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Editorial. Mustering the Troops towards Preventative Management in Lakes

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What is preventive management in lakes?

As researchers working on lake management, our focus can be drawn towards ecosystem restoration and recovery, and less so on preventing degradation, especially now that we have entered the United Nations Decade on Restoration (2021-2030). The need to prevent future degradation of ecosystems that have 'good status' (cf. European Union Water Framework Directive (WFD); European Commission 2000) is clear. Freshwater ecosystems are experiencing the fastest rate of biodiversity decline of all environmental domains (Tickner et al. 2020). As we strive to set global ambitious biodiversity targets, there are frequent calls for action along the lines to 'bend the curve on biodiversity decline' (WWF 2020). As Spears et al. (2022a) highlight in this Special Issue (SI) of *Inland Waters* on *Preventative Management in Lakes*, prevention of future degradation is embedded within many programmes and policies. Yet, the Alliance for Freshwater Life (Darwell et al. 2018), in its recent rallying call for a more coordinated response to the decline of freshwater biodiversity, argues that existing policies relevant to safeguarding freshwater ecosystems are failing due to a lack of conviction and enforcement in implementation. The curve is yet to bend.

In one of the most highly cited papers in *Inland Waters*, Moss et al. (2011) frame the argument eloquently, describing the impending effects of an Allied Attack from climate change and eutrophication on lakes: "we are realising that climate change is intensifying the symptoms of eutrophication in freshwaters and perhaps that eutrophication can concomitantly promote climate change. In future we will need to intensify nutrient control just to hold the line, let alone make improvements to water quality." In economic terms, the cost of responding to algal blooms is predicted to increase as a result of climate warming. For example, in the United Kingdom warming has been projected to increase costs of response actions from £173m (2018) to >£400m p.a. in the next 40 years (Jones et al. 2020). But the climate emergency is not the only example of impending environmental change.

The key will be to implement actions with urgency to avoid adding to the burden of restoration in the future. When the Editors first discussed this SI (pre-Covid) on *Preventative Management in Lakes*, we invited authors to explore and expand on this concept. We draw on the contributions in this SI to demonstrate the potential to benefit from preventative management, and highlight new perspectives offered by our authors on opportunities to 'flatten the curve' on the degradation of lake ecosystems in response to impending environmental change.

The concept of preventative management in limnology is not new. Ecosystem management to avoid species extinctions is probably the most relatable practice, but there is a need to widen the lens to consider ecosystem scale responses. Batterbee et al. (2005) published a conceptual model of lake ecosystem change in the context of future stressor scenarios. This model has been used to argue that the restoration of eutrophic lakes to historical 'un-impacted' or 'reference' conditions may be impossible to achieve by controlling single stressors, only. The effects of nutrients are often considered under Stressor 1 whilst manifestations of climate change are commonly considered under Stressor 2. However, the Batterbee Model can also be adapted to provide conceptual insights into the effects of future stressor *mitigation* and *adaptation* scenarios, allowing us to combine traditional restorative approaches with novel preventative ones (Fig. 1). Drawing on the definitions originally developed by the International Committee on Climate Change (IPCC 2001), we propose that adaptation in lake management requires "an adjustment of natural systems in response to actual or expected stressor stimuli or their effects, which moderates ecosystem degradation or exploits beneficial opportunities." *Mitigation*, on the other hand, deals with a reduction in present day stressor intensity at source.

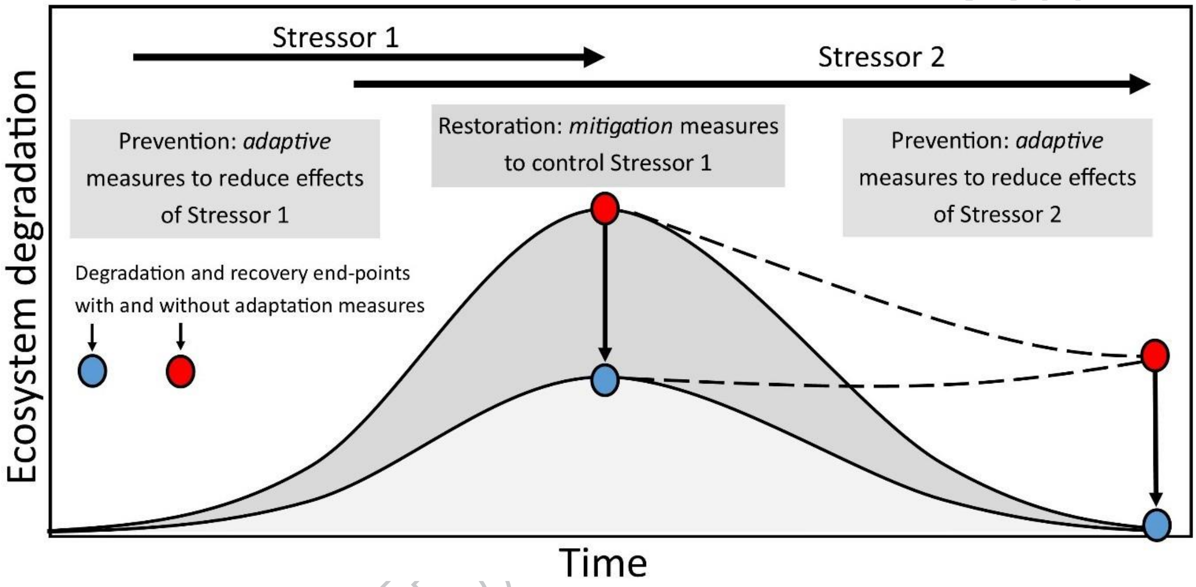

Figure 1. Modified Batterbee Model (after Batterbee et al. 2005) combining idealised preventative and restorative lake management interventions and ecosystem degradation responses in the context of two increasing stressors (e.g., Stressor 1 – nutrients; Stressor 2 – warming). The left hand side of the panel indicates ecosystem degradation following the onset of Stressor 1 (with and without adaptation measures) and the right hand side indicates ecosystem recovery following the control of Stressor 1 whilst Stressor 2 remains unabated (with and without adaptation measures). Dashed lines indicate recovery trajectories without adaptation measures.

The papers in this SI allow us to further frame this conceptual model. Steinman and Kindervater (2022) in their assessment on the need for preventative management in the Everglades and Great Lakes in North America suggest that: "Preventative management of lake ecosystems falls into two categories: (i) prevention before any impairment occurs; and (ii) prevention following degradation." Indeed, examples are presented by others on avoiding degradation (e.g., stopping the ingress of alien species; May et al. 2022) and averting relapse following recovery (e.g., van Oosterhout et al. 2022; Spears et al. 2022b).

As discussed in the case studies of Loch Leven (UK), Lake Erhai (CN) Lake Rotorua (NZ) (Spears et al. 2022a), the Everglades and the Laurentian Great Lakes (Steinman and Kindervater 2022) preventing future degradation using adaptation interventions can be challenging at the large scale. It requires evidence on the effects of stressors and their future projections to inform planning and implementation of novel management, monitoring and assessment approaches. It also requires the development of new supporting policies, which can be a slow process (Steinman and Kindervater 2022).

Where stressors are difficult to control (i.e., in some cases mitigation is unachievable), then other management solutions must be found to relieve stressor effects. Examples of such novel approaches in this SI include (i) where the effects of one stressor may be reduced through the management of another (Huser et al. 2022; Jones et al. 2022; Seelen et al. 2022; Spears et al. 2022b), (ii) where multiple management interventions are combined to ensure sustained recovery (Miranda et al. 2022), and (iii) considering preventative management using a topical treatment approach (e.g., geoengineering) that is aligned with long term recovery (van Oosterhout et al. 2022; Spears et al. 2022a).

Canaries in the coal mine

The case studies included in this SI highlight a range of emerging stressor effects that are common across lakes globally. The stressors include climate change, invasive species incursions and spread, salinisation, urbanisation and agricultural intensification. A common message is that preventative management is most effective when there is a rapid and targeted management response. Such a response requires early identification, communication and warning of impending degradation so that managers are fully aware of the consequences of failing to mitigate the stressors. The papers in this SI present an array of preventative interventions underpinned by robust process understanding that align with the words of British naturalist Sir David Attenborough (with reference to climate change): "I believe that if we better understand the threat we face, the more likely it is we can avoid such a catastrophic future".

Carey et al. (2022) demonstrate the use of aeration as a preventative management response for controlling water quality in drinking water reservoirs in Virginia, USA. They present a framework (and a language) for near-time, iterative ecological forecasting, designed to provide early warning system for water managers (i.e., a water supply authority). They note how a forecasting system increases capacity for urgent management tasks and requires high levels of interdependence among researchers running the system, water managers and stakeholders. Importantly, Carey et al. (2022) draw on their lessons learned to provide a blueprint for others to inform development of similar 'digital twin' approaches.

May et al. (2022) use Lake Victoria as a model system to consider measures for controlling water hyacinth (*Eichhornia crassipes*). They conclude that eradication may be impossible now that this species has invaded and become established. Further, they highlight the need to prevent further spread of water hyacinth using a combination of controlling water body connectivity between infested and non-infested sites, rapid detection of species ingress, and eradication during early stages of colonisation. Monitoring using environmental DNA approaches is a promising technique to provide an early warning to trigger preventative measures to limit aquatic invasive species spread.

Skeate et al. (2022) report on the successful recruitment of carp (*Cyprinus carpio*) in response to warming that may increase the impact of this introduced species on English Sites of Special Scientific Interest (SSSI) lakes. Carp recruited successfully in 44% of the lakes studied, so that even if stocking was reduced, the population would continue to grow. They highlight that the control of the carp population is critical for conserving the aquatic macrophyte communities of the SSSI lakes. Among their recommendations is a call to translocate carp from SSSI sites to sites specifically designated for recreational angling, to address the management conflict between recreation and conservation. Huser et al. (2022) demonstrate that macrophyte recovery and water quality improvement in eutrophic Pickerel Lake (Minnisota, USA) was achieved solely through the eradication of carp, and that repeated management of the fish community following this initial intervention may be necessary to sustain the positive effects on water quality.

Spears et al. (2022b) address the need for long-term forecasts with which to guide climate change adaptation. They show that historical lake monitoring data can be used to produce empirical multi-stressor models to inform adaptive nutrient abatement interventions. In their study lake, Loch Leven, UK, the effects of climate change (i.e., low flushing in summer leading to high chlorophyll *a* concentration) were most apparent at low nutrient concentrations, indicating that further nutrient reduction would be required to offset the effects of climate change. This statistical approach is transferable to other ecosystems where long-term monitoring data are available (Birk et al. 2020; Spears et al. 2021).

Jones et al. (2022) indicate that the form of nutrient loading to reservoirs in Iowa and Missouri, USA, is changing in response to increased industrialised animal production and associated waste application to surrounding fields. In this case, the authors propose a rethink of the application of best management practices and raise the potential for hydrological management to moderate water quality in these highly dynamic hydrological systems. The authors also reinforce earlier work (Jones and Bachmann 1978a & 1978b) which warned that expectations of reversing eutrophication in agricultural landscapes through nonpoint nutrient control measures should be tempered due to 'legacy phosphorus'. Therefore, protection of individual lakes of 'good status' becomes even more critical, especially in an era when food security is paramount as land degradation and climate change intensify (IPCC, 2019).

Fournier et al (2022) report on the effects of road salt run-off to the drinking water quality in Lake Saint-Charles, Canada, a problem that is of wider relevance to colder urban catchments. They indicate that an increase in road-salt application was linked to urban development and that run-off from road-side snow accumulations, containing salt, will change as a result of climate change. However, the picture is complex. The authors suggest that both road salt application and run-off events may increase, the former as a result of more extreme freezing conditions and the latter as a result of increased rain-on-snow events and melt days during winter. The proposed solution includes the use of preventative containment and desalinisation facilities while a transition to the use of low salt materials (e.g., rock and grit) is implemented. We note the discussion in the literature on the current Canadian environmental quality standards for chloride (120 mg L^{-1}) being too lenient, where effects on zooplankton (various *Daphnia* species) are possible down to 40 mg L^{-1} in low nutrient, soft water lakes of the Precambrian Shield (Arnott et al. 2020).

Preventing Recovery Relapses

In discussions on effective lake management at the recent Lahti Lakes 2021 Conference (Finland), one conclusion was that restorative management should consider multiple interventions to deliver more effective and sustained outcomes. That is, multiple and repeated interventions may be required to prevent a *recovery relapse*. We outline below papers in this SI that consider this issue.

van Oosterhout et al. (2022) report on a detailed study of eutrophication recovery relapse. The authors present impressive early recovery following the control of internal loading in Lake Rauwbraken (the Netherlands), although these positive effects began to recede 10 years following the initial treatment. Without also reducing the catchment nutrient load, which was difficult from a management perspective in this case (and for many others), repeated internal load control measures will be necessary to maintain water quality to support continued recreational use at this popular site. The *Systems Analysis* approach adopted by van Oosterhout et al. (2022) proved vital in identifying the relative magnitude of internal and external loads, and the constituents of each, and in informing water quality responses to future management.

Miranda et al. (2022) conducted a similar analysis in an urban lake in Brazil (Mapro Pond) suffering from cyanobacterial blooms. They combined a phosphorus mass balance analysis with process modelling (PCLake) to define the critical phosphorus loads to meet statutory water quality targets. A complicating factor in this study was the need to balance biodiversity enhancement policies with public health policies, in that a major nutrient source was identified to come from the waterfowl population, the culling of which would be controversial. In order to increase the carrying capacity of the lake to balance these needs, the authors identified a combination of internal load control with increased flushing rate, to avoid a recovery relapse. These measures are likely to require repeated applications.

Prevention in Practice and Policy

The need to prevent lake degradation is embedded within some large-scale programmes, directives and policies (Spears et al. 2022a, Steinman and Kindervater 2022). However, in some cases there is a lack of evidence on the effectiveness of such policies and preventative mechanisms, which may limit their implementation. For example, the 5th European Water Framework Directive (WFD) Implementation Report (European Commission 2021) highlighted that only 7% of all WFD surface water bodies had been classed as 'improved' or 'worsened' in their ecological status since the last reporting round. However, of the remaining water bodies, 12% were confirmed as having not changed and the situation for 81% (92% for lakes, alone) was unclear due to a lack of evidence. It is worth noting that the scale of such an assessment is challenging as a result of inconsistencies in monitoring and assessment approaches, both in time and among countries (Poikane et al. 2020). So, despite skilful interpretations of the available data (e.g., Poikane et al. 2020), firm evidence on whether or not the WFD has 'held the line' at an EU scale remains elusive.

It is easy to argue that a lake suffering fish kills and harmful algal blooms requires restoring. It is quite another challenge to influence investment towards preventing degradation of a lake that appears to have good ecological state. Addressing this challenge requires robust data and process understanding and effective communication between scientists, managers and policy makers. Dealing with transboundary lakes adds an additional challenge, as we learn from Steinman and Kindervater (2022) who review the impacts of billions of dollars of investment in the management of the Everglades and the Laurentian Great Lakes. The authors propose that the blueprint for success should be to combine restoration and preventative phases of management within, (i) a robust monitoring network (van Wijk et al. 2022); (ii) early warning and detection systems (Carey et al. 2022); and (iii) effective enforcement of regulations (Spears et al. 2022a). Steinman and Kindervater (2022) highlight the recommendations of the Great Lakes Early Warning System Report commission by the International Joint Commission Science Advisory Board. The report calls for the development of protocols and analytical tools capable of providing early warning (e.g., climate change effects emerging over years) and early detection (i.e., onset of harmful algal blooms using real-time alert-focussed monitoring) of future threats to trigger management responses. Given the nature of these large ecosystems, such management responses will have to be adaptive. Similar considerations are offered for the Everglades (Steinman and Kindervater 2022).

Examples of other large preventative management programmes referenced in this SI include lakes from New Zealand, China, and the UK (Spears et al., 2022a). All three case studies (Loch Leven UK, Lake Rotorua NZ, and Lake Erhai CN) focus on building resilience to climate change through nutrient management to safeguard the provision of ecosystem services, including biodiversity conservation and ecotourism. In a synthesis of the evidence supporting these programmes, the authors highlight high confidence in the effects of nutrients, weather variation and other stressors on indicators of biodiversity and water quality, but links among these indicators and the ecosystem services of interest remain weak (refer to Seelen et al. 2022 below). Despite this problem, the value of the lakes to the regional economy means that costly programmes of preventative measures are now being prioritised.

New Perspectives on Preventative Management

Finally, our SI includes two contributions in emerging areas that combine evidence-based reviews and synthesis to propose new directions for preventative management. Both contributions focus on approaches based on ecosystem services or use to inform management. Seelen et al. (2022) consider the management of novel ecosystems, so called 'quarry-pit lakes', in the Netherlands. These small waterbodies are often not included in regulatory monitoring programmes (with the exception of bathing waters), for example, under the WFD, and so offer a blank canvas with respect to management. The authors utilise the European Environment Agency Common International Classification of Ecosystem Services (CICES) model, combined with proposed ecological and water quality thresholds, to develop a framework to guide future management. This framework fuses restoration and prevention to consider multiple management goals in space and time. The authors conclude that "When valued services become endangered, they [legislators, managers, and communities] are likely to care more, thereby promoting environmental stewardship to preserve or improve the ecological quality of the water system." This is a conclusion that is likely applicable to all lakes.

The second new perspective is offered by van Wijk et al. (2022). Here the authors step back to consider the role of hydrological networks and their management as a means of enhancing nutrient sustainability, developing the concept of *nutrient conservation* through water quality management. The authors build on existing knowledge of ecosystem nutrient retention processes to develop a framework of Smart Nutrient Retention Basins (SLRNs), underpinned by a suite of process models. They draw on experiences from (sub)tropical lake districts where nutrient conservation practices are common. Through SLRNs they propose that management regimes may be developed in highly connected temperate systems to deliver high value ecosystem products (e.g., nutrient-rich sediments for fertilisers, fish, and macrophytes for harvest) whilst maintaining water quality for other provisioning services (e.g., for recreation or drinking water). The approach by van Wijk et al. (2022) may be useful in extending preventative actions from individual lakes to landscape and regional scale, providing a template for bending the curve on biodiversity decline (Tickner et al. 2020).

Time to muster the troops

A growing world population, urbanisation, agricultural intensification, and increasing global trade drive pressures on lake ecosystems through, for example, nutrients and pesticides from agricultural activities, plastics and pharmaceuticals pollution from urban wastewater, traditional (e.g. metals) and emerging (e.g. perfluoroalkyl and polyfluoroalkyl substances; PFAS) chemical pollutants from industrial discharges, water abstractions, hydrological alterations, alien species introductions and climate changes. The enemy is changing shape and in order to 'hold the line', as proposed by Moss et al. (2011), we must now secure our defences and muster the troops for a pre-emptive strike.

Despite the title, the UN Decade on Restoration is underwritten by a UN Resolution (A/RES/73/284 - E - A/RES/73/284 -Desktop (undocs.org) which includes a call on member countries to '…develop and implement policies and plans to prevent ecosystem degradation, in line with national laws and priorities, as appropriate.' The Decade has translated this into the goal to '…prevent, halt and reverse the degradation of ecosystems on every continent…'. Indeed, new laws on ecosystem restoration are being developed to reflect this ambition, including under the European Commission Biodiversity

Strategy (e.g., European Parliament, 2021), and others, with support from the scientific community on priority actions for freshwater biodiversity (van Rees et al., 2020) and the co-benefits of aligned terrestrial-freshwater conservation planning (Leal et al. 2020). Yet, as limnologists, we may be frustrated at the lack of progress to date on lake ecosystem management delivered through this global initiative, as well as on more well-established directives and policies. This is despite the strong evidence base to support lake management and the clear societal benefits of their protection. To address this, the United Nations Environment Programme coordinated World Water Quality Alliance (WWQA) has initiated the Working Group on Ecosystems. It aims to mobilise decision makers, politicians, academics, industry, water managers, as well as other stakeholders around an initial common goal: *to protect and restore lake ecosystems through an international coalition of the willing*. This is in addition to the WWQA's initiatives on global water quality monitoring and assessment and capacity development activities. The experiences offered in this SI and by the wider international limnology community will be vital in delivering such a goal.

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