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Editorial

Lake and River Restoration: Method, Evaluation and Management

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Abstract: Eutrophication has become one of the major environmental issues of global concern due to the adverse effects on water quality, public health and ecosystem sustainability. Fundamental research on the restoration of eutrophic freshwaters, i.e., lakes and rivers, is crucial to support further evidence-based practical implementations. This Special Issue successfully brings together recent research findings from scientists in this field and assembles contributions on lake and river restoration. The 12 published papers can be classified into, and contribute to, three major aspects of this topic. Firstly, a background investigation into the migration of nutrients, and the characteristics of submerged biota, will guide and assist the understanding of the mechanisms of future restoration. Secondly, various restoration strategies, including control of both external and internal nutrients loading, are studied and evaluated. Thirdly, an evaluation of the field sites after restoration treatment is reported in order to support the selection of appropriate restoration approaches. This paper focuses on the current environmental issues related to lake and river restoration and has conducted a comprehensive bibliometric analysis in order to emphasise the fast-growing attention being paid to the research topic. The research questions and main conclusions from all papers are summarised to focus the attention toward how the presented studies aid gains in scientific knowledge, engineering experience and support for policymakers.

Keywords: eutrophication control; external loads; harmful algal blooms (HABs); phosphorous recovery; sediment load control

1. Introduction

Harmful algal blooms (HABs) are one of the most notorious consequences of eutrophication of natural waters, e.g., lakes and rivers, and pose serious threats to water quality, human health, economic development, ecological balance, landscape aesthetics, and social stability [1]. Owing to rapid population growth and economic development, various human activities in industry, agricultural and transport sectors have deteriorated and globally intensified the freshwater eutrophication (Figure 1) [2–5]. In addition to the external loading of pollutants from anthropogenic discharge, the internal loading of pollutants from sediments is expected to further increase the occurrence of HABs and deliver continuous pressure on river and lake ecosystems over the coming decades [6].

Thus, it is urgent to draw the attention of researchers around the world in order to make great efforts towards lake and river restoration in order to eliminate the threat of eutrophication.

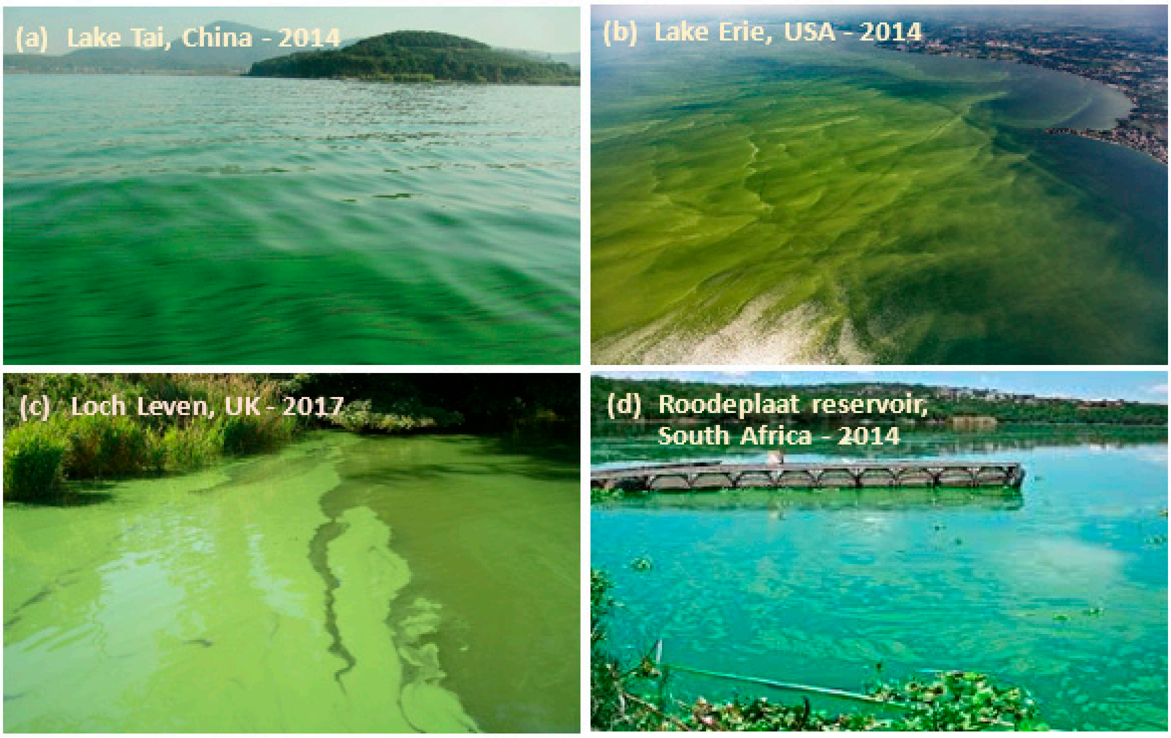

Figure 1. Cases of freshwater eutrophication in (**a**) China [2], (**b**) USA [3], (**c**) UK [4], and (**d**) South Africa [5]. Note: the photos were derived with modification from the original sources.

Both lake and river restoration depend heavily on integrated basin management and technical developments [7]. Integrated water restoration management aims to promote the coordinated development and management of water, land, and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. Nutrient recovery, e.g., phosphorous and residue biomass, e.g., algae biomass, are expected to be valuable resources to promote agricultural sustainability and aquatic ecology [8]. Long-term monitoring of water quality and ecological responses, as well as whole water experiments, are necessary for a comprehensive evaluation of innovative restoration methods [9].

This Special Issue of *Water* aims to compile the latest advances in lake and river restoration technology, in terms of advanced materials, applications, evaluation, and management. The research areas of the 12 papers cover site investigation prior to restoration, evaluations of various technologies for restoration, and long-term monitoring strategies post-treatment. These papers have successfully introduced studies to tackle the knowledge gaps between basic research and engineering implementation, which could significantly contribute to eutrophication control, natural water sustainability, and ecological restoration.

2. Research Development and Current Status

A comprehensive bibliometric analysis was conducted in order to understand the history and current trends of research into lake and river restoration. The Science Citation Index Expanded (SCI-EXPANDED) database, from the Web of Science, was used to search the following words and phrases: “lake restoration”, “river restoration”, “harmful algal blooms”, and “eutrophication”, to compile a bibliography of all papers before 2020 related to the research topic for this Special Issue.

A total of 35,305 publications resulted from the screening, and only research articles published in the English language were selected for further analysis.

The adjective eutrophe (literally “well fed”) was first used by the German botanist Weber in 1907, to describe the initially high nutrient conditions that occur in some types of ecosystems at the start of secondary succession [10]. Following the development of industrial and agricultural activities, excess nutrients entered into bodies of water and caused enhanced biomass and/or growth rates of algae and changes in water quality. Thus, the term ”eutrophication” came into common usage and has been a particular concern when public awareness of the problem was heightened by widespread HABs. The earliest two research articles from the database were both published in 1975 with the titles “Eutrophication of Microponds” and “Eutrophication”, demonstrating the historic concern of this environmental issue.

There is little reported research on river and lake restoration before 1990 (Figure 2a), however, the article tally increased markedly from 1991 and has exhibited a more marked increase in the present. This may be because the pollution of natural waters and their restoration has become a global issue, now attracting widespread interest worldwide. It should be noted that article abstract information was also not available in the SCI-EXPANDED database prior to 1991, which may contribute to the fact that only 1.2% (440 papers) of articles were collated through the literature search. Therefore, the cumulative numbers of articles from 1991 were further examined by model simulation (Figure 2b). From 1991 to 2019, the number of articles increased from 187 in 1991 to 3,251 in 2019. Two exponential models were established to describe the relationships between the annual cumulative number of articles, and the years in which they were published for the two periods (1991–2000, and 2001–2019), respectively. The rate of the increase in the number of articles published (0.2003) during 2001–2019 is slightly lower than that (0.1145) during 2001–2019, which may be attributed to more engineering projects and technology implementations being submitted in recent years, written with the aim of solving real environmental and public health problems, rather than the publishing of, exclusively, research papers. It is inappropriate to distinguish the publication numbers related to lakes or river systems in the current bibliometric analysis, because many laboratory-scale studies, e.g., HAB flocculation material development, can be applied in both systems. Nevertheless, it can be concluded from the literature that the research development on eutrophication restoration in both lake and river systems started from a mechanistic basis and evolved to an evidence-based implementation approach, e.g., integrated mitigation technology and management. Moreover, the exponential increase in published articles addressing lake and river restoration research indicates the current growing attention being paid to environmental protection, which also promises the publishing of more papers, and the recruitment of more researchers, in the near future.

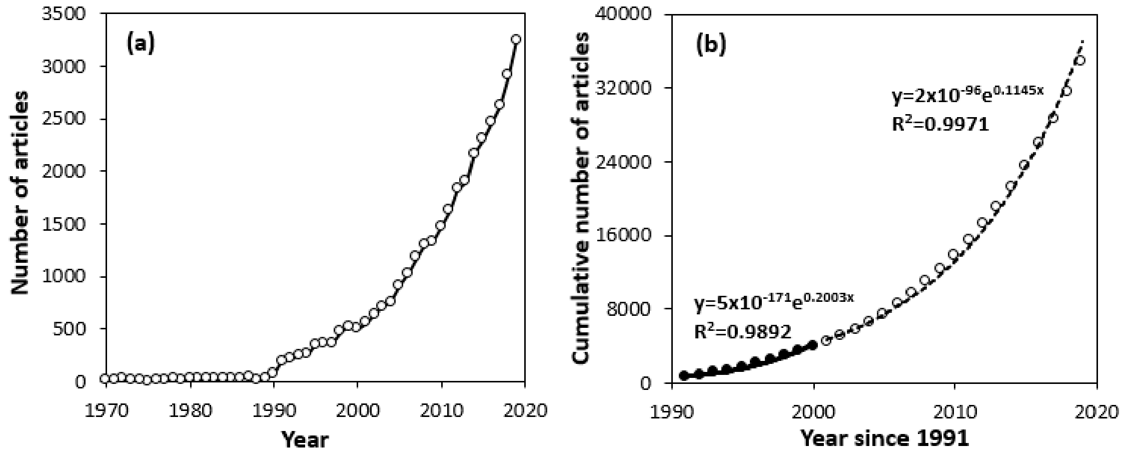

Figure 2. Publication patterns and modelled characteristics of papers addressing river and lake restoration ((**a**) the number of articles from 1970 to 2019; (**b**) the relationship between the cumulative number of articles and year published, since 1991).

3. Overview of the Special Issue

The top five most frequently used keywords in all of the articles selected from the database are "Eutrophication", "Phosphorus", "Algae" "Water quality" and "Nitrogen", which, coincidentally, show high correlation with the frequent keywords used in the 12 papers from this Special Issue (Figure 3a). Phosphorus and nitrogen have long been recognised as crucial nutrients for harmful algal growth in eutrophic waters [11]. In addition to the input of external pollutants from wastewater or runoff waters, the embedded sediment-bonded nutrients can be released back to the water column, especially under hypoxic conditions at sediment–water interfaces [12]. Thus, integrated restoration strategies always consider the control of both external and internal nutrient loadings. In order to select the appropriate restoration technology and estimate the potential risk to the surrounding biota, it is crucial to conduct a background site investigation and understand the potential effects of pollutant migration. Without a long-term monitoring plan and evaluation of the final restoration, it is impossible to assess the success or failure of the treatment. The studies from the current 12 papers in this Special Issue perfectly cover these three aspects (Figure 3b): background investigation, restoration strategies and post-treatment evaluation.

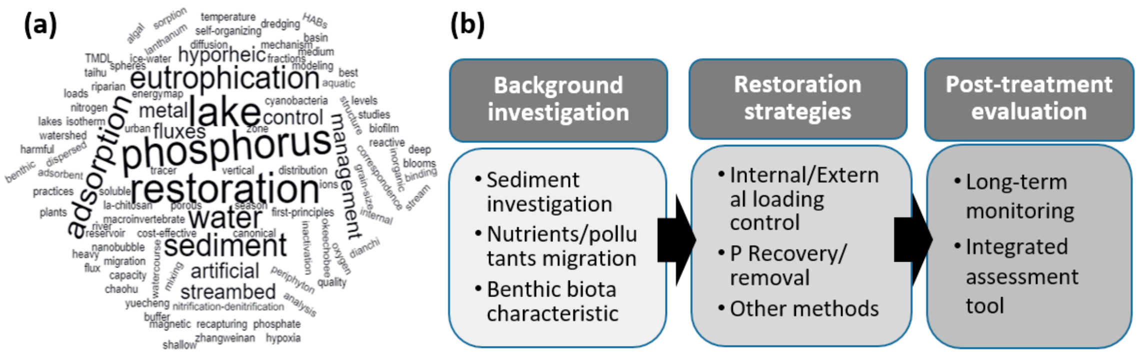

Figure 3. Distribution of keywords used in the 12 papers in the Special Issue (**a**), and the summarised procedure for research into (and applications in) lake and river restoration (**b**).

3.1. Background Investigation

Dang et al. [13] investigated the phosphorus (P) fractions and the relationships between environmental factors of a field reservoir, a main local water supply source of the municipal, industry and agricultural sectors. Their research aims to enhance the knowledge of P cycling in a high P concentration basin, so that water quality and trophic status can be better controlled in the future. The results demonstrated that, although the implementation of a large number of water conservancy projects in the upper reaches of the river resulted in a decrease in inflow runoff, pollution from terrestrial plants or materials played a key role in the dynamics of the sediment P fraction, highlighting that they should be emphasised in the environmental management of river basins.

Understanding the drivers of macroinvertebrate community structure is fundamental for adequately controlling pollutants and managing aquatic ecosystems under global change. Liu et al. [14] analysed the characteristics of the environment and macroinvertebrate community in a river basin over time. They have established an approach by which to reveal community–environment relationships and identified priority pollutants that need to be controlled from the perspective of water ecological health protection. The results could be used to control river pollutants, improve river health management and guide ecological restoration.

Lake freezing in natural conditions is a macroscopic and complex process, which may influence the translocation of pollutants between solid ice and liquid water in an aquatic system. In order to explore the mechanism for the migration of heavy metal ions (HMIs) from ice to water in a lake, Sun et al. [15] carried out a laboratory freezing experiment and simulated the distribution and migration of HMIs (Fe, Cu, Mn, Zn, Pb, Cd, and Hg) under different conditions. The results demonstrated that HMIs could migrate from ice to water as the lake froze, due to the binding energy in water being smaller than that in ice. The study is important for the better understanding of the mechanisms of lake ecosystems in cold regions, especially as a consequence of climate change.

3.2. Restoration Strategies

3.2.1. External Loading Control

Intercepting nutrients entering lakes from point or non-point sources is important for eutrophication control. Cao et al. [16] examined the efficiency of nutrient removal, including the quantity of nutrients and resultant water quality in the littoral zone of different types of riparian buffers in the watershed around a eutrophic lake, and estimated the optimal width for different types of riparian buffers for effective nutrient removal. Different riparian buffers contribute numerous efforts to the removal of nutrients due to vegetation and soil types. Overall, construction of wetland or grass/forest and grass riparian buffer strips is strongly recommended for effective total phosphorous (TP) and total nitrogen (TN) removal, respectively.

3.2.2. Internal Loading Control

Dredging is one of the few options available for the improvement of the ecological balance of lakes by removing contaminated sediments towards reduction in the internal loading of nutrients. However, determination of the season during which any dredging activity could provide the maximum effect, but minimise any adverse effects, is not clear. Zhong et al. [17] conducted experiments in all four seasons in order to evaluate the effects of dredging on the internal loading, and release from sediment of N and P. The results indicated that dredging could be a useful approach for decreasing internal loading and that seasons with low temperature (non-growing seasons) are suitable for performing these operations.

Considering the relatively high cost of dredging operations, in situ treatment through flocculating HABs and locking them onto the surface of sediment has been demonstrated to be sufficient in order to mitigate the loading of internal nutrients [18]. Following on from this concept, Pan et al. [19] summarised the main features of Modified Local Soil (MLS) technology by investigating the effect of this treatment in five pilot-scale whole-pond field experiments. Results showed that, combined with the integrated management of external loads, MLS can be used as an in-lake restoration technology through multiple functions of water quality improvement, sediment remediation, and ecological restoration.

These findings can serve as useful guidelines for researchers, engineers, and local governments for controlling eutrophication and accelerating lake restoration in an eco-friendly and sustainable manner.

3.2.3. Precapture from Water

The removal of P from the water column is crucial and effective for the control of eutrophication, and adsorption is one of the most effective treatment processes. Cheng et al. [20] synthesised a P adsorbent of lanthanum–chitosan magnetic spheres, and evaluated its capability under different conditions. A superior P adsorption ability was demonstrated and, furthermore, the adsorption kinetics, isotherms, and thermodynamic analyses of P by as-prepared adsorbents were studied to reveal the underpinning mechanisms. Owing to their unique hierarchical porous structures, high adsorption capacity and low cost, lanthanum–chitosan magnetic spheres are potentially applicable for eutrophic water treatment.

To study the application of an adsorbent in natural waters in order to achieve very low levels of P (10 μg L^{-1}) for potential eutrophication control, Pan et al. [21] evaluated a combined external and internal P control approach in a simulated pilot-scale river–lake system. Under such a strategy, a granulated lanthanum/aluminium hydroxide composite (LAH) adsorbent was demonstrated to be an effective material for maintaining the P concentration below 10 μg L^{-1} under low levels of additional P input. The results demonstrated that the synergy of external and internal phosphorus recapture by the LAH adsorbent material could be an effective and cost-effective strategy for the potential management of eutrophication under additional, mesotrophic, P inputs.

3.2.4. Other Methods

Stream restoration, designed specifically to enhance hyporheic processes, has seldom been contemplated. Bakke et al. [22] conducted such a project through the engineering of a streambed using a gravel mixture formulated to mimic natural streambed composition, filling an over-excavated channel to a minimum depth of 90 cm. Specially designed plunge pool structures, built with subsurface gravel extending down to 2.4 m, promoted greatly enhanced hyporheic circulation, path length, and residence time. Results from post-restoration monitoring demonstrated that this approach to enhanced hyporheic design successfully restored hyporheic processes and yielded significant water quality improvements compared to control and pre-project conditions.

In order to achieve the restoration of submerged vegetation and HABs mitigation in shallow eutrophic lakes, Wu et al. [23] introduced artificial aquatic plants (AAPs) into enclosures in the eutrophic lake and investigated their effect on the reduction in cyanobacterial blooms and promotion of the growth of submerged macrophytes. On the 60th day after the AAPs were installed, turbidity, total nitrogen (TN), total phosphorous (TP), and the cell density of phytoplankton (especially cyanobacteria) of the treated enclosures were significantly reduced compared with the control enclosures. The results supported that the application of AAPs with incubated periphyton could be an effective and environmentally friendly solution for the reduction in nutrients and for the control of phytoplankton, thereby promoting the restoration of submerged macrophytes in shallow eutrophic waters.

3.3. Post-Treatment Evaluation

Long-term monitoring following restoration engineering is essential in order to evaluate the feasibility and sustainability of a certain strategy. Długie Lake (Olsztyńskie Lakeland, Poland) was restored using both artificial mixing and phosphorus inactivation methods by aluminum compounds. Fifteen years after the termination of the restoration procedure, the investigation conducted by Augustyniak et al. [24] demonstrated that the alum-modified "active" sediment layer still possessed substantial P adsorption abilities, which could limit the internal loading of P. Moreover, research into the adsorptive properties of sediment can be used as a tool for the evaluation of lake restoration effects.

Khare et al. [25] developed a phased scenario analysis approach for the identification of a cost-effective restoration alternative using four TP control strategies—Best Management Practices

(BMPs), Dispersed Water Management (DWM), Wetland Restoration, and Stormwater Treatment Areas (STAs)—to achieve a flow-weighted mean TP concentration of 40 µg/L at lake inflow points. A Watershed Assessment Model was utilised to simulate flow and phosphorus dynamics and the results from a 10-year data collection, which supported that STAs are necessary components to achieve restoration of the Everglades' ecosystem and sustainability in south Florida.

4. Conclusions

This Special Issue concerns the environmental problems of freshwater eutrophication and focuses on solutions for lake and river restoration. Based on the bibliographic investigation, clearly, increasing attention has been attracted by scientists with the aim of solving this environmental problem, reflected by the exponential rise in article numbers. The 12 papers emphasise the research foci within three stages of the restoration, i.e., background investigation before restoration, various strategies selected for restoration, and long-term monitoring after the treatment. We believe this Special Issue will not only indicate coherent directions of research but will also support policy makers toward more sustainable and effective water restoration and assessment.

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