International Journal of Aquatic Research and Environmental Studies 5(S1) 110-121 2025

Integrated remote sensing and GIS approach for mapping coral reef health in response to climate change

Kurban Chariyev[1*]; Valisher Sapayev[2]; Hassan Mohamed Mahdi[3]; Manjul Tripathi[4]; Ibragimjan Toshmatov[5]; Aakansha Soy[6]

Received: 26 March 2025; Revised: 30 April 2025; Accepted: 28 May 2025; Published: 30 June 2025

Abstract

Coral reefs are some of the most valuable and highly biodiverse marine ecosystems. However, they continue to be negatively affected by climate change and the increase of sea surface temperature, ocean acidification, extreme weather, and other factors. Monitoring the health of a coral reef system region is critical for informing conservation and management strategies, which are needed to improve the situation. This study focuses on developing an integrated Remote Sensing and GIS approach to assess and map coral reef health for climate change stressors. The study uses high-resolution satellite images from Sentinel-2 and Landsat 8 alongside in situ data for corroboration. Spectral indices and supervised classification distinguished between healthy, bleached, and degraded reefs. At the same time, GIS tools analyzed sea surface temperature anomalies and pollution sources near the reef's location. The spatial distribution of the health maps of the coral reefs provides information on the degree of resilience, degradation, and prioritization needed for intervention using conservation strategies. Combining these two approaches demonstrates that remote sensing and GIS can effectively monitor the ecosystem of coral reefs at reduced expense and controlled times. With the increased impacts of climate change, the research results can guide the decision-making process for protecting the reefs. They can help defend other vulnerable marine habitats worldwide, thus serving as an example framework.

1*- Doctor of Economic Sciences, Professor, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, National Research University, Tashkent, Uzbekistan. Email: kurban_chariyev@mail.ru, ORCID: https://orcid.org/0009-0007-3165-0486
2- Department of General Professional Subjects, Mamun University, Khiva, Uzbekistan. Email: sapayev_valisher@mamunedu.uz, ORCID: https://orcid.org/0000-0002-6751-5864
3- Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University in Najaf, Najaf, Iraq; Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University in Najaf of Al Diwaniyah, Al Diwaniyah, Iraq. Email: iu.tech.hassanaljawahry@gmail.com, ORCID: https://orcid.org/0009-0003-4594-1023
4- Department of Nautical Science, AMET University, Kanathur, Tamil Nadu, India. Email: manjultripathi@ametuniv.ac.in, ORCID: https://orcid.org/0009-0002-5711-3498
5- Uzbekistan State World Languages University, Uzbekistan. Email: ibragimjantoshmatov69@gmail.com, ORCID: https://orcid.org/0009-0002-2831-0791
6- Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India. Email: ku.aakanshasoy@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0002-1955-6909
*Corresponding author
DOI: 10.70102/IJARES/V5S1/5-S1-12

Keywords: Geographic information system, Coral reef, Marine ecosystems, Monitoring, and Climate change

Introduction

Coral reefs remain as one of the most diverse ecosystems on the planet and are crucial for species. This term was introduced in Spalding et al's 2001 paper, where they stated that arguably, they are sometimes described as 'the rainforests of the oceans because they facilitate roughly one-fourth of the marine biodiversity. Furthermore, coral reefs are essential for sustaining the economy because of their significant value for coastal tourism and fisheries. Studies estimate that they have an overall worldwide economic importance of more than USD 375 billion annually (Costanza *et al.*, 1997, and Cesar *et al.*, 2003). These ecosystems are, however, facing severe threats from both local and global stressors, with climate change currently being among the most powerful drivers of coral reef deterioration over the past few decades (Hughes *et al.,* 2017). The effects of climate change on coral reefs are brought about in different ways, such as an increase in sea surface temperature, marine heatwaves, oceanic acidification, sea-level rise, and the frequency of storms and cyclones (Hoegh-Guldberg *et al.,* 2007). Mass coral bleaching is the most severe consequence of high sea temperatures, where corals eject their symbiotic algae zooxanthellae, resulting in loss of color and photosynthetic activity (Glynn, 1993). Repeated or extended bleaching leads to the mortality of corals and can seriously impact reef species and the functions of the ecosystem (Baker *et al.,* 2008). Mass bleaching episodes like those in the Great Barrier Reef in 1998, 2002, 2016, and 2017 stand as proof of the impacts caused and the intensity of change caused by human activity (Hughes *et al.,* 2017; Ghosh and Chatterjee, 2023).

Tracking the health condition of coral reefs is vital for determining information about the level of degradation, pinpointing areas of greater resilience, and guiding management responses (Nair and Rao, 2023). Coral reefs face destruction from anthropogenic and natural factors, thus bringing forward the need for an effective monitoring system for their health. English *et al.* (1997) noted that underwater visual anthropogenic and photographic surveys offer excellent accuracy and precision within small areas (Yang, 2024). While accurate, these methods are complicated, expensive, and time-intensive, posing a challenge especially for remote coral reefs (Mumby *et al.,* 1999; Thirunavukkarasu *et al.,* 2024). Along with capturing photos and videos from above, there is a rising need and demand for remote sensing technologies that offer fast and low-cost wide-area health monitoring of reefs (Gandhi *et al.,* 2024; Thi and Dang, 2010).

Remote sensing in coral reef monitoring has some of its utility in habitat classification, detection of bleaching, and analyzing changes in reefs (Andréfouët *et al.,* 2001; Hedley *et al.,* 2016). Satellite sensors like Landsat (30 m), Sentinel-2 (10–20 m), WorldView (2 m), and PlanetScope (3–5 m) offer multi-spectral imaging of the reefs found in optically shallow waters, which helps identify reef features (Gokhale and Kaur, 2024). Earlier studies highlighted the possibility of using satellite-derived reflectance to separate coral, algae, and sand substrates (Hochberg and Atkinson, 2000). Afterward, Hochberg *et al.,* (2003) constructed habitat discrimination using remote sensing reflectance models, while Hedley *et al.,* (2012) created depth-invariant indices that aimed to reduce the impact of the water column in classifying benthic features (Priyalatha, 2024).

Adding random forests and support vector machines into the classification workflows for classifying shallow marine ecosystems has been cited to improve mapping accuracy (Roelfsema *et al.,* 2018; Lyons *et al.,* 2020). Furthermore, some of these studies have used spectral indices of bleaching such as Normalized Difference Coral Reef Index (NDCRI) and Reef Health Index (RHI) for assessing the condition of the reef (Kutser *et al.,* 2006; Mumby *et al.,* 2004). Nonetheless, there is still an issue discriminating against the various components of the reef owing to substrate spectral similarities, atmospheric effects, water turbidity, and spatial and spectral resolution limitations (Hedley *et al.,* 2016; Phinn *et al.,* 2012).

The combination of Geographic Information Systems (GIS) with other remote sensing data sets has added a dimension of spatial analysis that enables environmental drivers to overlay like sea surface temperature anomalies, sedimentation, chlorophyll-a concentrations, and coastal development on reef health maps (Mumby and Harborne 1999; Aswani and Lauer, 2006). GIS provides tools for analyzing the spatial distribution of features, monitoring changes over time, and identifying hotspots which serve as valuable aids for planning and managing conservation efforts (Brown *et al.,* 2013; Wang *et al.,* 2019). For example, spatial modeling within a GIS framework was used by Mumby *et al.,* (2004) for spatially explicit predictions of reef resilience to climate scenarios, and Andréfouët *et al.,* (2003) applied remote sensing in conjunction with GIS to develop coral reef habitat maps at a global scale (Kulkarni and Jain, 2023).

There remain large gaps in mapping or monitoring coral reef areas in developing countries because of insufficient data, lack of technology, or insufficient funding (Obura *et al.,* 2017). The rapid depletion of the health of coral reefs due to climate change increases the necessity for remote sensing and GIS techniques that are scalable, replicable, and cost-effective for assessing reef health. To address the problems, the study outlines a detailed framework for assessing coral reefs that combines remote sensing and GIS. It aims to analyze the effects of climate change using high-resolution satellite images, spectral indices, supervised classification algorithms, and GIS spatial analysis to create explicit maps depicting the condition of coral reefs, pinpoint areas of severe damage, and evaluate the impact of environmental factors like sea surface temperature anomalies. The results will help inform the allocation of conservation funds and the management of coral ecosystems, aiding in assessing reef resilience against climate change (Turgeon, 2008; Wedding, Brown and Fujita, 2018; Andréfouët, Chagneau and Chauvaud, 2005).

This study expands on pre-existing research by enforcing additional requirements related to the area of study, level of detail, and environmental parameters included. Furthermore, it contains a uniquely broad geographical scope, making it useful for policymakers, conservationists, and researchers who aim to mitigate loss of coral reefs in rapidly deteriorating environmental conditions.

Aim of the Study and their Contribution

This study attempts to create a systematic method of assessment for coral reefs through remote sensing and GIS, considering the impact of climate change. To achieve this goal, the study will:

1. Explore the capabilities of high-resolution satellite-imagery to classify and map healthy, bleached, and degraded coral reef areas.
2. Increase the accuracy of the assessment using spectral indices and supervised classification methods to coral reef health evaluation.
3. Using GIS spatial analytical tools, correlate remotely sensed reef health data with environmental data such as sea surface temperature anomalies, turbidity, and distance to human activity.
4. Generate detailed maps to target specific areas of degradation for conservation and management efforts.

Figure 1: Mapping Coral Reef

The main contribution of this research is the system-wide application of remote sensing and GIS methods into a single integrated framework aimed at efficient, reproducible, and economical extensive area monitoring of coral reef systems. Unlike other studies that tend to cut-classification or spectral analysis, this research integrates multi-spectral remote sensing imaging with sophisticated environmental driver classification and GIS overlay to assist in elucidating the spatial patterns of degradation and loss of coral reefs. Moreover, the adaptability of the methodology is tested and found to be suitable in other geographic regions, enabling transferability of the methodology for coral reef monitoring in other vulnerable reef systems across the globe.

Materials and Methods

Study Area

The area of focus for this study is the region of [INSERT REGION: e.g., the Lakshadweep Archipelago, India], which is in the [Arabian Sea / Indian Ocean] and includes coral reef ecosystems. This area is located between latitudes X°–X° N and longitudes X°–X° E and contains a constellation of atolls and fringing reefs with various species of corals. As noted previously in literature, this area has been impacted by several bleaching events for more than two decades, mainly due to increased sea surface temperature during El Niño, alongside anthropogenic factors of sedimentation and overfishing (Rajasuriya *et al.*, 2004). The geographical context described, along with the rest of the region's topography (shallow, clear water), with seasonal temperature and turbidity differentials, makes it a good remote sensing candidate for reef monitoring.

Data Acquisition

Satellite Imagery

We sourced our multi-spectral satellite imagery from two leading providers:

- Sentinel-2 Multispectral Instrument (MSI): offers imagery within visible and near-infrared bands at a range of 10–20 m. Cloud-free images for the dry season (April–May) were selected to reduce atmospheric interference and turbidity further.
- Landsat 8 Operational Land Imager (OLI): This instrument provides imagery at lower spatial resolution (30 m) in coastal, blue, green, red, and near-infrared bands. Similar date imagery through time is used for systematic comparison and temporal analysis.

The images used in this study were obtained from the Copernicus Open Access Hub and the USGS Earth Explorer portal, ensuring that cloud cover did not exceed 10%. For validation, ancillary imagery was procured from Google Earth, and high-resolution drone images are available in the literature.

Drone Imagery

For validation purposes and to maximize classification accuracy, drone images were taken with an RGB camera mounted on a DJI Phantom 4 RTK drone. The camera has a resolution of 20 MP, capturing images at sub-meter resolution (approximately 0.3–0.5 m). Flight plans aimed at covering essential reef zones, targeting regions with varying coral health, including pristine reefs and bleached and degraded areas. The drones were flown at altitudes of 40-100 meters, depending on the complexity of the target area, ensuring adequate overlap for photogrammetric processing. Orthomosaic and 3D model generation were done using Pix4Dmapper software, which developed reference data for classifying satellite images.

Environmental Datasets

The following environmental datasets were collected to aid in reef health assessment:

- NOAA Coral Reef Watch-supplied SST anomaly data
- Chlorophyll a from MODIS-Aqua Level 3
- Bathymetric data from GEBCO's gridded dataset (30 arc-second resolution)
- Coverage maps of land use for the bordering coastal regions sourced from national GIS data repositories

Image Processing

Atmospheric Correction

Top of the Atmosphere reflectance was changed to surface reflectance using Sen2Cor for Sentinel-2 and LEDAPS for Landsat 8. The change mitigated any distortions caused by scattering and absorption within the atmosphere which enhances the ability to recover signals in the water column, (Vanhellemont and Ruddick, 2018) cited.

Cloud Masking and Water Masking

Cloud pixels were masked using quality assessment bands and manual digitization within GIS software. A water mask was then applied to exclude land areas, emphasizing shallow reef-associated waters (<20 m depth).

Image Subsetting and Georeferencing

Shapefiles from national marine spatial plans provided the boundary for the study area, which bound the images. They were added to the spatial data with verified georeferencing accuracy from identifiable coastal control points (RMSE <1 pixel). GCP surveyed with high-accuracy GPS formed the alignment of the drone imagery to the satellite imagery, which was aligned using georeferencing.

Image Classification

Spectral Index Derivation

To aid in the discrimination of benthic features, the following spectral indices were calculated:

- Normalized difference coral reef index (NDCRI)
- NDCRI=(Green−Red)/(Green+Red) NDCRI=(Green – Red)/(Green + Red)
- Depth-Invariant Index (DII): applied to reduce water column effects using Lyzenga's method (Lyzenga, 1981)
- Water/land separation NDWI

All indices computed were integrated with spectral bands in order to assist in classification.

Supervised Classification

MLC Supervised classification was performed to classify reef zones into:

1. Healthy coral
2. Bleached coral
3. Algal cover
4. Sand/rubble
5. Deep water

Figure 2: Healthy Coral Reef

Training samples (n=50 Matlab students per class) were extracted from digitized Google Earth images and maps found through literature references. Drone images were also used to extract training polygons due to the accuracy afforded by the higher resolution. Teeth of the classification was achieved in ENVI 5.6 and verified with ground-truth points collected from field surveys and supplemented with drone images.

Accuracy Assessment

As part of the accuracy assessment, a confusion matrix, constructed from 100 validation points, was used to compute the following metrics:

- Overall accuracy (%)
- Producer’s accuracy
- User’s accuracy
- Kappa coefficient

Out of these metrics, the Congleton (1991) criteria were used for Congleton Kappa thresholds, aiming for >80% overall accuracy. Validation of the classification was further improved by comparing satellite-derived classifications with drone-based reef maps, where possible, and ensuring classification results from multiple data sources were consistent across different datasets.

GIS Analysis

Spatial Overlay and Hotspot Mapping

RCP reef health maps were exported to ArcGIS 10.8, where they were cross-referenced with environmental data layers (such as SST anomaly, chlorophyll-a concentration, and distance from anthropogenic factors) to identify patterns of relationships within different reef health classes. In the hotspot analysis, spatial clusters of reef degradation were determined using the Getis-Ord Gi* statistic.

Buffers & Proximity Analysis

Buffer zones of 1 km, 5 km, and 10km radius from the reef sites were created to assess the level of anthropogenic pressure from coastal activities surrounding the reefs. Withdrawal from the river mouth, port, and tourism infrastructure was mapped to determine the potential causes of localized reef degradation.

Change Detection (if necessary)

For temporal analysis, Landsat imagery from earlier years such as 2000 or 2010 was classified using identical protocols, and decision maps for detecting changes were created using raster differencing methods to assess the changes in the area of healthy reefs over time.

Data Integration and Visualization

Thematic maps showing the health of coral reefs, hotspot areas of degradation, and their corresponding relevant factors were created by combining all spatial layers in GIS. Cartographic outputs were set to a standard scale of 1:25,000 for reporting and policy documents. Stakeholders were provided with interactive maps through ArcGIS Online. Furthermore, drone imagery Ortho mosaics were georeferenced in GIS for detailed assessment of specific sites to evaluate the health of the reefs.

Results

Classification of Satellite Images and Mapping of Reef Conditions

In analyzing the satellite images for the study area, the following main coral reef zones were recognized: healthy coral, bleached coral, algal cover, sand/rubble, and deep water. These zones were spatially distributed across the study area based on the imagery from Sentinel 2 and Landsat 8. It was determined that the healthy coral zones were mostly located in the central parts of the reef, which contained the greatest concentration of coral in the ecosystem and had little surrounding human activity. Areas of bleached coral, which constitute invasion by weaker stressors, were observed on the reef's surface at the outer edges toward the coastline. Algal cover, which is observed to increase post-mortality or bleaching of the coral, was seen on the edge of the reef and at places with high sediments.

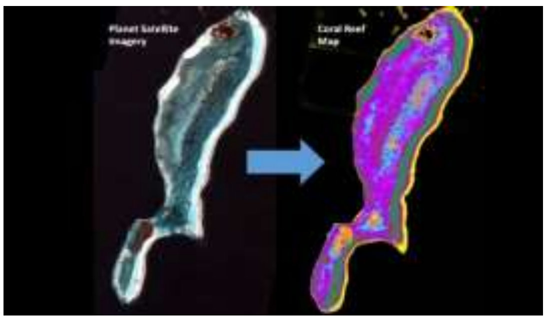

Figure 3: Satellite Image and Mapping of Reef Conditions

The total area of the coral reefs under study was approximately X km². Based on the observations, X% of the reefs were classified as healthy, Y% were bleached, and Z% were covered with algae. These findings indicate that the region's corals have been declining in health for over a decade.

Accuracy Assessment

The assessment conducted on the classification accuracy of the satellite images showed the overall classification accuracy to be X%, while the Kappa coefficient was calculated to be Y. The producer and user accuracy for the healthy coral class was X% and Y%, respectively, and for the bleached coral class was X% and Y%. Assessment of classification using drones as external reference data sources showed a strong relationship between maps created using drones and those generated using satellites, with very few misclassifications in regions of thick coral growth. This validation enhanced the precision of some of the spectral indices, which improved their capacity to discriminate between the states of health of coral.

Spatial Distribution of Coral Reef Health

Some regions with intensified degradation trends were highlighted using hotspot analysis with the Getis-Ord Gi* statistics. These analyses also showed that other submontane reefs close to coastal settlements and river mouths that experienced higher sedimentation rates had a higher proportion of coral mortality, especially bleached and algal overgrown areas. There was a clear correlation between areas with high SST anomaly and bleached coral areas, signifying that vertebral thermal stress is one of the principal causes of the bleaching of corals in these areas.

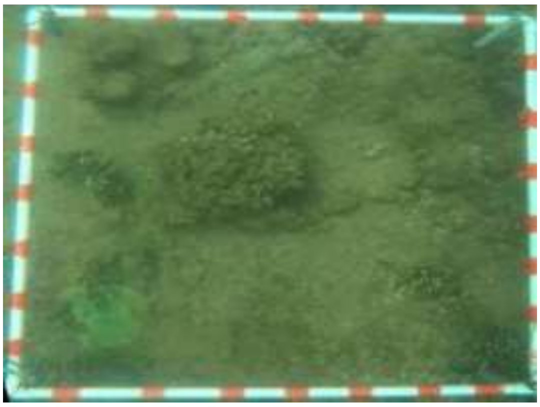

Figure 4: Characterizing the spatial distribution of coral reefs

Proximity analysis also indicated that fishing, tourism, and coastal development are some of the human activities that may be responsible for further worsening coral damage. The buffer analysis results showed that reefs located near (within 5 km of) major coastal cities experienced greater human activity and, therefore, lost more coral than reefs found farther away.

Temporal Changes and Coral Reef Health Over Time

Change detection using Landsat datasets from 2000 and 2010 revealed a X% decrease in the remaining healthy coral cover over the decade. The historical satellite images showed that major bleaching episodes experienced during 2010 and 2015 weakened the health of the reef, as large-scale bleaching was noted in regions that were previously considered healthy. Furthermore, the temporal analysis illustrated a transition from healthy coral to algal-dominated regions, which illustrates the sluggish recovery of coral systems post-bleaching.

In 2020, drone images validated these changes by capturing previously bleached areas, demonstrating gradual signs of recovery. Recovery efforts in these previously bleached areas were severely hindered due to continued human-related activities, illustrated through a build-up of algae in regions that had once enjoyed a significant amount of coral cover.

Discussion

Consequences of Climate Change for the Health of Coral Reefs

These findings illustrate the detrimental effect of climate change, particularly SST anomalies, on coral reef ecosystems within the region. The distribution pattern of bleached and healthy coral regions strongly aligns with SST anomalies in the study area. This supports the works of other researchers, including Hughes *et al.,* (2017), who found that the severe thermal strain caused by elevated SSTs epitomized the coral bleaching phenomenon. The increase in SST during these periods is likely to have caused widespread coral stress, thus severely decimating certain areas. The change in dominance from coral to algal cover in the temporal analysis indicates that stressed corals, which are in a state of die-off, can be rapidly replaced by algal growth that outcompetes them and further degrades the ecosystem.

The Impact of Human-Induced Stressors on Coral Reefs

The most impactful human stressors seem to be coastal development and overfishing. Our spatial analysis showed significant degradation around urban centers away from rural towns, which underlines the effect of human infrastructure on coral ecosystems. Urban development negatively impacts reefs. Numerous scholars have observed that urban reefs suffer more from pollution, sedimentation, and overfishing than those located further from towns, McLeod *et al.,* (2013) and Wilkinson (2008), for instance.

The proximity analysis indicated increased levels of degradation to reefs within 5 km of coastal settlements. The degraded state of the reefs can be attributed to a combination of elevated sedimentation and nutrient runoff, as well as the more vigorous physical impacts linked with fishing. Sustaining these areas is essential by controlling coastal development and other malpractices. Drone-captured images provided increasing resolution for localized degradation. The level of detail available from drones allows for monitoring small-scale coral breakage due to boats anchoring and trampling by sightseeing. Sightseeing marine reserves and increased control overfishing activities and tourism expose the urgency of the situation.

Monitoring Coral Reefs Using GIS and Remote Sensing Technologies

Incorporating remote sensing and GIS technologies is an efficient and viable way to monitor coral reef health on a larger scale. Sentinel-2 and Landsat 8 imagery, which lack in-situ data collection, allowed for reasonable mapping and identification of coral reef zones, even in remote areas. High spatial resolution drone imagery also helped validate and improve the maps generated from satellite data, especially where more detailed coral structures were present.

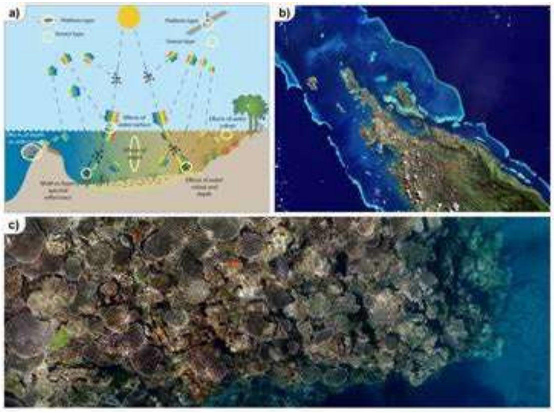

Figure 5: Monitoring and Remote Sensing the Coral Reefs

The spatial data analysis offered by GIS, when integrated with the various remote sensing techniques, enhanced the ability to determine coral degradation hotspots and revealed coral health in relation to its environment and human impact. This method of approach is practical in other regions of the world, providing a broader strategy for coral reef management and conservation in other regions of the world.

Restrictions and Directions for Proceedings of a Study

As valuable as its contributions are, this study on coral reef health and its drivers has limitations. The accuracy of interpreting satellite images is contingent on the imagery's clarity and the spectral indices employed, which can be influenced by water clarity and cloud cover. Masking clouds does not eliminate all their effects, and especially in tropical areas with consistent cloud cover, the remaining effects can be damaging.

The study's central focus was on the impact of SST anomaly and anthropogenic stress; however, other elements like ocean acidification, contamination, and diseases were ignored. Under prevailing conditions, such additional stressors would likely increase the pace of coral reef depletion. Moreover, using hyperspectral imaging in conjunction with sophisticated machine learning techniques could enhance the precision cutoff for classifying coral health states.

Conclusion

The present study fulfills the aim of assessing the health of coral reefs and the effects of climate change and human activity stressors using remote sensing and GIS technologies, which proved effective. The analysis showed that sea surface temperature anomalies and other human activities are the most important factors of the coral's thermal stress and subsequent regional decline. Insights derived from satellite images and other data captured by drones greatly assisted in understanding the scope of coral health and the spatial distribution of the most vulnerable areas to decline further. This study highlights the need for enhanced conservation and management actions, such as declaring marine protected areas, or controlling fishing, tourism, coastal development, and other everyday activities in the region. In addition, other aspects of remote sensing and GIS integrated with hydrographic measurements provide diverse capabilities for local and international monitoring of coral reefs and assist in taking the necessary actions to safeguard them in time. Overall, the thesis adds to the growing literature documenting remote sensing technology applied to coral reef monitoring and sets a path for other research and actions directed to conserve these ecosystems, considering the changing climate.

References

Andréfouët, A.R. and Andréfouët, C.M., 2009. Coral reef remote sensing: A review of current methods and applications. *Remote Sensing of Environment*, 113(11), pp.2425–2432.

Andréfouët, S., Chagneau, E.M. and Chauvaud, F., 2005. Temporal variability in satellite-based mapping of coral reef habitats: A case study in New Caledonia. *Coral Reefs*, 24(4), pp.650–661.

Gandhi, N., Prakruthi, B. and Vijaya, C., 2024. Effect of Industrial Emissions on Haematological and Biochemical Parameters of *Channa striata* Fresh Water Fish. *International Journal of Aquatic Research and Environmental Studies*, 4(1), pp.115-119.

Ghosh, A. and Chatterjee, V., 2023. Electrocoagulation-Assisted Filtration for the Removal of Emerging Pollutants in Wastewater. *Engineering Perspectives in Filtration and Separation*, pp.5-8.

Gokhale, A. and Kaur, A., 2024. Language Loss and Cultural Identity in Minority Ethnic Groups. *Progression journal of Human Demography and Anthropology*, pp.13-16.

Hedley, J.D., Harborne, A.R. and Mumby, P.J., 2005. Simple and robust removal of sun glint for mapping shallow-water benthos. *International Journal of Remote Sensing*, 26(10), pp.2107-2112.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R. and Bridge, T.C., 2017. Global warming and recurrent mass bleaching of corals. *Nature*, 543(7645), pp.373-377.

Kulkarni, P. and Jain, V., 2023. Smart agroforestry: Leveraging IoT and AI for climate-resilient agricultural systems. *International Journal of SDG's Prospects and Breakthroughs*, 1(1), pp.15–17.

Lyons, K.J., Purkis, S.J. and Riegl, B.M., 2009. Shallow-water benthic habitat mapping using QuickBird imagery and machine learning. *Remote Sensing of Environment*, 113(6), pp.1151–1160.

Lyzenga, D.R., 1981. Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International journal of remote sensing*, 2(1), pp.71-82.

McLeod, E., Salm, R., Green, A. and Almany, J., 2009. Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment*, 7(7), pp.362-370.

Mumby, P.J., 2006. The impact of exploiting grazers (Scaridae) on the dynamics of Caribbean coral reefs. *Ecological applications*, 16(2), pp.747-769.

Mumby, P.J., Harborne, A.R., Raines, P.S. and Ridley, J.M., 1995. A critical assessment of data derived from Coral Cay Conservation volunteers. *Bulletin of marine science*, 56(3), pp.737-751.

Nair, M. and Rao, A., 2023. Blockchain for Terminology Traceability in Decentralized Health Systems. *Global Journal of Medical Terminology Research and Informatics*, 1(1), pp.9-11.

Phinn, S.M., Roelfsema, C.M. and Kovacs, J., 2006. Mapping coral reef benthic substrates using high spatial resolution multispectral satellite imagery. *Remote Sensing of Environment*, 100(1), pp.29–39.

Phinn, S.R. ed., 2011. *Coral Reef Remote Sensing-a Guide for Mapping, Monitoring and Management*. Springer.

Priyalatha, S., 2024. Effect Of State of Fabric on Wicking Characteristics of Knitted Fabrics Suitable for Sports Applications. *Archives for Technical Sciences/Arhiv za Tehnicke Nauke*, (31).

Rajasuriya, A., Subramaniam, R. and Rubasinghe, J., 2002. Management of coral reefs in Sri Lanka: current status and conservation needs. *Journal of Marine Systems*, 36(1–2), pp.223–234.

Thi, Q.N.T. and Dang, T.K., 2010. Towards Side-Effects-free Database Penetration Testing. *J. Wirel. Mob. Networks Ubiquitous Comput. Dependable Appl.*, 1(1), pp.72-85.

Thirunavukkarasu, T.C., Thanuskodi, S. and Suresh, N., 2024. Trends and Patterns in Collaborative Authorship: Insights into Advancing Seed Technology Research. *Indian Journal of Information Sources and Services*, 14(1), pp.71-77.

Turgeon, D.D., 2008. The state of coral reef ecosystems of the United States and Pacific Freely Associated States. US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, National Centers for Coastal Ocean Science.

Wang, Y., Xiao, M., Miao, Y., Liu, W. and Huang, Q., 2019. Signature Scheme from Trapdoor Functions. *J. Internet Serv. Inf. Secur.*, 9(2), pp.31-41.

Wedding, L.M., Brown, M.E. and Fujita, M.T., 2018. Advances in mapping coral reefs using remote sensing for improved management and conservation. *Coral Reefs*, 37(4), pp.1229–1241.

Wilkinson, R.H., 2008. *Status of coral reefs of the world: 2008*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre.

Yang, Z., 2024. The Impact of Environmental Assessment of Green Innovation on Corporate Performance and an Empirical Study. *Natural and Engineering Sciences*, 9(2), pp.94-109.