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Evaluating the Effects of Shoreline Modification on Nursery Habitat Quality in Tropical Estuaries

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Abstract: Tropical estuaries offer vital nursery habitats for young fishes and other aquatic organisms because of the presence of food, shelter, and appropriate water conditions, among others. Shoreline modifications caused by the urbanization process, coastal development, artificial embankments, and shoreline hardening may impact such ecological processes and decrease nursery habitat quality. The current research seeks to analyze how different shoreline modification conditions might influence nursery habitat quality in tropical estuaries using a simulation approach. A comparative evaluation framework was proposed using five ecological factors: abundance of juvenile fishes, species diversity, vegetation cover, habitat connectivity, and suitability of water quality. Four shoreline conditions were assessed: natural vegetated shorelines, moderately modified shorelines, highly armored shorelines, and living shorelines. Datasets have been created to analyze the distinctions in ecological functioning among the four scenarios. Based on the simulations, the natural and restored living shorelines have relatively higher nursery habitat quality when compared to highly armored shorelines. Vegetation cover and connectivity have high correlations with the habitat-quality index. It is suggested that shoreline modifications may impact nursery functioning through structural complexity, ecological connectivity, and environmental favorability. The developed conceptual framework can be used as a foundation for assessing the alternative shoreline management scenarios and prioritizing restoration in tropical estuarine ecosystems.

Keywords: Tropical Estuaries; Shoreline Modification; Nursery Habitat Quality; Mangrove Ecosystems; Living Shorelines; Juvenile Fish; Habitat Restoration.

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I. Introduction

Tropical estuaries are considered very productive transitional ecosystems where fresh and saltwater systems converge and help form different ecosystems. Such environments serve the role of feeding, breeding, refuge, and nursery grounds for various types of fish and invertebrates. Such features as mangrove forests, tidal creeks, mudflats, submerged aquatic vegetation, and shallow waters in coastal areas add to ecological complexity and help juvenile organisms develop successfully. The role of estuarine ecosystems as nursery grounds depends not only on the availability of habitats but also on ecological connectivity, seasonal environment, resource availability, and movements of organisms (Sheaves et al., 2015).

The increase in human activity on tropical coastal zones has resulted in substantial changes in natural coastal formations. Growth of cities, building of ports, construction of seawalls and embankments, dredging, and deforestation of mangroves have resulted in changes in physical and ecological properties of estuary ecosystems. These changes might result in a lack of shallow vegetated habitats, interruption of natural water exchange, and changes in feeding and hiding ground distribution. Restoration of tropical estuaries should take into account not only physical habitat structures but also ecological processes sustaining them (Sheaves et al., 2014).

The alteration of shorelines may lead to cumulative ecological impacts that go beyond the specific sites of development. Such alterations may affect sediment transport, water circulation, vegetation distribution, and continuity of habitats. This is especially relevant with regard to fish and invertebrates, whose life cycles depend on continuous estuarine habitats. Thus, cumulative damage to the habitats may result in depletion of ecological resources, even in the absence of any apparent large-scale development (Peterson & Lowe, 2009).

Similarly, artificial urban shorelines lead to a complicated ecosystem because of structural differences between the two types of shorelines. The differences in the type of vegetation, substrate, water depth, and surface complexity can affect the provision of habitat resources and fisheries ecosystem services. The assessment of these differences is crucial to determine if the modified shorelines retain nursery services or need ecological rehabilitation (Benzeev et al., 2017).

Living shorelines techniques have become a viable alternative to traditional shoreline armouring due to their use of natural vegetation, sediment stabilization, and structures for habitats. They have the potential of improving the nursery function of endangered estuarine systems through shoreline protection. However, the success of such restoration projects will depend upon environmental conditions and ecological traits of the restored habitat (Gittman et al., 2016).

While the issue of shoreline alteration has been extensively studied in the field of coastal ecology, the need to compare nursery habitat quality under various modification conditions is still crucial in tropical estuaries. Specifically, the overall impact of vegetation cover, fish density, species diversity, connectivity, and water quality need to be evaluated using an integrative approach. Such research questions are being addressed in this study using computer simulations of natural, modified, armored, and restored shorelines.

Main goal of the research is to analyze possible impacts of changes in the shorelines on the nursery habitat quality in terms of multiple indicators approach. The research also analyzes the contribution of ecological indicators, habitat quality differences under different shoreline conditions, and restoration possibilities for the shorelines supporting estuarine nursery functions.

Structure of the paper: Section 2 describes the literature review of the impact of shoreline modification, nursery function of estuaries, and habitat restoration. The methodology of simulation, ecological indicators and the mathematical evaluation system are described in section 3. The simulation results are discussed in section 4 using comparative tables and graphs. Ecological implications of the results are described in section 5, and management strategies are discussed in section 6. Section 7 concludes the study and identifies directions for future research.

II. Literature Review

Shoreline Modification and Estuarine Ecological Structure

Coastal modifications lead to the alteration of the physical environment by replacing natural vegetation and sediments with artificial structures. Structures like seawalls, revetments, concrete walls, and other shorelines armoring techniques might have an impact on the existence of intertidal areas and interactions between terrestrial and aquatic ecosystems. Coastal modifications might also cause secondary impacts due to alterations of watershed land use, sediment transport, and hydrological processes. Hence, the environmental impacts of coastal modifications and shoreline armoring must be considered at local and estuarine levels (Prosser et al., 2018).

The effects of shoreline morphology have an impact not only on the submerged aquatic vegetation but also on the associated environmental characteristics. Natural characteristics of the shoreline and activities within the watershed may affect vegetation distribution and environmental characteristics. This means that when evaluating nursery habitat quality, the structure of the shoreline, along with environmental conditions, should be considered and not the shoreline morphology alone (Landry & Golden, 2018).

Land cover change along the coastline is also one of the factors affecting the quality of habitats through the alteration of the natural vegetation cover along the coast and other ecological land covers. Human activities may alter the distribution of favorable habitat conditions and affect the ecological status of the coastal region. These interactions are the basis for the inclusion of shoreline and land cover in estuarine evaluation (Lopes et al., 2022).

Effects of Shoreline Armouring on Fish Nursery Functions

The shoreline armoring process can impact fish communities by limiting structural diversity and altering the distribution of shallow water habitats. Overwater structures and shoreline armoring may have an effect on fish habitat utilization by providing varying amounts of shade, substrate type, and refuge. However, the impact is not always consistent among the various species due to differing habitat needs of fish communities (Munsch et al., 2017).

The nursery role of estuaries is not solely defined by the presence of fish. Other important factors affecting the quality of habitat include the survival chances, food availability, juvenile development, connectivity seasonally, and the transfer of organisms from one habitat type to another. Therefore, the evaluation of nursery habitats must take into account ecological complexity and time dynamics (Sheaves et al., 2015).

Living Shorelines and Habitat Restoration

Living shorelines use ecological features, such as native plants and natural/nature-based stabilizing materials, to achieve shoreline protection without compromising their ability to function as habitat. They have the potential to be ecologically superior to hardened shorelines in that they can maintain or enhance the complexity of the habitat and provide nurseries for fish populations (Bilkovic et al., 2016).

Biological indicator selection is an equally important consideration for restoration evaluation. The number and types of nekton species are good indicators of habitat usage, although varying sampling conditions and community structure may make comparison between restored and reference ecosystems difficult. Restoration success must therefore be evaluated based on several ecological indicators, rather than only one biological indicator (de Barros et al., 2023).

Environmental Constraints on Nursery Habitat Quality

The environment determines if the estuaries have nursery potential or not. The parameters such as salinity, oxygen levels, temperature, and turbidity affect the distribution and viability of the juvenile fish population. Even though physically suitable habitats may be present, their nursery potential is low when the environmental conditions go beyond the tolerance levels of the organisms in the ecosystem (Mattone et al., 2022).

Generally, prior studies provide evidence on the significance of the above features in evaluating habitat quality of estuaries. In this study, the mentioned parameters have been incorporated in a simulation approach in order to evaluate the ecological performance of the tropical estuarine shorelines.

III. Materials and Methods

Research Design

In this investigation, a simulated comparative research methodology will be used to assess the impact of shoreline alteration on nursery habitat quality in tropical estuaries. A simulated tropical estuary was created to serve as a model of different degrees of shoreline alteration and ecological rehabilitation. Four types of shoreline alteration were chosen for analysis: vegetated shoreline, moderately altered shoreline, heavily armored shoreline, and rehabilitated living shoreline.

In this simulation model, the difference in habitat characteristics is depicted by the standard ecological indicators in each shoreline condition. Each indicator was assigned with numerical values based on a normalization scale from 0 to 100. The simulation provides an analysis framework to examine the ecological impacts of shoreline alteration.

Shoreline Condition Classification

The four types of shoreline conditions have varying degrees of anthropogenic impacts and ecological modifications. Vegetated shorelines refer to those that are not impacted by human activity and have intact mangroves, natural sediment beds, and shallow water areas. Moderately impacted shorelines refer to areas where there has been some modification to the environment.

The heavily armored shorelines indicate the presence of artificial embankments and concrete infrastructure. This is also marked by low levels of natural vegetation and habitat complexity. On the other hand, restored living shorelines can be said to be the environment where there is inclusion of native vegetation and natural sediments in the shoreline restoration process.

Selection of Nursery Habitat Quality Indicators

Five parameters were chosen for evaluating the quality of nursery habitats. Abundance of juvenile fishes is the parameter which indicates the availability of juvenile fishes in nursery habitats. Diversity of species reflects the variety of fishes present in an ecological niche and also gives an idea about the suitability of habitat. The vegetation coverage includes mangroves and other vegetation.

Connectivity is an assessment of the level of ecological connectivity between the shore habitats, tidal channels, and surrounding water bodies. Water quality suitability is the overall suitability of environmental factors such as oxygen levels, salinity, water temperature, and turbidity. Both factors were rated using a score of 0 to 100.

Simulation Model and Habitat Quality Index

An NHQI for the five indicators was constructed to combine the indicators into one index. This index adopts an equal-weighted aggregation technique to enable a fair assessment of ecological performance of the various shoreline types.

The normalized indicator score is given by:

$$S_{ij} = \frac{X_{ij} - X_{j,\min}}{X_{j,\max} - X_{j,\min}} \times 100 \qquad (1)$$

Where S_{ij} represents the normalized score for indicator j under shoreline condition i, X_{ij} represents the corresponding indicator value, and $X_{j,\min}$ and $X_{j,\max}$ represent the minimum and maximum reference values. When the raw value for a particular indicator decreases the situation improves, then reverse normalization is done. Equation (1) provides a standard measure of scale for comparison of the five ecological indicators.

The habitat quality index is determined from:

$$NHQI_i = \sum_{j=1}^{n} w_j S_{ij} \qquad (2)$$

Where $NHQI_i$ represents the habitat-quality index for shoreline condition i, w_j represents the weight assigned to indicator j, and n represents the total number of indicators. Equal weighting is applied, with $w_j = 0.20$ for all five indicators. Equation (2) combines all normalized ecological indicators into one comparative score for habitat quality.

The relative difference in habitat quality from the natural shoreline baseline is calculated by:

$$RC_i = \frac{NHQI_i - NHQI_r}{NHQI_r} \times 100 \qquad (3)$$

Where RC_i represents the relative percentage change in habitat quality and $NHQI_r$ represents the index of the natural vegetated shoreline reference. Equation (3) offers a standard measure for habitat-quality differences between the modified/restored shoreline and the natural reference condition.

Simulation Procedure

These five steps comprised the simulation in order. The first step was the classification of shorelines; the next involved defining ecological indicators for each shoreline category, then normalization, and finally the calculation of the composite index and comparison. Value generation was carried out to show possible difference between all four types of shorelines.

The entire research process is shown in figure 1 below.

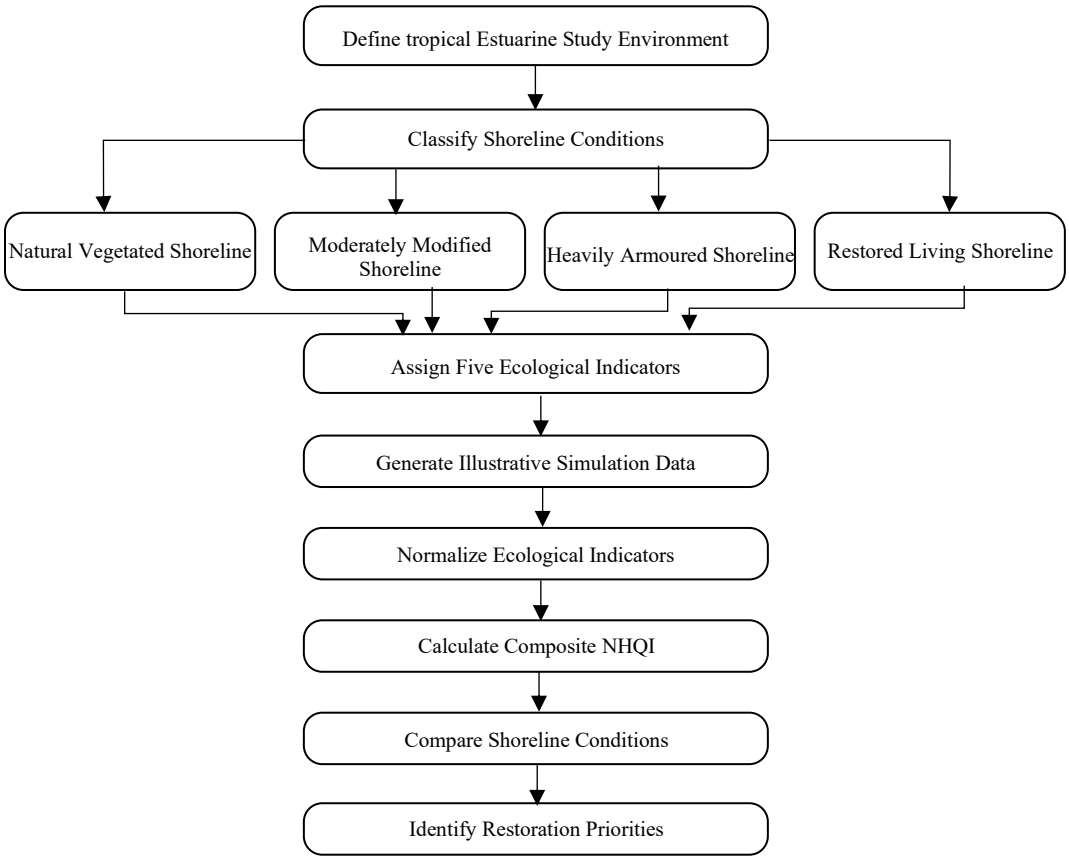


Figure 1: Framework for Evaluating Shoreline Modification Effects on Tropical Estuarine Nursery Habitat Quality

The research process as illustrated in figure 1 is a sequence of steps including shoreline classification and identification of the ecological indicators, data creation, data standardization, construction of composite indices, and comparison. The model enables a systematic method to differentiate nursery habitat quality and evaluate possible priority areas for shoreline restoration.

Data Analysis and Interpretation

The values of the simulated indicators were subjected to analysis via descriptive comparative assessment approach. Ecological mean scores for each condition of the shoreline were calculated before carrying out the habitat quality evaluation. Differences were assessed based on comparison to the vegetated natural shoreline reference point.

IV. Results

Comparative Assessment of Ecological Indicators

The simulation of the ecological indicator values revealed distinctions between the four shoreline conditions. The naturally vegetated shorelines scored high for all the five indicators, indicating their presumed ecological benefits regarding the nursery habitat function. The restored living shorelines were also ecologically favorable, especially in vegetation cover and habitat connectivity.

Ecological conditions in moderately armored shorelines fell in between those found in natural environments, but were less vegetation-covered and less diverse in terms of species composition. Ecological conditions in highly armored shorelines received the lowest scores regarding the abundance of juvenile fishes, diversity of species, vegetation coverage, and habitat connectivity. Water suitability was relatively higher in comparison with the other variables considered in the case of high armoration.

Composite Nursery Habitat Quality Index

The values of the five indicators and the computed NHQI have been shown in table 1. The weight assigned to each of these indicators is 20%.

Table 1: Simulated Ecological Indicator Scores and Composite Nursery Habitat Quality Index Across Shoreline Conditions

Ecological indicators	Natural vegetated	Moderately modified	Heavily armoured	Restored living
Juvenile fish abundance	90	65	38	82
Species diversity	85	62	35	78
Vegetation coverage	95	55	12	85
Habitat connectivity	92	60	28	88
Water-quality suitability	88	72	65	84
Composite NHQI	90.0	62.8	35.6	83.4

Naturally vegetated shorelines had the highest simulation NHQI of 90.0, while restored living shorelines had 83.4. Modified moderately had 62.8, while highly armoured shorelines had the least composite NHQI value of 35.6. From the above results, it can be observed that there is a direct relation between increasing shoreline modifications and decreased nursery habitat quality as simulated. Index values were computed using the equation 2.

Relative Changes in Nursery Habitat Quality

The vegetated natural shoreline served as the base condition against which changes were measured to determine the relative changes in the composite index. The moderately altered shoreline had a 30.2% decrease in habitat quality while the highly armour shorelines had a 60.4% decrease. Restored living shorelines, on the other hand, showed a 7.3% decrease.

Relative differences have been determined with the help of equation (3) taking the NHQI of natural vegetated shorelines to be 90.0. It is clear from the results that restoration may help in recovering a large part of the performance of ecology that natural shorelines represent. The restored shoreline showed better vegetation cover and connectivity of habitats as compared to moderately altered and highly armored shorelines.

Relationship Between Shoreline Condition and Habitat Quality

From the results that have been simulated, it can be seen that both the coverage of vegetation and habitat connectivity are essential elements in the overall evaluation of the nursery habitat. The difference between the two kinds of shorelines was more pronounced in terms of the coverage of vegetation, where the value fell from 95 to 12. Habitat connectivity also demonstrated a substantial reduction, from 92 to 28.

This indicates that physical manipulation of the shoreline could possibly affect nursery habitat quality due to degradation of vegetation cover and disturbance of connectivity of aquatic systems. Even though the heavily armored landscape achieved a water quality rating of 65, it still performed poorly in the other ecological indices, resulting in lower overall habitat quality index.

Graphical Comparison of Composite Habitat Quality

Composite NHQI for different shoreline conditions are presented in figure 2 below. This figure clearly shows the difference between natural, modified, armoured, and restored shorelines. The NHQI with the best value is seen in natural vegetated shorelines while armoured shorelines show the worst performance in the simulations.

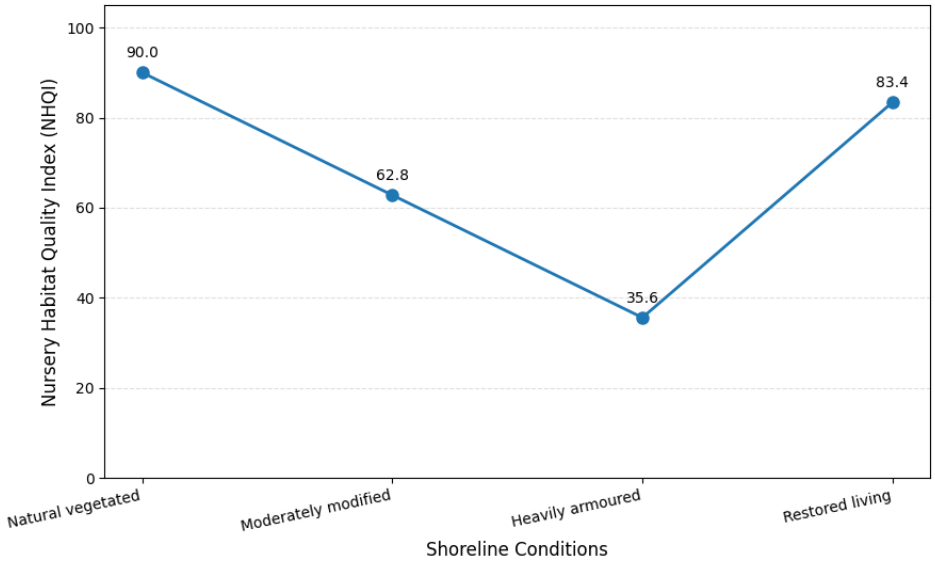


Figure 2: Comparison of Composite Nursery Habitat Quality Across Four Shoreline Conditions

Figure 2 illustrates NHQI scores and reveals how heavy armouring is linked to poorer habitat quality and how restoration living shorelines lead to better ecological performance.

V. Discussion

Ecological Implications of Shoreline Modification

The results of the simulation show that there are significant disparities in the quality of nursery habitats in each of the four types of shoreline. Natural vegetation-covered shorelines showed the highest composite index, proving the significance of having natural ecosystem structure to have estuary nursery functions. The relatively low score of heavily armoured shorelines shows the possibility of reducing the available suitable habitat for juveniles by constructing artificial structures along the shorelines.

The decrease in the coverage of vegetation poses a significant ecological issue because the mangrove ecosystem, as well as other types of coastal vegetation, offers feeding grounds and refuge, as well as providing structural complexity. The loss of such elements may have an impact on the ability of estuary systems to be suitable environments for various life stages of aquatic creatures. Moreover, the simulation of the decline in the numbers of juvenile fish and their biodiversity shows that changes in the structure of the habitat may have an effect on the ecological properties of nursery ecosystems.

Importance of Habitat Connectivity and Environmental Suitability

The connectivity of habitat revealed a considerable distinction between the two cases of natural and heavily armoured shoreline. Habitat connectivity ensures that organisms have an easier way to move within

tidal channels, mangrove habitats, shallow water, and other adjacent coastal habitats. Failure of habitat connectivity could result in a restriction of access to habitats for feeding and refuges.

Water quality was another factor considered in determining habitat quality. In this case, although there was a higher water quality value associated with the heavily armored shorelines, it could not make up for the lower levels of vegetation, fish, and connectivity. It can therefore be seen that the nursery habitat quality is multi-dimensional and cannot be determined by measuring water quality alone.

Effectiveness of Living Shoreline Restoration

The restored living shoreline had an NHQI of 83.4 that is close to the NHQI of 90.0 obtained from natural shoreline. It is indicated that a restoration strategy that incorporates native plants and habitat structure can create nursery habitats with better quality than a conventional shoreline stabilization technique. However, the gap still exists between the restored and natural habitat indicating that maturity of restoration is important.

Evaluation of restoration should be based on the presence and growth of vegetation, community structure, habitat usage, environmental variation, and nursery function maintenance. Monitoring of the project is critical to know if the initial biological response is sustainable for habitat restoration. Multiple ecological indicators provide a better insight into restoration success compared to individual measurements of nekton density.

Interpretation and Research Implications

This simulation will provide the basis for comparing the ecological impacts of altering the shoreline. This study's main strength lies in its use of various habitat indicators to assess different management scenarios. The findings show that natural vegetation, habitat connectivity, and biological indicators need to be considered when assessing the estuarine nursery habitats.

This framework also offers an opportunity to use scenario analysis in ecological planning. Various conditions related to development and restoration along shorelines may be analyzed through changes in indicator scores, weights, and suitability criteria. Additional modifications can include the incorporation of seasonal factors, tidal movement, sediment characteristics, and species preference habitat. Field work and ecological indicators can enhance the application of the NHQI framework in various tropical estuaries.

VI. Recommendations

Management of tropical estuaries should be guided by the importance of preserving natural mangrove flora, tidal channels, habitat characteristics of shallow waters, and ecologically connected coastal habitats. In the future, any construction projects along shorelines must adopt nature-friendly design features wherever feasible, avoiding unnecessary shoreline stabilization, and preserving habitat characteristics of intertidal zones. Any restoration project should target sites where native vegetation recruitment, sediment stabilization, and hydrological connections can be achieved simultaneously. The factors that should be considered when monitoring the success of restoration include the number of young fish, biodiversity, plant cover, habitat connectivity, and water quality. The NHQI index that was discussed above should be validated before being implemented.

VII. Conclusion

The study assessed the possible impacts of shoreline modification on the habitat quality of nursery functions in tropical estuaries through a simulated comparative analysis. Four different shoreline types were analyzed based on five indicators of ecological parameters, including the abundance of juveniles of fish, species diversity, vegetation, habitat connection, and water-quality suitability. The results showed that vegetated natural shorelines got the highest composite NHQI score of 90.0, whereas the living restored shorelines scored 83.4. The moderately modified shorelines scored 62.8, while heavily armored shorelines

scored 35.6. This study shows that there is a possibility for ecological features necessary for sustaining the function of estuarine nurseries to be reduced by the effects of shoreline hardening. The role of vegetation cover and habitat connectivity became evident as important parts of the suggested assessment system. Living shoreline restoration was found to have a positive effect on habitat quality; however, the simulated results do not show full return to the natural state. The study shows the need for an integrated ecological assessment and nature-based management of shorelines for sustainable tropical estuarine nurseries. Validation and monitoring of the ecological system is needed in the field environment.

References

[1] Sheaves, M., Brookes, J., Coles, R., Freckelton, M., Groves, P., Johnston, R., & Winberg, P. (2014). Repair and revitalisation of Australia's tropical estuaries and coastal wetlands: Opportunities and constraints for the reinstatement of lost function and productivity. *Marine Policy*, *47*, 23-38. https://doi.org/10.1016/j.marpol.2014.01.024

[2] Peterson, M. S., & Lowe, M. R. (2009). Implications of cumulative impacts to estuarine and marine habitat quality for fish and invertebrate resources. *Reviews in Fisheries Science*, *17*(4), 505-523. https://doi.org/10.1080/10641260903171803

[3] Benzeev, R., Hutchinson, N., & Friess, D. A. (2017). Quantifying fisheries ecosystem services of mangroves and tropical artificial urban shorelines. *Hydrobiologia*, *803*(1), 225-237. https://doi.org/10.1007/s10750-017-3299-8

[4] Gittman, R. K., Peterson, C. H., Currin, C. A., Joel Fodrie, F., Piehler, M. F., & Bruno, J. F. (2016). Living shorelines can enhance the nursery role of threatened estuarine habitats. *Ecological Applications*, *26*(1), 249-263. https://doi.org/10.1890/14-0716

[5] Munsch, S. H., Cordell, J. R., & Toft, J. D. (2017). Effects of shoreline armouring and overwater structures on coastal and estuarine fish: opportunities for habitat improvement. *Journal of Applied Ecology*, *54*(5), 1373-1384. https://doi.org/10.1111/1365-2664.12906

[6] Bilkovic, D. M., Mitchell, M., Mason, P., & Duhring, K. (2016). The role of living shorelines as estuarine habitat conservation strategies. *Coastal Management*, *44*(3), 161-174. https://doi.org/10.1080/08920753.2016.1160201

[7] Prosser, D. J., Jordan, T. E., Nagel, J. L., Seitz, R. D., Weller, D. E., & Whigham, D. F. (2018). Impacts of coastal land use and shoreline armoring on estuarine ecosystems: an introduction to a special issue. *Estuaries and Coasts*, *41*(Suppl 1), 2-18. https://doi.org/10.1007/s12237-017-0331-1

[8] Lopes, N. D. R., Li, T., Qian, D., Matomela, N., & Sá, R. M. (2022). Factors influencing coastal land cover change and corresponding impact on habitat quality in the North-western Coastline of Guinea-Bissau (NC-GB). *Ocean & Coastal Management*, *224*, 106181. https://doi.org/10.1016/j.ocecoaman.2022.106181

[9] Landry, J. B., & Golden, R. R. (2018). In situ effects of shoreline type and watershed land use on submerged aquatic vegetation habitat quality in the Chesapeake and Mid-Atlantic coastal bays. *Estuaries and Coasts*, *41*(Suppl 1), 101-113. https://doi.org/10.1007/s12237-017-0316-0

[10] de Barros, M.S.F., Rodriguez, A. R., Bland, A., & Baker, R. (2023). Assessing habitat enhancement by living shoreline restoration: exploring potential caveats of nekton community metrics. *Restoration Ecology*, *31*(5), e13935. https://doi.org/10.1111/rec.13935

[11] Sheaves, M., Baker, R., Nagelkerken, I., & Connolly, R. M. (2015). True value of estuarine and coastal nurseries for fish: incorporating complexity and dynamics. *Estuaries and Coasts*, *38*(2), 401-414. https://doi.org/10.1007/s12237-014-9846-x

[12] Mattone, C., Bradley, M., Barnett, A., Konovalov, D. A., & Sheaves, M. (2022). Environmental conditions constrain nursery habitat value in Australian sub-tropical estuaries. *Marine Environmental Research*, *175*, 105568. https://doi.org/10.1016/j.marenvres.2022.105568