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Remote Sensing-Based Assessment of Aquatic Habitat Transformation and Ecosystem Degradation Under Environmental Stress Conditions

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Abstract: Structural and functional changes are occurring rapidly in aquatic habitats due to increased variability in climate conditions, land use changes and pollution. This research used multi-temporal satellite data to analyze the changes in aquatic habitats and the degradation of ecosystems in a tropical river-wetland-lagoon complex that covers 1,250 km² between 2000 and 2024. Classification of images for five reference years obtained using Landsat and Sentinel-2 into seven types of land and water, along with indicators for water extent, aquatic vegetation health, water turbidity, algae, and surface water temperature, was performed. An index of environmental stress and a scale of five ecosystem degradation levels were constructed. The extent of open water decreased by 26.9%, that of aquatic and marsh vegetation by 37.1%, and that of mangrove and riparian vegetation by 26.6%; aquaculture ponds and built-up land grew more than fourfold and by 56.9%, respectively. Indicators of water turbidity and algae increased, the greenness of vegetation became worse, and surface water temperature increased by about 1.6 °C. Loss of habitat within 40 assessment units had a strong correlation with environmental stresses, and the lower wetlands and estuarine fringe were identified as the most vulnerable areas. Urbanization, aquaculture modification, and changes in water flow were recognized as the most dominant threats. The results reveal the importance of remote sensing of the environment in terms of detecting habitat degradation at an early stage.

Keywords: Remote Sensing; Aquatic Habitat; Wetland Change; Ecosystem Degradation; Environmental Stress; Water Quality, Conservation Planning.

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I. Introduction

Despite making up only a very small percentage of the surface area of the Earth, rivers, lakes, wetlands, estuaries and coastal lagoons contain a disproportionate number of the world's species and biodiversity. These habitats control flooding, provide fresh water sources, filter contaminants, store carbon, and are home to fish populations that feed hundreds of millions of people. In spite of their importance, aquatic habitats represent some of the most imperiled types of habitats on Earth, and degradation has increased dramatically with increased land and water use by humans. Habitats are drained for agricultural purposes, turned into aquaculture ponds along the shoreline, managed by dams and water diversions, and are subject to increased loads of sediments and nutrients from upstream.

The ability to know about the dynamics of aquatic environments and also about the distribution of environmental degradation and the factors causing such trends is very important for effective management. Field surveys give information that is very useful but are expensive, take a long time, and can only be done on a few accessible sites. Remote sensing from satellites can provide a practical way of doing this since it provides information that is repeatable, reliable, and obtained for large areas.

The majority of the current assessments, on the other hand, consider either the extent of habitat or water quality, and very few of these studies link these transformations to a unified indicator of environmental stress. Such integrated data sets that link habitat and water transitions and conditions together, and the degree of degradation, are currently lacking, especially in tropical rivers, wetlands, and coasts that experience overlapping pressures.

1. Estimating changes in the extent of aquatic habitat from 2000 to 2024.

2. Analyzing the spatiotemporal pattern of transformation of aquatic habitats throughout the study region.
3. Evaluating the differences in water and environmental conditions through remote-sensing-derived indicators.
4. Classifying the degrees of degradation in the ecosystems using habitat loss and environmental conditions.
5. Analyzing the correlation between environmental stress and changes in aquatic habitat within the assessment units.
6. Supporting decisions on conservation and management through mapping out the vulnerable sites and environmental stresses.

Section 1 presents the background, research problem, gap, and study objectives. Section 2 presents prior research on remote sensing, aquatic habitat change, environmental stress, and research gaps. Section 3 describes the study area, data collection, image processing, degradation assessment, and analytical methods. Results of habitat change, environmental conditions, degradation levels, and stress–habitat relationships are presented in Section 4. Major findings, conservation implications, conclusions, recommendations, limitations, and future research directions are outlined in Section 5 and Section 6.

II. Literature Review

Remote Sensing Applications in Aquatic Ecosystems

Satellite observations are essential for the assessment of inland and coastal waters, especially given the rapid rate of decline in freshwater biodiversity compared to terrestrial and marine ecosystems (Albert, J. S. et al., 2021). The Global Research Agenda for Freshwater Biodiversity highlighted better monitoring and data sharing capabilities as critical requirements for good management of aquatic environments (Maasri, A. et al., 2022). Historical reconstructions using a combination of satellite observations and historical data have revealed that one fifth of natural wetlands has disappeared since 1700, and the highest losses occurred in regions with intensive agriculture (Fluet-Chouinard, E. et al., 2023). The harmonized database of global lakes and wetlands is able to differentiate between natural and artificial lakes, rivers, and many kinds of wetlands (Lehner, B. et al., 2024). The maps of fine-resolution wetlands created based on long-term observations using optical and radar images are able to separate inland marsh, swamp, and flooded flats from coastal mangrove, salt marsh, and tidal flats (Zhang, X. et al., 2023). Daily observations of the open surface water over twenty years have also helped to detect seasonal flooding, reservoir filling and shrinking of lakes (Klein, I. et al., 2024).

Aquatic Habitat Transformation

Research on remote sensing indicates considerable transformations of aquatic habitat due to human-induced factors. Mapping using high-resolution data of mangrove forests suggests that there are serious threats to the vegetation cover in coastal environments in East and Southeast Asia, where, at the same time, there is an expansion of the covered areas for conservation purposes (Jia, M. et al., 2023). Analysis of the losses and gains of tidal wetlands on the global level between 1999 and 2019 indicated that losses were due to human-induced processes like conversion into agriculture and aquaculture, whereas gains were mostly due to natural changes (Murray, N. J. et al., 2022). Large lakes have been studied using satellite altimetry and optical sensors, which showed losses in water storage due to warming, higher evaporation rates, and consumption of water by humans (Yao, F. et al., 2023). Managed human reservoirs are responsible for much of the seasonal variability of the global surface water storage, showing how regulation influences the hydrology of aquatic habitats (Cooley, S. W. et al., 2021). There have been changes in the river sediment flux due to the construction of dams and changes in land use (Dethier, E. N. et al., 2022).

Environmental Stress and Ecosystem Degradation

The effect of environmental stress on the environment is experienced by aquatic ecosystems through physical and biological mechanisms. Research shows that there have been occurrences of greater algal blooms in the past decade, especially in Asian and African regions (Hou, X. et al., 2022). The daily observation of nearly two thousand large lakes shows that the frequency of blooms has increased in proportion to air temperature (Wang, Y. et al., 2025). Heat waves in lakes are expected to increase in duration and intensity, thus posing more thermal stress on organisms inhabiting them. There have also been occurrences of loss of oxygen in the water bodies from long-term observation of lakes in temperate climates. These findings suggest that the degradation is not due to one single cause but rather due to several factors, including warming, nutrient enrichment, flow regulation, and land use change (Albert, J. S. et al., 2021).

Research Gaps

Satellite-derived global datasets have enhanced the understanding of the extent of aquatic habitats, many existing studies examine only one habitat category or one indicator at a time. Relatively fewer studies have linked changes in habitat to environmental stress levels using a composite metric of environmental stress levels. Studies that link changes in habitat and water quality with the level of water degradation, and that have been done in the tropics with respect to riverine, wetland, and coastal areas where agricultural, urban, and aquaculture pressure overlaps, are very few.

III. Methodology

Study Area and Research Design

Assessment was conducted on the tropical river-floodplain-lagoon system measuring about 1,250 km², comprising an upper river stretch, a middle floodplain, a lower freshwater floodplain, estuary margins, and the coastal lagoon shown in figure 1. It has a monsoon-type climatic regime and is characterized by the presence of wet and dry seasons. This region houses agricultural activities, inland and coastal fishing, aquaculture, and growing settlements. Five habitat zones and 40 assessment units were identified, with nearly equal sizes. A longitudinal design approach was taken with the help of five reference years, namely 2000, 2006, 2012, 2018, and 2024, thus permitting consideration of change and variation within periods.

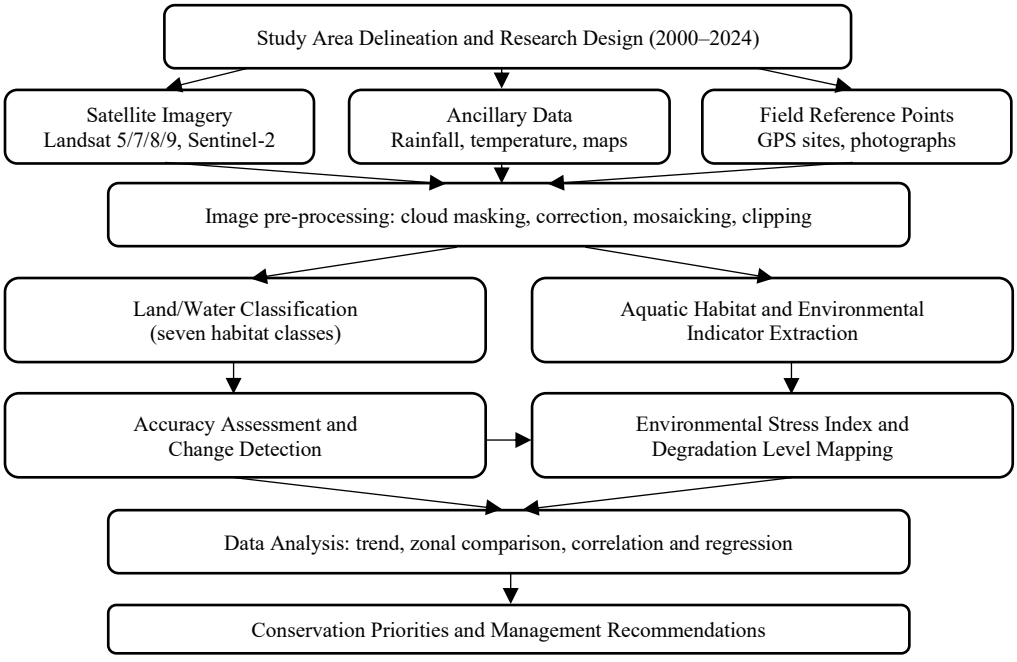


Figure 1: Methodological Flow of the Remote Sensing-Based Assessment

Remote Sensing Data Collection

Images with no or very few clouds were taken during the post-monsoon dry season to minimize variation in water body depth and vegetation conditions. Landsat images were utilized for older years, while Sentinel-2 images were also included in the analysis for more recent years to enhance spatial resolution. Additional data included records of annual rainfall and temperature, topographic maps, administrative boundaries, and existing land use maps. A total of 520 ground-truthing points were obtained through the hand-held satellite positioning system, along with photographs and descriptions of habitats, while historical high-resolution images were used to complement reference points for older years. Detailed data regarding satellite imagery is provided in table 1.

Table 1: Satellite Data Used in the Assessment

Reference year	Sensor	Spatial resolution	Season	Scenes used
2000	Landsat 5 TM / Landsat 7 ETM+	30 m	Post-monsoon dry	3
2006	Landsat 5 TM	30 m	Post-monsoon dry	3
2012	Landsat 7 ETM+	30 m	Post-monsoon dry	4
2018	Landsat 8 OLI and Sentinel-2	30 m / 10 m	Post-monsoon dry	5
2024	Landsat 9 OLI-2 and Sentinel-2	30 m / 10 m	Post-monsoon dry	5

Aquatic Habitat and Environmental Indicators

Seven habitat extent classes were identified, including: open water, aquatic/marsh vegetation, mangrove/riparian vegetation, mudflat/exposed bed, aquaculture ponds, and agricultural/built-up areas. Water and environmental conditions were assessed through four indices based on the brightness values in color bands. These indices include the turbidity index, which is indicative of the amount of suspended material; the algal presence index, which is indicative of water greening; the vegetation greenness index, which is indicative of vegetation vigor; and water temperature from the thermal band. Temperature index is the only index which is not scaled to 0-1 range for interannual comparison.

Image Processing and Land/Water Classification

All images were corrected for atmospheric corrections, masked for clouds and shadows, and stitched into seamless mosaics clipped to the area of interest. The classification process utilized a supervised learning algorithm; whereby field and interpreted image samples were used for training. Different samples were held aside for validation, where accuracy was assessed through comparison of classified data against the reference samples. Overall accuracy was between 86.4% to 91.8%, while Kappa coefficient was 0.83 to 0.90, signifying accurate classification for all the years shown in table 2. The maps were compared annually to establish the type and extent of change in the habitats.

Table 2: Classification Accuracy for Each Reference Year

Reference year	Overall accuracy (%)	Kappa coefficient	Reference points
2000	86.4	0.83	410
2006	87.9	0.85	430
2012	88.6	0.86	460
2018	90.7	0.89	500
2024	91.8	0.90	520

Ecosystem Degradation Assessment

Environmental Stress Index for each assessment unit was developed based on six pressures layers including expansion of built-up land, conversion of aquaculture, flow alteration as shown in figure 2 through loss of water extent, increase in surface water temperature, nutrient loading shown through presence of algae, and sediment change through turbidity.

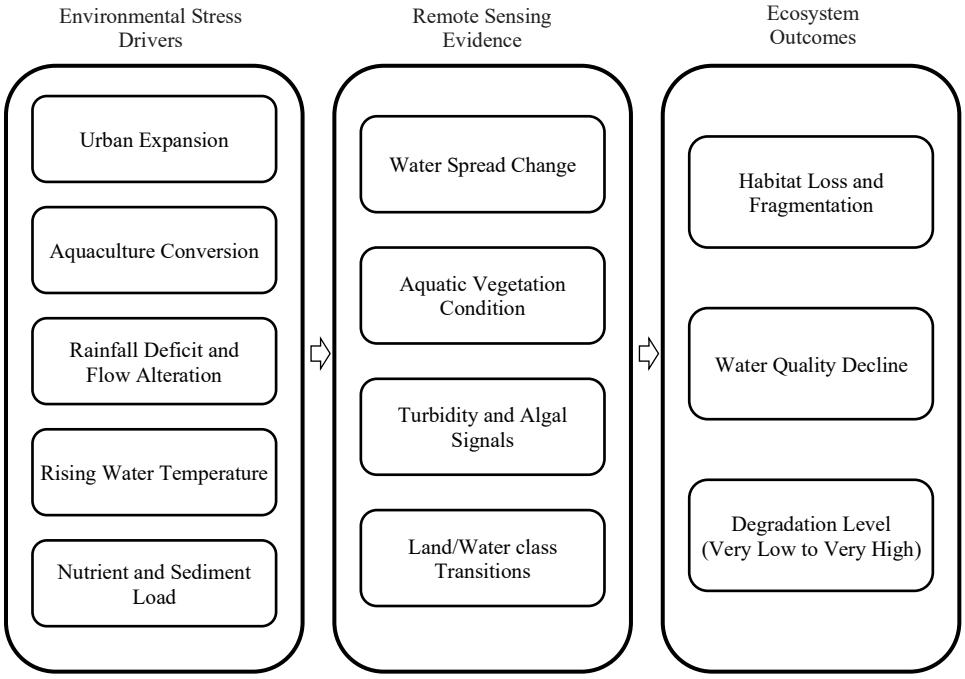


Figure 2: Conceptual Architecture Linking Environmental Stress, Remote Sensing Evidence and Ecosystem Outcomes

Each of the layers was normalized to a range of 0 to 1 and combined with a set of weights that were developed using expert ranking. Degradation levels ranged from very low to very high and was defined using combination of habitat loss, greenness of vegetation and water quality.

IV. Results

Changes in Aquatic Habitat Characteristics

Table 3: Area of Habitat Classes and Net Change, 2000–2024

Habitat class	2000 (km²)	2012 (km²)	2024 (km²)	Net change (km²)	Change (%)
Open water	312	276	228	−84	−26.9
Aquatic and marsh vegetation	186	152	117	−69	−37.1
Mangrove and riparian vegetation	94	81	69	−25	−26.6
Mudflat and exposed bed	58	79	104	+46	+79.3
Aquaculture ponds	21	57	89	+68	+323.8
Agriculture	412	398	381	−31	−7.5
Built-up land	167	207	262	+95	+56.9

The aquatic habitat underwent a considerable reduction between 2000 and 2024 are discussed table 3 and figure 3. There is a 26.9% reduction in open water from 312 km2 to 228 km2. There was a significant reduction in the area covered by aquatic and marsh vegetation, which shrank from 186 km2 to 117 km2

(37.1%), and mangrove and riparian vegetation which was reduced from 94 km2 to 69 km2 (26.6%). Conversely, there is a 79.3% increase in mudflat and exposed beds, while aquaculture ponds increased more than fourfold from 21 km2 to 89 km2. The built-up land increased by 56.9%, while agriculture decreased by 7.5%

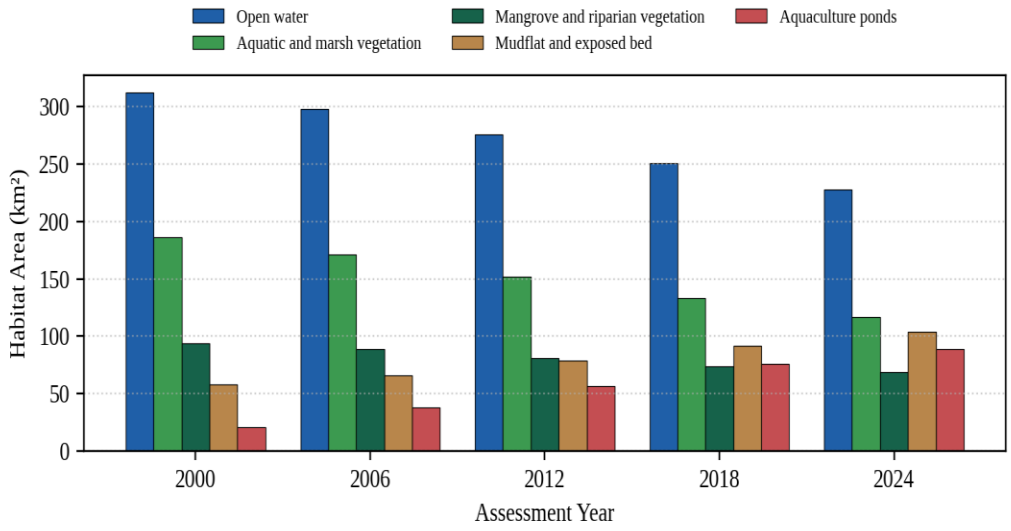


Figure 3: Change in Aquatic Habitat Area by Class Across the Five Reference Years

Spatial and Temporal Patterns of Habitat Transformation

Loss of habitat occurred unevenly throughout the study site and became severe during all periods in every zone in figure 4. Loss was most severe in the lower wetland zone in each period, increasing from 4.8% in 2000-2006 to 8.1% in 2018-2024, while second in terms of loss was the estuarine fringe, where loss increased from 3.9% to 7.7%. Loss was also very pronounced in the coastal lagoon zone in the latest period due to the creation of ponds within it. Finally, loss in the upper river reach zone was the lowest among all zones, but it still doubled from 2.1% to 4.2%.

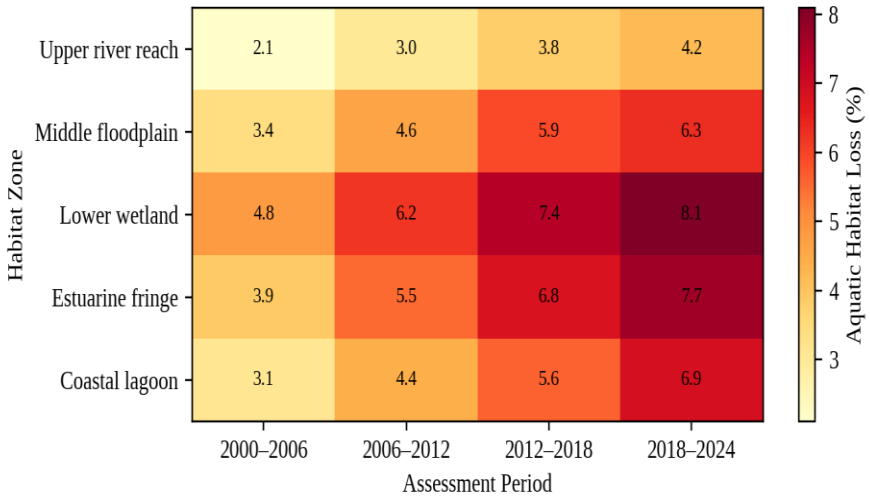


Figure 4: Zone-Wise Aquatic Habitat Loss Across four Assessment Periods

Variation in Water and Environmental Conditions

The water condition indicators depicted an almost steady and consistent fall in ecological integrity of the system using figure 5. There was an increase in the value of the turbidity index, from 0.31 to 0.56, signifying high levels of suspended sediments, while the index for the presence of algae doubled from 0.18 to 0.44, denoting enrichment of nutrients in the ecosystem. The index for vegetation greenness of the aquatic and wetland plants dropped from 0.62 to 0.44, implying reduced vitality in the plants. Temperature of the surface water increased from 27.6 °C to 29.2 °C, especially after 2012.

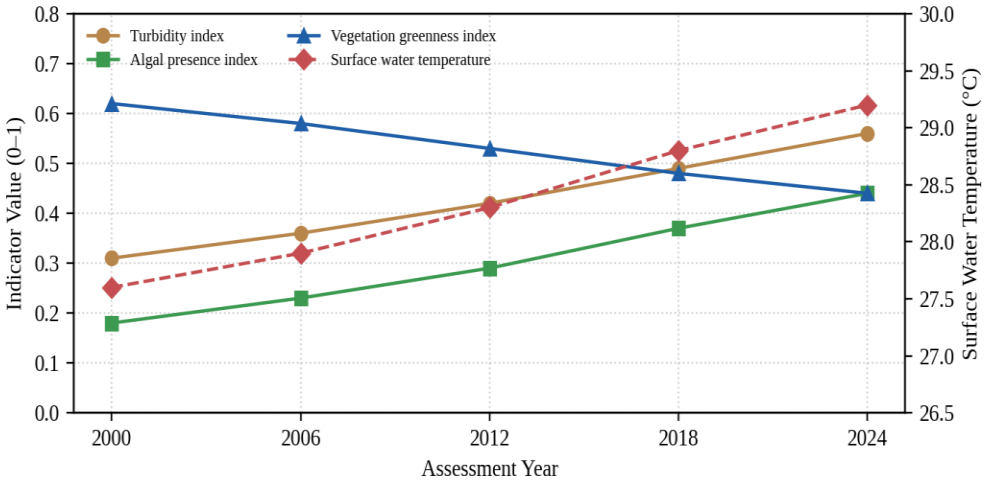


Figure 5: Temporal Variation in Water and Environmental Condition Indicators

Ecosystem Degradation Levels

However, there has been an increase in the proportion of areas with high or very high degradation in figure 6. For instance, in 2000, 63% of the total habitat area was under very low and low degradation while 16% had high or very high degradation. However, by 2024, this percentage had reduced to 31% for very low and low degradation while the areas with high and very high degradation had increased to 42% of the total habitat area. The very high degradation areas were mainly within the lower wetland and estuarine fringe.

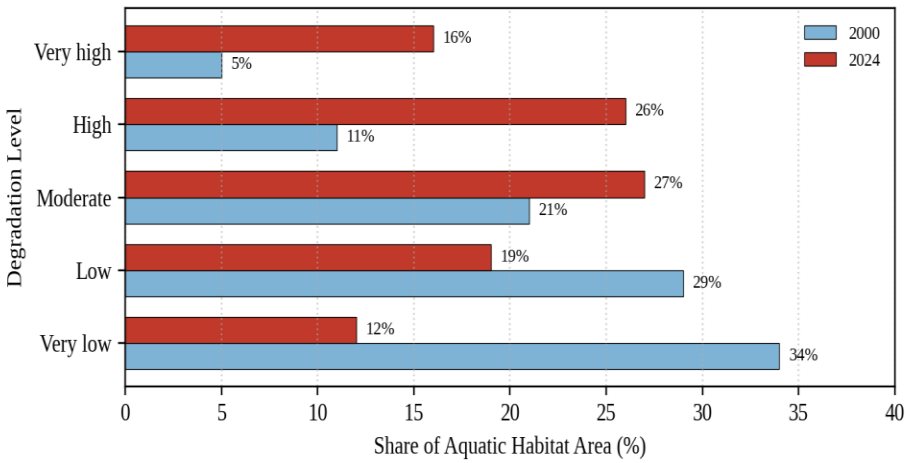


Figure 6: Distribution of Aquatic Habitat Area by Degradation Level in 2000 and 2024

Relationship Between Environmental Stress and Habitat Change

Loss of aquatic habitat area increased steadily with an increase in environmental stress index for the 40 units analyzed in figure 7. The relationship between the two factors was strong (r = 0.91), and the stress index explained about 83% of the changes in habitat loss. Areas where the stress index exceeded 0.6 generally experienced a loss of more than 25% in aquatic habitat, while those that recorded stress index less than 0.3 experienced loss in habitat of less than 15%. Among the stress factors, urbanization was the most influential (27%), followed by aquaculture conversion (22%), flow alteration (18%), temperature increases (13%), nutrients (12%) and sediment changes (8%) shown in figure 8.

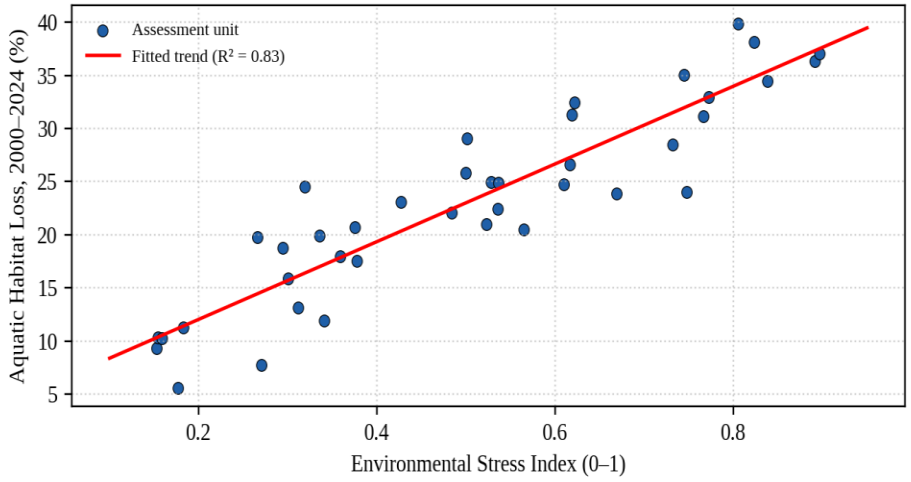


Figure 7: Relationship Between Environmental Stress Index and Aquatic Habitat Loss

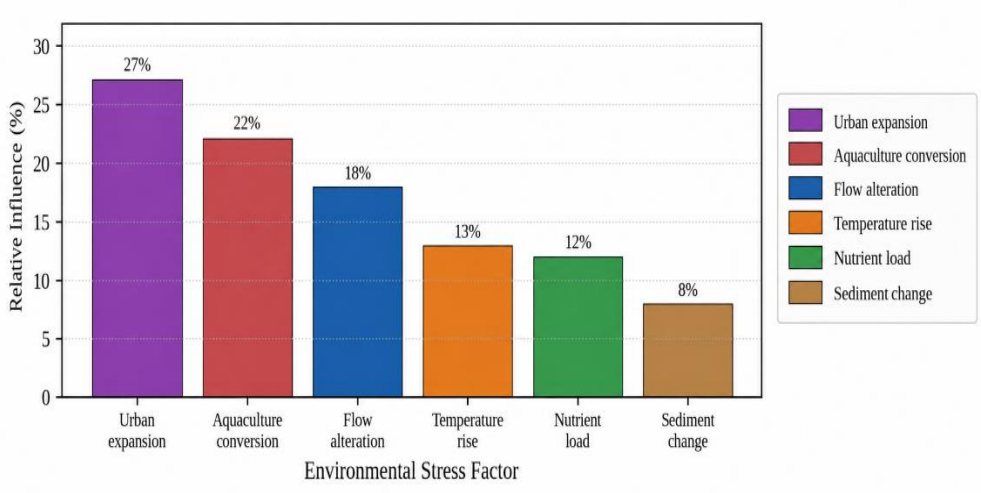


Figure 8: Relative Influence of Environmental Stress Factors on Aquatic Habitat Degradation

V. Discussion

Interpretation of Aquatic Habitat Changes

The findings show a gradual change in the aquatic environment within the 24-year period. With the reduction in the amount of open water and the increase in the area of the mudflat, it is evident that the environment is getting shallower and more seasonal in nature, which is consistent with the lower inflows and deposition of sediments. With the reduction in marsh vegetation and its replacement by aquaculture

ponds, there is a shift from a more natural and functional ecosystem to an agricultural-based environment. This is so because marsh vegetation serves as a breeding ground and source of food to various aquatic animals.

Major Environmental Stress Factors

Urbanization and aquaculture were found to have contributed to close to half of the impact exerted on the degradation of the area, indicating that the pressure from land conversion was indeed the predominant driver of change. These pressures prevailed in areas near human settlements as well as at the fringes of the estuaries where there was ample flatland as well as access to brackish water that favored pond creation. The flow alteration was the third largest pressure, resulting from the regulation and abstraction activities that limit the water distribution during the dry season.

Impacts on Aquatic Ecosystem Health

The increased turbidity, algae and water temperatures, coupled with reduced greenness of the vegetation, suggest an unhealthy status of the ecosystem. Turbidity decreases the penetration of light into the water body and inhibits the growth of submersed aquatic vegetation, while algal blooms might deplete the water body of oxygen, affecting fish and invertebrate life. The increasing extent of high and very high degradation status of the complex suggests that a significant portion of the complex is close to the state where recovery will be difficult and slow.

Implications for Aquatic Habitat Conservation and Management

The concentration of the impact of degradation in the lower wetlands and estuarine fringes provides a definite set of priorities for conservation and rehabilitation. Management of any additional expansion of the ponds, as well as the restoration of the mangroves and the maintenance of environmental flows would resolve the greatest stresses observed. The correlation between the stress index and the loss of habitat also demonstrates that the stress index can be used as a predictor by targeting units where stress is increasing and there is a danger of habitat destruction. Such satellite-based monitoring is easily conducted and inexpensive to repeat.

VI. Conclusion and Recommendations

The study has shown that multi-temporal remote sensing technique can be used for monitoring the changes in aquatic habitat transformation and degradation. In the period between 2000 and 2024, there has been a decrease in open water, aquatic vegetation, marsh vegetation, mangrove and riparian vegetation while aquaculture ponds, mudflat and built-up land have increased significantly. There is a reduction in water quality with an increase in turbidity, algae and water temperature and decreased vigour of vegetation. High and very high degradation has risen from 16% to 42% of aquatic habitat while the major drivers of habitat loss include environmental stress, especially urban development, aquaculture conversion and flow alteration. It is important to conserve the remaining marsh, mangrove and riparian habitats of the lower wetland and estuarine fringe through zoning and regulating land conversion. Degraded or abandoned aquaculture ponds can be restored as wetland habitat. Environmental flows can be determined and sustained to facilitate the spreading of water during dry periods. The inputs of nutrients and sediments need to be minimized by means of catchment management, buffer strips and wastewater treatment. A regular satellite-based monitoring program has to be developed, with the help of periodic ground observations and local communities' involvement for evaluating the results. The study was based on the information obtained in the dry season and using five reference years, which is not enough for revealing short-term impacts and seasonality effects. Medium resolution images might underestimate the narrow strips of riparian zone and small waterbodies, while the indicators of water conditions calculated based on imagery did not receive sufficient confirmation in laboratory measurements. Weights applied in the stress index calculation were chosen based on experts' assessments. In the future, there should be combined use of optical and radar images in order to deal with cloud cover, additional field measurements of water quality and biodiversity,

time-series analysis annually or seasonally and consideration of future scenarios of climate and land use changes.

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