Narrowing Data Gaps through effective use of AI Techniques in Environmental Assessment and Monitoring: Prospects from Red Sea Sustainable Tourism Development Projects

Paper submitted for Oral presentation at the International Association for Impact Assessment (IAIA) 2025 Conference, May 2025, Bologna, Italy.

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Abstract:

The Red Sea region, celebrated for its stunning beauty along the west coast of the Kingdom of Saudi Arabia (KSA), is embarking on a transformative initiative for sustainable tourism development. KSA envisions a future where nature-friendly tourism flourishes, balancing development with the preservation of pristine marine and terrestrial environments. Future Red Sea destinations will adhere to rigorous scientific, technical, and regulatory frameworks to foster regenerative and nature-based tourism assets aligned with international standards. To effectively address identified data gaps in environmental assessments, we are committed to employing robust scientific methodologies. Our approach will integrate advanced data collection techniques, including remote sensing, field surveys, and multi-disciplinary secondary data reviews, ensuring a thorough understanding of the local environment. Our teams will be developing a detailed set of data gaps within ecological, biological, environmental, social, and physical characteristics. These will guide the establishment of reliable databases and monitoring systems for informed environmental management. By leveraging AI-driven solutions alongside traditional methods, we aim to enhance data accuracy and facilitate dynamic analysis. Looking ahead, we continue to refine these methodologies, paving the way for long term sustainability and resilience within the ecosystem and associated regenerative tourism regimes at The Red Sea. This paper presents a novel approach which addresses current challenges while positioning RSG as a regenerative tourism developer in KSA.

Introduction:

Saudi Arabia's Vision 2030 focuses on diversifying the economy, prioritizing sustainable development, eco-tourism, and environmental conservation. The Red Sea region plays a central role in this vision, aiming to become a top eco-tourism destination while protecting its unique ecosystems. In 2018, Red Sea Global (RSG) was established to lead the development of destinations along the Red Sea coast. RSG aims to achieve a 30% net conservation benefit by 2040, enhancing habitats including mangroves, seagrass, corals, and land vegetation, while protecting vital species. Through innovative technologies and data-driven decisions, RSG aims to create socio-economic benefits while preserving the environment. The integration of these technologies is aimed at enhancing environmental monitoring, ensuring that data collected feeds directly into environmental assessments, thereby improving decision-making and management strategies.

RSG follows the guidance of International Finance Corporation (IFC) Performance Standard 6 and conducts multiple Critical Habitat Assessments (CHA) across its destinations as a proactive approach to environmental design. Through comprehensive environmental assessments, potential impacts are identified early, enabling proactive design choices that minimize harm and enhance surrounding ecosystems. This ensures that marine tourism development aligns with responsible stewardship, protecting the Red Sea's unique biodiversity.

Problem Statement:

To manage ecosystems effectively, access to accurate environmental databases is essential. However, current data collection methods for marine ecosystems such as the Red Sea have limitations, particularly with reference to scalability and real-time high-resolution information. Traditional methods, relying on frequent field surveys and scattered sensor networks, leave gaps in data and hinder informed decision-making. These conventional methods also struggle to capture the dynamic and interconnected nature of marine ecosystems, where changes in one species impact others. Technology like AI and machine learning can help quantify the natural world, offering valuable knowledge to protect ecosystems (UNC, 2023). Additionally, variations in physical marine parameters like water temperature and salinity can significantly impact ecosystems. Without a real-time, comprehensive view, responses to environmental threats remain reactive than proactive. The lack of timely, holistic data makes it harder to protect sensitive habitats from climate change, pollution, and habitat loss.

This paper outlines RSG's innovative methods to bridge data gaps in the complex marine environment, enabling informed decision-making for environmental monitoring. AI is advancing research in marine science, particularly in oceanographic forecasting, species monitoring, coral reef assessment, and marine robotics (Dogan et al. 2024). By combining AI-driven tools with traditional survey methods, RSG is enhancing data accuracy and efficiency, particularly for coral reefs and sea turtles. These advancements will shape RSG's continued efforts in the protection, conservation and management of the marine ecosystems.

Methodological Approach:

Biodiversity Significance in the Red Sea and Selection of Key Environmental Receptors

The Alwajh Lagoon, located within The Red Sea destination, is a critical habitat covering 2,081 km^2, with 92 islands and diverse ecosystems like coral reefs, mangroves, and seagrass (Chalastani et al., 2020). A 2022 study by Red Sea Global found that the region is home to several marine species, including threatened ones such as Halavi Guitarfish *(Glaucostegus halavi),* Whale shark *(Rhincodon typus),* Zebra shark *(Stegostoma fasciatum),* Scalloped Hammerhead *(Sphyrna lewini),* Great hammerhead *(Sphyrna mokarran),* Ocean Humpback Dolphin *(Sousa chinensis),* Hawksbill Sea turtle *(Eretmochelys imbricata),* and Green Sea turtle *(Chelonia mydas)* (RSG Baseline Survey, 2022).

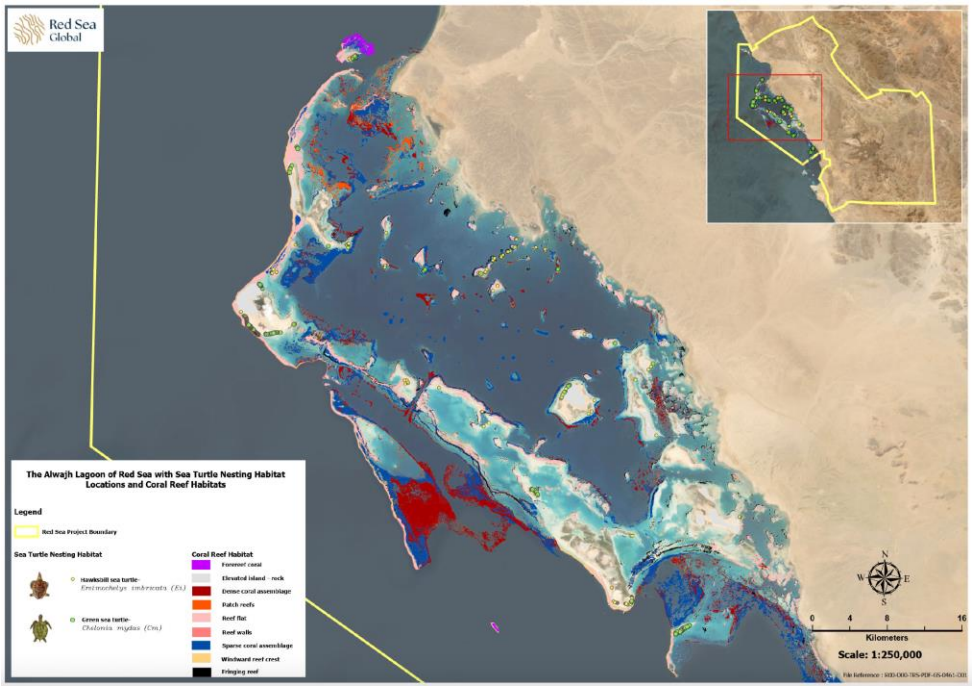

Figure 1: The Alwajh Lagoon in The Red Sea with identified Coral Reef and Turtle Nesting Habitat Locations.

RSG is enhancing environmental monitoring by developing its Environmental AI Data Platform, integrating satellite imagery, sensors, live cameras, drones, field surveys, and other inputs. RSG developed criteria to identify key ecological components of the landscape where significant data gaps need to be filled for effective monitoring at RSG destination sites. These criteria focus on the most sensitive and threatened receptors in the Alwajh lagoon. During the 2020 concept masterplan Environmental and Social Impact Assessment (ESIA), a detailed list of 106 Valued Environmental Receptors (VERs) was created, but not all were directly affected by the Red Sea Project (RSG, 2020). After evaluation, coral reefs and sea turtle habitats were selected for focus due to their significant international biodiversity value and high sensitivity. This selection is based on the data collected, emphasizing their importance in the ecosystem. Parts from VER assessment are provided in the following table:

Table 1: Valued Environmental Receptors List

VER	Value/ Sensitivity	VER Assessment
Coral reef habitats	International/Extreme	Vital habitat for marine biodiversity, likely supports evolutionary processes valuable to global climate change research, offers coastal protection, and provides tourism and research value.
Hawksbill turtle *(Eretmochelys imbricata),* declared Critically Endangered by IUCN	International/Extreme	Critically endangered, with both foraging and nesting in the project area. Key sites include Waqqadi Island and Breem Island.
Green turtle *(Chelonia mydas),* declared Endangered by IUCN	International/Extreme	Endangered globally, with foraging in seagrass and nesting on specific beaches. Waqqadi Island and Breem Island are key nesting areas.

(RSG,2020., Master ESIA for the Concept Master Plan)

Gap Analysis

Two critical gaps in environmental monitoring have been identified: coral reef health and sea turtle habitat monitoring. These gaps reflect challenges in the region's ability to assess and protect biodiversity effectively. The first gap focuses on improving coral reef health monitoring, which is essential for long-term conservation, given known threats such as rising seawater temperatures and anthropogenic activities. The second gap relates to sea turtle habitat monitoring, as the Red Sea is home to several endangered turtle species, including Green and Hawksbill turtles. Their nesting and foraging habitats require enhanced monitoring to guide effective conservation efforts. AI-driven tools have the potential to facilitate real-time, reliable data collection, improving population estimates, conservation of biodiversity and reducing the dependence on labor-intensive field surveys.

Coral Reef Health Monitoring

Coral reefs are among the most biodiverse and significant marine ecosystems. Coral reefs face multiple threats, including bleaching, ocean acidification, sedimentation, corallivore outbreaks, algal overgrowth from overfishing, eutrophication, and physical damage from anchoring and coastal development (BDC, 2021). Additionally, extreme seasonal temperature variations in the Red Sea push corals close to their physiological tolerance (PERSGA, 2002). Long-term monitoring of coral reefs is pivotal since it provides critical data to assist both marine managers and authorities to manage reefs properly and apply an adaptive management approach.

A series of factors underpin coral connectivity, including species diversity, percentage cover, spawning events, larval dispersal, settlement, interspecific variation, vertical connectivity, linked habitats (mangroves, seagrass), inter-reef distance, oceanography, and climate change (BDC, 2021).

RSG ensures coral conservation initiatives are supported by effective monitoring. Traditional methods like diver surveys, remote sensing, and satellite imaging provide valuable insights but have the following key limitations:

- Limited scalability

- Extensive physical work
- Slow response time
- Human subjectivity
- Low-resolution imagery

To address these gaps, AI and advanced technologies are being integrated into monitoring efforts. AI-driven tools, including robotics, machine learning, and deep learning, are enhancing data collection for coral reef identification and health tracking (Cardenas et al., 2024). These methods, described below are non-invasive and ensure minimal ecological disruption:

1. **Autonomous Underwater Vehicles (AUVs):** Equipped with high-resolution cameras, dynamic lighting, and AI image processing, AUVs enhance coral reef health monitoring and enable large-scale analysis.

Figure 2: Autonomous underwater vehicle deployed

Potential Outcomes:

- Using AI driven image processing to establish coral health, detect stress, 'bleaching/ threats, map coral reefs and produce 3D models.
- Leveraging deep learning models trained on large datasets to identify coral reef indicators and associated fauna
- Utilizing autonomous navigation systems to optimize movement while avoiding obstacles.
- Edge AI detects potential invasive species when they augment in numbers (e.g., crown-of-thorns starfish) in real time and sends georeferenced alerts.

2. **Underwater Camera Network:** Cutting-edge cameras installed in key coral reef areas capturing continuous imagery, which is integrated with RSG's AI Platform to enable AI-driven recognition.

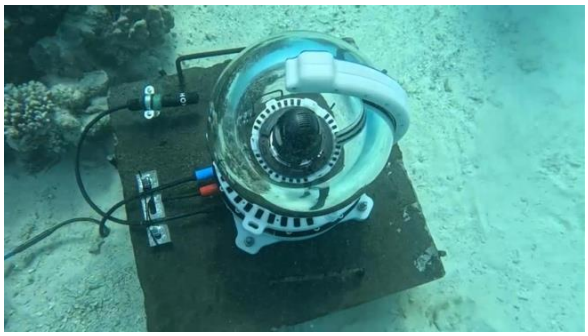

Figure 3: Underwater camera installed close by coral reefs at a Red Sea Destination.

Potential Outcomes:

- Analyzing real-time video to detect bleaching, coral growth, and potential ecosystem changes.
- Classifying coral species and tracking biodiversity shifts.
- Applying predictive analytics to anticipate reef conditions.

3. **Smart Water Buoy System:** Nearshore and deep-sea buoys deployed at RSG destinations feed real-time oceanographic data into the AI platform to support accurate coral health and environmental modeling.

Figure 4: Nearshore water quality buoy installed around Red Sea Destination.

Potential Outcomes:

- Machine learning models analyze oceanographic data (e.g., temperature, pH, salinity, dissolved oxygen) to detect environmental shifts.
- Correlating water conditions with coral health trends.
- Developing AI-driven early warning systems for reef stress.

These systems significantly enhance coral health monitoring. However, their true value lies in transforming data into actionable insights. RSG is actively installing these systems across Red Sea sites. Once fully integrated into the AI Platform, they will establish a centralized intelligence system, enabling real-time monitoring, early detection, and predictive analysis to augment protection of coral reef ecosystems.

Sea Turtle Habitats Monitoring

Sea turtles are among the most iconic and endangered species in the Red Sea. However, their habitats face increasing threats from rising global temperatures, beach erosion, and sea level rise (Wildermann et al., 2024). These challenges have prompted RSG to enhance conservation initiatives and improve monitoring efforts to ensure long-term protection. A turtle nesting habitat includes beaches for laying eggs, nearshore waters for access, and hinterlands for orientation and safety. Turtles cannot reproduce without suitable nesting beaches, which have distinct physical and chemical features such as sand grain size, moisture, salinity, temperature, slope, light levels, and nearshore approach. These features are difficult to replicate, making it crucial to leave nesting areas undisturbed. Traditional monitoring involves night patrols walking proposed sites to locate nesting turtles, as most marine turtles lay eggs at night (Alvarado & Murphy, 1999). Once a turtle is observed (digging, laying eggs, covering the nest, camouflaging, or returning to sea), its activity is recorded, and some turtles are also tagged with GPS satellite tracking devices. However, these surveys have limitations: limited spatial coverage, resource intensity, habitat disturbance, slow response times, and low-resolution imaging.

To address these challenges, AI and advanced technologies are transforming ecological data collection. Technologies like image recognition, machine learning, and environmental modeling improve habitat assessments, providing more accurate tracking (Noguchi et al., 2025) and enhanced detection through drone imagery (Chen et al., 2024). All monitoring methods used are non-invasive to prevent habitat disruption. RSG has begun implementing an advanced AI-driven monitoring program integrated into its Environmental AI Data Platform, including:

1. **Unmanned Aerial Vehicles (UAV):** Deploying fixed-wing drones capturing high-resolution imagery of nesting areas, and utilizing AI-driven models to enable tracking of sea turtle activities, nesting patterns, and habitat conditions

Potential Outcomes:

- Utilizing AI-driven image processing to classify sea turtle nesting activities, detect disturbances, and assess habitat conditions.
- Leveraging deep learning models trained on large datasets to identify key nesting patterns and environmental threats.
- Deploying autonomous flight systems to optimize aerial surveys while minimizing human interference in nesting areas.

2. **Acoustic Monitoring Network:** Underwater hydrophones capturing sea turtle activities in foraging areas, feeding data into the AI platform for behavioral analysis.

Potential Outcomes:

- Applying advanced machine learning algorithms to analyze underwater acoustic data, detecting sea turtle activities in foraging areas.
- Utilizing AI models to distinguish sea turtle sounds from background noise, ensuring precise monitoring of behavioral patterns.
- Implementing predictive analytics to anticipate behaviors based on detected acoustic signals over time.

3. **Smart Water Buoy System:** Nearshore and deep-sea buoys monitoring environmental conditions, integrating data in the AI platform to model foraging site health.

Potential Outcomes:

- Processing real-time oceanographic data (e.g., temperature, salinity, turbidity, and dissolved oxygen) using machine learning models to assess sea turtle foraging habitat conditions.
- Linking environmental conditions to sea turtle foraging patterns, pinpointing critical feeding areas

Figure 5: Nearshore water quality buoy installed at Red Sea Destination

and measuring habitat viability through machine learning models.
- Applying predictive analytics to establish early warning systems for habitat changes.

Beyond data collection, these systems transform information into actionable insights. Integrating drones, hydrophones, and buoys into RSG's AI Data Platform enhances sea turtle habitat monitoring by enabling early detection of changes. This will strengthen RSG's conservation efforts for nesting and foraging habitats. RSG is currently installing these systems, and their full integration will provide valuable insights over time.

Prospects for Environmental Monitoring:

RSG's environmental monitoring program is in its early phase, with key equipment deployed and the AI platform nearing completion. Upon full execution, the program will enable seamless data integration from multiple sources, supporting advanced environmental analysis and enhancing marine environmental assessments. Additionally, RSG is investing in a robust communication infrastructure, including the deployment of 5G technology. This high-speed, low-latency communication network will significantly improve the speed and reliability of data transfer to centralized servers, enabling near-instantaneous integration of field data into the Environmental AI Data Platform. This will accelerate analytics and facilitate more responsive, data-driven decision-making in environmental management.

Coral Reef Monitoring

RSG is in its first phases of applying AI interventions to improve marine habitat monitoring in the Red Sea. The deployment of autonomous underwater vehicles will expand survey coverage to deeper, larger coral reef areas, reducing time and resources. AI health classification will enhance data reliability, while high-resolution 3D modeling will support long-term monitoring. The underwater camera network will enable continuous monitoring, minimizing extensive field surveys. Similarly, the smart water buoy system will provide real-time water health data, detecting environmental stressors before they visibly impact coral health. Once these systems are fully integrated, RSG will set a new benchmark for coral reef conservation and proactive environmental management.

Sea Turtle Habitats Monitoring

The integration of unmanned aerial vehicles will improve sea turtle nesting habitat monitoring with better outreach and by covering larger coastal areas more efficiently while minimizing human interference. AI-powered image recognition will enhance data accuracy, improving tracking of nesting patterns and habitat conditions. The acoustic monitoring network will offer continuous, non-invasive observation of sea turtle activities in foraging areas, reducing the need for frequent field surveys. Additionally, the smart water buoy system will allow real-time monitoring of foraging habitats, detecting environmental changes that may affect sea turtle feeding behavior. This comprehensive approach will improve long-term habitat protection, ensure adaptive management, and strengthen conservation efforts for sea turtle nesting and foraging areas.

Conclusion

The use of non-invasive tools, such as drones, acoustic sensors, and smart buoys, will provide accurate, efficient insights into sea water quality, coral reef health, and sea turtle movements, all while minimizing impact on the ecosystem. This integration will support data-driven decision-making and adaptive management, ensuring long-term protection of the Red Sea's marine habitats. As RSG continues to deploy advanced monitoring technologies, it will enhance its ability to collect real-time data. By integrating these technologies with AI-driven analytics, RSG will have an enhanced management of marine ecosystem health, identify critical areas for conservation, and applying future intervention strategies to safeguard sensitive receptors and foster adaptive management across board.

These monitoring tools, will feed into environmental assessments, ensuring that management efforts are informed by the latest and most accurate information. Furthermore, it will allow for more proactive conservation efforts, guiding restoration initiatives and highlighting areas in need of urgent attention. With continuous advancements in AI and monitoring tools, RSG will strengthen its commitment to preserving the integrity of the marine environment and ensuring its long-term resilience for the future generations.

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