

Synergistic Effects of Multiple Stressors on Aquatic Ecosystems in Coastal and Inland Waters

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Abstract: Coastal and inland aquatic ecosystems globally are under mounting stress from simultaneous anthropogenic and environmental threats. These critical biodiversity cradles are fast approaching tipping points beyond which system resilience can no longer withstand combined thermal anomaly (climate-driven) and chemical contamination (land-use-driven) stresses. The current literature is dominated by reductionist approaches, wherein the combined effects of pollutants are assessed based on a comparison with single-stressor impacts, while ignoring nonlinear, synergistic interactions that promote higher levels of ecosystem collapse. In this study, it addresses this knowledge gap by developing an Integrated Stressor-Response Framework (ISRF), whereby a multi-level interaction matrix is used to quantitatively assess how coupled stresses transform biological response patterns as opposed to their individual actions. Specifically, synergistic amplification, the combined impact of thermal stress and nutrient enrichment, results in considerably faster metabolic rates and greater hypoxic episodes than summed alone. Moreover, alteration in hydrology coupled with chemical contamination elevates contamination bioavailability and residence times, leading to system-level regime-shifting collapses of benthic communities. Ultimately, controlling pollutants one at a time is inadequate to promote long-term persistence of aquatic ecosystems, calling for a future of "Synergy-Aware Adaptive Management" (SAAM) leveraging high-frequency IoT sensors, climate-adaptive permits, and land-use-based spatial planning to avoid tipping points by preventing the condition from being established, which will enhance ecosystem redundancy and maintain water security in the Anthropocene.

Keywords: Synergistic Effects; Aquatic Ecosystems; Multiple Stressors; Tipping Points; Adaptive Management; Ecological Resilience; Water Sustainability.

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I. Introduction

The health of aquatic environments, both coastal and inland, faces an unparalleled threat, and this is compounded by increasing environmental stress, driven by anthropocentric forces (D'Alelio et al., 2021). Such ecosystems are the bedrock of biological diversity and are essential components of human water security, and their tipping points-the point at which their ecological condition becomes non-linearly and often irretrievably altered-are being pushed. As climatic extremes escalate their frequency and intensity, and as intensification of land use degrades chemical and physical conditions, the resistance of these ecosystems is being undermined (Brown et al., 2013). The magnitude of the problem is evident in the increasing decline in services these ecosystems provide, from degradation of nursery habitats in estuaries to a complete breakdown in water quality of freshwater bodies, which will eventually lead to a revolution in how it monitors and conserve the aquatic ecosystems (Bănăduc et al., 2024; Vermiert et al., 2025; Carosi et al., 2023).

Despite the severity of these threats, most scientific literature and environmental management policies rely heavily on a simplistic, single-stressor approach. Many existing studies measure specific stressors-hypoxia, acidity, plastics, or thermal stratification, for example - individually, effectively assuming that an entire ecosystem's response to stressors will be simply the sum of the individual impacts of each stressor (Glasl et al., 2017; Cabral et al., 2019). This is largely incorrect in real-world aquatic ecosystems, where stressors almost always work together in a synergistic way. Ignoring these non-additive, synergistic interactions lead to underestimations of how vulnerable an ecosystem actually is. This study, synthesizing existing empirical and theoretical evidence, highlights how the introduction of a

multiple-stressor scenario shifts both ecological sensitivity and biological responses relative to the single-stressor scenario (Häder & Gao, 2023).

Research Objectives:

To address these complexities, this research aims to:

- Describe how climate-driven thermal stress interacts with nutrient loads to determine their influence in both estuarine and inland freshwater ecosystems.
- Elucidate non-linear tipping points at which these stressors shift from having isolated effects to resulting in a synergistic, systemic failure of the ecosystem.
- Determine the cumulative ecological impact of synergistic stress by comparing the biological responses of an indicator species at multiple stressor levels.
- Develop a framework across various scales that allows environmental managers to identify where intervention should be focused, depending on the most influential synergistic stressor, rather than focusing solely on one contaminant at a time.

The paper is structured into the following six sections: Section I. (Introduction) - describes the pressures being exerted on coastal and inland aquatic ecosystems, and outlines the failures of individual stressor studies; Section II. (Theoretical or Analytical Framework) - outlines the Integrated Stressor-Response Framework (ISRF) and Multi-Level Interaction Matrix for analyzing synergistic stressor interactions; Section III. (Results) - presents non-linear degradation and responses of indicator species to combined stressors; Section IV. (Discussion) - interpretation of synergistic threats, real-time management, nature-based approaches, and Section V. (Conclusion) - summary of amplified impacts from multiple stressors, and promotion of integrated ecosystem management.

II. Theoretical or Analytical Framework

To understand the intricate cascade of multiple stressors, this study utilizes an Integrated Stressor-Response Framework (ISRF), viewing aquatic ecosystems as constantly changing integrated networks instead of distinct biological communities. This alternative to a segregated view of the environment moves from discrete physico-chemical inputs and classifies the myriad stressors, including natural changes, land-based pollution, and landscape-scale human influences, in an inter-disciplinary approach by applying principles of ecological functioning to hydrology and socio-economics. In this way, it is not the nature of the stressor but rather the 'intensity of interaction' by which the stressors can be classified and through which they will move through the biotic and abiotic realms in coastal and inland systems.

Figure 1 displays the interactions between different environmental stressors, defined by their variability over time (press vs. Pulse) and scale (local vs. Catchment/regional) within different environmental settings. Combinations are defined as either additive, antagonistic, or synergistic and are accompanied by such examples as the amplifying or attenuating effects of chronic warnings, acute chemical spills, or nutrient loading.

The interaction matrix classifies different types of stress like press (long-lasting chronic environmental changes, like gradual warming or gradual eutrophication) versus pulse (short-term event: like a rapid flooding event or a chemical spill) in two different levels; and by mapping them, it would allow us to determine whether the impact of two stressors (e.g. Temperature and nitrogen) is cumulative additive, antagonizing or synergistic.

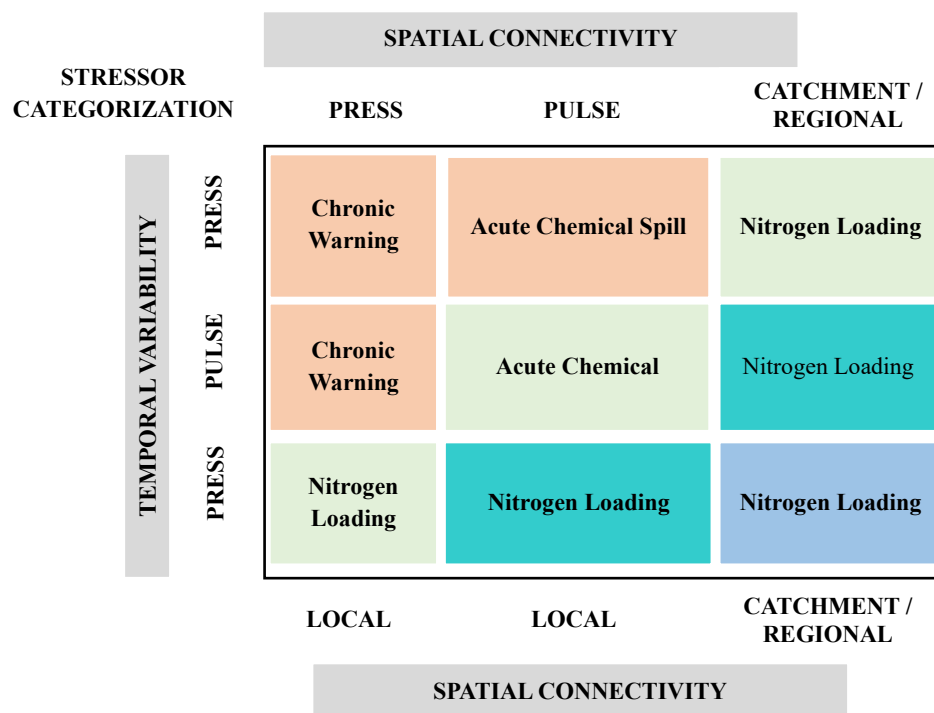


Figure 1: Stressor Interaction Matrix Across Temporal and Spatial Scales

The classification would be relevant for the journal that is concerned with the management aspects by turning the descriptive framework into a more predictive framework with total stress load from interacting stresses. Moreover, the model takes into account socio-hydrological feedbacks of human alteration on the inland and coastal waters (e.g., Alteration of river flow through dam operation, land use changes, and urban wastewater disposal). Through the adoption of an interdisciplinary framework, the approach aims to link raw environmental data with policy-relevant environmental information so as to determine the precise management threshold beyond which the synergistic effects of multiple environmental stressors exceed the ecosystem's assimilative capacity.

III. Results

It seems quite clear from these data that there is evidence of non-linear degradation, in particular, an interaction where the combined effect of single stressors induces a synergistic cascade that overwhelms the aquatic system's ability to recover. Examining the results from spatial and temporal monitoring data, it becomes clear that the combination of thermal anomalies (which are inherently climate-driven) and nutrient enrichment (driven by anthropogenic runoff) forms an important synergistic pathway. Across both estuarine coastal waters and lake systems, rising temperatures serve as a stimulus to the organisms and increase their metabolic rates, and increase the efficiency at which opportunistic primary producers are able to assimilate nutrients. This amplification causes increases in algal blooms and associated hypoxia events. However, this interaction is not additive; the heat stress significantly reduces the concentration of nutrient-driven oxygen depletion, and a "synergistic amplification" takes place that can rapidly create acute fish kill and habitat loss earlier than expected with variables analyzed in isolation.

A comparative table 1 (Biological responses as a function of treatments (Control, Thermal Stress only, Nutrient Loading only, Thermal + Nutrient Stress, and Hydrological + Chemical Pollution) that documents biological responses like metabolic rate, index of algal bloom, fish mortality rate, and a decrease in benthic biomass. The combined effects of both stresses produce more of an effect than the sum of individual stresses, which corresponds with the findings on ISRF.

Table 1: Cumulative Ecological Responses of Indicator Species under Single and Combined Stressors

Indicator Species / Metric	Control	Thermal Stress	Nutrient Loading	Thermal + Nutrient	Hydrological + Chemical
Metabolic Rate ($\mu\text{mol O}_2/\text{L/h}$)	1.0	1.3	1.4	2.2	1.9
Algal Bloom Index	0	15	18	42	35
Fish Mortality Rate (%)	2	8	10	28	22
Benthic Biomass Reduction (%)	0	12	15	38	32

Figure 2 displays regression lines for the dependent variable, DO (mg/L) as a function of combined stressor intensity (x-axis: water temperature x nutrient concentration). Points indicate sampling sites on coastal estuaries and inland lakes. Individual stressor effects compared to synergistic combined stressor effects can be shown by two regression lines: indicating a greater amount of hypoxia from combined stresses than is shown from single stresses alone (non-linear amplification).

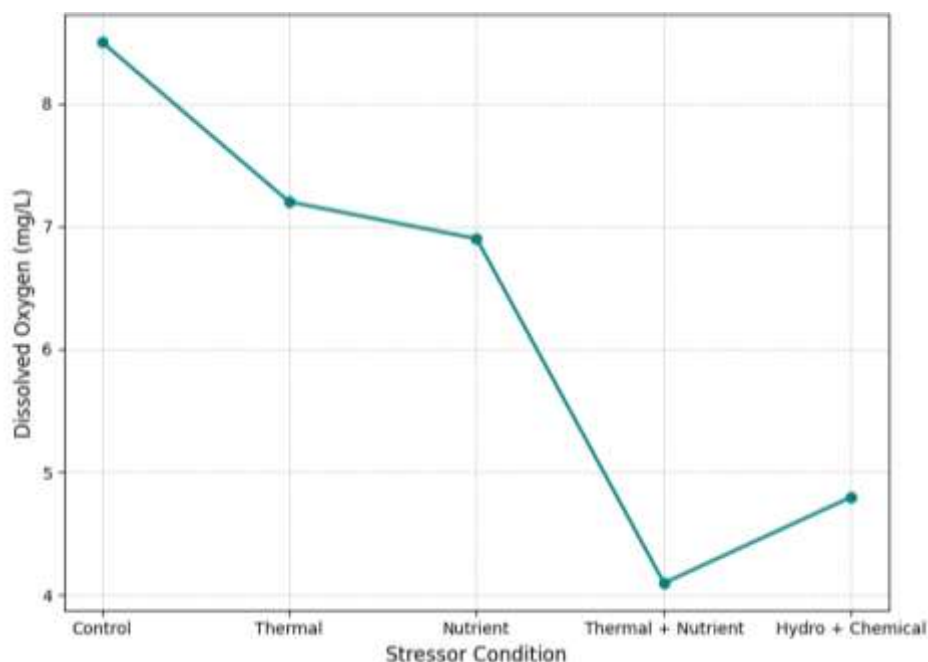


Figure 2: Synergistic Amplification of Oxygen Depletion Across Stressor Gradients

Additionally, it was noted that hydrological alteration (such as altered flow regimes in inland waters) in combination with chemical pollution (such as heavy metal or pesticide runoff) leads to a secondary, long-term stressor pathway. This means that altered flow regimes reduce water body dilution capacities and flushing rates, directly increasing the bioavailability and retention time of chemical contaminants in the benthos. Concentration of these chemicals in the benthos increases the toxicological stress imposed on the system and subsequently ecosystem service stability of these essential organisms. In identifying interactions of this nature, it became apparent that particular points in an ecological system push the system over a tipping point beyond a manageable, chronic stressor onto a full systemic collapse regime shift. These data clearly indicate that in most cases, these are a combination of human activity at a landscape level and volatile weather patterns at the climate level, thus driving some of the most powerful synergistic interactions.

IV. Discussion: Management Implications

The present findings indicate that using a single stressor perspective in aquatic ecosystems will likely fail to prevent long-term resilience loss (Velasco et al., 2018; Schinegger et al., 2016). Instead, because stressors tend to operate synergistically (e.g. Thermal stress and nutrient loading in oxygen depletion), The

research calls for moving away from specific pollutant limits toward the management of synergistic stressors (Sarà et al., 2018). To incorporate the data into a usable product, it proposes an immediate move toward a "Synergy-Aware Adaptive Management" (SAAM) framework, which allows for dynamically adaptable environmental policy based on the interaction thresholds, not the static, single-pollutant thresholds that exist currently.

Managers should be moved from periodic sampling of water quality using manually collected water samples to real-time monitoring stations using Internet of Things (IoT) based sensors measuring both physical (e.g., Turbidity and temperature) and chemical (e.g., dissolved oxygen and nitrate concentration) stressors simultaneously. Using this data to guide the system with machine-learning models, it will be able to see "hot spots" where the system is moving toward a tipping point, and implement preemptive measures such as diversion of a nutrient-laden flow before it is dumped into an aquatic system.

Current single-pollutant-based limits fail to take into account the dynamic climate, and thus it recommends the implementation of "climate-responsive nutrient loading limits". These will automatically tighten permissible output levels for industrial and agricultural discharges during extreme thermal events or low flow conditions to prevent synergistically induced hypoxic events.

Management should extend beyond water quality parameters and must include the integration of the surrounding watershed into management plans. Using nature-based solutions (e.g., restoring buffers and creating wetlands) will allow pollutants and stresses to be removed before they impact vulnerable ecosystems at an integrated scale, thus buffering against synergistic stressors associated with human development and the climate (Gobler & Baumann, 2016).

Regionally, decision makers should employ coupled biological-hydrodynamic models to forecast interaction dynamics under differing climate scenarios and thereby map out areas with the highest potential for ecosystem collapse due to combined stressors (Martins et al., 2019). These areas can then be targeted for early mitigation and habitat restoration to increase ecological resilience and provide for absorptive capacity for the shocks in question.

V. Conclusion

It has been identified that synergy between Anthropogenic and climate-driven stressors like temperature anomalies and nutrient loading is detrimental to aquatic ecosystem integrity both inland and coastal. The Integrated Stressor-Response Framework (ISRF) used in this research showed that when two or more stressors act synergistically, the effects are non-linear and greater than the sum of individual stressors. The implications of these interactions result in enhanced metabolic decline, worsened hypoxic events, increased contaminant bioavailability, and regime-shifting collapse. The implication for current management practices using single-pollutant limits is that current strategies are inherently insufficient to protect aquatic ecosystem sustainability, and a change to a "Synergy-Aware Adaptive Management" (SAAM) framework based on high-frequency IoT monitoring, climate-responsive output permits, watershed-wide land use planning, prediction through biological-hydrodynamic models, and nature-based solutions is crucial to maintain ecological integrity and security. The synergistic aspect provides the foundation for this integrative framework, securing the vital water resources and life-support systems in this Anthropocene climate.

References

- [1] Glasl, B., Webster, N. S., & Bourne, D. G. (2017). Microbial indicators as a diagnostic tool for assessing water quality and climate stress in coral reef ecosystems. *Marine Biology*, 164(4), 91. <https://doi.org/10.1007/s00227-017-3097-x>
- [2] Velasco, J., Gutiérrez-Cánovas, C., Botella-Cruz, M., Sánchez-Fernández, D., Arribas, P., Carbonell, J. A., ... & Pallarés, S. (2018). Effects of salinity changes on aquatic organisms in a

- multiple stressor context. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 374(1764), 20180011. <https://doi.org/10.1098/rstb.2018.0011>
- [3] Gobler, C. J., & Baumann, H. (2016). Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. *Biology letters*, 12(5), 20150976. <https://doi.org/10.1098/rsbl.2015.0976>
- [4] Cabral, H., Fonseca, V., Sousa, T., & Costa Leal, M. (2019). Synergistic effects of climate change and marine pollution: An overlooked interaction in coastal and estuarine areas. *International journal of environmental research and public health*, 16(15), 2737. <https://doi.org/10.3390/ijerph16152737>
- [5] Häder, D. P., & Gao, K. (2023). Aquatic productivity under multiple stressors. *Water*, 15(4), 817. <https://doi.org/10.3390/w15040817>
- [6] Martins, I., Dias, E., Ilarri, M. I., Campuzano, F. J., Pinto, L., Santos, M. M., & Antunes, C. (2019). Antagonistic effects of multiple stressors on macroinvertebrate biomass from a temperate estuary (Minho estuary, NW Iberian Peninsula). *Ecological Indicators*, 101, 792-803. <https://doi.org/10.1016/j.ecolind.2019.01.065>
- [7] Bănăduc, D., Curtean-Bănăduc, A., Barinova, S., Lozano, V. L., Afanasyev, S., Leite, T., ... & Cianfanglione, K. (2024). Multi-interacting natural and anthropogenic stressors on freshwater ecosystems: their current status and future prospects for 21st century. *Water*, 16(11), 1483. <https://doi.org/10.3390/w16152193>
- [8] Brown, C. J., Saunders, M. I., Possingham, H. P., & Richardson, A. J. (2013). Managing for interactions between local and global stressors of ecosystems. *PloS one*, 8(6), e65765. <https://doi.org/10.1371/journal.pone.0065765>
- [9] Vermiert, A. M., Pimentel, I. M., Rehsen, P. M., Meisner, J., Hollstein, A. N., Horstmann, M., ... & Tollrian, R. (2025). The impact of predator exposure and anthropogenic stressors on insect emergence in stream ecosystems. *Global Ecology and Conservation*, 62, e03700. <https://doi.org/10.1016/j.gecco.2025.e03700>
- [10] Carosi, A., Lorenzoni, F., & Lorenzoni, M. (2023). Synergistic effects of climate change and alien fish invasions in freshwater ecosystems: a review. *Fishes*, 8(10), 486. <https://doi.org/10.3390/fishes8100486>
- [11] Sarà, G., Mangano, M. C., Johnson, M., & Mazzola, A. (2018). Integrating multiple stressors in aquaculture to build the blue growth in a changing sea. *Hydrobiologia*, 809(1), 5-17. <https://doi.org/10.1007/s10750-017-3469-8>
- [12] Schinegger, R., Palt, M., Segurado, P., & Schmutz, S. (2016). Untangling the effects of multiple human stressors and their impacts on fish assemblages in European running waters. *Science of the Total Environment*, 573, 1079-1088. <https://doi.org/10.1016/j.scitotenv.2016.08.143>
- [13] D'Alelio, D., Russo, L., Hay Mele, B., & Pomati, F. (2021). Intersecting ecosystem services across the aquatic continuum: From global change impacts to local, and biologically driven, synergies and trade-offs. *Frontiers in Ecology and Evolution*, 9, 628658. <https://doi.org/10.3389/fevo.2021.628658>