implications of data governance for environmental policies, emphasizing the need to balance openness with privacy and commercial interests.

Moreover, open science policies can facilitate the integration of emerging digital tools, such as blockchain and remote sensing, into aquatic biodiversity monitoring, enhancing transparency, traceability, and trust in data—essential elements for robust policy implementation and public accountability (Satilmisoglu et al., 2024a) (Suter, 2024). Satilmisoglu et al. (2024a) suggest that blockchain can address administrative issues, build trust, and align with open science objectives for water governance and aquatic biodiversity monitoring. Citizen science, as an extension of open science,

Public Engagement and Scientific Democratisation

Trust building in aquatic biodiversity monitoring is essential, particularly through digital tools and citizen science initiatives. Public engagement enhances transparency, legitimacy, and interest, while involving the public in climate change and environmental sustainability discussions. This engagement fosters science literacy and awareness, which are vital for informed decision-making and societal support for conservation actions (McClure et al., 2020). Open science practices further democratize science by promoting knowledge exchange and a deeper understanding of the scientific process, making research more representative of public interests. For instance, in Europe, there are 18 citizen scientists for every research scientist in species monitoring, showcasing citizen science's potential to amplify scientific research's reach and impact (Suter, 2024).

Digital technologies, such as smartphones, facilitate citizen participation in data collection and analysis, lowering barriers and increasing diversity. Tools like electronic field guides and taxonomy interfaces enhance data quality and transparency. Crowdsourcing platforms, like the Notes from Nature project, enrich scientific databases by allowing participants to transcribe and validate biological records, fostering a sense of shared ownership and responsibility (Arts et al., 2015). The social aspect of citizen science, where observations are shared within a community, strengthens trust by making the process visible and participatory (Dionisio et al., 2022).

Trust is further reinforced when citizen science data inform policy and management decisions. Successful integration of open data from projects like eBird into conservation policy illustrates the tangible impacts of citizen-generated information. When stakeholders see their contributions reflected in real-world outcomes, their confidence in the scientific process grows (Suter, 2024). Hermoso et al. (2016) argue that collaboration among scientists, NGOs, and decision-makers in freshwater protected area management enhances planning processes, builds trust, and aligns citizen science with community issues, making it more trustworthy.

Indicators that resonate with citizen concerns are likely to attract sustained engagement and support, as participants see a direct connection between their efforts and meaningful outcomes (Fraisl et al., 2020).

Additionally, citizen science complements other data sources, such as Earth observation, enhancing the credibility and utility of the information produced. Advanced data quality assurance mechanisms, like algorithms that rank user data or detect discrepancies, further bolster trustworthiness. For example, platforms like eBird utilize such methods to ensure that data from enthusiasts and experts meet rigorous standards before being used in scientific analyses or policy recommendations (McClure et al., 2020). Overall, integrating technological safeguards and community validation in aquatic biodiversity monitoring addresses data reliability concerns, fostering trust among stakeholders and promoting a more inclusive and credible scientific enterprise.

Science Communication in the Digital Era

Digital tools such as blockchain, remote sensing, and AI are increasingly utilized in aquatic biodiversity monitoring, yet significant knowledge gaps remain, particularly regarding data standardization and interoperability. This fragmentation complicates comprehensive assessments of ecosystem health and biodiversity across various regions and projects. Validation and calibration of remote sensing and AI-driven classification models also require further exploration. Miller et al. (Miller et al., 2025) note advancements in deep learning methods for automating habitat classification and environmental change detection, but limited ground-truth data in aquatic environments hampers ecological accuracy, highlighting the need for expanded field campaigns and citizen science integration.

Moreover, the integration of social and economic datasets into digital conservation planning is still underdeveloped. Ban et al. (2023) emphasize the necessity for comprehensive freshwater management that addresses access, ownership, governance, and local community needs, which calls for frameworks that incorporate ecological, social, and economic data. Transparency and trust in environmental data are critical, especially as digital monitoring becomes decentralized. Liu et al. (Liu et al., 2019) describe how blockchain technology can verify the completeness, accuracy, and timeliness of environmental data submissions. Vladucu et al. (2024) stress the importance of empirical studies to assess the effectiveness of blockchain in real-world conservation, as its motivations and features are still being defined.

Challenges in the widespread adoption of blockchain in hydrological applications arise from its diverse range and lack of standardization, as noted by Satilmisoglu et al. The spatial and taxonomic biases in conservation research and investment also persist, with Sayer et al. (2025) highlighting a bias in aquatic biodiversity, where certain areas and habitats receive disproportionate attention. Addressing this issue

requires targeted investment in underrepresented areas and the use of cost-effective digital tools.

The intersection of climate change and digital conservation remains largely theoretical, with limited data-driven studies quantifying the impacts of climate variability on protected area design or management. Hermoso et al. (2016) point out that most literature in this area consists of conceptual frameworks rather than empirical analyses, which restricts the adaptation of digital monitoring and management strategies to the dynamic challenges posed by climate change.

Acoustic monitoring is gaining recognition for assessing anthropogenic impacts on aquatic soundscapes, yet it faces challenges in interpreting complex acoustic data and attributing observed changes to specific stressors. Farina and Gage (2017) highlight the need for further development of eco-acoustic approaches to manage multiple noise sources effectively and provide actionable insights for conservation.

Scaling Up and Sustaining Digital Approaches

Blockchain technology enhances transparency and trust in aquatic biodiversity monitoring through secure data sharing, stakeholder engagement, and data integrity, which are crucial for long-term conservation (Satilmisoglu et al., 2024a). It also automates compliance and reporting in water abstraction permits, reducing administrative burdens (Satilmisoglu et al., n.d.). However, successful scaling relies on robust governance frameworks and addressing trust issues among user groups (Satilmisoglu et al., 2024a). Remote sensing technologies provide high-resolution data for aquatic habitat assessments but require ongoing infrastructure and capacity building for sustainability (Yadav et al., 2013). Ganie et al. discuss advancements in remote sensing, digital twins, and aquatic robotics that enhance monitoring accuracy and enable rapid responses to environmental changes. Citizen science can significantly scale data collection in inaccessible areas, filling knowledge gaps and improving biodiversity understanding (Callaghan et al., 2021). Engaging local communities through citizen science strengthens the foundation for long-term monitoring and builds awareness of conservation goals (Sayer et al., 2025) (Callaghan et al., 2021). Sayer et al. stress the need to reshape societal relationships with freshwater systems towards stewardship, facilitated by participatory digital tools (Sayer et al., 2025). Sustaining digital approaches requires addressing funding, institutional support, and data governance issues. Long-term backing is essential for monitoring programs and database integration, especially as efforts expand (Arts et al., 2015). Interdisciplinary collaboration is vital for scaling digital conservation technologies, combining expertise from ecology, computer science, and social science. Additionally, a critical examination of the political economy of digital technologies is necessary to ensure equitable access and ethical data use (Arts et al., 2015). The growing research on ecosystem services and digital conservation tools highlights their transformative potential (Boulton et al., 2016).

However, the gap between freshwater ecology and conservation science remains

Addressing Remaining Knowledge Gaps

Digital tools such as blockchain, remote sensing, and AI are increasingly utilized in aquatic biodiversity monitoring; however, significant knowledge gaps remain, particularly regarding data standardization and interoperability. This fragmentation complicates comprehensive assessments of ecosystem health and biodiversity across various regions and projects. Validation and calibration of remote sensing and AI-driven classification models also require further exploration. Miller et al. (Miller et al., 2025) highlight that advancements in deep learning methods, particularly with satellite and drone imagery, have improved habitat classification and environmental change detection. However, the scarcity of ground-truth data in aquatic environments limits the ecological accuracy of these models, indicating a need for expanded field campaigns and citizen science integration to enhance reliability and relevance.

Moreover, the integration of social and economic datasets into digital conservation planning is still underdeveloped. Ban et al. (2023) emphasize the importance of comprehensive freshwater management that addresses access, ownership, governance, and local community needs, necessitating frameworks that merge ecological, social, and economic data. Transparency and trust in environmental data are critical, especially as digital monitoring becomes decentralized. Liu et al. (Liu et al., 2019) describe how blockchain technology can verify the completeness, accuracy, and timeliness of environmental data submissions. Vladucu et al. (2024) call for empirical studies to assess the effectiveness of blockchain in real-world conservation contexts, as its motivations and features are still being defined. Additionally, Satilmisoglu et al. note the challenges of adopting blockchain in hydrological applications due to its diversity and lack of standardization.

Spatial and taxonomic biases in conservation research and investment also persist. Sayer et al. (2025) point out a bias in aquatic biodiversity, where certain areas and habitats receive disproportionate attention, highlighting the need for targeted investment in underrepresented regions and cost-effective digital tools. The intersection of climate change and digital conservation remains largely theoretical, with few data-driven studies quantifying climate variability's impacts on protected area design or management. Hermoso et al. (2016) indicate that most literature in this area consists of conceptual frameworks rather than empirical analyses, limiting the adaptation of digital monitoring and management strategies to the challenges posed by climate change.

Acoustic monitoring, recognized for its value in assessing anthropogenic impacts on aquatic soundscapes, faces challenges in interpreting complex acoustic data and attributing changes to specific stressors. Farina and Gage (2017) stress the need for further development of ecoacoustic approaches to manage multiple noise sources effectively and

provide actionable conservation insights.

Vision for Integrated Aquatic Biodiversity Monitoring

The integration of digital tools such as remote sensing, blockchain, and citizen science is transforming data collection and application for aquatic ecosystem conservation. Remote sensing allows for quick acquisition of spatial data on species and habitats, aiding in the identification of areas at risk of species endangerment (Pimm et al., 2015). Blockchain enhances data security and traceability in aquatic monitoring, particularly for unmanned aerial vehicles (UAVs) collecting data at dam sites, ensuring the integrity of records (Satilmisoglu et al., 2024a) (Satilmisoglu et al., 2024b). Citizen science initiatives improve public awareness and data reliability, particularly in water quality monitoring, where community involvement helps detect environmental issues (Lameira et al., 2025). Open science practices are gaining traction, promoting transparency and collaboration in biodiversity monitoring, despite historical challenges (Suter, 2024). The development of biodiversity indicators is crucial for effective management and policy decisions (Teixeira et al., 2016). However, there are challenges, such as the need for broader taxonomic coverage in extinction risk assessments for freshwater species (Sayer et al., 2025). Recognizing the ecosystem services provided by aquatic habitats is essential for conservation targets (Boulton et al., 2016) (Geist, 2011). Overall, while digital tools can enhance conservation efforts, careful evaluation is necessary to ensure meaningful changes, with a vision for integrated monitoring that emphasizes advanced technologies, participatory science, and collaborative governance (Tickner et al., 2020).

II. CONCLUSION

The integration of digital technologies is revolutionizing aquatic biodiversity monitoring, enhancing precision, transparency, and inclusivity in ecosystem assessment and management. Blockchain, remote sensing, and citizen science platforms enable secure data recording, large-scale observations, and public participation. These innovations support comprehensive conservation strategies for freshwater and marine environments. However, challenges remain, such as data standardization, interoperability, and data privacy. Interdisciplinary collaboration is crucial for successful implementation, requiring ecological expertise, technological innovation, social science insights, and policy frameworks. Artificial intelligence and machine learning are expected to enhance automated species identification, predictive modeling, and anomaly detection. Gamification and blockchain-based reputation systems can motivate and retain citizen scientists, expanding data collection reach. International collaboration and data sharing are essential for addressing transboundary aquatic biodiversity challenges and achieving global conservation targets.

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