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A global assessment of lake restoration in practice: New insights and future perspectives

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ABSTRACT

A global survey of 179 restoration practitioners spanning 65 countries identified the extent of stakeholder engagement as a key factor determining the success or failure of restoration projects. Lack of support across sectors and for funding, policy, monitoring, governance and knowledge assessment of pressures and their effects were most frequently cited as factors contributing to restoration failure.

The responses indicate that, although nutrient enrichment is perceived to be the primary issue for lakes globally, the impacts of climate change, hydrological modifications and invasive species are widely recognized as pervasive anthropogenic pressures of global importance. Practitioners recognized that the ecosystem services most impacted by these pressures were recreation and tourism, although in low income countries the provisioning service, aquaculture, was considered most impacted. Ecology-based and/or pressure-related restoration targets had been set for most restoration programs in our survey. However, the strength of the evidence underpinning these targets was often weak and the effects of climate change were rarely considered when setting targets.

The most effective and widely used restoration measures target nutrient loading (both catchment and in-lake) while hydrological modifications and the implementation of nature-based solutions are used to a lesser extent. Measures for the control of non-native invasive species are rarely applied and are viewed as being largely ineffective.

The results of the survey provide direction for future work. New and emerging pressures, singly and in combination, may require new approaches to lake restoration: for both setting restoration targets and devising restoration strategies. The future of lake restoration depends on joined-up thinking that better integrates science into policy and practice and, most importantly, ensures strong and inclusive stakeholder engagement and collaboration across multiple sectors.

1. Introduction

There are reported to be 117 million lakes on Earth, covering about 4 % of the planet's non-glaciated land surface (Verpoorter et al., 2014). These lakes provide essential services for surrounding communities and are major foci of recreation and well-being. Increasing demand for natural resources has led to widespread degradation of lakes (Jenny et al., 2020); however, programs to restore lakes are widely perceived to have a high rate of failure (Gulati et al., 2008; Søndergaard et al., 2007). This is a particular concern for less economically developed countries

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where communities have a high degree of exposure to the impacts of lake degradation and where monitoring, assessment and restoration programs may be in their infancy. This risks impacting the well-being of communities and the viability of economic growth, ultimately challenging the United Nations General Assembly resolution (United Nations General Assembly, 2022) that recognizes access to a clean, healthy and sustainable environment to be a universal human right.

The factors affecting the success and failure of restoration programs can be expected to vary geographically and with the economic status of communities tasked with implementing them (Roni et al., 2008). Geographical variation extends not only to the nature of the pressure(s) responsible for degradation but also to their intensity and duration (Kennedy et al., 2019). The willingness of stakeholders to co-operate may be affected by social and industry cultural norms, and by national and regional governance systems. It is, inevitably, a complex process, requiring consideration of ecological, economic and regulatory systems. However, no global baseline evidence exists with which to systematically assess these factors.

As a result of various international initiatives (e.g., United Nations (UN): Sustainable Development Goals, European Union: Water Framework Directive [WFD], USA: Clean Water Act) and now the EU Nature Restoration Law, there is a growing community of practice on lake restoration. This community has considerable expertise in implementing restoration programs under highly variable social, political and geographic conditions and represents a potentially powerful resource with which to assess the effectiveness of restoration of impacted lakes across the globe. The challenges required to engage this community has hitherto limited knowledge exchange and awareness of best management practices as well as uptake of restoration approaches envisaged under global initiatives (e.g., UN Decade on Ecosystem Restoration), and ensuring restoration programs are 'future-proofed' through adaptation to include potential future pressure changes (e.g., climate change).

We addressed this knowledge gap using an online survey of the global community of lake restoration experts conducted over a 12-month period. In common with other similar surveys of environmental practitioners (e.g., Lyhne et al., 2016; Runhaar et al., 2019), we developed an online survey to relatively quickly and cheaply survey lake manger perceptions as a proxy for lake restoration approaches which can be difficult to quantify objectively. Our survey elicited responses from 179 practitioners representing 65 countries. The survey design was based on the DPSIR (drivers, pressures, state, impact, and response) framework, allowing a systematic baseline assessment of pressures and ecosystem service impacts, common management approaches and their perceived effectiveness, and factors necessary for success and/or responsible for failure. This framework has served as a basis for identifying effective pathways for sustainability research in other surveys with similar numbers of participants in (Yee et al., 2012).

We explore variation in responses as a function of Gross Domestic Product (GDP), summarizing economic development and make preliminary recommendations for improving lake restoration globally. This paper is a companion to the recent White Paper on Embedding Lakes into the Global Sustainability Agenda (WWQA Ecosystems, 2023). This sets out a policy-focused agenda to support sustainable lake and reservoir management globally. This paper provides a detailed analysis of the evidence used to inform the key messages of WWQA Ecosystems (2023).

2. Material and methods

2.1. Survey structure and approach

A survey was conducted to collate the experiences of lake restoration practitioners from around the world, to identify the key factors leading to success or failure of lake restoration and to draw conclusions for priority actions to improve restoration globally: https://forms.office.com/r/uFnKsxLT5M. The questionnaire was advertised broadly via email, social media, conferences and relevant societies and was made available via the WWQA website [World Water Quality Alliance (WWQA) – a partnership effort | UNEP - UN Environment Programme]. The survey represents an overview of the experiences and opinions of practitioners with different professional backgrounds. Some based their answers on their experience of a single lake while some worked on several lakes in a region. The respondents specified their role as science based (82 %), policy (8 %), practitioners (4 %), or other (6 %). The source organizations of the 82 % of respondents defining themselves as science based were dominated by universities or aquatic institutes (Table A1).

The survey addressed six aspects of lake restoration: 1) pressures affecting lakes; 2) ecosystem services affected by these pressures; 3) restoration targets; 4) restoration measures and their effectiveness; 5) factors behind the success and failure of lake restoration; and 6) the main constraints to successful lake restoration. Respondents were offered a range of choices; the section on pressures, for example, offered a choice to quantify effects as 'don't know', 'none', 'low', 'moderate', or 'severe'. Other questions had a binary yes/no option such as "Are there pressure-related targets for your lake(s)?" Additional questions required respondents to rank factors in ascending importance, for example for restoration success (Knowledge, Governance, Engagement, Resources).

2.2. Survey properties and categorization

A total of 179 responses were obtained by the cut-off date of 1 August 2022. Ninety responses (48 %) were received from Europe, leading to a skewed response if a simple geographical categorization was used (Fig. 1). A key factor determining the approaches and options available for restoration was expected to be funding, therefore responses were assessed in relation to per capita GDP as an indicator of 'capacity'. Per capita GDP in 2020 was available for 195 countries including the 65 included in this survey (World Bank, 2022). These were sorted from lowest to highest and divided into four equally sized groups which roughly aligned with four quartiles when per capita GDP was arranged on a $\log_{10}$ scale. Q1 countries have the lowest per capita GDP and Q4 the highest. Per capita GDP is strongly correlated with the Human Development Index (r = 0.95) demonstrated by Kirschke et al. (2020) in their study of development needs in water quality monitoring.

There was a bias towards Q4 countries with 103 responses (54 %). Most of these were from Europe, but Q4 also includes North America (USA, Canada), Asia (Japan and South Korea) and Australasia (Australia and New Zealand) (Map 1). There were, however, insufficient responses

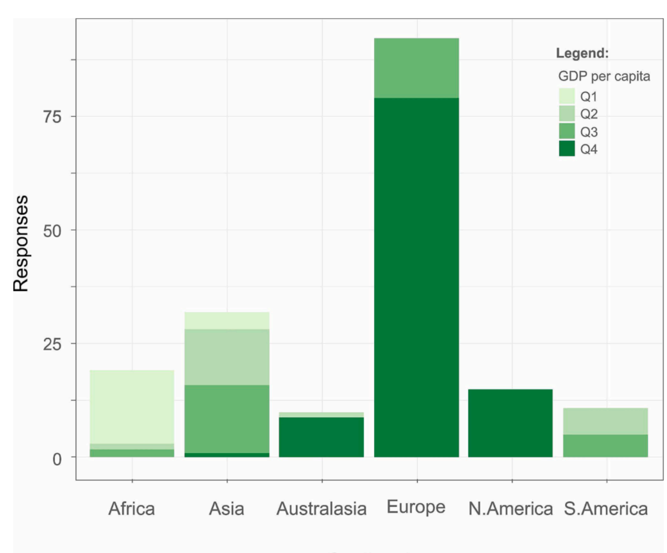
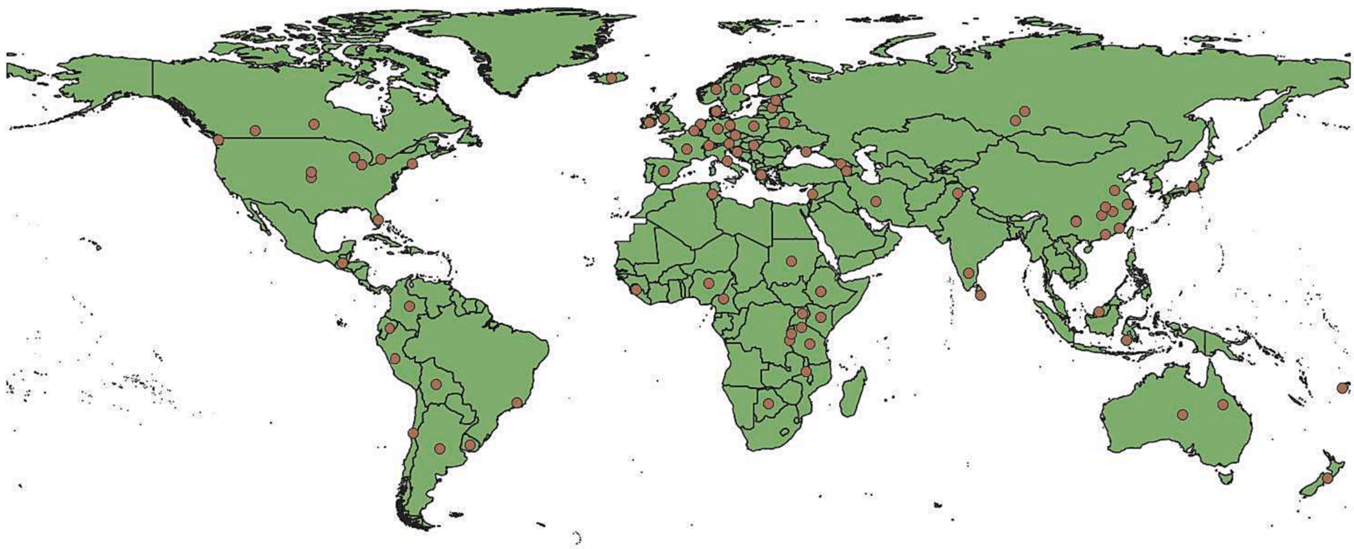


Fig. 1. Distribution of questionnaire responses by continent and per capita GDP.



Map 1. Global distribution of questionnaire responses.

to allow meaningful stratification or sub-setting (i.e. to look at how responses amongst Q1 countries varied between continents) but we included a case study of New Zealand to qualitatively examine responses for one country against those from all survey respondents.

In order to understand if broad climatic difference influenced respondents answers, data on air temperature were obtained from ERA5, the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF)reanalysis for the global climate and weather (monthly data for 10-year period from 2012 to 2021) [https://cds.climate.copernicus.eu/cdsapp#!/home]. The values for temperature anomaly were also obtained for the same period from the HadCRUT global temperature dataset [https://crudata.uea.ac.uk/cru/data/temperature/].

2.3. Statistical analysis

Summary graphs were produced which aggregated the strongest two response categories (e.g. "moderate" and "severe" in the case of pressures), allowing insights into those pressures, impacts and responses that are most widespread, on a global scale. This does not mean that a pressure, impact or response may not be significant on a local scale, but only that the frequency of such occurrences is low in our survey.

Statistical analysis was carried out on **ranked data** in the R statistical package (R Core Team, 2019) with mean rank calculated on data aggregated into a summary matrix (rankings with their corresponding frequencies) using the 'destat' function of the package 'pmr' (Lee and Yu, 2013). This allowed the replies to be ordered into overall preferential rank. Tests for an overall difference and a difference between each of the ranked responses were carried out using chi-squared tests implemented through the 'compareGroups' software package in R (Subirana et al., 2014) with additional post hoc tests with standardized residuals carried out using the 'chisq.posthoc.test' package (Ebbert, 2019). Logistic regression was performed to analyse **binary responses** regarding target setting and applied approaches to restoration (R Core Team, 2019) with calculation of McFadden's R^2 using the 'pscl' package (Jackman, 2020).

Non-Metric Multidimensional Scaling (NMDS) was applied using the 'vegan' package in R using Bray-Curtis similarity to ordinate pressures and restoration measures (Oksanen et al., 2022). To facilitate interpretation, ordinations were rotated by GDP, but this did not change the distances among points in the ordination - only the orientation of the axes (Oksanen et al., 2022).

Nonparametric Multiplicative Regression (NPMR) (McCune, 2006a; McCune, 2006b) was used to estimate the response of **quantitative** variables to climate and per capita GDP. NPMR can define response surfaces using predictors in a multiplicative rather than in an additive way. This method is better for defining unimodal responses than other methods such as multiple regression (McCune, 2006b). NPMR was applied using the software HyperNiche version 2.3 (McCune & Mefford, 2009). The response was estimated using a local mean multiplicative smoothing function with Gaussian weighting. NPMR models were produced by adding predictors stepwise with fit expressed as a cross-validated R^2 (xR^2) which can be interpreted in a similar way as a measure of fit, as for a traditional R^2. The sensitivity, a measure of influence of each parameter included in the NPMR model, was estimated by altering the range of predictors by 0.05 (i.e., 5 %) with resulting deviations scaled as a proportion of the observed range of the response variable. Sensitivity is used to evaluate the relative importance of variables included in models because NPMR models, unlike linear regression, have no fixed coefficients or slopes.

In order to compare whether the absence or under-representation of many countries in the survey was also reflected in the published scientific literature we carried out a bibliographic mapping analysis using VosViewer (Van Eck & Waltman, 2010; version 1.6.19). We searched the Scopus database from 1970 to 2023 (up to July 18) using the key words "lake restoration" or "lake remediation".

3. Results

3.1. Importance of pressures

Responses to the present survey indicated moderate and severe impacts from all of the pressures identified, with nutrient pollution from agriculture cited most frequently, followed by climate change and hydrological alterations, and then by nutrient pollution from wastewater, invasive species and morphological alterations (Fig. 2a). All were recognized as significant problems across all four per capita GDP categories, although the relative importance of pressures varied (Fig. B1). Further analyses indicated that GDP had a statistically significant influence on the perceived importance of some of these pressures (Fig. 2b). Industrial pollution, plastics, overfishing and aquaculture, in particular, were all seen as more important problems in Q1-Q3 countries, compared with Q4 countries (Fig. 2.b, Fig. B1).

Two pressures, plastics and climate change, show contrasting trends (Fig. B1). Plastics are largely perceived as having relatively low impacts on a worldwide scale; albeit with greater impacts in Q1-Q3 than in Q4

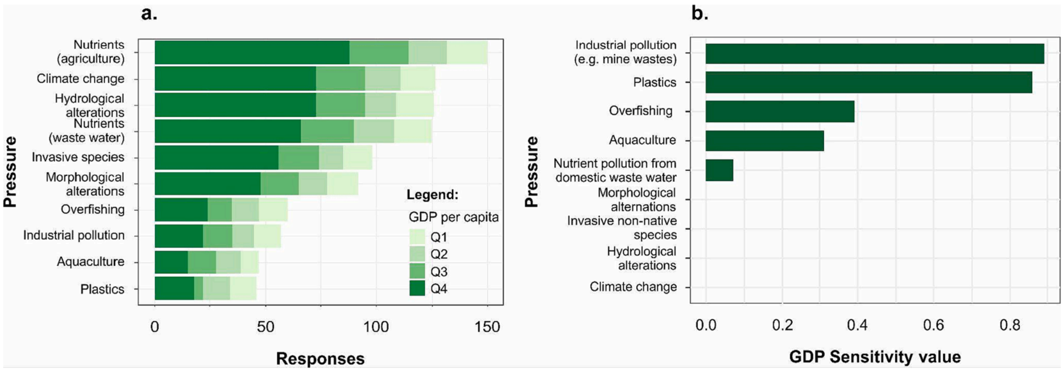


Fig. 2. a. Relative ranking of pressures by perceived importance (number or respondents classifying the pressure as severe or moderate); and b. Sensitivity values indicating the relative importance of GDP in the models for the pressures. Sensitivity is scaled as a proportion of the observed range of the response variable. See Table C1 for results.

(Fig. 2b). Climate change, by contrast, was the second most important pressure, ranked as "moderate" or "severe" across all continents and all GDP categories (Fig. B1-j). Interestingly, the assignment of importance of climate change as a pressure was not influenced by the respondent's country's GDP, the current mean or maximum temperatures or by the temperature anomaly ($p = 0.17$; see table C1).

3.2. Effect on ecosystem services

Survey responses indicated recreation to be the ecosystem service that is most likely to be affected by pressures, followed by conservation and biodiversity, human and animal health and fisheries (Fig. 3a, Fig. B2). Once again, Q4 countries dominated the "moderate" and "severe" responses for the first three but, for fisheries, drinking water and irrigation, half or more of these responses were from Q1-Q3 countries. This suggests that economic conditions influence how a resource's importance is perceived (Fig. 3b).

Several of these categories are not mutually exclusive. "Fisheries", for example, may represent one element of a broader "recreation" ecosystem service in Q4 whilst being an important source of protein for Q1 and Q2. Similarly, the lines between "human and animal health" and "drinking water" may be blurred, depending on the prevalence of waterborne diseases and local treatment regimes.

Several ecosystem services - aquaculture and fisheries, cultural and religious benefits and hydro-electric power generation - were significantly more important in low GDP countries, as indicated by the inclusion of GDP in NPMR models and the resulting response surfaces (see Table C1, Fig. C3, Fig. C4, Fig. C5).

Irrigation and drinking water supply also had significant interactions with temperature, with high sensitivity values reported (1.25 and 0.46 respectively, see Table C1). These were rated as more important and valued ecosystem services in regions where mean air temperature was high (Fig. C6 and C7). In contrast, there was no significant influence of GDP or temperature on conservation, human and animal health or recreation and tourism.

3.3. Target setting

The survey asked participants if restoration targets existed for the lakes with which they were concerned, and whether such targets were based on beneficial uses, ecological criteria or pressures (Fig. 4). All but 21 answered "yes" to at least one of these questions, suggesting that targets are widely used. Different approaches have been applied to target setting: 109 respondents indicated that beneficial use targets existed (Fig. 4a), 130 respondents indicated ecological targets (Fig. 4b), and 114 respondents indicated pressure-based targets existed (Fig. 4c). A further question on the strength of evidence for pressure-based targets showed that 26 % evaluated the evidence as strong and 10 % as weak or variable, while 64 % did not know or did not reply. Finally, it was clear that relatively few targets (less than a third) take account of the effects of climate change (Fig. 4d).

Per capita GDP was a significant influence only for the likelihood of ecology-based targets being used (Table C2) with countries with higher per capita GDP more likely to have these. The model predicted that countries with a per capita GDP above $45,000 had an 85 % likelihood of having an ecology-based target compared to a 57 % likelihood when

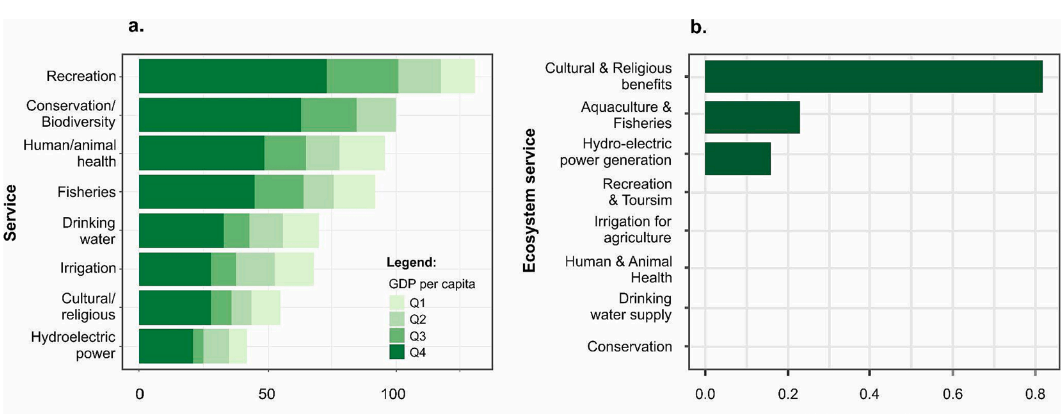


Fig. 3. . a. 4 Relative ranking of perceived impact of pressures on ecosystem services (number or respondents classifying service as moderately or strongly impacted); and b. ecosystem services where sensitivity values indicate the relative importance of gdp in the models. sensitivity is scaled as a proportion of the observed range of the response variable. see appendix 1 for table of results.

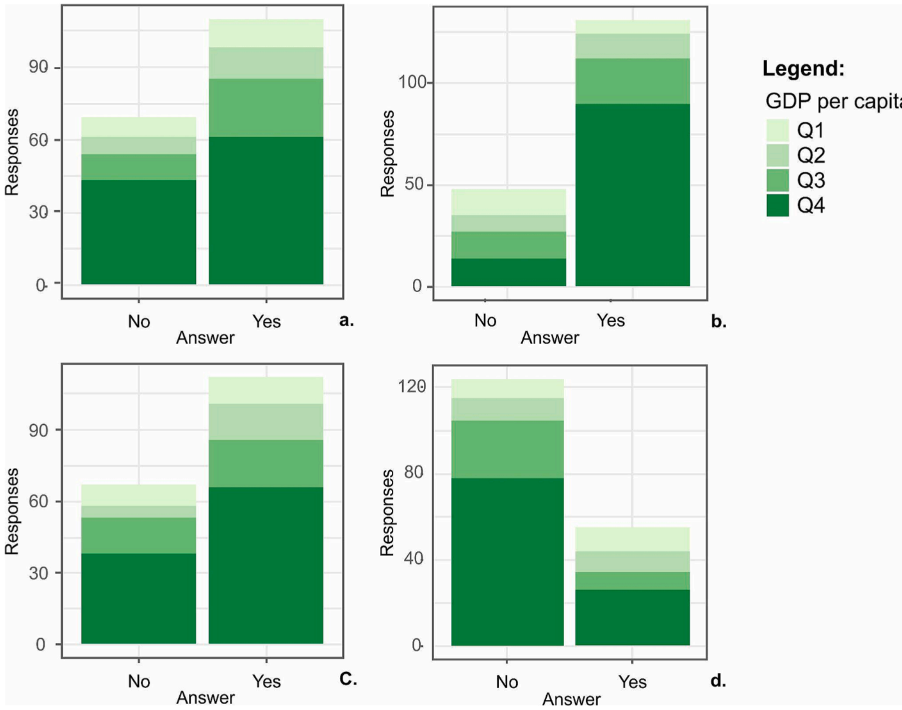


Fig. 4. Use of statutory targets for lake restoration. a. Beneficial use targets; b. Ecology-based targets; c. Pressure-related targets; and d. Do targets account for the effects of climate change?

per capita GDP was $10,000.

3.4. Restoration approaches

Nutrient load reduction from the catchment was perceived to be the most effective measure for lake restoration (Fig. 5), followed by internal load reduction (applied in 67 % and 46 % of lakes affected by nutrient enrichment, respectively). This is in line with nutrient enrichment being reported as the most important pressure. However, for these measures, more positive responses were received by Q4 respondents than Q1-Q3. Per capita GDP was found to have a significant positive influence on the implementation of catchment nutrient reduction in a logistic regression model (z value = 2.24, p = 0.03) (Fig. C1). Similarly, other potentially expensive interventions such as internal load reduction and

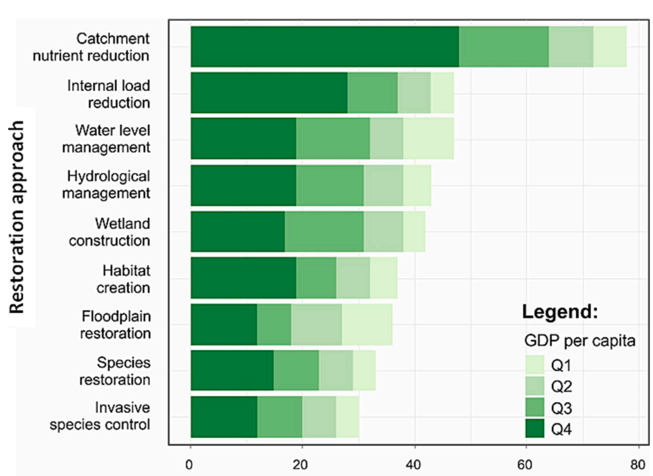


Fig. 5. Relative ranking of perceived effectiveness of approaches to lake remediation (number or respondents classifying approach as moderately or strongly effective).

constructed wetlands increased with a country's per capita GDP (Fig. C1).

Managing water levels and hydrological regimes were the next most widely used lake restoration measures, judged to be moderately-strongly effective in 27 % and 25 % of lakes affected by hydrological alterations, respectively. They were more likely to be used in countries with lower per capita GDP (z value = −2.33, p = 0.02) (Fig. C1), although we do not have information on specific geographical and lake characteristics that would also be important.

Species-reintroduction and the control of invasive species were viewed as being least effective, perhaps indicating that the reasons behind the loss of desirable species are nested amongst other pressures and that once invasive species are established, they are extremely difficult to eradicate. Measures were only judged to be moderately to strongly effective by 17 % of respondents, although we acknowledge that not all respondents may have lakes strongly impaired by alien species invasions.

In order to compare the incidence and strength of pressures in the context of the above remediation measures, a non-metric multidimensional scaling analysis was carried out. Results were rotated by per capita GDP to facilitate visualization (Fig. C2). In both ordinations there was a visible division in pressures and remediation measures between the richer global north and poorer south. For countries with high per capita GDP, nutrient pollution from agriculture was a key pressure and the restoration measure of reducing nutrients in the catchment was positioned in a similar ordination space. In poorer countries, or in countries in the south and east, the pressures of aquaculture, industrial pollution, overfishing and plastics were more prominent. Restoration measures located in a similar ordination position were species reintroduction, floodplain restoration, wetlands construction and habitat creation.

3.5. Factors contributing to restoration success and failure

Stakeholder engagement was identified by 44 % of the respondents as a key factor behind the success of restoration projects, with governance following at 21 % (Fig. 6). Although the importance of engagement is clear from Fig. 6, it considers only the first preference in a univariate way, while the responses are more complex, with factors ranked in different orders by respondents. It is more appropriate to consider a mean rank of the results (Lee and Yu, 2013) which ranked the reasons for success as: Engagement > Resources > Knowledge > Governance. The rankings were found to be significantly different overall ($X^2 = 98$, $p < 0.001$, df = 9).

Conversely, reasons for failure were ranked as: Engagement > Knowledge > Resources > Governance. Again, stakeholder engagement (or, rather, its absence) was considered to be the factor most likely to precipitate restoration failure. Again, the rankings were found to be significantly different overall ($X^2 = 64$, $p < 0.001$, df = 9). Engagement, as well as being ranked first for both success and failure, was also found in chi-squared post hoc analysis of first preferences to be significantly different from other factors (residual = 5.6, $p < 0.001$).

However, the additional comments supplied by respondents alongside their rankings underlined the importance of all factors and their interlinkages. For example, respondents stated that engagement can increase knowledge on how to acquire funding resources, while governance enables all steps. Whilst it is clear from Fig. 6 that a lack of engagement will lead to restoration failure, one respondent commented that over-enthusiastic engagement may lead to an over-ambitious plan being developed.

3.6. Constraints to effective remediation

The importance of engagement is reflected, again, in the responses to the following questions, concerning constraints to effective remediation. Poor support across sectors was most frequently cited, even amongst Q4 countries (Fig. 7, Fig, B4). This underlines the importance of engagement not just at local level but across a wide spectrum of sectoral stakeholders. The second most frequently cited factor was insufficient finance, presumably because spending constraints are likely to limit achievement of restoration goals, irrespective of per capita GDP. Supporting this was the observation that GDP was not significant in NPMR regarding respondents rating of the importance on finance (Table C3).

Weak policy support and governance, both linked, were the next most important constraints. Governance contributes to the framework within which other factors operate. Knowledge, for example, embraces issues such as frequency of monitoring which is often determined and/or commissioned by regulators. Only 63 of 193 UN Member States reported on lake water quality in 2020 (UNEP, 2021), highlighting the low capacity to conduct monitoring and assessment in many countries. Even when data are available, temporal and spatial scales are often not adequate, or existing databases are limited because they are project-specific. A low extent of data sharing and existing protocols further restricts data sharing.

Insufficient monitoring was highlighted as a relatively large constraint in Q1 countries where financing of baseline monitoring

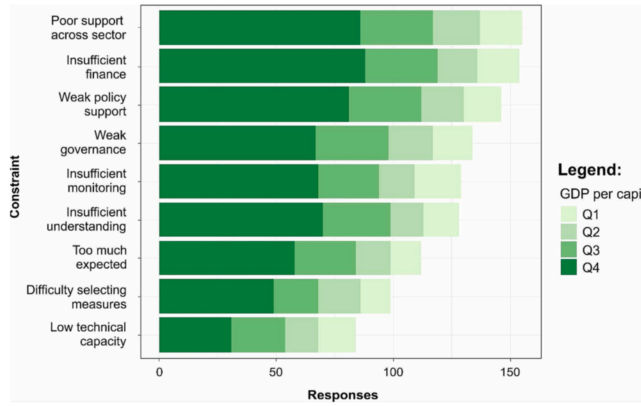


Fig. 7. Ranking of perceived constraints to effective remediation.

programs is likely to be an issue (Fig. 7, Fig. B4-b). While GDP was not found to have a significant effect on monitoring, a related constraint 'low technical capacity' was significant (Appendix Table C3). Participants commented that conventional monitoring programs do not enable data collection at a sufficiently high resolution, that monitoring of transboundary waters is particularly problematic and that short-term monitoring linked to discrete projects can cause inconsistencies in data collection and availability. Together, these have the potential to derail decision-making on management measures needed. Little information, or disagreement, on what comprises baseline conditions is a fundamental issue influencing restoration success, accentuated in the face of environmental and climate change.

Insufficient understanding of pressures and their effects was ranked as one of the most important reasons behind failure in lake restoration. This agrees generally with the reported presence of multiple (and potentially interacting) pressures (3.1), and the lack of effective management measures with which to manage pressures that are not related to nutrient loading (3.4). A broader issue is that project funding is largely directed towards 'doing something' rather than generating a good understanding of the system and predicting the effects that a restoration activity might achieve.

3.7. Limitations inherent in the global survey

In surveys of this nature, it is difficult to ensure a balanced response globally. This was clearly reflected in our survey recording more responses from Q3 and Q4 GDP countries. In order to compare whether the absence or under-representation of many countries in the survey was also reflected in the published scientific literature we carried out a bibliographic mapping analysis using the key words "lake restoration" or "lake remediation". A total of 1312 records were found from 67 countries, 52 of which had a minimum of two publications, and these

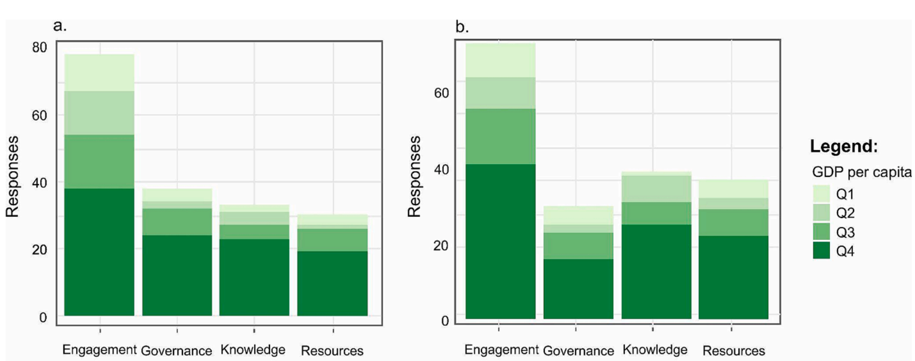


Fig. 6. Reasons that were ranked 1st for restoration: a. success; and b. failure (i.e., absence of factor).

were used to produce a co-authorship map by country (Figure D1). The top five countries were: United States, China, Netherlands, Denmark and Germany, with strong collaborative links among many countries. The number of responses to the survey per country was positively correlated with the number of co-authored publications ($r_S = 0.45$, $p \leq 0.01$, $n = 87$, Figure D2).

In order to examine if the responses to the survey could be influenced by the global distribution of lakes, we examined the HydroLAKES database of 1.4 million lakes above 10 ha in area (Meyer et al., 2020). A higher number of survey responses were recorded from countries where there were more lakes, typically in the northern hemisphere ($r_S = 0.46$, $p \leq 0.01$, $n = 251$) (Fig. D3). However, these countries also tended to have higher GDP, with a positive correlation between the number of lakes in a country and GDP ($r_S = 0.64$, $p \leq 0.01$, $n = 251$).

4. Discussion

4.1. Importance of pressures

That many lakes around the world are degraded to the extent that they are not providing essential ecosystem services is not in doubt (Jenny et al., 2020). Traditionally, nutrient enrichment has been perceived as the overriding stressor for lakes (Birk et al., 2020), and lake restoration programs have focused exclusively or predominantly on reducing nutrient loads and mitigation of eutrophication effects (Abell et al., 2022). However, our analysis of responses from 179 lake restoration practitioners reveals three important findings:

- Although nutrient enrichment remains the primary pressure of concern to lake managers globally, being estimated as "severe" or "moderate" by 84 % of respondents, other pressures are also important. In particular, climate change, hydrological (70 %), and morphological (51 %) alterations and alien species (55 %) impact a large percentage of lakes globally;
- Climate change, notably, is the second most important pressure of concern after nutrient enrichment, ranked as "moderate" or "severe" for 71 % lakes across all continents and GDP clusters;
- In most cases, these pressures are not acting in isolation. Responses implied that few lakes were regarded as subject to one single pressure. On average, practitioners evaluated their lakes as being subject to seven pressures (including those acting at low levels), while the most common severe pressures acting together were nutrients from agriculture and hydrological modification.

Our study also noted differences in the importance of pressures depending upon per capita GDP. Industrial pollution and plastics, overfishing and aquaculture were more often perceived as pressures in countries with lower per capita GDP than in those with high per capita GDP (Fig. 2b). This may reflect two situations. Industrial pollution (mining and extraction in particular) has been moved away from countries with long histories of industrial development (now mostly in Q4) to less developed regions (Zhou et al., 2020). Alongside this, there is a longer tradition of regulation of toxic effluent in Q4 countries (e.g. the Dangerous Substances Directive in the EU, first implemented in 1976) compared to Q1-Q3 countries. Poorer countries (Q1 and Q2 in particular), by necessity, place greater emphasis on feeding their populations than on environmental protection, leading not just to pollution from agricultural sources (Teklu et al., 2018) and abstraction for irrigation water, but also to overfishing and high intensity aquaculture (Hasimuna et al., 2019). Linked to this are well-intentioned, but often ecologically damaging, introductions of non-native fish (e.g. Nile perch into Lake Victoria: Taabu-Munyaho et al., 2016).

Our study shows that plastics are not widely perceived as being important globally. It is hard to know whether the survey result reflects under-reporting, a lack of awareness on impacts, or if impacts are indeed genuinely too low to affect ecosystem services. Interestingly, plastics were perceived as more important in low-income countries. This is corroborated by the study of Lebreton et al. (2017) which revealed that the top 20 plastic-polluted rivers, accounting for 67 % of the global total plastic waste, are located in low-income countries in Asia, Africa and South America, and by Nava et al. (2023) who identified that plastic pollution was widespread in 38 lakes across remote to highly urbanized areas across the world.

In contrast, the survey identified climate change as the second most important pressure on a global scale (Fig. 2a). Surprisingly, our analysis did not show any relationship between the importance of climate change as a pressure and the respondent's country's per capita GDP, the mean or maximum temperatures, or the temperature anomaly. The recent media focus and scientific research in this area have likely played a role in informing all survey participants about the influence of climate change globally, in addition to direct restoration experience.

Last but not least, our study shows that lake degradation is a result of cumulative effects of eutrophication, climate change and additional pressures, such as hydrological alteration and invasive species. So far, studies on multiple pressures mainly address rivers, though it is clear from the literature that many pressures often act simultaneously on the same lake (Birk et al., 2020; Spears et al., 2021). Lake Victoria in East Africa offers an excellent example, being subject to both introduction of a non-native fish and cultural eutrophication, with the added stress in recent decades of a warming climate (Hecky et al., 2010). Similarly, lakes in the Yangtze River Basin are subject to wide variety of anthropogenic impacts: nutrients from agriculture, industry, animal husbandry and aquaculture, hydrological modifications due to extensive dam and reservoir construction; their effects all exacerbated by climate change (Zeng et al., 2018, Zhang et al., 2018).

4.2. Effects on ecosystem services

Our study underscores differing perceptions across the global community of lake restoration practitioners on the importance of pressures and the vulnerability of lake ecosystem services to these. Overall, responses indicated that recreation and tourism were the ecosystem services that are most likely to be affected by pressures (strong or moderate effects recorded in 73 % responses), followed by conservation and biodiversity (strong or moderate effect in 63 % responses). These results broadly correspond to a global *meta*-analysis (Reynaud and Lanzanova, 2017) where the "recreation service" (split into fishing, boating, swimming and sightseeing) was by far the most important service provided by lakes in 699 observations drawn from 133 studies. However, this publication, and our overall results, may well be influenced by overrepresentation of lakes from North America and Europe. There may also be differences in interpretation of ecosystem services among respondents, notably between regulation (e.g., nutrient and sediment processing, sequestration, hydrological regulation) and provisioning (e.g., drinking water, fisheries, recreation) that are specific to lake, practitioner knowledge or resources (Schallenberg et al., 2013).

We noted that per capita GDP was responsible for clear differences in the effect on ecosystem services: recreation and conservation, in particular, were regarded as more significant in countries with higher per capita GDP whilst aquaculture was considered more important in countries where per capita GDP is lower. Though the effects are generally weak, these results indicate ways in which lakes - and, by extension, restoration efforts - interact with local communities and economies. Lower income countries may recognize the provisioning services of aquaculture, water supply for drinking and irrigation and hydro-electric power generation more explicitly, for example. This closely aligns with the UN view that water, food and energy form a nexus at the heart of sustainable development (United Nations General Assembly, 2022). This key nexus across different sectors highlights the urgent need for engagement and governance to include influential stakeholders (decision-makers and policy-makers) from these other sectors in all three domains (including water supply and wastewater treatment).

Effectiveness of restoration may also be viewed differently by different stakeholders, valuing different ecosystem services. For example, the restoration of Lake Kralingse Plas (the Netherlands) can be attributed to external and internal nutrient load control, resulting in fewer cyanobacteria blooms but promoting canopy-forming macrophytes. Opinions of success were split amongst stakeholders (Janssen et al., 2021). This case provides an example of trade-offs between ecosystem services and emphasizes the importance of understanding the sometimes divergent views of different stakeholders when negotiating desirable outcomes and targets. In addition to managing stakeholder's expectations, the economics of the restoration itself need to be addressed. Authorities generally demand that investments should pay off, yet often both lakes and their restoration are undervalued, because some values (e.g., recreation) are not easily monetized and those who benefit may not only be from communities in close proximity (Reynaud and Lanzanova, 2017; Zulian et al., 2018). It was only possible to include a limited number of questions on ecosystem services in the questionnaire. Janssen et al. (2021) identified 39 ecosystem services for lakes including provisioning and cultural as well as supporting and regulating. The latter includes flood protection and climate regulation which, while addressed in other aspects of the survey, would be useful to include in future surveys.

4.3. Approaches to restoration targets

An important principle underlying any efforts at ecosystem restoration is the need for clear objectives. At its simplest, these may be descriptive phrases encapsulating the gap between the present and desired state of a water body, but they are often expressed in quantitative terms. The targets can be described in ecological terms, e.g., abundance and composition of phytoplankton (Carvalho et al., 2013; Poikane et al., 2014), macrophytes (Penning et al., 2008; Poikane et al., 2018), phytobenthos (Kelly et al., 2014; Charles et al., 2021) and fish fauna (Ritterbusch et al., 2022). However, for management reasons, the targets have to be expressed in pressure–related terms, as nutrient loads and concentration (Poikane et al., 2022), levels of hydrological or morphological alterations (Mjelde et al., 2013; Poikane et al., 2020a) or salinity levels (Kelly et al., 2023). Last but not least, use-related targets express the ability to use a lake in ways deemed to be "beneficial" to the local community or visitors, e.g., for swimming or food (WHO, 2021) or aquaculture, irrigation or water supply (Goyal et al., 2021).

In the present survey, most respondents indicated that some form of target was relevant for their case study, although 21 respondents indicated that restoration programs were proceeding without targets. The dominance of ecological targets most probably reflects the large proportion of respondents from Europe where the Water Framework Directive requires ecological target setting (Commission, 2000). Our analyses indicated that ecology-based targets, in particular, were less often reported for low income countries (<GDP $45,000). The reasons behind this result require exploration, although the need for capacity development in water management, including ecological assessment, in low GDP countries is well recognized by the international community (Kirschke et al., 2020). We had expected that beneficial-use targets (i.e., food or water provision) would be more common in low GDP countries where communities were expected to be more directly reliant on ecosystem services. This is the case in some lower GDP countries, such as India, where water quality standards for "designated best use" exist (Central Pollution Control Board, 2019), however, this was not confirmed as a general pattern by our statistical analysis.

The strength of evidence underpinning target-setting and the process-understanding linking pressures, ecology and ecosystem services should be a key focus for all lake managers (Spears et al., 2022). Ideally, targets and their measurable indicators would allow assessment of pressures, ecology, and beneficial uses, reflecting the processes driving lake responses to pressures (Poikane et al., 2020b). The lack of such an approach is inferred from many responses to the survey, as only 41 % of responses indicated all three types of targets, while 19 % reported only one type and for 12 % no targets were set. Moreover, only 26 % of respondents thought that their evidence for target setting was 'strong'. This can be linked to poor understanding of pressures and their effects, reported as one of the main reasons behind lake restoration failures (3.5). While knowledge of nutrient management is relatively advanced, the other pressures, are much less well understood (Poikane et al., 2020b).

We did not ask questions on adaptive management approaches in our survey, but clearly continuous evidence-based review of targets is a sensible approach (Stow et al., 2020). However, a significant proportion of our respondents indicated that evidence was insufficient to support existing targets and so the capacity for an adaptive approach to target setting will be limited for this group.

Climate change effects represent just one example of future pressures that may require targets to be revised, but less than a third of our respondents indicated that their targets accounted for climate change. For example, changes in weather and lake processes as a result of climate change can exacerbate the effects of nutrients on lake ecological indicators (e.g., harmful cyanobacteria biomass). One apparently logical management response may be to reduce nutrient concentrations further than existing targets to adapt to the climate change effects. However, without first determining the form of interaction between the key pressures, this approach carries a high degree of uncertainty. Spears et al. (2021) propose conceptual, empirical and process modelling approaches to support adaptive management in lakes, providing guidance on managing multiple pressures and their interactions. A consistent approach to adapting existing targets to address climate change effects is urgently needed; this may require a fundamentally different approach to restoration where we reduce a pressure to alleviate a symptom. For climate change adaptation, it may be appropriate to reduce one pressure in order to avoid the effects of another; strictly speaking this is *prevention* rather than *restoration*.

4.4. Effectiveness of restoration approaches

Successful intervention always starts with a thorough diagnosis, which not only requires adequate engagement, but also monitoring and measurements, and thus resources. These factors were identified in the survey as those most important for successful restoration and correspond to the so-called *lake system analysis* approach, which identifies the magnitude of the issue(s), the drivers, impacts, costs and benefits to guide the selection of restoration measures (Moss, 2007). The success of restoration may also need to be moderated by factors such as lake size, depth, retention time and catchment area, each of which is usually represented in mechanistic loading models that have a long history of use for predicting steady state lake phosphorus concentrations for the purpose of eutrophication control (Khorasani and Zhu, 2021).

The survey indicated that catchment nutrient control measures and internal load reduction were perceived to be the most effective approaches to lake remediation. This agrees with evidence from the literature indicating that nutrient pollution is the most prevalent water quality issue worldwide (Downing, 2014; OECD, 2017). These two restoration approaches were also the only ones where there were more positive responses from Q4 countries than from Q1-Q3 countries, perhaps reflecting the high cost and the need for relatively sophisticated governance and regulatory structures to manage catchment-scale interventions.

Good examples of successful catchment nutrient control include *peri*-Alpine lakes in France, Germany and Switzerland (Gerdeaux et al., 2006; Murphy et al., 2018). However, many lakes do not show recovery in the years following external nutrient load control (Søndergaard et al., 2007), or their recovery takes decades (Fastner et al., 2016). Such limited, or long-term, beneficial return on restoration investments may need to be supported by in-lake measures in order to speed up recovery. This is especially important when ongoing diffuse nutrient pollution and changed ecosystem structure may strongly delay improvements in ecological services (Jarvie et al., 2013).

Internal nutrient load reduction was identified as one of the most effective restoration measures. The key techniques and approaches for internal nutrient load control are sediment removal via excavation and dredging, aeration, oxygenation, hypolimnetic withdrawal and additions of materials to immobilize P (Abell et al., 2022; Lürling, 2020). These interventions are generally not feasible in large lakes, but have been used on many occasions in smaller, shallow lakes. Alongside techniques to control internal nutrient load, a wide range of other biological, chemical and/or physical in-lake measures without proven efficacy are being implemented world-wide in attempts to restore impaired lake ecosystems (Lürling and Mucci, 2020). Realistically, decisions about the relative importance of external and internal loads need to be considered for each lake and based on credible evidence (Steinman and Ogdahl, 2015).

Management of water levels and hydrological regimes were rated by participants as moderately to strongly effective for only 25–27 % of lakes affected by hydrological alterations. Fluctuations in water level are a natural phenomenon in most parts of the world, and many organisms will be adapted to cope. Macrophyte assemblages in shallow lakes in the Netherlands, for example, may depend upon periods of shallow water and, in turn, sustain food webs that mitigate against lakes "flipping" to a plankton-dominated state (Coops and Hosper, 2002; Gulati et al., 2008). At the other extreme, alteration of natural water levels (e.g. by disconnecting a lake from feeder streams) can have negative effects on macrophytes (Mjelde et al., 2013). Once again, details vary from case-to-case. In contrast to nutrient enrichment, hydrological and morphological alterations are less well understood (Poikane et al., 2020b) and management measures are not well developed.

Most respondents perceived species reintroductions and control of invasive species to be ineffective, relative to other measures (Fig. B3e, f). For re-introductions it is important to first ascertain the causes of local extinctions. For example, where this is related to habitat quality then it is logical to first restore habitat prior to species re-introduction (Collier et al., 2022). In contrast, if the species has been hunted to extinction then a "rewilding" approach may be successful (Willby et al., 2018). The species range may have been constrained as a result of climate shifts. In this case, re-introductions, regardless of the original cause of local extinction will be futile.

Control of invasive species received the most negative responses in this part of the survey. The key here is effective and preventative biosecurity so that problematic and expensive eradication measures are not necessary (Escobar et al., 2018). Non-native species control is a very clear example of where prevention is better than cure (the economic cost of water hyacinth on fisheries is estimated to be ~ USD 150 million per year in Lake Victoria; May et al., 2022). Once a non-native species is established, eradication seems almost impossible, as case studies of Nile perch (Taabu-Munyaho et al., 2016), zebra mussels (Strayer, 2009) and numerous other species have demonstrated. However, our study reported that measures have been moderately to strongly effective in 17 % lakes affected by alien species invasion. We stress here the need for innovative tools to control invasive species that address the drivers of invasion (Kowalski et al., 2015) as well as exchange of experience and best practices for managing these invasions.

4.5. Factors contributing to restoration success and failure

A number of factors emerge that are linked in our survey to the success of lake restoration. Engagement, especially interaction across sectors, was identified by over half of the respondents as a key factor behind the success of restoration projects, (Fig. 6), and is widely considered to be essential for successful water resources management (Holifield and Williams, 2019; Krantzberg et al., 2015). However, engagement takes many forms and is hard to disentangle from other factors such as governance, knowledge and resources. We were surprised that governance ranked relatively low in respondents' estimations, as it creates the framework within which most other management actions operate (Akhmouch and Correia, 2016). We speculate that as most practitioners work largely within a single governance framework, the wider governance perspective was not always apparent. Several of the perceived constraints to effective restoration (Fig. 7) depend upon a strong governance framework.

Restoration of surface waters is strongly linked to policy and appropriate political facilitation, strikingly illustrated by the European WFD (Commission, 2000) and also large national investments in lake restoration from public finances prior to the WFD, notably in Denmark and the Netherlands (Gulati and van Donk, 2002). Søndergaard et al. (2007) reviewed the success of restoration of over 70 shallow lakes in those countries over a 30-year period. The nature of the pressure (nutrients) and the role of in-lake food webs in controlling algae growth in those lakes prompted an era of nutrient load reduction coupled with food web manipulations. Critical factors were the re-establishment within a few years of fish populations that preferentially ate larger-bodied zooplankton, and persistence of internal nutrient cycling from nutrient-rich sediments. A key conclusion of Søndergaard et al. (2007) was that for the nutrient enriched lakes included in their study, restoration should be perceived as a "management tool rather than a once and for all solution". This statement is, however, inherently and understandably time bound in its thinking.

In North America, a long history of lake restoration attempts over the last half century provides similar insights. A review of restoration practices (Carpenter and Cottingham, 1997; Carpenter et al., 1999) laid the foundations for successful lake restoration, and effective investment. The key factor was not deficiencies in the science, but in the appreciation of uncertainty for successful restoration, the need to set precautionary targets and consider the drivers of pollution, and those who benefit: "the fundamental problem of lake restoration is an economic mismatch: those who cause the problem do not benefit sufficiently from the remediation" (Carpenter and Cottingham, 1997).

These considerations raise a number of crucial points for lake restoration, which are also apparent in our survey. First, the uncertainty of prognosis for lake recovery relates to nutrient (or other pollutant) dynamics. The biochemical mechanisms and long-term effects are often unclear because restoration typically involves many simultaneous actions (Søndergaard et al., 2007). Second, the time frame for success is frequently underestimated because of lag-times in nutrient movement into and out of the lake (Rippey et al., 2021). Third, communication of lake restoration likelihood is either not effective, or overly ambitious. For lakes subject to multiple catchment processes, realistic timescales for restoration could be decades. This also means that factors which contribute to restoration failure are not always discussed and analysed. Together, these factors highlight the need for a critical review of lessons learned to guide future restoration attempts and depart from the trial-and-error approaches that have historically guided restoration (Coleman et al., 2020; Søndergaard et al., 2007; Weber et al., 2020). Finally, the need for engagement in lake restoration inevitably involves several stakeholders each with their own economic interests, and that requires patience and understanding on all fronts.

As the most pervasive pressure on lakes, nutrient reduction is widely regarded as the primary restoration action. It is clear that effective policies and management are the exception rather than the rule. Tackling the persistent problems of excess nutrient loads requires not only sufficient knowledge of sources (land based) and sinks (lakes), but embracing the governance challenges common to many natural resource management situations (e.g., Brownlie et al., 2021). This inevitably includes informed engagement on social benefits and costs - an area traditionally lacking in estimating true costs of environmental degradation (Carpenter et al., 1999; Russi et al., 2013). Costs also include direct capital and operating costs for nutrient reduction activities within the catchment (Sánchez et al., 2022), recoupable, ideally, via the "polluter pays'' principle. However, these can also be considered as short or medium term “opportunity costs” for regulated sectors in terms of lower output or higher treatment costs. The latter, in turn, may result in pushback from agricultural sectors with strong lobbying capacity. There is a clear need for international engagement and leadership across relevant UN bodies and polluting sectors if nutrient pollution is to be tackled in line with global ambitions (e.g. CBD 30x30 target).

Climate change is another substantial challenge (Fig. 2, Fig. B1). For example, how will a switch from carbon-based energy to renewables influence the way that hydroelectric power is valued, and what will this do to the perceived costs and benefits of morphological and flow alteration relative to ecological ideals? From a climate change mitigation perspective, how do we value (globally? locally? both?) the reduction in greenhouse gas emissions delivered through nutrient reduction to standing waters as eutrophication of lakes and reservoirs is now recognized as an important source of methane to the atmosphere (Downing et al., 2021). Once again, this is a matter that transcends scientific “knowledge” and will require sensitive “engagement” and, no doubt, modifications to existing frameworks of “governance”. More challenging is that the environmental impact per unit of nutrient pollution increases with water temperature (Rodgers, 2021). This has the consequence that negotiated financial or social contracts with land users may rapidly become outdated, with commensurate loss in confidence in policy and interventions.

A key message from the survey and from many case studies on lake restoration is that dealing with multiple pressures requires approaches that connect various pillars such as community, governance models, governments (central, regional, and district) and scientific support. This was well illustrated by a case study in New Zealand in our survey which highlights the importance of lake water quality for indigenous Māori communities (Williams et al., 2019). Cultural and religious services were identified as strongly impacted in the New Zealand case study although the GDP categorization of this country is Q4. European settlements and farming only commenced in the early 1800 s in New Zealand, and were followed by large-scale clearing of native vegetation, extensive hydrological modification of waterways, and displacement of Māori communities from tribal lands. In this context, the cultural pillar of lake restoration and the indigenous knowledge (“matauranga”) associated with it are integral to successful lake restoration. One of many novel developments in freshwater management in New Zealand is the granting of ‘personhood’ status to a river (Whanganui) which is likely to set a precedent for similar actions for lakes and rivers more widely. Co-governance models (between government and Māori organizations) have become normalized through treaty obligations that include lake ecosystem restoration as a core part of treaty redress (Parsons and Fisher, 2020).

The case study of New Zealand provides insights into reasons why responses at national scale may differ from a global cohort and indicates an opportunity in future work to mine the existing dataset or supplement it with additional national surveys. The overwhelming identification of nutrients from agriculture as a pressure on lake ecosystem services is consistent with large increases in fertilizer application in agricultural systems in New Zealand; the difference between total nutrients entering and leaving these systems increased 644 % from 59,265 tonne/yr in 2001 to 441,000 tonne/yr in 2021 (OECD, 2021). Surprisingly, total fertilizer applications have still increased by 22 % from 2011, when a National Policy Statement for Freshwater Management (NPS-FM, 2011) was first introduced, to 2021. The NPS-FM has undergone several iterations prior to its current form (NPS-FM, 2020) and these iterations have sought to reduce diffuse pollution from agriculture and improve water management nationally. In common with the global cohort of respondents, there was a diversity of opinion by the New Zealand respondents about the recognition and effectiveness of pressure-related targets such as those contained in the NPS-FM (2020).

Of the other pressures, introductions of invasive non-native species featured strongly in the New Zealand responses. This ranking is closely related to the relative isolation and island status of New Zealand, with > 80 % of freshwater species being endemic but severe impacts on lake biodiversity from invasions and establishment of non-indigenous freshwater fish, invertebrates and plants (Duggan and Collier, 2018; Hofstra et al., 2018).

4.6. Limitations inherent in the global survey

While the survey had more representation of the Q3 and Q4 countries, this probably reflected the fact that more scientific work on restoration has been done in these countries, and also that they tend to have more lakes. The co-author map on lake restoration publications indicated a dominance by western countries and China, and the number of respondents to the survey was positively correlated to the number of publications per country (Figure D1). This underlines that there is a global imbalance in restoration expertise and implementation. Our approach, to ensure that interpretation was relevant in a global context, was to include GDP as a key factor in analysis. This was done in graphical presentation of results but also in the non-parametric multiplicative regression (NPMR) which allowed complex response surfaces to be modelled and the significance of factors such as GDP to be tested for via randomization tests (McCune, 2006b). This, showed, for example, the importance of aquaculture as a significant pressure for lower GDP countries (Table C1, Figure C4).

Surveys like ours that involve environmental assessment rely primarily on perceptions because of a lack of common metrics or indicators that could provide a common quantitative methodology (Runhaar et al., 2019). An objective assessment would require each respondent to document before and after case studies of lake restoration, including relevant indicators, which was beyond the scope of our paper. In considering the quality of responses, there will be a range of expertise and experience represented, but the benefits of a survey of practitioners is in the distillation and dissemination of information that reflects a diversity of experience, geographies, and knowledge. It is possible that some respondents had limited expertise to address some questions, but they were still likely to have had informed opinions on a diversity of issues related to lake management. It is common for lakes globally to suffer from multiple pressures (Birk et al., 2020; Ormerod, et al., 2010), which makes it challenging to identify common methodologies and criteria for successful restoration. We sought to collate and unify perceptions on factors that contribute to restoration success from a community of experts familiar with restoration practice and theory.

5. A final perspective

The purpose of this review has not been to dwell on where we are, but to plot a course towards where we want to be. The variable success of lake restoration programmes provides important lessons for future endeavours. This draws on both a philosophical perspective and empirical evidence, illustrated by the global survey. The former was well illustrated by the “The Myths of Restoration Ecology” by Hilderbrand et al. (2005). Effectively, this provided for a more modest expectation of the ecological structure that can be realistically anticipated following restoration, which is itself a form of disturbance. The communication of expectations and uncertainty in outcomes allows for a less deterministic projection of the future. This also alleviates the sense of failure if things do not follow the planned, and financially committed, path. This very much is a part of the science-policy dialogue. However, it also resonates strongly with the institutional structures involved in lake and catchment management, and the financing necessary for restoration projects, many of which are discussed above and can involve extended timeframes.

The economics of lake restoration is a necessary new frontier. The last two decades have seen an intensive discussion on the importance of ecosystem services and their financial benefits (Grizzetti et al., 2016). Yet, unless the financial costs of environmental degradation are carried by the economic and policy interests that drive the pressures, restoration efforts will inevitably be viewed as expensive post-hoc actions, and subject to being undermined by the slow pace of success, or limited in scope through technical and governance impediments (Carpenter et al., 1999). A key element for lake restoration must, therefore, be the mainstreaming of societal and economic costs of lake degradation (and, conversely, the economic benefits of protection and restoration) into the social consciousness.

6. Conclusions

- Although nutrient pollution remains the primary issue in lakes globally, climate change impacts, hydrological modifications and invasive species were perceived to be equally important across our survey of lake restoration practitioners. In low GDP countries, the pressures of aquaculture, industrial pollution, overfishing and plastics were more prominent while, for high GDP countries, nutrient pollution from agriculture was a key pressure.
- Differing perceptions on the ecosystem services impacted by pressures were apparent across GDP classes. Provisioning services were perceived to be most impacted in low GDP countries whereas recreation and biodiversity were perceived to be most impacted in higher GDP countries.
- The most effective restoration measures were related to reducing nutrient loading from both catchment and in-lake sources. Hydrological modifications and the implementation of nature-based solutions were also commonly used while measures for the control of non-native invasive species were rarely applied, or viewed as being ineffective. In low GDP countries species reintroduction, floodplain restoration, wetlands construction and habitat creation were widely used, while in high GDP countries catchment nutrient load reduction was most common.
- Ecology-based and/or pressure-related restoration targets had been set for many restoration programs (>60 %); however, the strength of evidence underpinning these targets was often "weak" or "unknown". Only 30 % of responses considered climate change adaptation within their target setting. Ecology-based targets, in particular, were less often reported for low GDP countries.
- Most respondents viewed stakeholder engagement as the most important factor in determining the success or failure of lake restoration programs, followed by knowledge and resources.
- Poor support across sectors, insufficient funding, poor policy support and weak governance, insufficient monitoring and poor understanding of pressures and their effects were most frequently cited as factors contributing to restoration failure.
- Our study noted some clear trends related to GDP per capita that may have remained hidden if the survey had been analysed using just regional factors. A "one size fits all" applied across countries of differing economic status and capacity is likely to be unsuccessful and a more nuanced approach is needed.
- Finally, novel and emerging pressures, alone and in combination with others, may require new approaches to lake restoration, both in setting restoration targets and devising restoration strategies. Collaboration will be needed to improve understanding of these novel pressures, their effects, restoration measures needed to manage them efficiently. The future of lake restoration depends on joined-up thinking that better integrates science into policy and practice and, most importantly, ensures strong and inclusive stakeholder engagement and collaboration across multiple sectors.

CRediT authorship contribution statement

Sandra Poikane: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Martyn G. Kelly:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Gary Free:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Laurence Carvalho:** Conceptualization, Writing – original draft, Writing – review & editing. **David P. Hamilton:** Conceptualization, Writing – original draft, Writing – review & editing. **Konstantina Katsanou:** Conceptualization, Writing – original draft, Writing – review & editing. **Miquel Lürling:** Conceptualization, Writing – original draft, Writing – review & editing. **Stuart Warner:** Conceptualization, Writing – original draft, Writing – review & editing. **Bryan M. Spears:** Conceptualization, Writing – original draft, Writing – review & editing. **Kenneth Irvine:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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Further reading

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