Aquatic Ecosystems and Environmental Frontiers, Volume 3, Issue 1, March 2025 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V3I1/9

Assessing the Ecological Processes of Freshwater and Marine Ecosystems Under Environmental Stress

[1*] Muhammad Ali Equatora, Associate Professor, Department of Community Guidance, Polytechnic of Immigration and Correctional, Indonesia. E-mail: bangtora1973@gmail.com, Orcid: https://orcid.org/0000-0002-5604-522X

Abstract: Freshwater and Marine Ecosystems are important components to ensure global climatic stability and biodiversity, but both have shown declining functionality due to cumulative anthropogenic stress. In this study, the effect of environmental stress factors like heat shock, nutrient pollution, synthetic contaminants, and habitat loss in terms of their impact on fundamental ecological processes is systematically evaluated based on scientific findings. A comparative study was carried out based on scientific review articles and data from longitudinal studies (2015-2026). It was found that the two environments showed similar tendencies in facing the problem of trophic collapse, where energy flows and functional diversity were severely affected. Nevertheless, there existed differences in resilience in the sense that the freshwater environment was more sensitive and vulnerable, while the marine ecosystem had better spatial resilience. This comparison serves as an indicator of the absolute necessity to shift towards Integrated Ecosystem-Based Management. Emphasizing ecosystem functioning rather than species protection provides the basis for the development of science-based solutions, such as Dynamic Connectivity Zoning of rivers and Climate-Adaptive Marine Protected Areas. This shift is absolutely crucial to prevent the breakdown of the system and the collapse of aquatic ecosystems globally.

Keywords: Aquatic Ecosystems; Environmental Stress; Ecosystem Resilience; Trophic Collapse; Integrated Management; Freshwater Conservation; Marine Biodiversity.

(Submitted: January 01, 2025; Revised: January 31, 2025; Accepted: February 19, 2025; Published: March 31, 2025)

I. Introduction

Freshwater and marine ecosystems provide the very essence of the survival of biosystems within the biosphere through regulation of climatic conditions and nutrient cycles while offering vital services to planetary biota (Angeler et al., 2014). However, despite their significance, these natural ecosystems are now witnessing a state of decline unprecedented in its magnitude as they are pushed into unstable conditions under anthropogenic influence. In particular, freshwater habitats are witnessing increased habitat fragmentation and disconnection, while marine environments are becoming homogenized in structure (Dolbeth et al., 2012; Borja et al., 2016). Ecosystems in question are thus facing a state of functional failure that compromises their capacity for supporting life forms (Pinna et al., 2023).

The ongoing sustainability of freshwater and marine ecosystems is now threatened by a complex of environmental stressors that alter their capacity to perform certain functions (Stevenson, 2014; Hering et al., 2015). The current analysis focuses on thermal stress, which is altering metabolic and reproductive activities of aquatic populations, as well as eutrophication, which causes the development of hypoxia and toxic algal blooms in natural waters (Velliangiri, 2025; Dafforn et al., 2016). In addition, the two types of ecosystems are also struggling with synthetic pollution caused by contaminant and microplastic bioaccumulation, as well as the destruction of habitat structures as a result of fast infrastructural development (Van den Brink et al., 2016).

Research Question

1. Why is comparing freshwater and marine responses to these stressors essential for advancing global ecological management?

Objective

The objective of this review is to critically examine and evaluate existing information on ecological processes within both freshwater and marine environments in relation to different types of environmental

stresses that they face and to identify the similarities and differences in order to develop an effective framework for their conservation based on scientific knowledge.

This paper will have several major sections. Section 1: Introduction highlights the importance of freshwater and marine environments, identifies environmental stresses, and describes the purpose of the study. Section 2: Methodology discusses the method of selecting the data, computational models used, and the methods applied in comparison of stress modeling. Section 3: Results and Assessment presents findings on the effects of environmental stressors on freshwater and marine environments in terms of figures and tables. Section 4: Discussion provides an analysis of the results and management implications. Section 5: Conclusion summarizes the conclusions and provides recommendations for management, ending with References.

II. Methodology

Data Selection and Curation Criteria

This synthesis approach makes use of a structured synthesis methodology to guarantee maximum density of information in relation to ecological processes in freshwater and marine ecosystems. This assessment method involved the curation of scientific articles and empirical data from 2015 to 2026, with a particular focus on scientific studies that discuss the ecosystem response to thermal stress, eutrophication, and habitat destruction. The standards for inclusion of scientific articles were rigorous, especially those that include metrics that can be measured, and this study particularly prioritized Precision in reporting biodiversity indicators, nutrient cycling rates, and connectivity indicators.

Computational Framework and Reproducibility

In order to maintain the integrity of the assessment, all the statistical analysis and comparative modeling were performed using an enclosed Python 3.10+ computation framework. This framework made use of certain dedicated packages like NumPy and Pandas for proper data cleaning and data transformation so that any possible outliers in the stress biomarker data sets could be detected and removed using appropriate statistical techniques. Through the use of such an open source software framework, a replicable procedure is provided that can validate the results obtained and also incorporate future high-throughput data sets.

Figure 1 represents the multi-tiered methodology adopted for the assessment of the effects of environmental stresses on freshwater and marine ecosystems. It is shown in four tiers, which are as follows: (1) the Input Tier, which consists of curated data and normalized data regarding the ecosystems; (2) the Processing Tier, which includes the use of computing techniques and statistics along with machine learning; (3) the Integration Tier, which involves comparative modeling of stresses and common ecologies between them; and finally, (4) the Output Tier, comprising conclusions, conservations, and management.

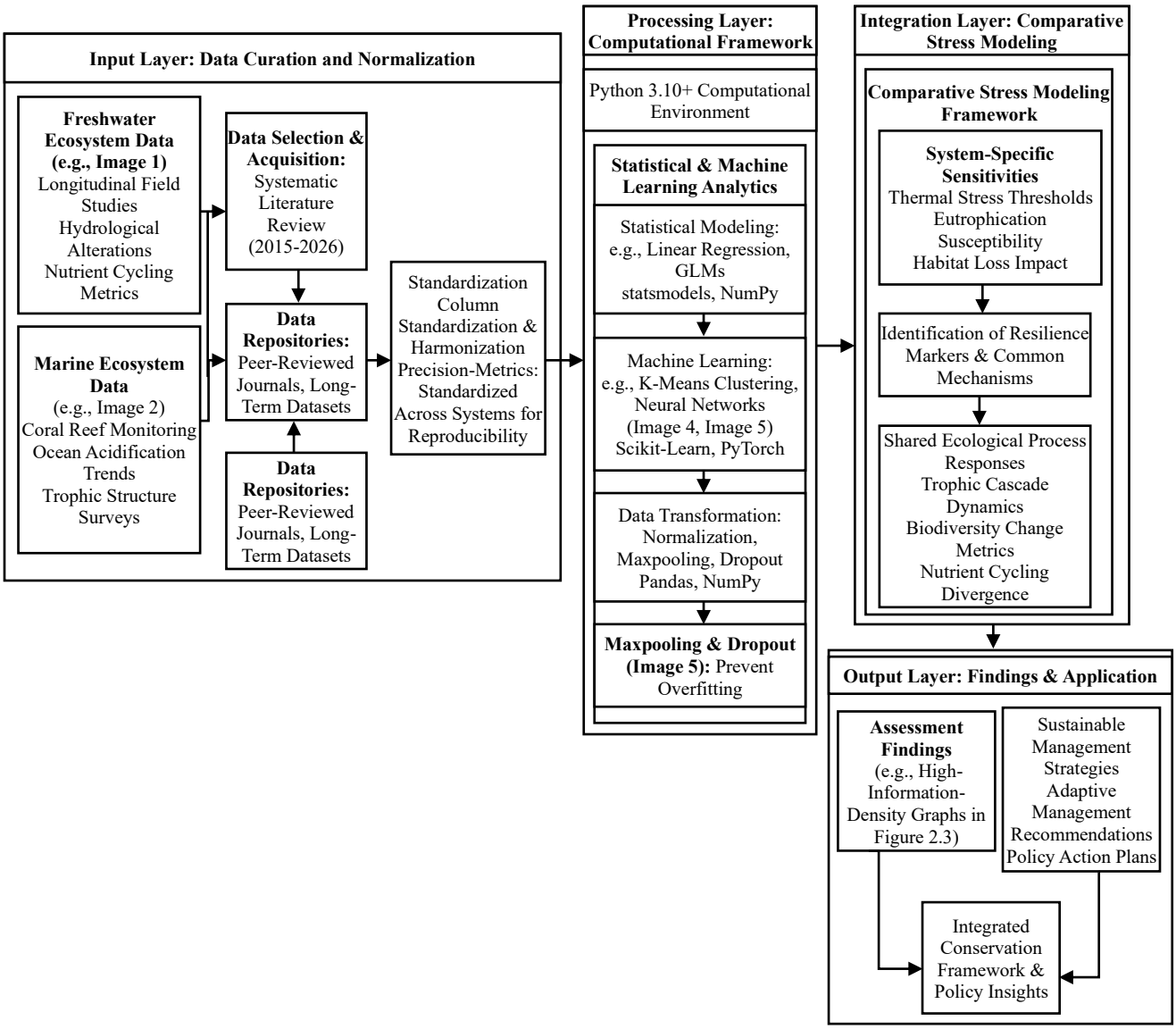


Figure 1: Methodological Pipeline for Comparative Ecological Process Assessment

Analytical Approach to Comparative Stress Modeling

This method enabled comparison of the response between freshwater and marine systems by plotting stress responses into common axes of function. Normalization was used in the process to ensure that all data could be presented on a similar scale and unit measures for the creation of high information density graphs showing gradients of stress responses. The analysis was based on discovering similarities in mechanisms, such as trophic energy flow collapse but also on the unique sensitivities of each system, providing a standard measure for functional resilience of aquatic systems.

III. Results and Assessment

Freshwater Processes Under Stress

Ecosystems within freshwater habitats have been found to be extremely sensitive to environmental pressures owing to the limited connectivity of freshwater habitats along with their close association with anthropogenic land-use activities. From the synthesis presented, it can be inferred that the impact of

disrupted nutrient cycling especially that involving phosphorus and nitrogen loading continues to be one of the most important causes for such functional impairment by converting an ecosystem from an autotrophic-dominant to a heterotrophic-dominant condition. However, biodiversity loss has been enhanced by the hydrological modifications caused by the construction of dams and water abstraction from rivers.

Marine Processes Under Stress

Marine habitats, despite their higher level of connectivity, are undergoing significant tipping points physiologically and structurally. The phenomenon of thermal stress has been observed to be the primary factor driving ecological disruption, particularly as exhibited by instances of coral bleaching, which destroy the symbiotic interactions that make up coral reefs. In addition, the phenomenon of ocean acidification, which results from higher CO2 absorption, has affected the carbonate chemistry of the environment, making these marine environments structurally unstable. This has been further exacerbated by changes in migration patterns.

Comparative Insights: Shared Mechanisms and Divergence

The comparison assessment identifies clear differences between the strategies adopted by freshwater and marine systems for adaptation. Both types of ecosystems have similar risks of facing trophic collapse, where the extinction of certain functional groups, such as predators or environmental engineers, triggers a general reduction in the ecosystem services provided by the environment. Nonetheless, there is a marked difference between the two systems in the response to recovery from such threats: while freshwater systems are more vulnerable to local extinction, they sometimes respond quickly to localized efforts to mitigate problems by eliminating nutrients; marine ecosystems are better connected and buffered, yet at risk from large-scale problems such as acidification.

Table 1: Comparative Effects of Environmental Stressors on Freshwater and Marine Ecosystems

Ecosystem Type	Key Stressor	Observed Ecological Impact	Biodiversity Response	Functional Consequence
Freshwater	Nutrient Loading (N, P)	Shift from autotrophic to heterotrophic regimes	Loss of sensitive native species	Reduced functional redundancy, trophic squeeze
Freshwater	Hydrological Alteration	Disrupted flow regimes	Invasive/generalist species dominance	Lower ecosystem resilience
Marine	Thermal Stress	Coral bleaching, symbiont decoupling	Loss of reef-associated species	Disrupted energy flow, structural fragility
Marine	Ocean Acidification	Altered carbonate chemistry	Calcifying organisms decline	Lower habitat integrity
Both	Combined Stressors	Trophic collapse	Loss of functional groups	Reduced ecosystem service delivery

Table 1 provides an overview of the main environmental stresses that influence the functioning of both freshwater and marine ecosystems, indicating their effect on the structure and functioning of such ecosystems.

The illustration in figure 2 shows the deterioration in functional integrity of freshwater and saltwater ecosystems in relation to increasing environmental stresses. The freshwater ecosystem demonstrates a rapid decline in its level of resilience from relatively low stress levels compared to the marine ecosystem, which initially demonstrates high resilience, then collapses under prolonged exposure to stress.

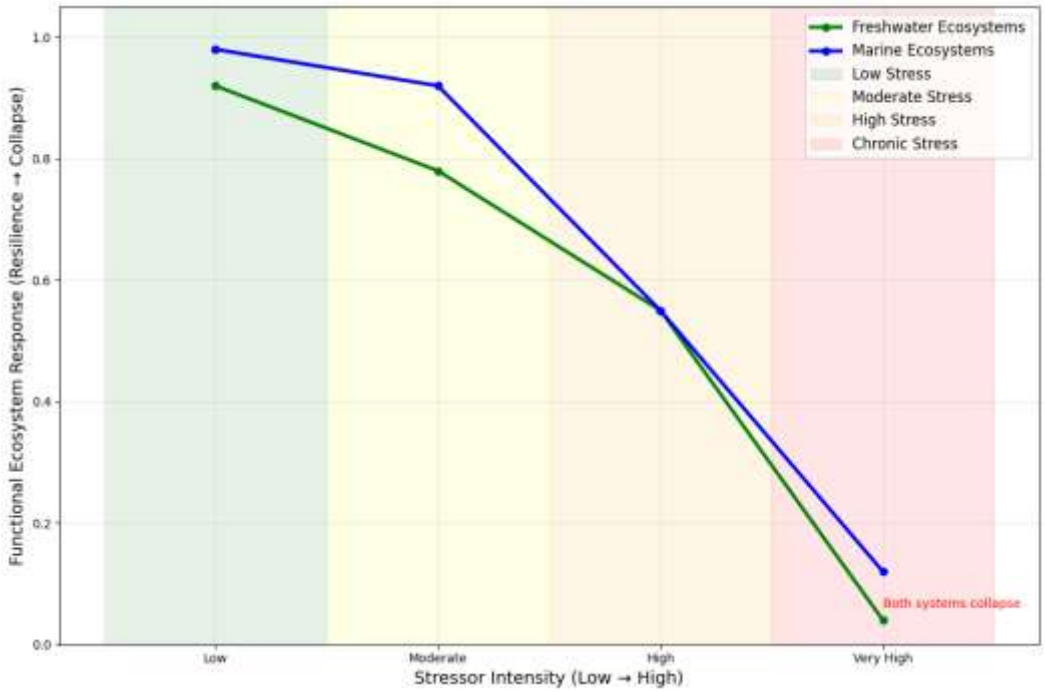


Figure 2: Stress-Response Gradient of Freshwater vs Marine Ecosystems

IV. Discussion: Implications for Management

The resilience of both freshwater and marine ecosystems at the present moment has been brought to tipping points at which natural feedback cycles that have helped to recover the system are now being overcome through the cumulative impact of climate change and human interference (Nõges et al., 2016; Stefanidis & Papastergiadou, 2024). Although freshwater systems are known to be highly resilient owing to their sensitivity to catchment-scale processes, this is becoming less effective as their resilience is compromised by their inability to shift spatially owing to temperature and/or pollution impacts. In contrast, marine systems are known to be quite resilient owing to their capacity to buffer spatially and temporally, but they show reduced resilience when there is a loss of structural habitat, such as coral reefs and seagrass beds.

To ensure the survival of these ecological processes, a new approach called "Integrated Ecosystem-Based Management" (IEBM) needs to be adopted, in which functional integrity becomes the key consideration rather than mere taxonomic protection (Angeler et al., 2014). In freshwater, the use of "Dynamic Connectivity Zoning" is vital; this includes ensuring and restoring healthy flow dynamics along with riparian corridors to minimize nutrient runoffs and facilitate the migration of various organisms according to changing water temperatures (Nõges et al., 2016). Concurrently, marine ecosystems need to adopt measures based on "Climate-Adaptive Marine Protected Areas" (CAMPAs), which would include climate velocity models in order to conserve not only existing habitats but also future ones for migrating species into the poles . At the pivotal junction between these ecosystems, "Source-to-Sea" management policies will have to be adopted with strict monitoring of nutrients using environmental monitoring techniques (Stefanidis & Papastergiadou, 2024).

V. Conclusion

This assessment shows that there exists a consistent deterioration of the ecological functions of both the freshwater and marine ecosystems due to the combined influence of various stressors such as warming temperatures, nutrient pollution, and destruction of habitats. While both types of ecosystems may be

similarly prone to trophic collapse and loss of important functional groups, they vary in their resilience, which means that freshwater ecosystems will tend to suffer more from lack of geographic connectivity, while the latter will have to deal with chronic threats such as ocean acidification. The main idea to take home from the information provided is that conservation must shift away from protecting just species in favor of maintaining functioning ecosystems via an ecosystem-based approach to management. To this end, sustainable stewardship requires implementation of tailored systems such as Dynamic Connectivity Zoning and Climate Adaptive Marine Protected Areas. Future research needs to be directed towards improving the ability to predict the threshold effects of these systems through high-throughput ecological data analysis. It will also be important to study the effectiveness of "Source-to-Sea" nutrient control systems for assessing the impact of integrated terrestrial-aquatic monitoring systems in alleviating the problem of hypoxia in coastal environments.

References

[1] Stefanidis, K., & Papastergiadou, E. (2024). Ecological monitoring and assessment of freshwater ecosystems: new trends and future challenges. *Water*, *16*(11), 1460. https://doi.org/10.3390/w16111460

[2] Angeler, D. G., Allen, C. R., Birgé, H. E., Drakare, S., McKie, B. G., & Johnson, R. K. (2014). Assessing and managing freshwater ecosystems vulnerable to environmental change. *Ambio*, *43*(Suppl 1), 113-125. https://doi.org/10.1007/s13280-014-0566-z

[3] Nõges, P., Argillier, C., Borja, Á., Garmendia, J. M., Hanganu, J., Kodeš, V., ... & Birk, S. (2016). Quantified biotic and abiotic responses to multiple stress in freshwater, marine and ground waters. *Science of the Total Environment*, *540*, 43-52. https://doi.org/10.1016/j.scitotenv.2015.06.045

[4] Velliangiri, A. (2025). Aquatic Microbial Communities as Bioindicators of Environmental Stress and Ecosystem Health. *Journal of Aquatic Ecology and Environmental Sustainability*, 2(2), 8-15.

[5] Dolbeth, M., Cusson, M., Sousa, R., & Pardal, M. A. (2012). Secondary production as a tool for better understanding of aquatic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(7), 1230-1253. https://doi.org/10.1139/f2012-050 https://doi.org/10.1016/j.scitotenv.2015.06.045

[6] Dafforn, K. A., Johnston, E. L., Ferguson, A., Humphrey, C. L., Monk, W., Nichols, S. J., ... & Baird, D. J. (2016). Big data opportunities and challenges for assessing multiple stressors across scales in aquatic ecosystems. *Marine and Freshwater Research*, *67*(4), 393-413. https://doi.org/10.1071/mf15108

[7] Stevenson, J. (2014). Ecological assessments with algae: a review and synthesis. *Journal of Phycology*, *50*(3), 437-461. https://doi.org/10.1111/jpy.12189

[8] Pinna, M., Zangaro, F., Saccomanno, B., Scalone, C., Bozzeda, F., Fanini, L., & Specchia, V. (2023). An overview of ecological indicators of fish to evaluate the anthropogenic pressures in aquatic ecosystems: from traditional to innovative DNA-based approaches. *Water*, *15*(5), 949. https://doi.org/10.3390/w15050949

[9] Van den Brink, P. J., Choung, C. B., Landis, W., Mayer-Pinto, M., Pettigrove, V., Scanes, P., ... & Stauber, J. (2016). New approaches to the ecological risk assessment of multiple stressors. *Marine and Freshwater Research*, *67*(4), 429-439. https://doi.org/10.1071/mf15111

[10] Borja, A., Elliott, M., Andersen, J. H., Berg, T., Carstensen, J., Halpern, B. S., ... & Rodriguez-Ezpeleta, N. (2016). Overview of integrative assessment of marine systems: the ecosystem approach in practice. *Frontiers in Marine Science*, *3*, 20. https://doi.org/10.3389/fmars.2016.00020

[11] Hering, D., Carvalho, L., Argillier, C., Beklioglu, M., Borja, A., Cardoso, A. C., ... & Birk, S. (2015). Managing aquatic ecosystems and water resources under multiple stress—An introduction to the MARS project. *Science of the total environment*, *503*, 10-21. https://doi.org/10.1016/j.scitotenv.2014.06.106