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Editorial

Assessing the Effects of Multiple Stressors on Aquatic Systems across Temporal and Spatial Scales: From Measurement to Management

Pedro Segurado *, Teresa Ferreira and Paulo Branco

Forest Research Centre, School of Agronomy, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal; terferreira@isa.ulisboa.pt (T.F.); pjbranco@isa.ulisboa.pt (P.B.)
* Correspondence: psegurado@isa.ulisboa.pt

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Freshwater habitats are home to a disproportionately high biodiversity, given the total area they cover worldwide, hosting 10% of all species while occupying less than 1% of the Earth's surface [1]. These habitats have long been affected by a wide range of co-occurring environmental stressors that disrupt freshwater biodiversity and ecosystem functioning, hence menacing the provision of ecosystem services that are vital to human well-being, including water supply and food security [2–4]. Despite the increasing governance awareness in many parts of the world, as evidenced by the implementation of legislation, policies and regulations such as the Clean Water Act in USA, the Water Framework Directive in the EU and the Water Act in Australia, freshwater ecosystems are far from recovery and most likely to be exposed to new stressors, given the escalade of emerging threats [4–7]. This is evidenced by the also disproportionate percentage of endangered fauna and flora: of the freshwater dependent species so far assessed in the IUCN Red List, 27% are classified as threatened with extinction [8].

Despite the ever-increasing body of research on multiple stressor effects, the efforts made so far to apply the acquired knowledge on concrete management actions on freshwater habitats, including environmental restoration and protection programmes, have resulted in improvements that fall well below the expectations [9,10]. This overall inefficiency is often claimed to be the consequence of knowledge gaps on how individual stressors act in concert [10,11], especially by limiting our capacity to generalise, and therefore predict, ecological responses under strategies involving single stressor reduction [12]. At the same time, these multiple stressors act simultaneously at different spatial and time scales, with their effects being susceptible to vary with climate changes [13,14], local natural conditions [15] and spatial scale [16]. There are still many challenges to implement efficient management practices, such as by improving the understanding of the mechanisms underlying stressor interactions, adapting monitoring programmes to new evidence on the relationships between multiple-stressor interactions and ecological responses, and shifting the focus from ecosystem degradation pathways—which has been so far the main focus of multiple stressor research—to the processes that govern recovery [5,12].

By acknowledging these important research challenges, in this Special Issue we proposed to bring together research advances on the topic of stressors interplay across spatial and temporal scales and its consequences for management of aquatic systems. This Special Issue gathers six very diverse publications, including one review and five research articles, from four continents: Europe [17–19], Oceania [20], Africa [21] and North America [22]. The research articles include studies focused on fish [17,18], macroinvertebrates [19,20], and phytoplankton [17], and are based either on field data [17,19,20], historical data [18] and interviews/expert knowledge [21]. The analysed stressors include physical and chemical barriers [18], hydromorphology, land use and water quality [19], nutrient enrichment and temperature [17], livestock farming and flow reduction [20], water level and temperature [21], and diffuse pollution from croplands and rangelands [22].

In Europe, Le Pichon and her colleagues [18] took advantage of a multitude of historical sources to evaluate the historical evolution of the potential cumulative impacts of physical (weirs, locks, and hydropower plants) and chemical (dissolved oxygen) barriers on the habitat accessibility of diadromous fish species in the Lower Seine River, France. They thoroughly combined historical data sources, such as engineering projects, navigation maps, records of monthly average dissolved oxygen, with knowledge on engineering sciences and fish ecology to develop a least-cost-based connectivity model for three migratory species with distinct migratory behaviours (Atlantic salmon, allis shad, and sea lamprey) at three time periods (1900s, 1970s and 2000s). They found that accessibility, as measured by effective functional distances, varied with fish migration behaviour, time period, and the level of tolerance to low dissolved oxygen. The highest disruptions of ecological connectivity were estimated for the 1970s, corresponding to the post-war industrialization period, due to the joint effect of wide hypoxic river segments together with the installation of impassable navigation weirs (in which many fish passes were only later installed). Several management recommendations are discussed in light of the main findings, namely the importance of controlling chemical water quality while maintaining or increasing the effectiveness of fish passages.

In a study also conducted in France, Bouraï et al. [17], based on a biomonitoring dataset comprising 204 lakes, investigated how two major stressors in lakes related to climate changes—nutrient enrichment and temperature increase—interact in their impacts on the community structure of two biological groups occupying extreme positions of lake food webs (phytoplankton and fish). They modelled the effects of these two stressors on different community metrics related to abundance, composition, size structure, and size spectra, taking also into account the natural environmental variability. Among the significantly responsive metrics, the majority (four metrics) were affected by a single stressor and only fish-based metrics were affected by more than one stressor: one—the number of individuals caught per sampling unit—responded additively to temperature and eutrophication, and two—the perch/roach biomass ratio and the average fish size—were impacted by antagonistic interactions, in which one stressor was found to attenuate the effect of the other. They also stress that modelled patterns for stressor combinations outside the range of existing conditions in the dataset (for example lakes that are simultaneously cold and eutrophic) are due to statistical artifacts.

Heading slightly eastwards, Urbanic and his colleagues [19] examined the single and joint effects of natural factors and three major stressor groups—hydromorphology, land use, and water quality—on the benthic macroinvertebrate community structure in five large rivers of Slovenia and Croatia, based on field data collected over a wide range of environmental conditions, from near-natural sites to heavily altered rivers. This study represents a huge challenge, since biological sampling is very demanding in large rivers, as they typically are affected by a complex combination of stressors that in great measure result from the cumulative conditions that converge from the upstream tributaries. Their analyses were based on multivariate constrained ordination techniques to extract the major community gradients as the response to stressors combinations and river typology, followed by a variation partitioning approach. They found that the pure contribution of hydromorphological, land use, and water quality gradients dominated over both river typology and shared effects in structuring large river macroinvertebrate assemblages. They claim that the dominance of pure stressor contributions found in this study will help managers to better understand the ecological changes that large rivers have experienced in the past and to predict how ecological status and ecosystem services will evolve under future environmental changes.

Moving to the extreme Southeast of the globe, Lange and her colleagues [20], conducted an innovative study that use nitrogen stable isotope values (δ_{15}N) of three invertebrate grazers as potential indicators of land-use intensification to investigate the combined effects of farming intensity and flow reduction in the Manuherikia River catchment in South Island, New Zealand. They found that variations of δ_{15}N values along stressor gradients were not consistent among the targeted primary consumers. The larvae of mayfly *Deleatidium* spp. belonged to the only species for which the $\delta_{15}N$ values showed the expected positive relationship with sheep/beef farming intensity, which was found to interact antagonistically with flow reduction, i.e., the latter attenuated the effect of former stressor. The positive response of $\delta_{15}N$ values to farming intensity was attributed to processes such as inputs of industrial fertilizers, animal waste products and nitrogen transformation processes (e.g., denitrification and ammonia volatilization in agricultural soils and streams). The antagonistic effect may arise when nitrogen input under flow reduction decreases to such an extent that weakens the positive effect of increased farming intensity. In contrast, the $\delta_{15}N$ of the two analyzed snail species either showed a positive response to farming intensity (*Physella* spp.) or no significant response (*Potamopyrgus* spp.). The differences found in consumer $\delta_{15}N$ values were attributed to the likely ingestion of different components of the periphytic community, probably driven by differences in microhabitat use, something the authors recommend to be investigated in future studies. The authors also conclude that the mayfly *Deleatidium* spp. is likely well-suited as a bioindicator in stable isotope studies on agricultural impacts in New Zealand, given its high density, widespread distribution, strict dietary preference, and the clear response of $\delta_{15}N$ values to farming intensity.

In the Sahel region of Africa, Sanon and colleagues [21] conducted an ambitious study that fills important knowledge gaps in freshwater ecosystems of semi-arid and resource-poor countries. Their study aimed at understanding the joint effects of multiple socio-ecological stressors on the ecological integrity of aquatic ecosystems in the Nakambe River (or White Volta), in Burkina Faso, to support and improve fishery management efforts under ongoing climate changes. For that purpose, they gathered a wide range of qualitative data from literature reviews, interviews and strategic simulations (i.e., interactive participatory methods involving experts and stakeholders) as multiple lines of evidence across a Drivers–Pressure–State–Impact–Response (DPSIR) framework. They show how fish productivity, abundance, and average body size, and consequently social well-being indicators such as food and nutrition security, are affected by human impacts as well as climate change effects, namely on water level and surface water temperature. These impacts are further exacerbated by the ongoing nutrition transition towards a greater demand on proteins. They recommend a series of policy responses such as increasing measures for family planning, encouraging and empowering the participation of the different actors to reinforce fisheries regulation and develop the provision of alternative livelihood, such as aquaculture. These measures would help achieving the sustainable management of aquatic ecosystems, promoting the recovery of fish stocks in natural ecosystems, reducing fishermen's vulnerability and preventing further poverty and food insecurity.

Finally, in the USA, a country that, despite having pioneered environmental legislation on freshwaters with one of the most worldwide influential environmental laws, the Clean Water Act from the 1970s, still has a long way to go on the environmental protection of freshwaters according to the literature review conducted by Hughes and Vadas [22]. They focus their review on the effects of croplands and rangelands on freshwaters, by posing a series of questions and presenting a list of case studies. Only 26–30% of the entire stream/river length of conterminous USA streams and rivers were estimated to be in good conditions. Agriculture has been pointed out as a main driver of water quality impairment in USA surface waters and in their review, Hughes and Vadas give some examples where the prevalence of multiple stressors contexts related with a range of cropland and rangeland activities support this view. They summarize the main outputs of research case studies on best management practices and livestock exclosures to provide a general picture of how multiple stressors are affecting biotic indicators and list a series of management challenges for improving the biotic condition of streams draining croplands and rangelands. They end their review by discussing management and governance recommendations to mitigate the problems of diffuse pollution from croplands and rangelands, such as the need to reinforce the focus on biotic and groundwater variables.

Overall, the articles included in this Special Issue provide a representative view of how multiple stressors in freshwaters, notably river fragmentation, nutrient enrichment, flow reduction and surface temperature, are currently being addressed by researchers, managers and decision-makers. Despite pointing out important limitations and challenges that need to be faced to tackle multiple stressor effects on freshwaters, they all end up showing some optimistic perspectives for the future of freshwater ecosystems, either by referring to promising outcomes of previous and ongoing management and protection measures [18,22], demonstrating some benefits from technical advances [20], disentangling multiple stressor effects that will ease management planning [17,19] and, last but not least, indicating how international cooperation between researchers and local stakeholders of undeveloped countries with serious natural resource limitations might contribute to the environmental sustainability of their freshwater ecosystems, as well as the services they provide [21].

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