Reviews into evidence for sediment enrichment and lake restoration best practice for the Windermere catchment III: Implications and recommendations

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Contents

1. Introduction

This final report section draws together the findings from the two evidence reviews and identifies both broad implications and recommendations arising from the work.

2. Implications and Recommendations

2.1 Implications

Current evidence for sediment nutrient enrichment and internal phosphorus (P) loading across the major lakes of the Windermere catchment is incomplete. Considering the first two of the three lines of evidence that we investigated: 1) evidence for oxygen depletion, 2) evidence for sediment P enrichment, 3) evidence of internal loading, existing research using both contemporary measurements and palaeolimnological methods suggests that:

- historical and contemporary nutrient enrichment has occurred across all the lakes considered, and that

- all lakes undergo some level of deep-water oxygen depletion and, in many cases, anoxia.

Taken together, this evidence allows us to infer that *all lakes are <u>likely</u> to have nutrient enriched sediments and are <u>potentially</u> at risk from internal P loading*.

The confidence with which we can assess the overall importance of internal loading for lake P budgets is, however, severely diminished by a lack of direct evidence of sediment enrichment, which is either limited to only a few sites, or based on very old data. In addition, directly measured evidence of internal P loading is even more limited. This has been quantified at only one site, Esthwaite Water, whilst evidence for elevated P concentrations in hypolimnetic water relative to the surface has been found in a further four lakes, including Windermere. Once again, these data are largely historical, dating from the mid-2000s. There are no comparative data available to inform on current conditions.

Given current evidence, *we simply do not currently know how important internal P loading is for the P budget of these systems or the role it plays in fuelling phytoplankton growth in the lakes*. Given this lack of confidence, there is currently insufficient evidence to justify and design effective in-lake mitigation measures, and to commit significant investment to such works. Progressing such works at this stage could be misguided, if external (catchment) sources account for the majority of the overall nutrient budget of these sites.

Developing an integrated management plan to address eutrophication issues is an important part of the process of lake restoration. Lessons learned from the systematic review of in-lake measures identified five key elements that could be used to form the basis for this plan:

1. Clearly define the restoration goals and water quality targets for each lake in collaboration with the different stakeholder communities.
2. Carry out a thorough lake system characterisation, including a nutrient budget to quantify the importance of different nutrient sources, timings and pathways. Use pre-intervention monitoring to establish the baseline of conditions compared to the target values.
3. Where external loads dominate the nutrient budget, implement measures to minimise external loading of nutrients to each lake, prior to consideration of in-lake measures.
4. Where internal loading is identified as a significant component of the nutrient budget, use the lake system characterisation to inform the selection of the most appropriate option(s) using cost-benefit analysis and approaches developed as part of previous investigations into internal P control (see Brett and Pitt, 2013). In-lake measures must only be taken following a robust assessment of possible, though unintended, impacts upon the wider ecosystem such as sensitive species and habitats.
5. During and following the implementation of the chosen in-lake intervention(s) continue monitoring to: i) evaluate internal P control effectiveness and non-target effects of the measure(s), ii) ensure optimal treatment conditions and no adverse impacts on lake biota and iii) identify change in lake water conditions relative to the baseline and water quality targets. Monitoring data can also be used to inform adaptive management where implementation or operation of the measure(s) does not perform as anticipated, and to understand the consequences of weather events on the measure(s) and the likely resilience of measures in the future.

It is clear from this review that monitoring at temporal and spatial resolutions that capture lake and catchment dynamics of lake ecosystems where management and restoration is planned is a pre-requisite for the effective implementation of in-lake measures. Basing restoration planning decision making on contemporary regulatory data will be insufficient to provide the evidence required to fulfil the approach above. It is also important to note that the cost of gathering the evidence required to make informed decisions on what lake management measures are viable for an individual lake is likely to be only a fraction (£10,000s - £100,000s) of the cost associated with the implementation of measures (many £100,000s – £10,000,000s), depending on the lake, catchment, pressure, measures considered. Appropriate monitoring and system understanding may also avoid costly re-treatments or failure to attain restoration goals through the uninformed targeting of actions, saving money over the longer term.

2.2 Recommendations

Drawing together the evidence presented in the systematic reviews, we suggest the following approach and key recommendations for taking forward the work on the role of internal P cycling in the ongoing eutrophication of the Windermere lakes:

1. Create or review management plans for each lake to ensure restoration goals are clear and water quality targets are agreed among stakeholders.
2. Collate existing data and review existing monitoring programmes to inform lake system characterisation and identify evidence gaps that require attention for effective nutrient management at each site.
3. Based on the assessment carried out in the sediment enrichment review, there is a key gap in our understanding of the relative importance of internal vs external nutrient inputs to these lakes. Therefore, our key recommendation is *to enhance the monitoring activities currently under way by establishing nutrient mass balances to quantify the different components of the nutrient budget for each lake and its catchment, and to understand the relative importance of the different nutrient sources over time for water quality and algal blooms.*
4. We propose that a series of knowledge exchange events be established to learn from the experiences of catchment management groups from other lakes in the UK, where nutrient management programmes are being implemented or are under development (e.g. Loch Leven, Linlithgow Loch, Barton Broad, Lough Neagh), towards establishing best practice guidance on monitoring and assessment of nutrient loads in nutrient-sensitive lake catchments in the UK.

A comprehensive quantification of external and internal nutrient loads is essential to underpin the effective design and implementation of lake management programmes, for all lakes. Data required to estimate these loads are insufficient for the Cumbrian Lakes, generally, but have been collected and applied successfully to inform restoration programmes in other lakes in the UK. This would require regular monitoring of nutrient concentrations and water discharge across major inflows and outflows (the product of which provides an estimate of nutrient load) as well as nutrient fluxes through the water column to and from bed sediments, and to downstream sites to be quantified. This would allow identification of the major sources of nutrients to be targeted through management, both in the catchment and in lake bed sediments. This work would underpin a 'systems analysis' approach, as advocated by lake restoration researchers and practitioners across the world. Two recent examples of the successful implementation of such assessments in UK settings are provided below. The first, for Loch Leven in Scotland, includes roughly ten-yearly, annual nutrient budget studies at weekly sampling frequency that have been conducted since the 1980s, and used to successfully target restoration efforts. The second, for Barton Broad in Norfolk, details the implementation of successive management measures alongside continuous monitoring of inflows, outflows and in-lake to improve water quality at the site.

Loch Leven: Using repeated lake P budgets to inform evidence-based restoration and adaptive management

Site: *large, 13.7km^2 surface area, shallow, 4.5m average depth, eutrophic lake in lowland Scotland. Catchment area 159 km^2, composed of improved grassland (35%), arable and horticulture (27%) and more natural habitats.*

Issues: *History of eutrophication and water level management for industry. Catchment P inputs increased from around 5 tonnes per year in early 1900s to 20 tonnes per year by 1985. High nutrient loading resulted in large algal blooms on the lake and prompted action to reduce external nutrient loads.*

P budgets to inform adaptative management: *Since 1985, every 10 years, a P budget for the lake is calculated based on intensive monitoring of catchment inflows, approximately every eight days for one year. The data from the P budget were used to inform management actions to reduce the external P load to the lake. Industrial point sources of P were targeted from 1976 to 1986, waste water treatment works were upgraded from 1987 to 1999 and farmers were encouraged to change management practices and reduce fertilizer applications. As a result of these actions, winter and spring TP concentrations decreased by around 75% and 60% compared to pre-management levels and following upgrades to the treatment works, spring concentrations decreased by a further 50%. However, summer TP concentrations remained high, and the seasonal TP pattern is indicative of a switch from external to internal P load dominance in the P budget.*

Sources: UK Lakes Portal: https://eip.ceh.ac.uk/apps/lakes/, Loch Leven Portal: https://eip.ceh.ac.uk/apps/loch-leven., Sharpley et al. (2013).

Barton Broad: Quantifying the impact of restoration measures over time

Site: *Small, surface area 0.7 km^2, shallow, average depth 1.3 m, lake in the Norfolk Broads National Park. Catchment area 109.5 km^2, composed of arable and horticulture (67%), improved grassland (12%) and other land covers. The lake is a SSSI site, and a SAC, as a national nature reserve and RAMSAR site.*

Issues: *Monitoring carried out during the 1970s identified nutrient enrichment as the major driver of water quality and ecological decline in the lake. The main source was the external load, particularly from the waste water treatment works upstream of the lake. Catchment loads were estimated to be 26.8 mg P m^{-2} d^{-1} which resulted in frequent algal blooms and low water clarity.*

Application of inflow-lake-outflow monitoring to identify source dynamics and target catchment-lake restoration and management: *Catchment P concentrations from the main inflow, in-lake and outflow were monitored on a fortnightly to monthly basis between 1978 and 2015. Combined with data on flow, the catchment P load to the lake was estimated and evaluated over time as gradual reductions to point P inputs were carried out during the late 1970s and early 1980s. Annual catchment P load reduced by over 50% during this time period, with additional treatment works upgrades and industrial P source removal in the 1990s resulting in the catchment load reaching 5.5 mg P m^{-2} d^{-1} by 2015. During the 1990s an investigation of sediment P release identified the potential for a substantial internal P source, so a combination of grab and suction dredging was used across 80% of the lake surface area in an effort to reduce P content of sediments and re-expose buried aquatic macrophyte propagules. Despite a reduction in sediment P content, internal loading continues in the lake, at a lower rate, and the lake has a small net export of P annually. The annual mean TP concentration in the lake is however, still mostly dependent on the catchment load.*

Source: Phillips et al. (2020).

Nutrient budget considerations

Delivery of the nutrient budget work would ideally require frequent in-person visits to field sites for sample collection, and then subsequent sample analysis in professional laboratories, followed by data interpretation. This would necessarily require investment to cover the staffing and laboratory costs of such work, but examples from Steinmann and Spears (2020), including Loch Leven, Barton Broad and Esthwaite Water, show that such an approach can provide important insights into processes occurring within the lake and be highly effective at guiding evidence-based management, providing an excellent return on that investment. For example, load estimates for Loch Leven are likely to cost ~£150k for the next survey (L. May pers. com.)

Sampling frequency would be a key consideration prior to undertaking such sampling, given that external nutrient delivery to lakes can be episodic in nature (e.g. following weather events). Decisions around sampling frequency could, however, be informed by previous studies that have sought to quantify how varying collection routines affect statistical power and the accuracy of loading estimates (Johnes, 2007; Cassidy and Jordan, 2011; Defew et al. 2013; Torres et al. 2022). For example, Figure 2.1 from Jordan and Cassidy, (2011) provides an assessment of how sampling frequency influences load estimation based on the disaggregation of a very high frequency (20 minute) dataset. It demonstrates that low frequency (e.g. monthly) monitoring underestimates the true load and are highly uncertain. This work has proved informative in the recent re-design of the nutrient budget studies for Lough Neagh, where samples collected every seven hours (n=24 per week) using refrigerated auto-samplers have been recommended to best capture high flow events, whilst minimising sampling costs (P. Jordan, pers com.).

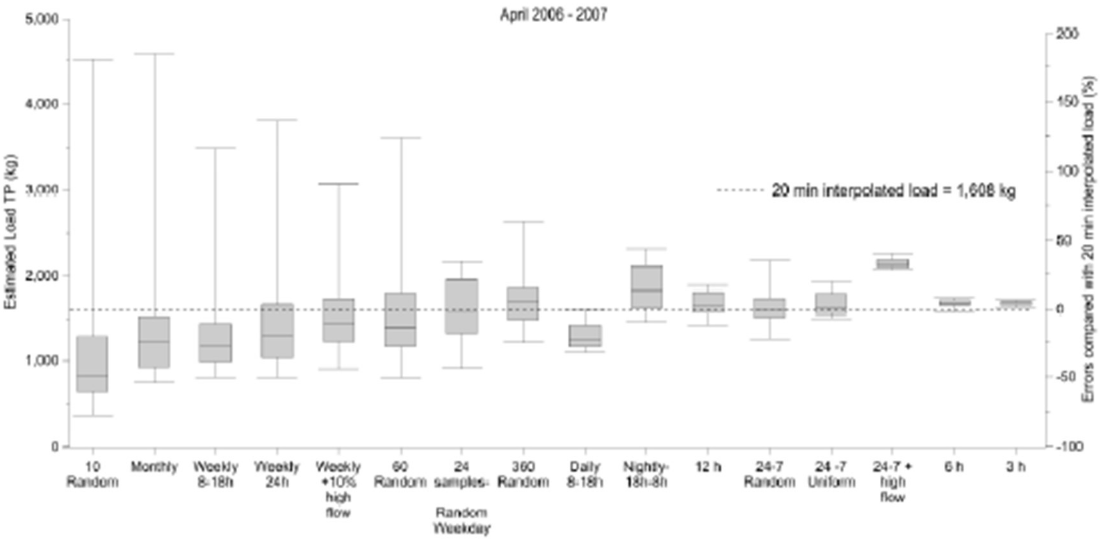

Figure 2.1. Boxplots showing how TP load estimates change depending on the frequency of sampling, relative to the best estimate (dashed line). From Jordan and Cassidy (2011).

Other sampling options may be considered when designing the nutrient budget campaign, however. Specifically, the deployment of nutrient sensors could potentially deliver data at a temporal frequency that would capture the highly dynamic nature of nutrient delivery. Such an approach could provide insights into catchment nutrient delivery processes that are not possible using conventional manual sampling. However, it would require a large capital investment in equipment and still require trained personnel to visit sites on a regular basis. Sufficient resources for in-person visits are essential to maintain, calibrate, repair and replace sensors, to ensure sustained, decision-grade data delivery. In addition, the measurement of TP concentrations is currently only possible via relatively large bankside deployments, requiring sufficient infrastructure and power to operate. A typical system would cost in the region of ~65k to purchase, with reagent costs ~£1.2k per year and maintenance ~£4k per year (M. Bowes, pers com.). A structured citizen science approach to collecting samples may also offer opportunities, in the light of the committed volunteer base that has been mobilised by the Big Windermere Survey, and more localised initiatives. However, the need for relatively frequent sample collection across multiple sites and the current low accuracy of cheap nutrient sensors, which also lack the ability to provide a TP measurement, mean that laboratory analysis of samples and sufficient staff resource in the role of scheme coordinator would still be required and should not be underestimated. In addition, in both cases, data analysis and interpretation by a trained professionals would remain an essential component of the work.

Given all of this, it may be possible to blend monitoring approaches (*in situ* professional sampling, sensor deployment, citizen science) to deliver the data required. As such, as a follow up action to this report, a detailed monitoring programme (including data management considerations) could be developed, that would combine the strengths, and manage the potential risks, associated with each data collection method.

The development of a plan for a nutrient budget must consider the key primary objective(s) of the work, such as the need to quantify all external nutrient loads and internal nutrient release in the Windermere lakes and the costs associated with delivering data that can answer these objectives. This will require new investment in data collection and interpretation beyond current monitoring activities. However, understanding where there may be synergies between existing monitoring activity and the new data needs for the nutrient budget work could offer opportunities to make the best use of existing resources and provide a long-term investment in improving monitoring capacity across the catchment. This will ultimately provide key understanding of lake and catchment processes that can inform the catchment management plan for Windermere.

Proposed timeline of action

- 0 – 3 months – **R1** Create or review management plans for each lake. **R4** engage with wider lake catchment management groups from the UK. UKILN Conference in October 2024 could be a good opportunity to discuss nutrient management issues with other groups dealing with similar issues.
- 3 – 6 months – **R2** Collate existing data and review existing monitoring programmes for system characterisation and evidence gaps. Develop costed options for nutrient budget work.
- 6 – 24 months – **R3** Carry out nutrient budget data collection and analysis. Identify sites dominant nutrient sources for each lake and use the information to update management plan and actions for mitigation.

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