Reviews into evidence for sediment enrichment and lake restoration best practice for the Windermere catchment I: sediment enrichment review

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Contents

1. Glossary of key terms

Alkali-Extractable Phosphorus (AEP) = Alkali-extractable phosphorus or AEP is considered the release-sensitive phosphorus or mobile phosphorus fraction in sediments. It is comprised of labile, reductant-sensitive, and organic phosphorus. AEP refers to the alkali extraction reagent used to determine its concentration in sediments.

Anoxia or anoxic = the complete absence of oxygen. In terms of this report, anoxia is the complete absence of dissolved oxygen (DO) in the lake water or where concentrations of DO = 0 mg l^{-1}.

Dissolved oxygen (DO) = The oxygen which is dissolved in water. It can be measured as the concentration per litre of water or the percent saturation. The latter is the relative measure of DO in the water compared to the maximum amount of DO that can be held in water at a given temperature or pressure, expressed as a %.

Epilimnion = The surface mixed layer or the top layer of a waterbody in a thermally stratified lake. It is typically warmer than the hypolimnion.

Eutrophication = The process whereby a waterbody becomes enriched with nutrients, notably nitrogen and phosphorus, increasing algal growth, which leads to water quality and ecological issues. Increased algal biomass can cause the water to become turbid and as the algae respire or are decomposed on death, oxygen is consumed, which can lead to hypoxic and anoxic conditions detrimental to aerobic organisms.

Eutrophic = A lake with high concentrations of nitrogen and phosphorus, with high levels of primary productivity, usually algal growth. The Water Framework Directive classifies lakes as eutrophic when annual mean total phosphorus concentrations are 35 µg l^{-1} for deep lakes (>15m) and 50 µg l^{-1} for very shallow lakes (<3m) (JNCC,2015).

Hypolimnion = The bottom layer or deep waters of a waterbody in a thermally stratified lake. It is typically cooler than the epilimnion.

Hypoxia = low oxygen conditions or where concentrations of DO are less than = 2 mg l^{-1}. Hypoxia can be detrimental for aerobic organisms such as fish and can lead to mortality if conditions are sustained.

Internal loading = A process where nutrients are re-introduced from lake sediments back into the water column. Phosphorus is a key nutrient that can be internally released but other nutrients, compounds and metals including ammonia and mercury can also be released and cause water quality issues. It often occurs in stratified lakes, as the reduction in DO at depth during the stratified period promotes biogeochemical changes at the sediment-water interface, including the release of iron-bound phosphorus in the sediments back into the water column. It can cause delays in the recovery of lakes which have undergone eutrophication.

Mesotrophic = A lake with an intermediate concentration of nutrients and primary productivity. The Water Framework Directive classifies lakes as mesotrophic when annual mean total phosphorus concentrations are 15 µg l^{-1} for deep lakes (>15m) and 20 µg l^{-1} for very shallow lakes (<3m) (JNCC,2015).

Metalimnion = Another term for the thermocline, the region in a lake where there is a large temperature and density gradient between the surface, epilimnion and bottom, hypolimion waters.

Mixing of the water column or overturn = Heat loss from a lake, due to a reduction in heating and/ or increases in turbulent energy from wind, for example, leads to a cooling of the surface layers of water. They become denser and sink, and therefore, mixing with the deeper cooler layers. This can result in the breakdown of thermal stratification and a reduction in gradient of temperature/ density change with depth. At overturn, the lake mixes fully from the surface to the bottom. Other mixing events, which only partially mix the water column can occur in response to storm events. Mixing can result in bottom waters becoming replenished with DO from the surface layers and mix upwards nutrients which have accumulated in the hypolimnion during stratification to surface waters. Lakes can be categorised according to their propensity to stratify and mix at an annual level. Lakes which undergo one seasonal mixing event per year are called monomictic. Lakes which undergo two seasonal mixing events are called dimictic (usually lakes which experience ice cover in winter) and lakes which mix frequently and do not become seasonally stratified are called polymictic (tend to be shallower and wind exposed).

Oligotrophic = A lake with low algal productivity and a low concentration of nutrients. Often rich in aerobic species and have clear water. The Water Framework Directive classifies lakes as oligotrophic when annual mean total phosphorus concentrations are 10 µg l^{-1} for lakes of all depths (JNCC,2015).

Redox-sensitive = Redox is a chemical reaction which involves a change in state of the reactants through oxidation and reduction. Oxidation of a reactant occurs when a substance loses an electron and reduction is when a substance gains an electron.

Soluble Reactive Phosphorus = A dissolved inorganic form of phosphorus which can pass through a filter and is the fraction of phosphorus that can be readily utilised by plants and algae.

Thermal Stratification or Stratification = The separation of a waterbody into distinct layers by a gradient of density change with depth. Usually develops as the lake warms during the spring, the epilimnion or surface water warms by absorbing heat and are therefore less dense than the water below it. This sets up a density gradient where three distinct ‘layers’ of water are usually defined: 1) The surface mixed layer or epilimnion receives most heating from the sun, creating a water layer with a similar temperature and density, 2) the cool, dense bottom waters or hypolimnion, which is relatively similar in temperature and density and 3) the region of rapid change in temperature and density known as the thermocline. The depths of these layers are highly dynamic over a variety of timescales from hours to seasons. Lake cooling during autumn/ winter usually results in a loss of the density structure and the lake overturns and is fully mixed from the surface to the bottom. Stratification reduces mixing between the lake layers which can result in gradients of light and chemicals. The reduction of mixing also affects phytoplankton that cannot regulate their buoyancy, resulting in them sinking out of the surface community. Under stratified conditions, the vertical movement of DO is supressed. Conditions in the hypolimnion can become hypoxic or anoxic particularly if the respiration of organic matter (such as algal material which has sunk) is high. The length and stability of stratification is dependent on the lake basin shape and seasonal weather patterns.

Thermocline = The layer of greatest temperature change with depth in a waterbody.

Total Phosphorus = The measure of all phosphorus in a sample, including dissolved and particulate fractions.

2. Introduction

Like many lakes and fresh waters across the globe, the lowland lakes in the Windermere catchment, English Lake District, UK, have undergone eutrophication to various extents over the past century related to agricultural and wastewater inputs (Moorhouse et al., 2018). However, understanding of the role of internal P loading in these systems has received relatively little attention to date. We currently lack a synthesis of the evidence and assessment of how internal nutrient loads may be affecting the water quality of these iconic lakes. To address this gap in our understanding, this study collates existing information on indicators for internal loading potential. These are 1) the occurrence of stratification and hypolimnetic anoxia, 2) evidence of surface sediment P enrichment and 3) evidence or quantification of internal P loading across the eight larger lakes of the Windermere catchment. By synthesising this evidence, our goal is to enable the identification of potential internal loading issues in these lakes, and the most pressing evidence gaps that currently limit our understanding of the likely importance of internal loading in contributing to sustained water quality issues.

Phosphorus (P) is a key limiting nutrient for phytoplankton growth in fresh waters (Schindler et al., 2008) and as such, water column concentrations of P are often used to determine a lake's trophic status. It is widely accepted that in the last century, anthropogenic activity has increased P loading into freshwaters, through agricultural intensification and wastewater disposal (e.g. Jarvie et al., 2006). A proportion of these catchment sources, known as external inputs to lake ecosystems, can be retained in lake sediments, forming a legacy store that can prolong ecosystem recovery or be permanently buried. Sediment P consists of stable or loosely particulate-bound fractions, including those associated with iron, aluminium, or manganese, or in organic forms following biological uptake and decomposition (Boström et al., 1988; Reynolds and Davies, 2008). Following deposition of P into the sediments, some fractions of P can be recycled back into the water column, a process known as internal loading (Boström et al., 1988). Internal nutrient loading has been found to reduce and delay eutrophication recovery in many lakes which have undergone remediation of external nutrient sources (e.g. Jeppesen et al., 2005).

Internal P release from lake sediments is variable, depending upon the history of nutrient inputs to a lake, sediment binding capacity for P, the potential for physical disturbance of sediment, and changing biogeochemical conditions at the sediment-water interface. Enhanced sediment P release in stratifying lakes is frequently associated with hypolimnetic oxygen depletion, water column anoxia and changes to the redox potential at the sediment-water interface. In other words, as algal organic matter is respired, oxygen becomes depleted, leading to hypoxia (low dissolved oxygen (DO) conditions) and anoxia (minimal to no DO) in bottom waters (hypolimnion) particularly those which are strongly stratified (Smith and Schindler, 2009).

This feedback loop between eutrophication, hypolimnetic anoxia and the release of P back into the water column is often associated with P bound to Iron (Fe)(III) complexes. Fe(III) is reduced to Fe(II) under low redox potential, following the loss of deep water oxygen (Mortimer 1941) and the progressive change in the terminal electron acceptor along the redox series: nitrate reduction, manganese reduction, iron reduction. This process has been well-documented in many lakes.

Contemporary studies investigate the total and mobile fractions of P in sediments to determine internal loading potential more precisely. For instance, the alkali-extractable phosphorus (AEP) fraction is commonly used as to determine the "mobile phosphorus" fraction, comprising labile, reductant-soluble, and organic P (Anderson, 2018). The sum of these fractions is considered to represent the release-sensitive P pool (Boström et al., 1982; Søndergaard et al., 2003). Following P deposition in the sediments, numerous biological and chemical processes will over time determine the fraction of P that is permanently buried in the sediments and the fraction of P available for release back into the water column via interstitial water (Søndergaard et al., 2001). In addition, the concentration of Fe in the lake is also important, with evidence indicating lakes with high iron concentrations are at a lower risk of P recycling, as P coprecipitates with ferric hydroxide when oxygen concentrations are high and are then deposited in the sediment (Smith and Schindler, 2009).

Many studies have examined and attempted to identify the different mechanisms that can result in internal loading. There are several biological (e.g., bacterial metabolism, macrophyte production), chemical (e.g., Fe:P ratios) and physical (e.g., wind-induced sediment resuspension) processes which can modify the release of P from sediments into the water column (Søndergaard et al., 2001). For instance, elevated pH from photosynthesis can lead to the release of P particularly in littoral areas where aquatic plants are abundant, whilst sediment redox changes from anoxia or changing oxygen conditions in the hypolimnion can lead to the release of sediment-bound P into the water column (Søndergaard et al., 2001).

Different characteristics of lake types can lead to a dominance of certain P processes. For instance, shallow lakes are particularly susceptible to internal nutrient loading driven by the high sediment surface to water column ratio, proximity to the photic zone despite often oxic conditions and wind-induced turbulence delivering unbound P directly to the photic zone (Søndergaard et al., 2003). Deep lakes exhibit stronger stratification and P accumulation in the anoxic hypolimnion from the suitable redox conditions at the sediment-water interface (Søndergaard et al., 2003). Eutrophication increases the risk of internal nutrient loading. Stratified eutrophic lakes which develop anoxic hypolimnions in the summer and have elevated pH levels from primary production have been found to undergo considerable redox-dependent release of iron-bound P (Søndergaard et al., 2001). Findings also indicate that eutrophic lakes typically have higher concentrations of P in superficial sediments compared to deeper layers meaning a greater risk of recycling of P back into the water column. Mesotrophic lakes tend to have more consistent P concentrations with increasing sediment depth and are therefore more susceptible to the effects of external loading compared to oligotrophic lakes, as they are at their maximal sediment P burial flux (Carey and Rydin, 2011). In other words, mesotrophic lakes will already have sediment saturated with P, so any more additions of P could lead to an oversaturation of P sediment stores, making them less able to permanently bury or store P, increasing the risk of internal P loading. Oligotrophic lakes will have sediment P concentrations below saturation level, and therefore have a greater capacity to store more P.

To ensure successful nutrient remediation of lake ecosystems, we must identify the relative contribution of sources (Kowalczewska-Madura et al., 2022). Ultimately, reducing external nutrient loading remains the most effective strategy but consideration into how internal nutrient loading may delay restoration is also key (Janssen et al., 2019). If external nutrient loads remain low, internal nutrient loading will become gradually less important as sediments release the nutrients and fractions become biologically incorporated, flushed, or permanently buried (Jeppesen et al., 2007). Therefore, to ensure successful internal nutrient remediation, the external sources need to be managed before any in-lake remediation is considered.

3. Methodology

3.1 Study sites – Windermere catchment lakes

The Windermere catchment is situated in the Lake District National Park, a UNESCO heritage site in northwest England, United Kingdom. This catchment consists of 11 upland and lowland lakes which feed into Windermere, England's largest and longest lake (Moorhouse et al., 2018). Table 1. details the characteristics of the eight lowland lakes of the catchment (<100 metres above ordnance datum (m.A.O.D.)). For the purposes of this study, Windermere is considered as two basins: the North and South Basins, which are the focus of this study. Whilst the South Basin was historically eutrophic, both basins are now considered mesotrophic (Mackay et al., 2023). There are two distinct geological areas within the Windermere catchment; the Borrowdale Volcanic Group (BVG) to the north and the Silurian Coniston Flags and Slates (SIL) to the south, where the easily weathered bedrock of the SIL geology has resulted in overlying surface waters having a higher number of ions or electrolytes ("charged solutes") such as chloride, potassium and sulphate in their waters meaning they have a higher buffering capacity or ability to neutralise acid (Sutcliffe et al., 1982). In most of the lowland lakes, algal growth is P limited (Maberly et al., 2002). However, agricultural intensification, and treated and untreated sewage effluent from mains and non-mains wastewater systems has led to P enrichment and the eutrophication of most of the lowland lakes in the catchment (Moorhouse et al., 2018). More recently, the cultural significance of Windermere has meant that the water quality or "health" of these iconic fresh waters have garnered more scrutiny from campaign groups and the media with much focus on the external sources of nutrients, and a growing interest in the role of internal nutrient loading.

The lakes of the Windermere catchment have been studied for decades, with the Freshwater Biological Association initiating the long-term monitoring programme in the 1940s which has been continued by UK Centre for Ecology & Hydrology (UKCEH) since the 1980s. The wealth of research and monitoring of this group of lakes has, and will continue to be, imperative in ensuring that any mitigation approaches adopted are evidence-based. As such, to identify and assess the current state of evidence into the internal P loading potential within the lowland lakes of the Windermere catchment, a rapid literature review was conducted.

Table 1. The characteristics of the study lakes and their catchments. Data taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023 and Moorhouse et al., (2018).

Lake	Grid reference	Surface area (km^2)	Mean depth (m)	Max. depth (m)	Catchment area (km^2)	Elevation (m. A.O.D.)	Mean residence time (days)	Geology typology	Mean catchment elevation (m)
Blelham Tarn	NY36600048	0.11	6.8	14.5	4.25	47	50	Moderate alkalinity	105.41
Elterwater	NY33370413	0.18	3	7.5	51.3	53	106 – inner 26- middle 20 - outer	Moderate alkalinity	308.47
Esthwaite Water	SD36039642	0.96	6.4	15.5	17.01	65	100	Moderate alkalinity	148.17
Grasmere	NY33850651	0.61	7.7	21.5	28.73	61	25	Low alkalinity	314.63
Loughrigg Tarn	NY34450436	0.07	4.6	10.3	0.95	97	117	Moderate alkalinity	174.86
Rydal Water	NY35660613	0.3	5.3	17	32.38	53	9	Low alkalinity	299.03
Windermere North Basin	SD39229584	8.05	25.1	64	248.77	40	180	Moderate alkalinity	229.32
Windermere South Basin	SD39229584	6.72	16.7	42	248.77	40	100	Moderate alkalinity	229.32

3.2 Web of Science and Google Scholar search terms

To undertake a rapid evidence review, regulatory agency and research staff working in the Windermere catchment agreed several search terms which would return publications suitable to answer the following question: *“What is the evidence for sediment phosphorus enrichment or internal phosphorus loading in the eight lakes of the Windermere catchment?”*

The eight lakes of interest are Blelham Tarn, Elterwater, Esthwaite Water, Grasmere, Loughrigg Tarn, Rydal Water, and Windermere, North and South Basins.

The agreed search terms were selected to address the What, Where and When of our research question:

What: sediment phosphorus OR internal loading OR internal phosphorus loading OR internal phosphorus recycling OR internal phosphorus release OR nutrient enrichment.

Where: Blelham Tarn OR Elterwater OR Esthwaite Water OR Grasmere OR Loughrigg Tarn OR Rydal Water OR Windermere OR Leven catchment.

When: 1980 - 2023. Despite earlier reports (i.e. prior to the 1980s) on the condition of the Windermere lakes, this timeframe was selected in an attempt to keep the reports as relevant to the cultural eutrophication issues the catchment faces in the present, with many reports before this time focussed on describing the ecology and glacial history of these lakes. In a pragmatic sense, it also constrained the number of reports to fully review in the short timeframe of this assessment.

These search terms were entered into Web of Science (WoS) on 05/02/2024, returning the following results:

- sediment phosphorus OR internal loading OR internal phosphorus loading OR internal phosphorus recycling OR internal phosphorus release OR nutrient enrichment) AND 1980 – 2023 = returned 534 records.
- Blelham Tarn OR Elterwater OR Esthwaite Water OR Grasmere OR Loughrigg Tarn OR Rydal Water OR Windermere OR Leven catchment) AND 1980 – 2023 = returned 5615 records.
- A final search using all the What, Where, and When terms detailed above = returned 47 publications.

This provides an insight into the wealth of research undertaken on the Windermere catchment, and that the study of internal loading specifically remains relatively limited in comparison.

The titles and abstracts of the 47 returned publications were then checked for relevance. Specifically, if references to one of the above search terms in both the What and Where categories were made, this title was kept for further review. The first filter of the title left 29 publications for further review. The second filter through the abstracts returned 9 publications of relevance. The search terms were then entered into Google Scholar on 05/02/2024, returning 22 records. Any duplicates to the WoS search were removed and titles and abstracts were checked for relevance using the same protocol as for the WoS records. This left 1 additional publication relevant for review. Table 2. below shows in further detail how references were filtered noting the criterion met and any missing key search terms. Those publications in the Table with a * before the citation indicate missing search terms such as "internal nutrient loading", "internal phosphorus loading", therefore these references may not be as likely to contain relevant information but should still be reviewed for any additional evidence.

Table 2. The citations returned from Web of Science and Google Scholar searches for review with detail of search terms in citation and any missing search terms.

Lake	Total no. of publications retrieved	Citations of retrieved publications	Reasons for meeting abstract selection criteria – key words in abstract	Search terms missing
North and South Basin of Windermere	2	*Fielding, J. J., Croudace, I. W., Kemp, A. E., Pearce, R. B., Cotterill, C. J., Langdon, P., & Avery, R. (2020). Tracing lake pollution, eutrophication and partial recovery from the sediments of Windermere, UK, using geochemistry and sediment microfabrics. *Science of The Total Environment*, *722*, 137745.	"North and South Basins of Windermere", "eutrophication" "sediment anoxia"	"Phosphorus", "internal phosphorus loading"
		*Heaney, S. I., Parker, J. E., Butterwick, C., & Clarke, K. J. (1996). Interannual variability of algal populations and their influence on lake metabolism. *Freshwater Biology*, *35*(3), 561-577.	"North and South Basins of Windermere"," total phosphorus loading"	"internal phosphorus loading"
Esthwaite Water	5	Drake, J. C., & Heaney, S. I. (1987). Occurrence of phosphorus and its potential remohilization in the littoral sediments of a productive English	"Esthwaite Water", "Phosphorus release from littoral sediments",	

Lake	Total no. of publications retrieved	Citations of retrieved publications	Reasons for meeting abstract selection criteria – key words in abstract	Search terms missing
		lake. *Freshwater Biology*, *17*(3), 513-523.	"sediment", "phosphorus"	
		*Stockdale, A., Davison, W., & Zhang, H. (2008). High-resolution two-dimensional quantitative analysis of phosphorus, vanadium and arsenic, and qualitative analysis of sulfide, in a freshwater sediment. *Environmental Chemistry*, *5*(2), 143-149.	"Esthwaite Water", "Phosphate", "sediment core"	"internal phosphorus loading"
		Mackay, E. B., Jones, I. D., Folkard, A. M., & Barker, P. (2012). Contribution of sediment focussing to heterogeneity of organic carbon and phosphorus burial in small lakes. *Freshwater Biology*, *57*(2), 290-304.	"Esthwaite Water", "internal phosphorus loading", "phosphorus", "sediments"	
		*George, D. G. (2000). Remote sensing evidence for the episodic transport of phosphorus from the littoral zone of a thermally stratified lake. *Freshwater Biology*, *43*(4), 571-578.	"Esthwaite Water", "phosphorus"	"internal phosphorus loading"
		Mackay, E. B., Folkard, A. M., & Jones, I. D. (2014). Interannual variations in atmospheric forcing determine trajectories of hypolimnetic soluble reactive phosphorus supply in a eutrophic lake. *Freshwater Biology*, *59*(8), 1646-1658.	"Esthwaite Water", "phosphorus", "internal loading"	
Elterwater	3	Olsson, F., Mackay, E. B., Barker, P., Davies, S., Hall, R., Spears, B., ... & Jones, I. D. (2022). Can reductions in water residence time be used to	"Elterwater", "internal loading", "phosphorus", "internal P loading	

Lake	Total no. of publications retrieved	Citations of retrieved publications	Reasons for meeting abstract selection criteria – key words in abstract	Search terms missing
		disrupt seasonal stratification and control internal loading in a eutrophic monomictic lake?. *Journal of Environmental Management, 304*, 114169.		
		Olsson, F., Mackay, E. B., Moore, T., Barker, P., Davies, S., Hall, R., ... & Jones, I. D. (2022). Annual water residence time effects on thermal structure: A potential lake restoration measure?. *Journal of environmental management*, *314*, 115082.	"Elterwater", "internal loading", "phosphorus", "internal nutrient loading"	
		*Zinger-Gize, I., Hartland, A., Saxby-Rouen, K. J., & Beattie, L. (1999). Protecting the oligotrophic lakes of the English Lake District. In *The Ecological Bases for Lake and Reservoir Management: Proceedings of the Ecological Bases for Management of Lakes and Reservoirs Symposium, held 19–22 March 1996, Leicester, United Kingdom* (pp. 265-280). Springer Netherlands.	"Elterwater", "nutrient enrichment"	"internal phosphorus loading", "internal nutrient loading", "phosphorus"

3.3 NORA and Library archive searches

To access reports or other published work that might not be accessible on the global search platforms of WoS and Google Scholar, we searched for records from the NERC Open Research Archive (NORA) (https://nora.nerc.ac.uk/), an institutional repository for publications and reports conducted by NERC research centres including UKCEH. We decided only to use the **Where** category of search terms (i.e. Blelham Tarn OR Elterwater OR Esthwaite Water OR Grasmere OR Loughrigg Tarn OR Rydal Water OR Windermere OR Leven catchment) to capture as many reports as possible. We ran the same search in the UKCEH Library Archive. No records were returned from Loughrigg Tarn, Rydal Water or the Leven catchment. As the returned records for these searches were title only, we broadened the filtering of the title to reduce the risk of missing any relevant evidence. We therefore included the following **What** terms to the title filter:

What: water quality OR state OR condition OR phosphorus OR phosphate OR sediment OR restoration.

We then requested access to the publications whose titles matched these terms. Both searches and requests of these two archives were conducted on the 21/02/2024.

3.4 PhD theses

During initial workshops, three relevant UKCEH student theses were noted as containing relevant work for this review and consequently retrieved. These were:

Anderson, A. M. (2018). *Lake remediation by top-down and bottom-up management: An ecosystem-scale experiment in the English Lake District*. Lancaster University (United Kingdom).

Gray, E. (2019). *Meteorological and climatic impacts on the phytoplankton community of a small meso-eutrophic lake*. Lancaster University (United Kingdom).

Olsson, F. (2021). *Impacts of water residence time on lake thermal structure: Implications for management and climate change*. Lancaster University (United Kingdom).

3.5 The rapid review

The publications from the web platform searches, NORA and library archive searches plus PhD theses were then reviewed. This involved the extraction of data or supporting text which provided evidence of three key characteristics used to assess a lake's susceptibility to nutrient loading. Ordered by ascending strength of evidence, these are:

- Evidence of anoxia or depletion of oxygen in the hypolimnion (and therefore the potential for P release).
- Evidence for enrichment of the P concentration of lake sediments, where ideally, details on the concentrations of different fractions of P (i.e. mobile and non-mobile) were measured thereby allowing for greater precision in determining the probability of internal loading.

- Direct evidence of internal loading. For example, this may have been quantified as part of a lake's P budget or modelled using apportionment tools, supported by monitoring data.

Extracting information in this systematic way, enabled an assessment of confidence or assurance in the information obtained and is detailed as part of the review.

3.6 Additional evidence

Further supporting evidence was obtained from the most recent iteration of UKCEH's Lakes Tour in 2021 (Mackay et al., 2023). Temperature-oxygen depth profiles for each season had been collected for many lakes in the Windermere catchment including the eight lowland lakes of interest in this study. These temperature-oxygen depth profiles enabled the comparison of seasonal response across multiple basins, thereby helping to identify which basins in the catchment already experience anoxia and to what extent. Spring data were collected in early April 2021, summer data in July 2021, autumn data in November 2021 and winter data in either February 2021 or 2022. The exact dates for each lake are provided in the profile figure legends.

In addition, historic (1985-2008) temperature-oxygen, total phosphorus (TP) and soluble reactive phosphorus (SRP) depth profiles from Esthwaite Water, and the North and South Basins of Windermere were also obtained, collected as part of the UKCEH long-term lakes monitoring programme. These datasets enabled interannual comparisons of vertical nutrient profiles and anoxia for the three basins.

4. Evidence for phosphorus enrichment of sediment or internal P loading across eight lakes in the Windermere catchment.

4.1 Results of rapid evidence review

The North and South Basins of Windermere returned the most records, followed by Esthwaite Water, with the three lakes Grasmere, Elterwater and Blelham Tarn returning <10 relevant records each (Table 3.). Loughrigg Tarn, Rydal Water and Leven catchment returned no records across all the searches. This highlights a bias in the amount of information available on each of the lakes. However, the relevance of the publications is also important to assess and will be briefly described within the individual lake chapters below.

Table 3.. Numbers of records returned, and selected for further review, from Web of Science, Google Scholar, the NERC Open Research Archive, and UKCEH Library Archive.

Lake	No. of records retrieved from WoS	No. of records selected for further review	No. of records retrieved from Google Scholar	No. of records selected for further review	No. of records retrieved from NORA	No. of records selected for further review	No. of records retrieved from UKCEH Library Archive	No. of records selected for further review	No. of records where copies not available	No. of UKCEH PhD Theses	Total no. of records for lake
Elterwater	3	3	0	0	1	1	3	3	1	**1**	**7**
Esthwaite Water	11	5	2	0	9	1	39	16	2	**1**	**21**
Grasmere	2	0	0	0	6	6	26	6	3		**9**
North and South Basin of Windermere	7	2	2	1	62	8	252	29	6		**34**
Blelham Tarn	3	1	0	0	3	1	26	5	2	**1**	**6**

4.2 Blelham Tarn

Figure 3.1. Satellite map of Blelham Tarn taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Blelham Tarn is a small, eutrophic lake whose catchment is comprised of improved and unimproved pasture, and whose main inflow; Ford Wood Beck receives the outflow of a small Wastewater Treatment Works (WwTW) from the hamlet of Outgate (Fig. 3.1) (Moorhouse, 2016). It is fringed by the Blelham Bog National Nature Reserve, designated for its wet woodland and rare moss species (Natural England, 2023), which also forms part of a SSSI designation which includes the Tarn itself (Natural England, 2023). The SSSI is in unfavourable condition due to elevated P concentrations and depletion of oxygen at depth in the summer months.

4.2.1 Oxygen conditions

Hypolimnetic anoxia has been recorded in studies at Blelham Tarn since the late 1970s (Reynolds, 1996a). A study by Foley et al. (2012) was not returned by the search terms of this rapid review, however, the publications which were returned reference its work on hypolimnetic anoxia at Blelham Tarn. Using oxygen depth profiles from 1968-2008, Foley et al., (2012) found that across the study period hypolimnetic anoxia began 28±7 days earlier in the more recent data than historically, thereby increasing the longevity of anoxia over time to 82±13 days per year. This resulted in an increase in the proportion or area of the hypolimnion with anoxia by 16%. The variation of anoxia over this period did vary considerably from 27 to 168 days. Studies on Blelham tarn and elsewhere identified the importance of variables such as wind speed in impacting oxygen depletion processes through mixing, which can lead to interannual variation in lake thermal stratification and therefore, the development and duration of hypolimnetic anoxia (Foley et al., 2012).

The Lakes Tour 2021 temperature-oxygen profiles for Blelham Tarn indicate that whilst spring temperatures are slightly higher, the temperature profile infers that the lake is fully mixed. A slight increase in oxygen content in the epilimnion at this time, could be indicative of spring bloom productivity, with a subtle decrease down the water column as organisms/biological material decay with depth (Fig. 3.2). Clear thermal stratification by summer is evident with a thermocline from 2-6m separating epilimnion temperatures of ~18°C and hypolimnion temperatures just below 10°C. The extent of anoxia is greatest in summer, extending from the lake bottom up to ~6m water depth. By autumn, the thermocline has extended deeper, indicating complete overturn has not yet occurred, and this is supported by the continuation of anoxia in the hypolimnion (albeit reduced in vertical extent by ~2m). Winter exhibits the lowest and most consistent temperatures and highest oxygen content with water depth, at 5°C and 11 mg/l respectively.

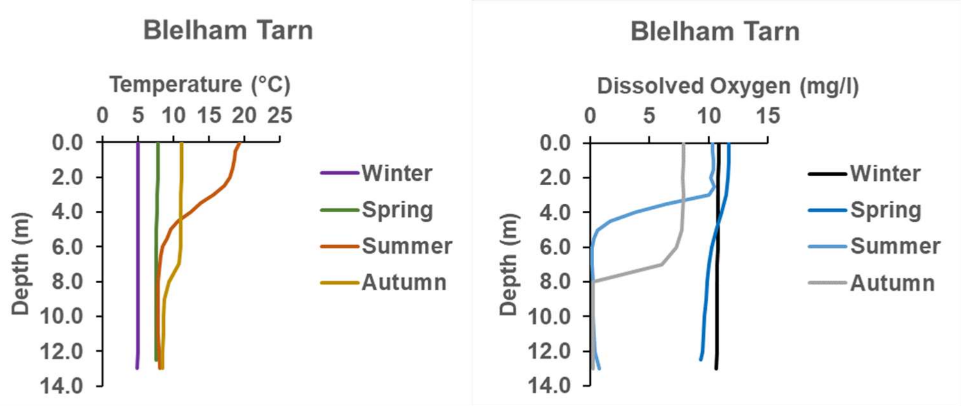


Figure 3.2. Seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Blelham Tarn, taken as part of the Lakes Tour 2021 (UKCEH). Spring data collected 13/04/2021, summer data collected 07/07/2024, autumn data collected 25/11/2021 and winter data collected 17/01/2022.

4.2.2 Sediment P enrichment

Only one study from the rapid review (Pennington et al., 1977) had quantified the P content of the sediments at Blelham Tarn and unfortunately, this was earlier than the period of interest (i.e. from the 1980s onwards). However, Pennington et al., (1977) did record an increase in P in the sediment horizons dated in the 1950s-60s which corresponded to an increase in septic tanks in the catchment, detergent use and domestic sewage entering the lake. Cyanobacterial sterols and diatom abundances also increased within the same horizons indicating an enrichment of the Tarn during this period (Pennington et al., 1977).

In more recent sediments, Van der Post et al., (1997) details an increase in sediment deposition and allocthonous organic material, which corresponded to increased sheep grazing numbers in the catchment in the 1980s. This implies a progressive nutrient enrichment of the Tarn and its sediments. Recent direct evidence of sediment P conditions is lacking at Blelham Tarn.

4.2.3 Evidence for internal P loading

Gasca et al. (2015) do not attempt a direct quantification of internal P loading as part of their P source-apportionment model at Blelham Tarn but provide an estimated figure. Here land-cover changes and P assessments from studies conducted at multiple locations are used to estimate external P sources. The source-apportionment model indicates that 85% of sources to the tarn are from the catchment and therefore, by difference, that 15% of the lakes budget is likely to be attributable to internal loading (Gasca et al., 2015). The study determines that contributions could be up to ~40% in mid-late summer, corresponding to the thermally stratified period, which occurs in May-October (Gasca et al., 2015). The extent of the sediment area contributing to internal loads was determined to be 50% of the total lake plan area though it is unclear how this was quantified. The study recommends further investigation into the mixing regime of the lake and size of the nutrient pool in the water column and sediments, noting estimates are based on limited data (Gasca et al., 2015).

A nutrient loading experiment using limnetic enclosures in Blelham Tarn, to test the relationship between P and phytoplankton biomass, or yields, and found that lake sediments complicated this response (Reynolds, 1996a). An increase in water column TP was recorded following destratification and attributed to the release of P from superficial sediments following shear stress at overturn (Reynolds, 1996a).

Vertical TP and SRP depth profiles from Blelham Tarn were collected between June to October in 2016 by Gray (2019). These profiles indicate an enrichment of the hypolimnion in summer and autumn, with elevated concentrations of total and biologically available P coinciding with anoxia under stratification (Fig. 3.3) (Foley et al., 2012).

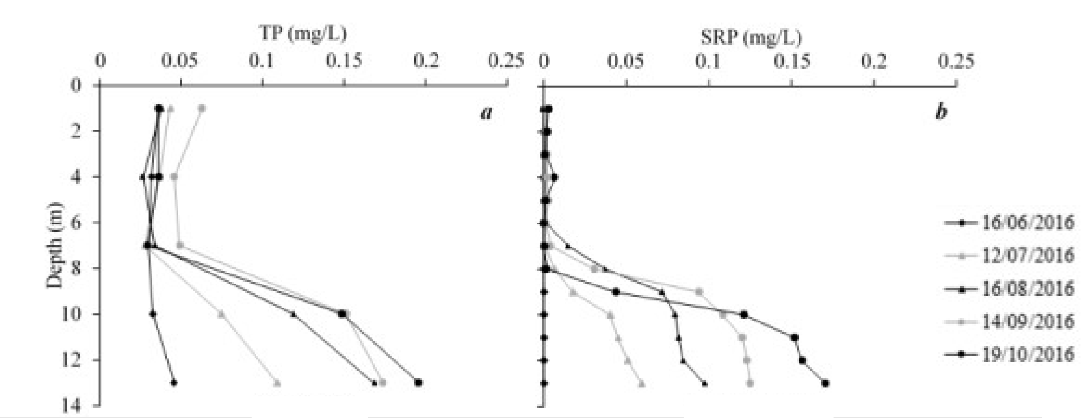


Figure 3.3. Depth profiles of (a) Total Phosphorus and (b) Soluble Reactive Phosphorus at Blelham Tarn between June-October 2016. Adapted from Figure 3.6. in Gray (2019).

4.2.4 Assessment of evidence

Most research on Blelham Tarn has quantified the historic enrichment of its waters with P concentrations enabling an indirect assessment of the potential for internal P loading, but no clear indication as to the concentration or composition of P in the sediments. Historic and recent oxygen profiles indicate an expansion in the duration and extent of hypolimnetic anoxia. This suggests that the period over which internal P loading could occur each year has expanded over the long-term. Internal P loading has not however, been directly measured at the lake, although a modelling study of catchment inputs has identified that an internal source of P is accountable for the higher in-lake P concentrations during the summer period. More recently, measurements of P enrichment and anoxia at depth compared to surface waters during the summer indicates a high risk of internal P loading.

4.3 Elterwater

Figure 3.4. Satellite map of Elterwater taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Elterwater is a small, shallow, lowland lake consisting of three chemically distinct interconnected basins; the inner, middle and outer basins (Fig. 3.4). The inner basin was historically classed as hyper-eutrophic when, between 1973-1991, 45% of its hydraulic load came from effluent from Elterwater WwTW (Haworth et al., 2003). In 2001, the outflow from the WwTW was moved downstream to remove this nutrient source. However, TP concentrations in the lake remained high following this intervention. Since 2016, additional water has been diverted into the inner basin to reduce stratification and internal nutrient loading, although the impact of this intervention has been limited (Olsson et al., 2022a). The middle basin was classed as meso-eutrophic as its renewal only occurred during flooding and attendant overflowing from the inner and outer basins (Goldsmith et al., 2003). However, more recently, Little Langdale Beck was re-connected to the middle basin to improve flushing and reduce nutrient concentrations. The outer basin receives the highest hydraulic load of the three basins and as such has a high siltation rate and was classed as oligo-mesotrophic (Zinger-Gize et al., 1999) and in good ecological status in the last cycle of the Water framework Directive (Environment Agency | Catchment

Data Explorer, 2024). The water residence time, therefore, varies considerably between the basins with retention times of 15-20 days for the inner and middle basins and as short as 0.5 days for the outer basin (APEM, 2012; Beattie et al., 1996). The lake and its margins are designated as a SSSI on account of diverse successional habitats including aquatic macrophytes such as the rare six-stamened waterwort *Elatine hexandra* (Lapierre), fen to marshy grasslands to oak woodland. Recently, the condition of the SSSI has been classified as being in a declining state (Haworth et al., 2003; APEM, 2012).

4.3.1 Oxygen conditions

Hypolimnetic anoxia in the inner basin has been recorded from the 1990s and was typical from May to September, though more recently its onset has been recorded in mid-March (Zinger-Gize et al., 1999; Olsson, 2021). Monitoring of conditions in the inner basin between 1994-1995 found hypolimnetic anoxia occupied 50% of the basin area with some de-oxygenation at the surface during certain events (Zinger-Gize et al., 1999).

The Lakes Tour 2021 temperature-oxygen depth profiles, recorded in the shallow inner basin, indicate summer stratification with ~10°C difference between the surface and bottom temperatures (Fig. 3.5). Hypolimnetic anoxia during the summer extends only 1m from the sediment surface upwards to 5m depth. By autumn, temperatures are consistent throughout the water column and DO concentrations are constant at ~10mg/l throughout the lake. The relatively short-lived anoxic period in this lake compared to others in the area is likely attributed to the basin's short mean retention time and the cooling influence of the inflow on the lakes heat budget during the stratification onset and overturn periods (Olsson et al., 2022b). During the main summer period, during the strongest stratification, the combination of generally lower flow and strong heating of the lake surface result in a limited impact of the inflow on the heat budget of the lake.

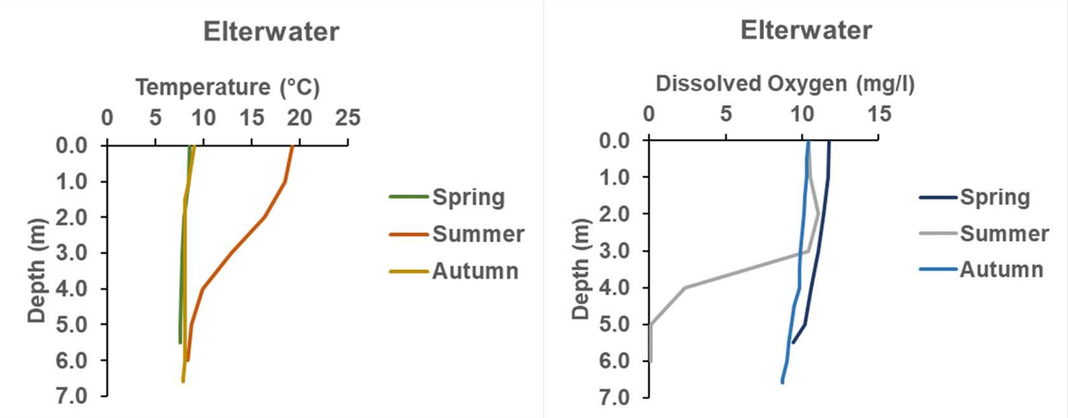


Figure 3.5. The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Elterwater inner basin taken as part of the Lakes Tour 2021 (UKCEH). Spring data collected 13/04/2021, summer data collected 06/07/2021 and autumn data collected 10/11/2021.

4.3.2 Sediment P enrichment

Enrichment of P in the sediments of the inner and middle basin began in the 1970s when the WwTW was established (Haworth et al., 1997). Though it was noted that the inner basin already had a slightly higher baseline of P concentration in its sediments than those prior to the 1900s (Haworth et al., 1997). Sediment horizons from the 1990s recorded TP concentrations between 8007 and 8940 μg g^{-1} dry weight (DW) in the inner basin sediments, approximately eight times higher than other lakes in the area (Cranwell et al., 1995). More recently, TP in the sediments from the deepest part of the inner basin have exceeded 5000 μg g$^{-1,}$ suggesting very high potential for internal nutrient loading here (Mackay et al., 2015). This is consistent with findings from other reports which noted enrichment of sediment phosphorus in the inner basin despite evidence of some recovery in TP values since 2001/2002 (APEM, 2012). The diversion of the WwTW outflow into the lake occurred in 1999, with these findings indicating a slow reduction of sediment P concentrations.

Parker et al. (2003) measured the TP and Alkali-Extractable P (AEP) from the top 0-4cm in all 3 basins, recording the highest concentrations in the deeper inner basin (mean TP= 9631 μg g−1 DW and mean AEP = 5906 μg g^{-1} DW) sediments compared to the shallower sites of the same basin (mean TP= 4753 μg g−1 DW and mean AEP = 2067 μg g^{-1} DW), with the outer basin having the lowest concentrations overall (mean TP from outer basin deepest sites= 2713 and mean AEP from outer basin deepest sites= 874 μg g^{-1} DW). No difference in concentrations was found between sediments dated 1991-1996 and 2001-2002 despite the re-routing of the WwTW outflow/inner basin inflow, with this linked to the attendant reduction of flushing (Parker et al., 2003). An update of this work twelve years later by Mackay et al., (2015) found reductions in TP and AEP concentrations in sediments of the inner basins compared to the previous survey by Parker et al., (2003) (mean TP= ~5000 μg g−1 DW and mean AEP=~3900 μg g^{-1} DW). However, for the deep sediments in the inner basin and one site at the outer basin, the AEP fraction comprised a larger proportion of the TP content (TP: AEP ration >0.6) compared to the middle basin (TP: AEP ratio <0.5). AEP is considered the most readily released form of P and was reported to comprise two-thirds of the deep-water sediment TP concentration. As such, the risk of internal loading in the lake is still considered high (Mackay et al., 2015). A subsequent sediment survey in 2019, revealed that average sediment TP concentrations has not significantly declined since the 2014 survey and were on average 3702 μg g−1, 2574 μg g−1 and 2356 μg g−1 in the inner, middle and outer basins, respectively (Mackay et al. 2020), this survey will be repeated in 2024. An analysis of lake sediment TP concentrations by Carey and Rydin (2011), identified a pattern of sediment P enrichment across a trophic gradient. Their data revealed that eutrophic lakes, on average had surface TP concentrations of 3100 (±400) μg g-1 dry sediment, mesotrophic lakes, 2000 (±200) μg g^{-1} dry sediment and oligotrophic lakes, 1600 (±100) μg g^{-1} dry sediment. This places Elterwater's sediment P concentrations within the eutrophic and mesotrophic categories.

4.3.3 Evidence for internal P loading

Mass-balance estimates suggest that internal loading contributed 3 times more TP to the inner basin compared to external loads in the summer after the intervention in 2016 (Olsson, 2021). In addition, biologically available P concentrations in the water column 6m and below were 5 times higher than those at 0.5m during the summer stratified periods of 2018 and 2019 (Olsson, 2021). The water source of the intervention is lower in nutrients which implies that either the intervention is not having a dilution effect or more likely the effect of dilution is being compensated by the addition of an internal supply (Olsson et al., 2022a). The high P content of sediments particularly in the inner basin, coupled with the anoxia recorded during the summer stratification period, which has increased in duration over time and not been strongly impacted by the intervention in 2016, indicates the continued occurrence of internal loading here (APEM, 2012; Mackay et al., 2015; Olsson, 2021).

4.3.4 Assessment of evidence

Investigations into sediment P enrichment, which include assessments of non-mobile and mobile fractions, and the nature of oxygen depletion are readily available for Elterwater. Studies have also assessed key processes such as stratification and residence time, which impact on the former, as well as inter-basin comparisons. Mass-balance estimates have further helped conclude the likely incidence of internal loading particularly in the inner basin, though again this has not directly been quantified.

4.4 Esthwaite Water

Figure 3.6. Satellite map of Esthwaite Water taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Esthwaite Water is a shallow eutrophic basin, with a small catchment and has an average residence time of 100 days (Maberly et al., 2006) (Fig. 3.6). The lake is a designated SSSI, Environmentally Sensitive Area (ESA), Ramsar Site and National Nature Reserve, supporting a severely reduced community of the nationally important aquatic macrophyte slender naiad (*Najas flexilis*). Its main inflow, Black Beck, drains around 50% of the catchment, including the village of Hawkshead which has a small resident population, which is significantly enlarged by seasonal tourism in the summer months (Mackay et al., 2014). A key historical and current external source of P in the catchment is Hawkshead WwTW, which was the dominant P source during the 1980s. Additionally, a fish farm situated on the lake, became the key P source by the 1990s (Maberly et al., 2011). Other external catchment loads originate from improved grassland and grazing, and non-mains sewerage. However, internal P loading from lake sediments has been identified as an important component to the P budget of the lake, particularly in the summer months (Mackay et al., 2014). The high alkalinity and redox potential of its sediments further indicate optimum conditions for internal loading (Hilton and Gibbs, 1984).

4.4.1 Oxygen conditions

Records of oxygen data from the lake, suggest that at least as early as the 1980s, oxygen concentrations in the hypolimnion in summer months have been close to zero, although year to year variation in the duration and volume of anoxia occurs (Maberly et al., 2011). The variation in anoxia is attributed to weather conditions which determine the timing and depth of mixing, which replenishes oxygen in deeper water layers (Mackay et al., 2014; Heaney and Butterwick, 1989).

The Lakes Tour 2021 seasonal temperature-oxygen profiles at Esthwaite Water show that during summer, anoxia extends from the bottom ~5m and water remains relatively low in DO up to the top few metres of the epilimnion (Fig. 3.7). Whilst the temperature profile in autumn suggests that overturn had commenced due to no visible thermocline being apparent, the temperature difference between the surface and bottom of the lake was still ~2°C, enabling anoxia and low oxygen concentrations to persist throughout much of the water column.

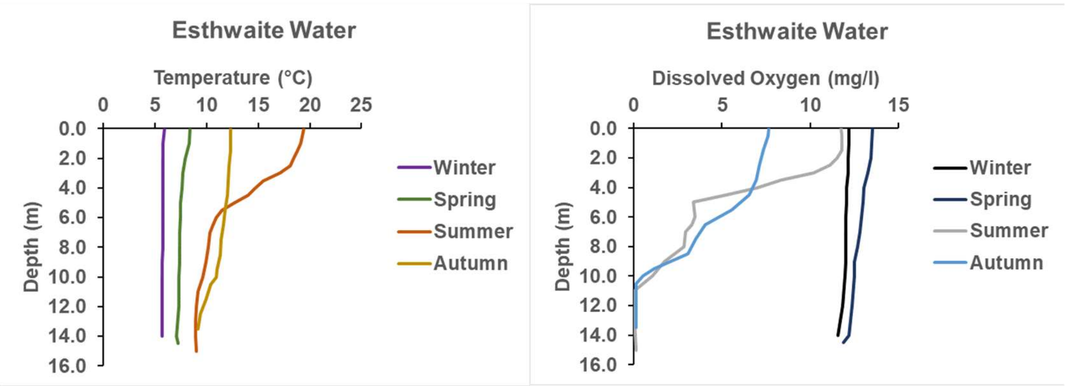


Figure 3.7. The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Esthwaite Water taken as part of the Lakes Tour 2021

(UKCEH). Spring data collected 13/04/2021, summer data collected 06/07/2021, autumn data collected 12/11/2021 and winter data collected 14/02/2022.

4.4.2 Sediment P enrichment

Several studies have investigated sediment P concentrations in Esthwaite Water. Many studies have noted an enrichment and higher sediment P concentration in deeper rather than shallow water depths. For example, Mackay et al., (2012) found a significant increase in sediment P concentration with depth (R^2=0.82), from 1 g per kg^{-1} of sediment in shallow waters to about 5 g per kg^{-1} of sediment at 14 to 15 m. In addition, estimates suggest that up to 55% of P is retained in the sediments at Esthwaite Water, with wind-induced, water-current driven resuspension a key physical control of spatial variability in P content and sedimentation rate in the lake (Mackay et al., 2012).

Other temporal and spatial studies which have looked at the AEP and TP fractions in the sediments at Esthwaite Water found a decrease in the AEP fraction following the commencement of tertiary treatment at Hawkshead WwTW in the late 1980s (Heaney et al., 1990). However, sediments in the locations of the fish farm cages were found to be enriched in AEP from the waste food and faecal material from the fish farm (Hall et al., 2001). A more recent survey of surface sediments (2014) was compared to those collected between 1986-2001 when the fish farm was in operation and found that the mean TP content (3034 µg g^{-1} DW) was higher in the centrally impacted area where the fish farm had been active (Anderson, 2018). These concentrations place the lake in the eutrophic category of Carey and Rydin (2011). The mean AEP content of the central basin was 2628 µg g^{-1} DW (Anderson, 2018). The TP content comprised reactive apatite and metal-oxide bound P which can persist in the sediment and was attributed to the historic fish farm activity (Anderson, 2018).

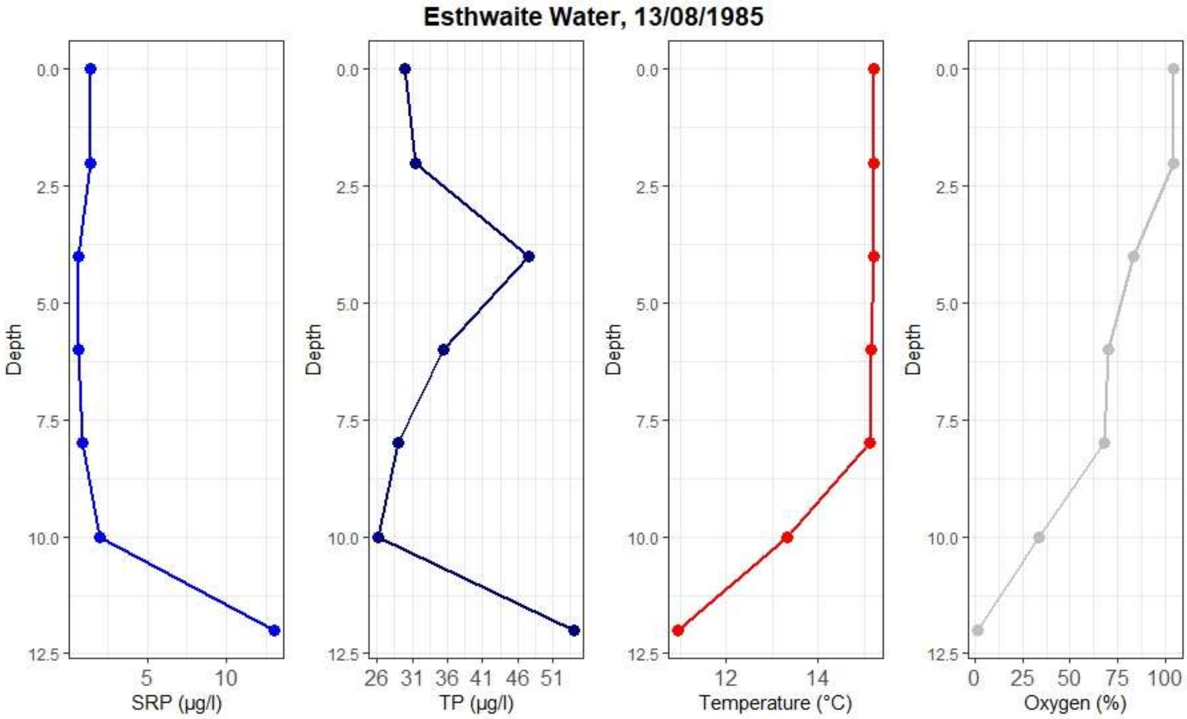
The littoral sediments i.e. those where depths do not exceed 5m (0.45 km^2) were also found to be enriched in mobile P and TP at Esthwaite Water, with shallow or more recently deposited horizons having higher concentrations than deeper, older sediment horizons. This enrichment in P in littoral sediments is likely to be due to sedimentation of P enriched material and the remobilisation of P within the sediment layers, including the upward diffusion of soluble P in sediment pore waters (i.e. the water contained within the pores or interstices of aquatic sediments) and resorption of P within surface sediments (Drake & Heaney, 1987). The fringing vegetation and high organic production in the littoral zone at Esthwaite Water, often results in high pH values due to CO_2 removal via photosynthesis. As mentioned above, high pH conditions provide another mechanism for sediment P release, which occurs under oxic conditions. The net release of P from the littoral sediments of Esthwaite Water, under these conditions, was estimated as ranging from 0.5-1 kg day^{-1} to >5kg day^{-1} (Drake & Heaney, 1987). For comparison, the orthophosphate load from Black Beck was determined to be 1.6 kg day^{-1} (FBA. unpublished results).

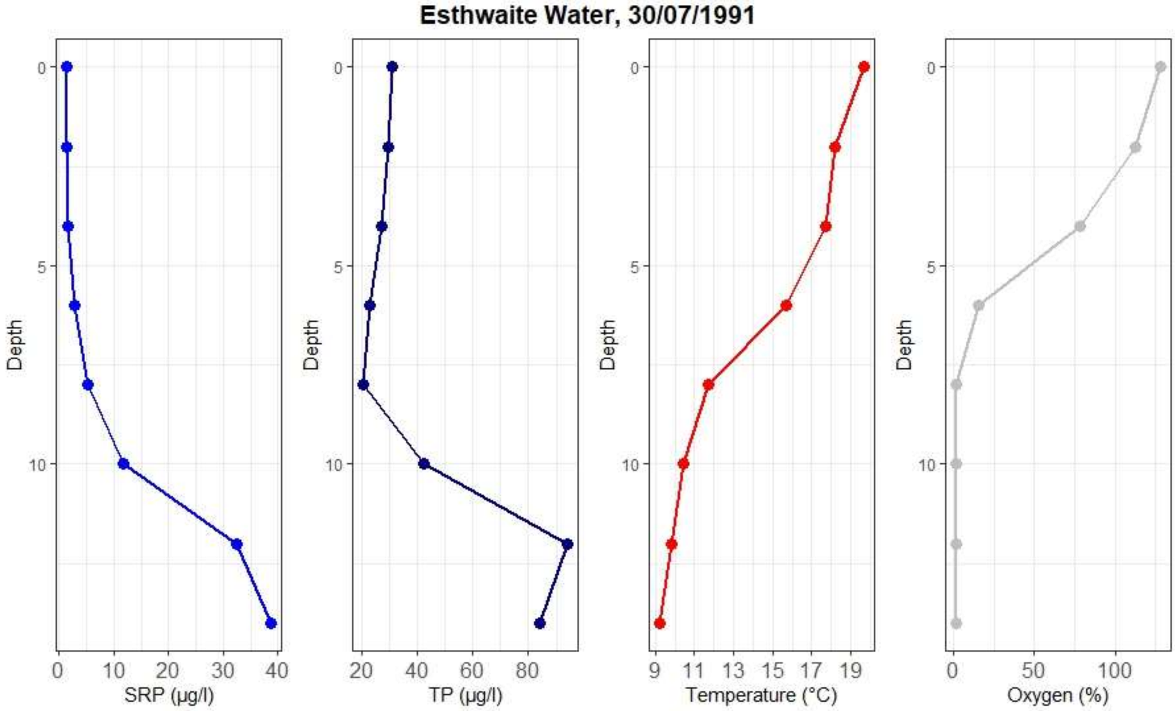
The studies reviewed above indicate high concentrations of mobile P in the sediments at Esthwaite Water particularly at deeper water depths, pointing to the considerable likelihood of internal loading here.

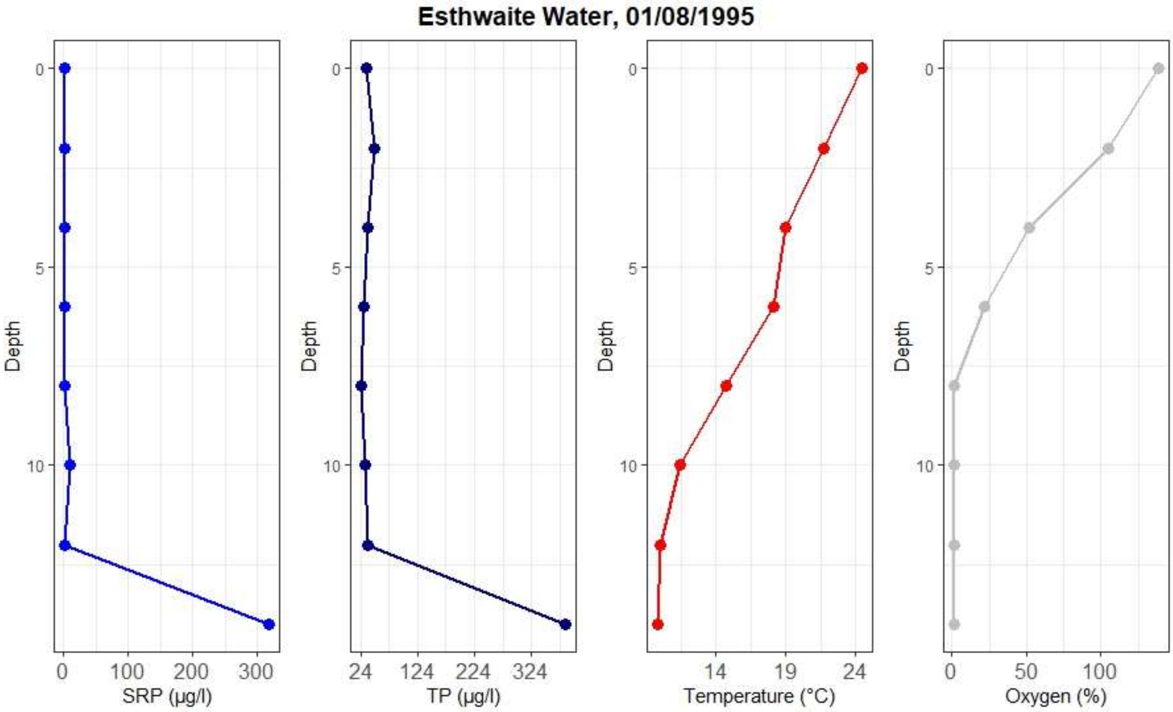
4.4.3 Evidence for internal P loading

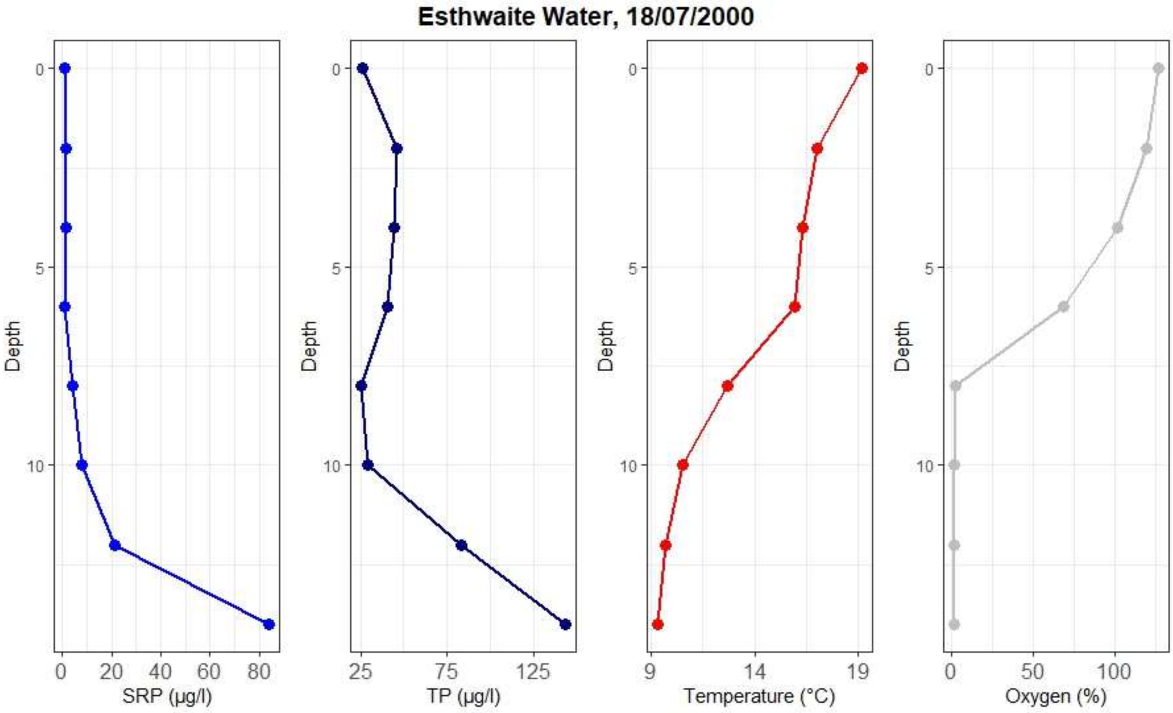
Various studies noted a strong seasonality of hypolimnetic P concentrations at Esthwaite Water, suggesting P is released from the sediment to the water column during summer, driven by temperature-controlled bacterial decomposition of organic matter and associated changes in redox conditions at the sediment-water interface (Maberly et al., 2011; Mackay et al., 2014; Anderson, 2018). Esthwaite Water also experiences high pH in the summer from inorganic carbon depletion due to high algal productivity, which can result in internal loading from littoral regions (Drake & Heaney, 1987). In addition, George (2000) noted that horizontal plumes of dissolved reactive P from the littoral to the pelagic zone caused by wind-induced mixing and currents were also a key mechanism of P transfer within the lake, with the anaerobic sediments of the reedbed an important source for this horizontal movement of P.

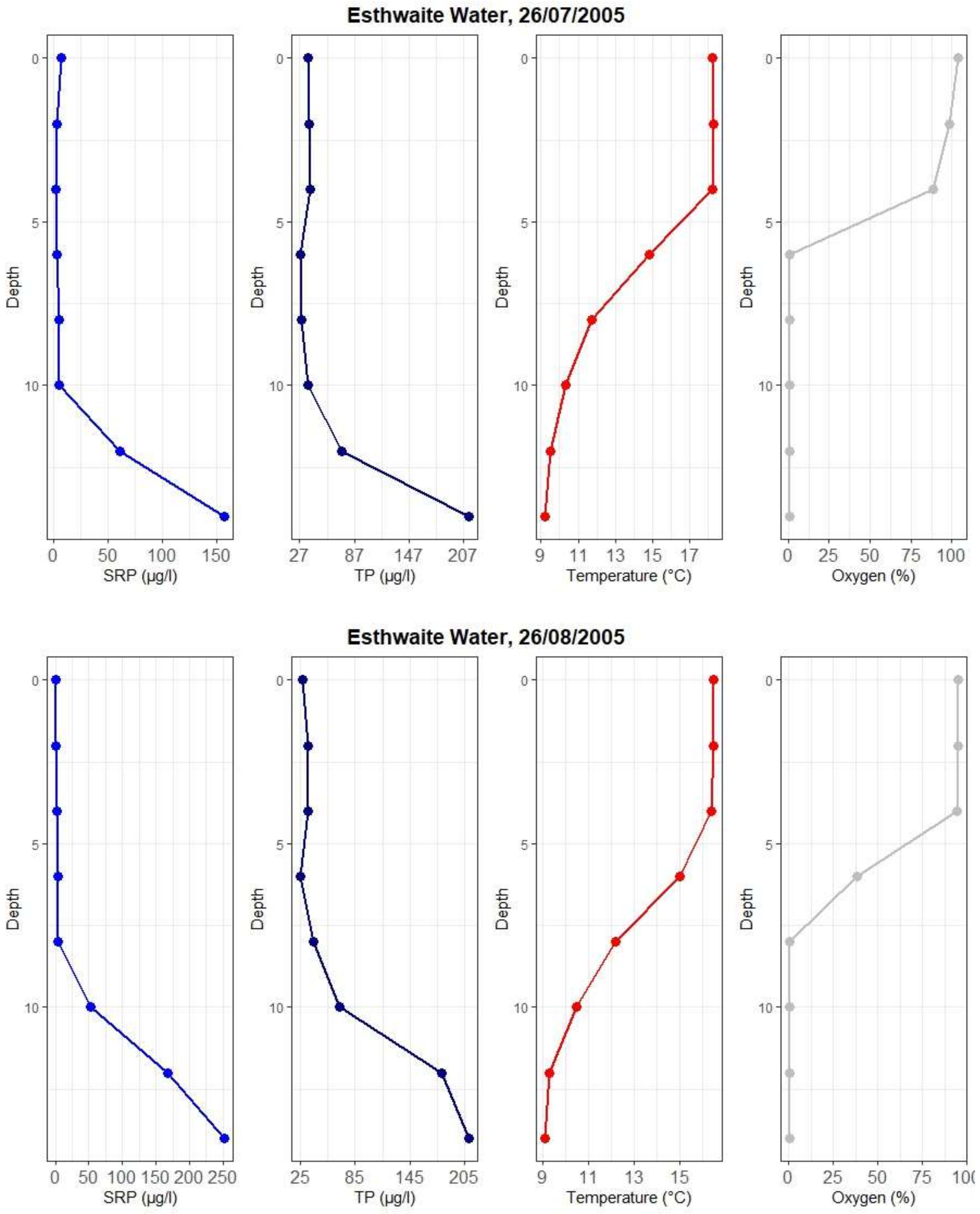
The UKCEH long-term monitoring depth profiles at Esthwaite Water from 1985-2008 had the highest concentrations of TP/SRP at depth compared to those recorded at the North and South Basins of Windermere (Fig. 3.8; 3.18 & 3.22). Peak concentrations of TP/SRP at Esthwaite Water occur in the hypolimnion, just below the thermocline, corresponding to the region of anoxia, thus suggesting internal loading may be contributing to the P concentrations at depth here. The surface water concentrations of TP/SRP appear low in comparison. Interestingly in 1995, there was a marked increase in concentrations of TP/SRP (400/300 µg/l) from those prior to this date (<100 µg/l). Temperatures in 1995 were the highest recorded (~25°C). Deep water TP/SRP concentrations thereafter show some improvement but remain ~200 µg/l, with the concentration increasing with water depth from just below the thermocline. From 2000, TP and SRP concentrations start to increase at shallower depths (~10m), which could coincide with an expansion of hypolimnetic anoxia which begins to expand after 1985 to ~8-7m but reaches its most shallow in 2005 at ~6m. These profiles reinforce the research conducted on internal loading at Esthwaite Water, indicating the importance of summer months for internal contributions.


Esthwaite Water, 13/08/1985
Depth
0.0
2.5
5.0
7.5
10.0
12.5
5
10
SRP (µg/l)
26
31
36
41
46
51
TP (µg/l)
12
14
Temperature (°C)
0
25
50
75
100
Oxygen (%)


Esthwaite Water, 30/07/1991
Depth
0
5
10
0
10
20
30
40
SRP (µg/l)
20
40
60
80
TP (µg/l)
9
11
13
15
17
19
Temperature (°C)
0
50
100
Oxygen (%)


Esthwaite Water, 01/08/1995
Depth
0
5
10
0
100
200
300
SRP (µg/l)
24
124
224
324
TP (µg/l)
14
19
24
Temperature (°C)
0
50
100
Oxygen (%)


Esthwaite Water, 18/07/2000
Depth
0
5
10
0
20
40
60
80
SRP (µg/l)
25
75
125
TP (µg/l)
9
14
19
Temperature (°C)
0
50
100
Oxygen (%)



Esthwaite Water, 26/07/2005

Esthwaite Water, 26/08/2005

Figure 3.8. Depth profiles for the determinands Soluble Reactive Phosphorus (µg/l), Total Phosphorus (µg/l), Temperature (°C) and Dissolved Oxygen (mg/l) from Esthwaite Water from 1985-2008 at roughly every 5 years and including most recent dataset in 2008 (data for 1991 provided as data for 1990 were missing).

Measurements taken on a single date in the year (detailed in the plot title) as part of UKCEH long-term lakes monitoring programme.

The SRP concentrations at the deepest depth (14m) from 1985-2008 show no clear trend over time (Fig. 3.9). They are much higher than the SRP values taken from the deepest depths of the Windermere North and South Basins however, which consistently remain below 20µg l^{-1} and 70 µg l^{-1} respectively (Fig.3.18 & 3.22). The variability of these values over the years is likely to be due to the time of year sampling was conducted and the variability in weather conditions, which as detailed above, can influence both the external and internal P loadings to the basin.

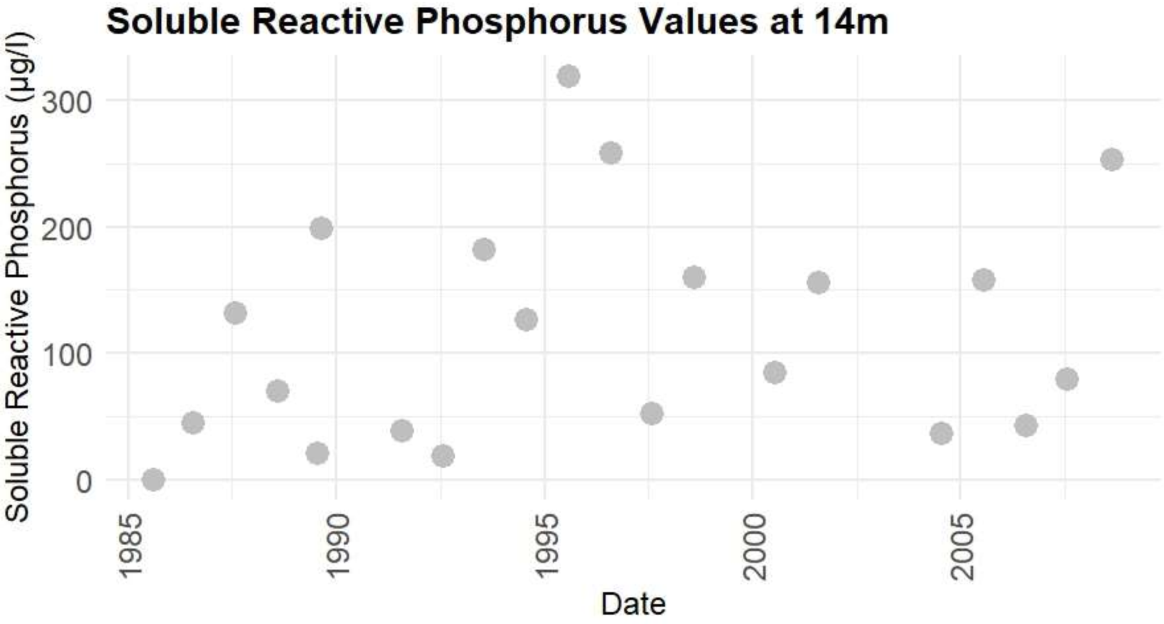


Figure 3.9. Annual Soluble Reactive Phosphorus concentrations (µg/l) of Esthwaite Water from water samples taken from the deepest depth (14m) from 1985-2008.

Attempts to quantify the internal P loading contributions at Esthwaite Water have demonstrated that interannual variation in this P source can be large. For example, Mackay et al., (2014) measured the external (Black Beck and upstream of Hawkshead WwTW) and internal (hypolimnion) P fluxes to the lake, finding that in 2008 internal fluxes contributed an estimated 50% to the summer SRP loading of the lake, while in 2009 this was 38%. In 2008, a net-warming of the lake occurred relative to 2009, resulting in more stable stratification and prolonged hypolimnetic SRP loading. However, both years were wetter than average summer conditions, resulting in higher external event driven loads, implying that in drier years this source could be more important to the P budget (Mackay et al., 2014). Assessments of the importance of internal P loading at an annual level via nutrient mass balances, estimate internal loads to account for 14% of the annual TP budget, albeit as a P fraction with high bioavailability (Anderson, 2018). External loading was found to remain the most significant P source to Esthwaite Water, continuing the enrichment of water column P concentrations.

4.4.4 Assessment of evidence

Esthwaite Water is one of the most-well studied sites, not only in this review, but globally, particularly in the context for understanding the temporal and spatial processes involved in sediment P loading and transport. The evidence for mobile P in the sediments and pervasive anoxia, plus historical mass-balances all indicate internal loading is a key source of P here. More recent depth profiles of P and oxygen would be helpful (albeit a much coarser and less accurate approach than mass-balances) to understand the current extent of internal loading at this site.

4.5 Grasmere

Figure 3.10. Satellite map of Grasmere taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Grasmere is a medium-sized, deep lake (Fig. 3.10). Its mountainous catchment and the variability of rainfall intensity in the Lake District result in retention times ranging from 9 to >65 days (Reynolds, 1997). Due to its high hydraulic loading and base-poor geology, the lake is naturally low in major ions and nutrients, implying that the baseline condition of Grasmere should be one of relative infertility and low biological productivity (Reynolds, 1997). However, the lake has been classified as meso-eutrophic due to nutrient loading from the River Rothay WwTW installed in 1971 (Reynolds et al., 2012). The WwTW was calculated to be the source of 74% of P loading to the lake in the mid-1990s (Reynolds et al., 2012). In an attempt to reduce biological productivity at Grasmere, the WwTW outfall was diverted into its hypolimnion in 1982.

4.5.1 Oxygen conditions

Following the establishment of the WwTW in 1971, the areal hypolimnetic oxygen depletion in the lake increased during the summer stratified period (Hall et al., 1978). Since the outfall re-direction in the early 1980s, hypolimnetic anoxia has increased in extent and longevity in response to increasing stratification (Reynolds, 1997, Reynolds et al., 2001a).

Monitoring conducted by UKCEH as part of the Urban Wastewater Treatment Directive between 2001-2007 measured the seasonal hypolimnetic oxygen in Grasmere amongst other larger lakes in the English Lake District including the Windermere basins. Overall, Grasmere had the lowest oxygen concentrations at depth and in 2005, experienced 5 months over the summer with concentrations less than 1 mg/l, the longest period of de-oxygenation since 1997 (Maberly et al., 2006). Despite some years showing seasonal differences due to weather conditions, there has been a general increasing trend in the duration of anoxia at Grasmere (Maberly et al., 2003; 2006; 2007; Reynolds et al., 2001c; 2002).

The Lakes Tour 2021 temperature profile from Grasmere in summer shows a distinct character where the thermocline is apparent in the top 5m, with the water temperature below showing a steady decline to 10 m then near the bottom of the profile at 15m a subtle increase to 8.4°C from 7.5°C (Fig. 3.11). The oxygen profiles reveal that oxygen depletion at depth has already commenced in spring, and by summer show a very distinct oxygen depletion profile, with a rapid drop in DO concentration in the top 5m of surface water, corresponding to the depth of the thermocline, but between 7m and 10m there is a slight increase in oxygen concentration before it drops to 0 mg/l at the lakebed. From 5m down, DO concentrations remain below 5 mg/l. This atypical pattern of oxygen depletion in Grasmere was also documented by Reynolds et al (2001a) who noted the oxygen minima occurred at 7-8m and not at the deepest depth as is typical elsewhere. This might indicate deepwater photosynthetic production, with certain cyanobacterial spp. able to bloom under low light irradiance.

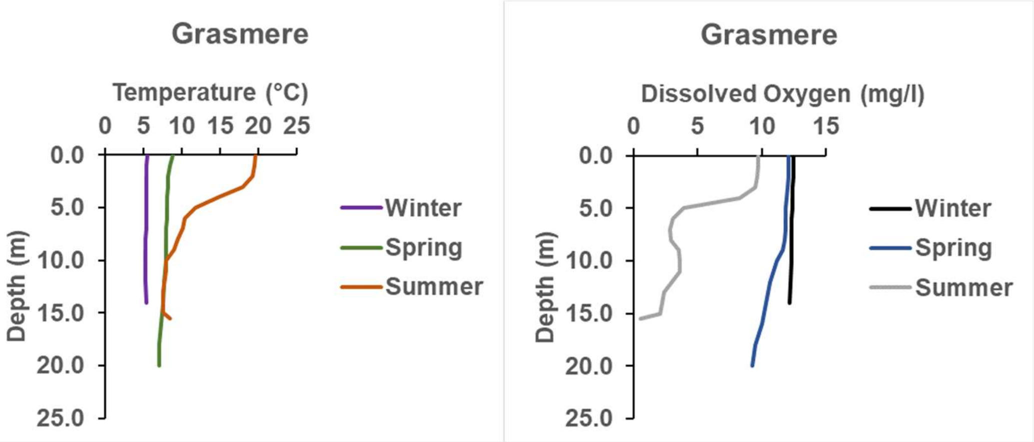


Figure 3.11. The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Grasmere taken as part of the Lakes Tour 2021 (UKCEH).

Spring data collected 12/04/2021, summer data collected 15/07/2021 and winter data collected 02/02/2022.

4.5.2 Sediment P enrichment

No studies retrieved in the rapid review had quantified the P content of the sediments at Grasmere, however several historical studies had analysed P loads and budgets to the lake. The most recent P budget, conducted over 20 years ago by Reynolds et al., (2001b) estimated loads between 1530 to 1830 kg P year^{-1}, with under 300 kg P year^{-1} from external sources in the catchment, and the rest from the WwTW. The direct P delivery from the WwTW outfall to the hypolimnion, suggests that the lake sediments may assimilate a large proportion of the P load, assuming that the sediment binding capacity has not been exceeded. Indeed, following the diversion, organic carbon and P concentrations increased rapidly in the hypolimnion (Reynolds, 1997). In addition, estimates suggest 58% of the lake's TP load is biologically available, with up to 72% of this fraction being retained in the lake (Reynolds et al., 2012). This therefore suggests that the sediments of Grasmere could be enriched with mobile P, which would be readily released under anoxia.

4.5.3 Evidence for internal P loading

Diatom-inferred TP from lake sediments at Grasmere further support the evidence of enrichment following WwTW establishment in 1971. There was some recovery when the outfall was transferred to the hypolimnion though not to pre-1965 conditions (Barker et al., 2005). However, as the delivery of nutrients was to the hypolimnion, photic species including diatoms, which rely on the entrainment of these nutrients into the epilimnion would experience growth limitation. This work suggests the success of this strategy in controlling algal biomass.

Direct measurement of hypolimnetic P or the quantification of internal P loading has not been carried out in Grasmere. However, indirect evidence from surface measurements suggests that the accumulation of P in the hypolimnion in summer has increased, for instance, epilimnetic concentrations of TP exceeded 40-60 mg m^{-3} following autumnal overturn in the early 2000s (Reynolds et al., 2001a). These autumnal loads are also transferred downstream to Rydal Water and Windermere (Reynolds et al., 2001a). Further, Reynolds et al. (2001a) reported large cyanobacterial and phytoplankton crops in the summers between 1997-2000 following weather-related entrainment of hypolimnetic water to the epilimnion, noting increasing vulnerability of eutrophication under climate variability. Monitoring in the 2000s by UKCEH as part of the Urban Wastewater Treatment Directive noted a significant increase in the annual mean SRP concentration of the lake (though this was lower in 2005, coinciding with a breakdown of summer stratification from heavy rainfall, Maberly et al. (2006)).

4.5.4 Assessment of evidence

The enrichment, phytoplankton ecology and hypolimnetic control of wastewater has been studied at Grasmere but no direct quantification of sediment P or internal loading was returned in this review. Most studies on the lake also pre-date 2005. However, there is clear evidence to suggest the delivery of organic matter to the hypolimnion affects deoxygenation, as well as weather conditions which control the timing and strength of stratification. These are key processes in modifying in-lake nutrient and oxygen budgets at Grasmere (Maberly et al., 2006). The deoxygenation and high P concentrations of the hypolimnion indicate the possibility of severe sediment P enrichment and high risk of internal loading. We recommend investigating internal loading at this site given the hypolimnetic management of its wastewater, sensitivity to hydraulic variation and associated risks to water quality not only in the lake itself but also in closely connected downstream basins.

4.6 Loughrigg Tarn

Figure 3.12. Satellite map of Loughrigg Tarn taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Loughrigg Tarn is one of the most eutrophic basins in the Windermere catchment, with a long mean retention time (117 days), a catchment comprised largely of livestock grazing and a small campsite not connected to mains sewerage (Moorhouse et al., 2018) (Fig. 3.12).

The rapid review did not retrieve any publications of relevance for this basin based on the search terms. Therefore, other sources of evidence were needed to indirectly infer the internal loading risk here.

4.6.1 Oxygen conditions

The summer temperature profile from the Lakes Tour 2021 at Loughrigg Tarn shows the development of stratification, though less distinct than at other basins (Fig. 3.13). The spring depth profile indicated a lowering of DO concentrations below 4m from the surface to the sediments, despite only a relatively small temperature gradient from the surface. By summer, a temperature difference of 8.6°C between measurements taken at 3m and 6m was and a rapid decline in DO concentration to anoxia, occurred from 5m below the surface. The absence of an autumn profile means it is not possible to see if or how this anoxia developed, but the summer profile suggests that anoxia is less extensive than in other shallow basins in the catchment at this time. The peak in oxygen at around 4m could be due to sub-surface production by the phytoplankton community.

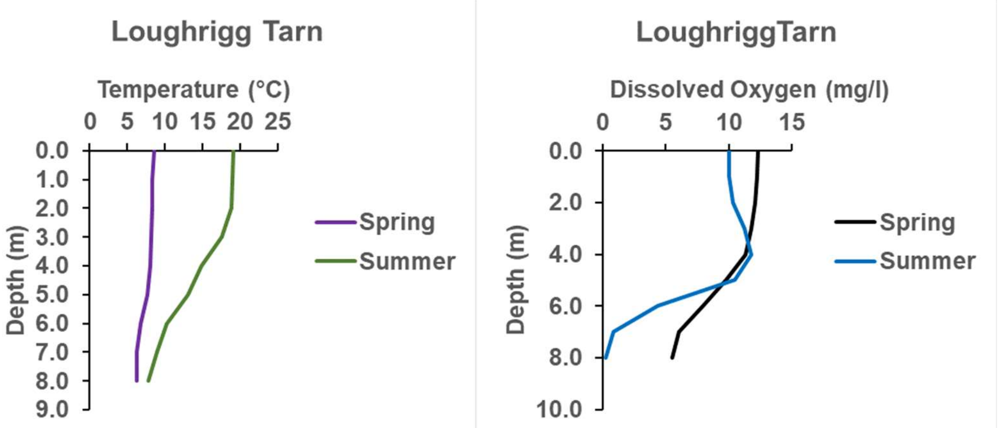


Figure 3.13. The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Loughrigg Tarn taken as part of the Lakes Tour 2021 (UKCEH). Spring data collected 13/04/2021, summer data collected 06/07/2021.

4.6.2 Sediment P enrichment

There were no records of sediment P concentration at Loughrigg Tarn. Moorhouse et al. (2018) recorded an increase in all algal pigments in Loughrigg sediments from the last ~200 years indicating a continuous increase in algal productivity and therefore, nutrient enrichment of the lake. It is therefore likely that a concomitant enrichment of the sediments with P has also occurred, considering both the organic-rich nature of the sediment and eutrophication of the lake (Moorhouse, 2016).

4.6.3 Evidence for internal P loading

Internal P loading has not been quantified in Loughrigg. However, a high risk of internal loading at Loughrigg Tarn is likely due to evidence of historic eutrophication combined with the low DO concentrations (i.e. below 5 mg/l), to anoxia in the bottom few metres of the water column during summer. This coupled with the shallow depth of the Tarn and its relatively long retention time suggests conditions for redox-driven P release from the sediments are likely.

4.6.4 Assessment of evidence

As no records were returned to provide direct evidence of internal P loading in Loughrigg Tarn, the contribution of this source to the lake's nutrient budget cannot be quantified. However, indirect evidence from the eutrophic condition of this site, coupled with its long retention time and evidence of anoxia at the sediment/water interface suggest it may be important. Seasonal temperature-oxygen depth profiles would be particularly useful at this site to understand the development of stratification and anoxia, as would the direct quantification of P in the sediments.

4.7 Rydal Water

Figure 3.14. Satellite map of Rydal Water taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Rydal Water is a small lake, with a short mean residence time located directly downstream from Grasmere (Fig.3.14). It is a meso-eutrophic system whose water quality and algal community is very similar to, and influenced by, Grasmere upstream (Haworth et al., 2003). It has extensive reed beds which fringe the shore and organic-rich sediments ascribed to its fen habitat and the entrapment of minerogenic material upstream in the larger Grasmere basin (Haworth et al., 2003).

The rapid review did not retrieve any publications of relevance for this basin. Therefore, other indirect evidence is required to infer the internal loading risk in this lake.

4.7.1 Oxygen conditions

The Lakes Tour 2021 temperature profiles indicate that despite the relatively short retention time of the basin, the lake stratifies, with overturn still not fully complete by autumn (Fig. 3.15). Interestingly, in summer, DO concentrations decrease steadily below the thermocline, whereas in autumn there is a rapid depletion of DO from 9m where temperatures fall below 10°C and concentrations drop from 8 to 0 mg/l over a 3m change in depth.

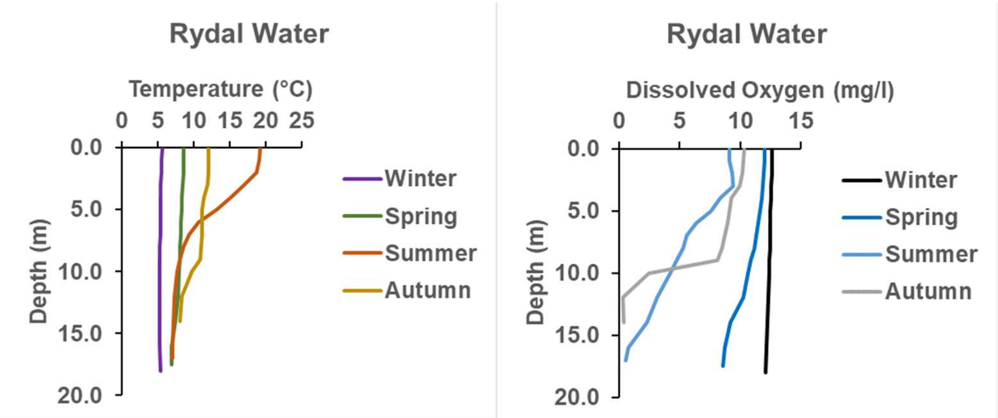


Figure 3.15. The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Rydal Water taken as part of the Lakes Tour 2021 (UKCEH). Spring data collected 13/04/2021, summer data collected 06/07/2021, autumn data collected 11/10/2021 and winter data collected 02/02/2021.

4.7.2 Sediment P enrichment

There were no records of sediment P content in the sediments of Rydal Water. Moorhouse et al. (2018) recorded an increase in all algal pigments in sediments from the last ~200 years indicating a continuous increase in algal productivity at this lake. Most of the variance in the pigment composition at Rydal Water was explained by activity at River Rothay WwTW upstream and attributed to the consequent nutrient enrichment. As the hypolimnion receives the outflow of the WwTW at Grasmere, it has been suggested that nutrients flushed downstream to Rydal Water are typically in dissolved rather than particulate form, which results in a more mobile and biologically available external load (Reynolds et al., 2001). As these nutrients may increase in the water column following the overturn of Grasmere, it is likely that external nutrient loading to Rydal Water increases outside of the growing season. As a result, nutrients are likely to be more readily sedimented to the bed sediments, rather than utilised by phytoplankton (Reynolds et al., 2001).

4.7.3 Evidence for internal P loading

There was no direct evidence for internal P loading returned by the searches. Indirect evidence suggests that the lake might be at risk. Rydal Water is a meso-eutrophic basin which undergoes stratification and a lowering of DO concentrations from below 5 mg/l to anoxia in its deepest waters in summer/autumn. Coupled with increasing fossilised algal pigments from its sediment records, the available evidence suggests that there has been an enrichment of P in the basin, attributed to wastewater treatment activity in Grasmere upstream.

In addition, the organic-rich sediments particularly in the fringing reed beds may increase the release of P as oxygen concentrations are lower and pH is increased from photosynthesis (Søndergaard et al., 2003). This is further supported by work at Esthwaite Water which found increased mobile P fractions in the littoral sediments associated with vegetation (see section 3.4.2).

4.7.4 Assessment of evidence

No literature for Rydal Water was returned in this rapid review. Therefore, the available evidence from sediment enrichment and internal P loading is indirect. It constitutes observations of basin characteristics, limited limnological monitoring and applied research on internal P loading conducted elsewhere. This highlights a need for further investigation at this site, further justified by the autumnal hypolimnetic anoxia, which if eutrophication has been consistent with that of Grasmere, indicates both the nutrient and redox conditions are present for internal P recycling.

4.8 Windermere North Basin

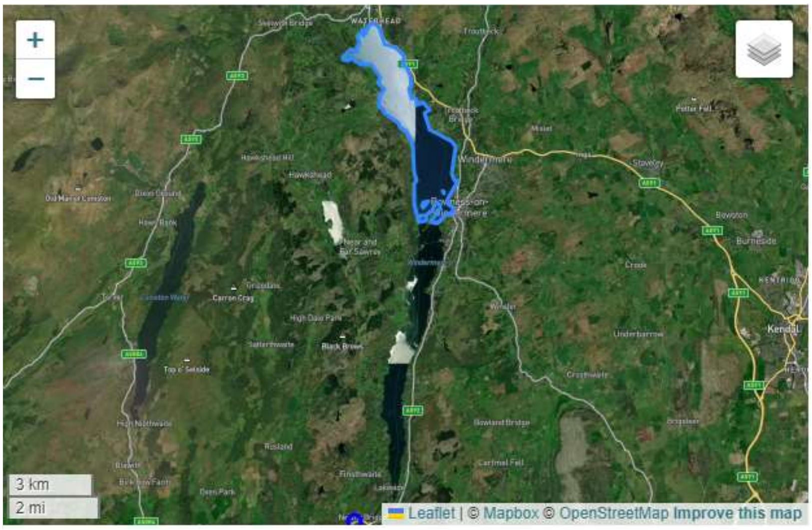


Figure 3.16. Satellite map of Windermere North Basin taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

Windermere's North Basin is larger (8.05 km^2) and deeper (max depth 64m) than its South Basin (area=6.72 km^2 and max depth 42m). The two basins are separated by an area of shallows and small islands (Fig. 3.16), which limits water exchange and results in basins having a sufficiently different character to be considered separately here. The main inflows to the North Basin are the Rivers Brathay and Rothay (McGowan et al., 2012). WwTWs within its catchment include those received by lakes upstream such as Elterwater, Blelham Tarn and Grasmere and that in the urban centre of Ambleside. The latter is often cited as driving the increasing SRP concentrations in the basin until the mid-1990s when values stabilised as treatment improved (McGowan et al., 2012; Thackeray et al., 2016). It is now considered mesotrophic and has an algal community typical of northern temperate lakes, whose phenology is governed by thermal stratification (Reynolds & Irish, 2000). Windermere like many other lakes in the catchment is monomictic, however, due to its size and thermal capacity, overturn often occurs later in the year in the North Basin (November-December) compared to the South (October-November) (Pickering, 2001). More recent work indicates that water temperature change, stratification and increasing nutrient availability are driving inter-annual variation in multiple trophic level phenological de-synchronisation in the lake (Thackeray et al., 2013).

4.8.1 Oxygen conditions

Nutrient enrichment in the North Basin has increased algal productivity resulting in greater deposition of organic carbon to the sediments. This has been attributed as the cause in the reduction of hypolimnetic DO (Heaney et al., 1989; Moorhouse et al., 2018). By the 1980s, hypolimnetic DO had reduced by 50% from a baseline condition of 33.5 mg l^{-1} determined by Lund et al., (1963) as the basin-wide hypolimnetic DO value (using data collected in the late 1940s in late autumn when oxygen levels were most depleted) and an annual minimum of 2.2 mg/l was reached (Heaney et al., 1989; Maberly et al., 2008). DO concentrations in the hypolimnion of the North Basin have continued to show a significant decrease over time, despite evidence for some recovery following the start of tertiary treatment of P in 1992 (Reynolds et al., 2000; Maberly et al., 2008). For example, in 2006, DO at depth reached 3.5 mg/l, the lowest recorded since 1992, with statistically significant declines in values since (Maberly et al., 2007; Maberly et al., 2008). More recent assessment of DO decline was not returned in the searches for this review.

Unlike the shallower lakes of the catchment, anoxia was not recorded in the deep waters of Windermere North Basin in summer/autumn 2021 as part of the UKCEH Lakes Tour 2021 monitoring. The lowest DO concentrations at ~5 mg/l at 60-62m depth occurred in autumn (Fig. 3.17). Whilst stratification is most pronounced in summer, autumn DO concentrations below ~10m from the surface are lower than those in summer, indicating that although stratification has weakened, it is still sufficient to prevent re-oxygenation from the surface waters. Ongoing respiration of organic material continues to draw down oxygen concentrations in the deep water.

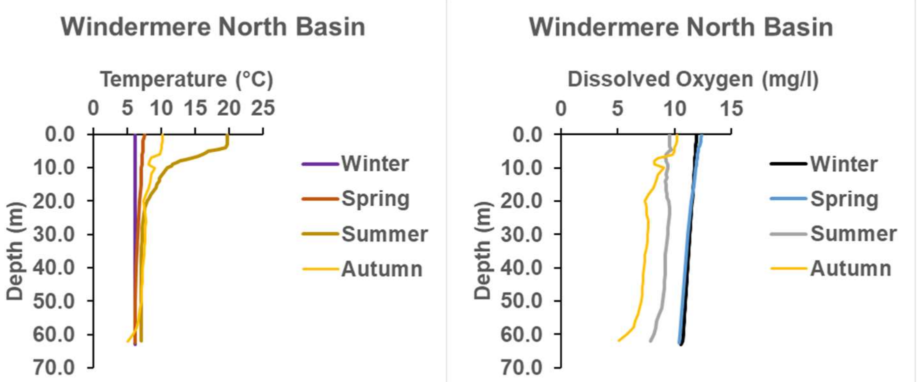


Figure 3.17. The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Windermere North Basin taken as part of the Lakes Tour 2021 (UKCEH). Spring data collected 14/04/2021, summer data collected 06/07/2021, autumn data collected 13/10/2021 and winter data collected 14/02/2022.

4.8.2 Sediment P enrichment

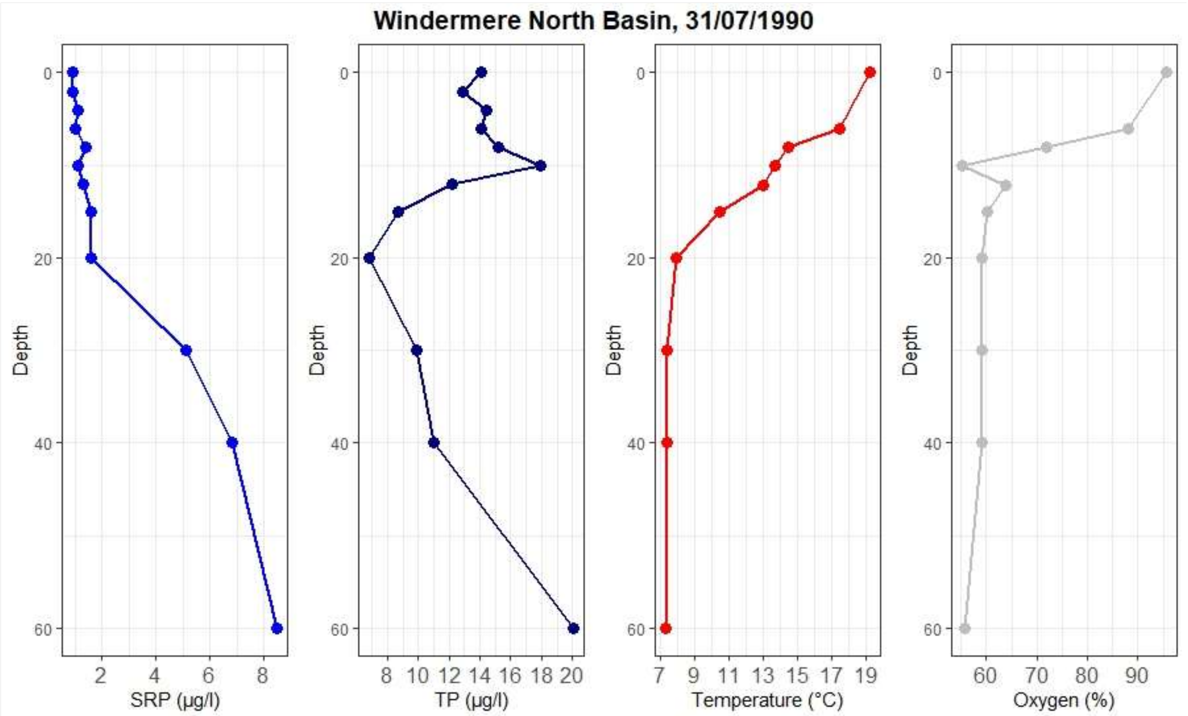
Direct quantification of sediment P in the North Basin was very limited, apart from one study conducted by Corry et al., documented across several interim reports from 1990-1992, which investigated sediment P dynamics in the Windermere basins from samples collected between 1989-1990. The reports suggest that 50% of the total P in the sediments is the mobile AEP fraction, which is likely iron-bound and sensitive to changes in the redox conditions (Corry et al., 1992; Reynolds et al., 1994). The South Basin had slightly higher concentrations of sedimentary mobile AEP of the two basins (e.g. mean AEP from the North Basin at sites >10m = 1577.7 μg g^{-1} DW, and from the South Basin at sites >10m = 1849.6 μg g^{-1} DW). These were attributed to the higher P loadings of Tower Wood WwTW compared to Ambleside WwTW (Corry et al., 1990; Maberly, 2008). A substantial body of work has been carried out investigating the eutrophication of the basin, although the most recent studies on this largely date from the mid-2000s. Most evidence indicates that eutrophication in Windermere from the 1980s onwards has been driven by WwTW and has been most pervasive in the South Basin (see Section 3.9.3).

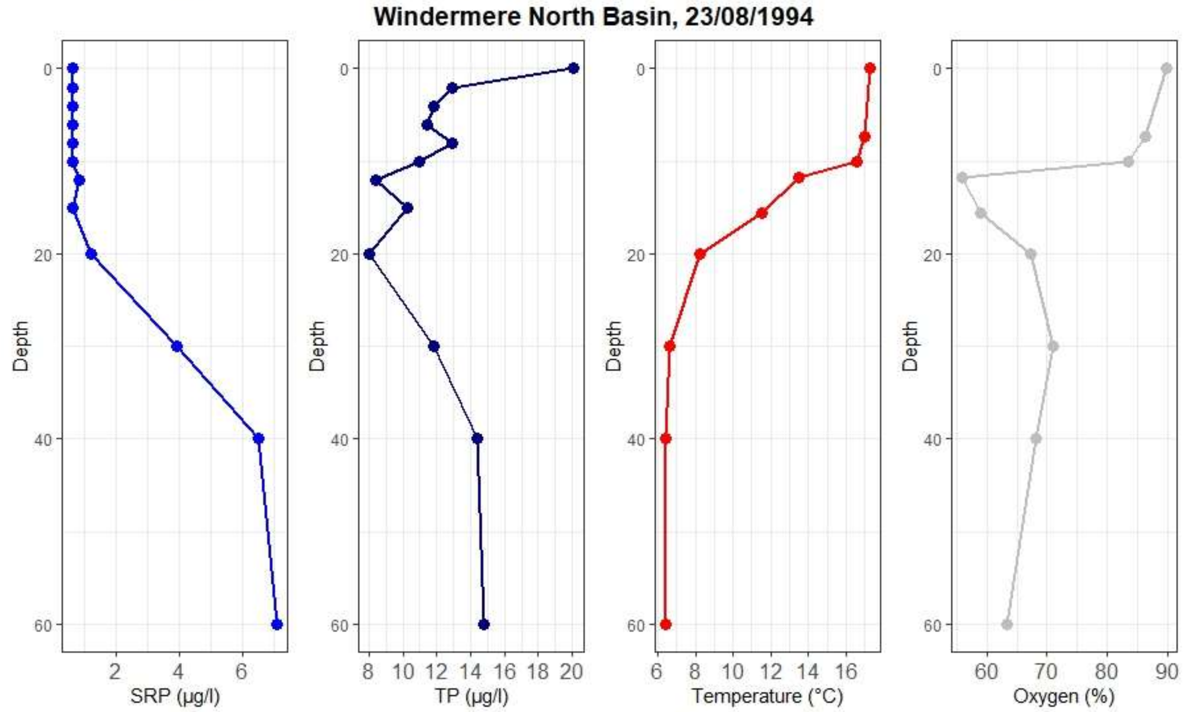
4.8.3 Evidence for internal P loading

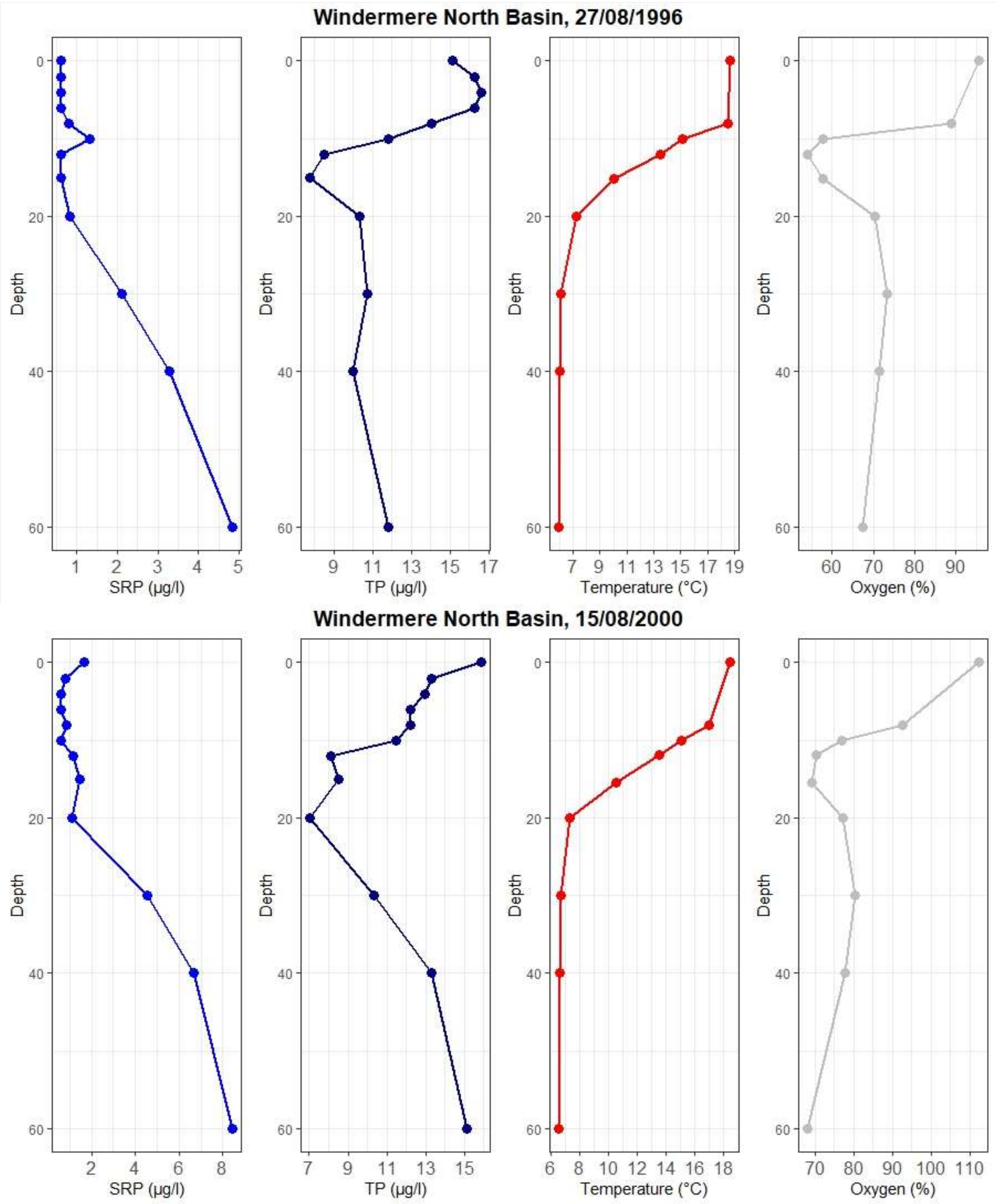
No evidence for the direct quantification of internal P loads were found for the North Basin. However, the lower biologically available P loads and larger volume of the North Basin has been attributed to its higher nutrient assimilation capacity in comparison to the South Basin (Reynolds et al., 2000; Maberly, 2008). Additionally, unlike the shallower basins in the catchment, hypolimnetic anoxia has not been recorded in the North Basin (see Section 3.8.1). Therefore, the less pervasive eutrophication and lack of benthic anoxia, indicate a lower risk of internal P loading here (Zhang et al., 2020). Despite this, there is still evidence of altered P dynamics which should not be discounted. For example, historic trends in TP indicate increasing loads and P budgets indicate key contributions from wastewater and inflows that will likely contribute to sediment P enrichment (Maberly, 2009). Tertiary P-removal was established in 1992 at both Ambleside WwTW whose outflow is in the North Basin and Tower Wood in the South, and again the most pronounced changes in P loads were evident in the South Basin (see Section 3.9.2), though P loads from Ambleside decreased from 2.2 to 1.09 Mg y^{-1} as estimated from data between 1978-1991 and 1993-2007 (Maberly, 2008). However, whilst estimates vary, tertiary treatment has been cited as reducing SRP concentrations by up to 50% in the North Basin, though no significant change in particulate P flux was noted (Reynolds et al., 1997). This may be due to the high TP content of the inflows which primarily drain into the North Basin (Maberly, 2009), with a significantly increasing trend in TP recorded from 1997 to 2005, corresponding to an increase in the average concentration of phytoplankton but no significantly significant trends in SRP (Maberly et al., 2006). Evidence from sedimentary biomarkers also indicates increasing algal productivity in the North Basin in recent years suggesting changes to the P dynamics in this basin (Moorhouse et al., 2018).

Depth profiles from the summer months between 1990-2008, as part of UKCEH long-term monitoring, provide evidence for historic changes in the water column (Fig. 3.18; Fig. 3.19). In the North Basin, TP and SRP concentrations in the surface 10m are as high as those concentrations at depth and declined within the thermocline, before increasing again from 20m to the deepest depth. SRP behaves slightly differently, with typically much lower concentrations in the surface ~20m and increasing below this point, though concentrations remain below 10 µg/l (Fig. 3.18). This pattern is likely a result of algal uptake depleting the surface biologically available P, with the accumulation of SRP at depth indicating either recycling of organic material within the water column and/or evidence for some internal loading. SRP concentrations from the deepest depth in Windermere's North Basin remained below 20 µg/l across the 1990-2008 period, though with some subtle changes (Fig. 3.19). From 1990-2000 values remained below 10 µg/l but with some years reaching 7-8 µg/l, but in 2001 values increased to 13 µg/l then fell to 6 µg/l before increasing to 10 µg/l in 2004, after which they declined to <8 µg/l again until 2008 (Fig. 3.19). Whilst there is interannual variation in the concentrations, the relatively low concentrations indicate that P accumulation at depth in the North Basin was not pronounced (Fig. 3.19). In addition, whilst oxygen values drop with depth, there is no evidence of anoxia (Fig. 3.18).

The low hypolimnetic SRP/TP concentrations suggests that historically, internal loading contributed relatively little to the P budget of the North Basin. However, the most recent of these depth profiles was carried out sixteen years ago, and therefore an up-to-date assessment of the conditions is not possible.


Windermere North Basin, 31/07/1990
Depth
0
20
40
60
2
4
6
8
SRP (µg/l)
8
10
12
14
16
18
20
TP (µg/l)
7
9
11
13
15
17
19
Temperature (°C)
60
70
80
90
Oxygen (%)


Windermere North Basin, 23/08/1994
Depth
0
20
40
60
2
4
6
SRP (µg/l)
8
10
12
14
16
18
20
TP (µg/l)
6
8
10
12
14
16
Temperature (°C)
60
70
80
90
Oxygen (%)


Windermere North Basin, 27/08/1996
Depth
0
20
40
60
1 2 3 4 5
SRP (µg/l)
9 11 13 15 17
TP (µg/l)
7 9 11 13 15 17 19
Temperature (°C)
60 70 80 90
Oxygen (%)
Windermere North Basin, 15/08/2000
2 4 6 8
SRP (µg/l)
7 9 11 13 15
TP (µg/l)
6 8 10 12 14 16 18
Temperature (°C)
70 80 90 100 110
Oxygen (%)

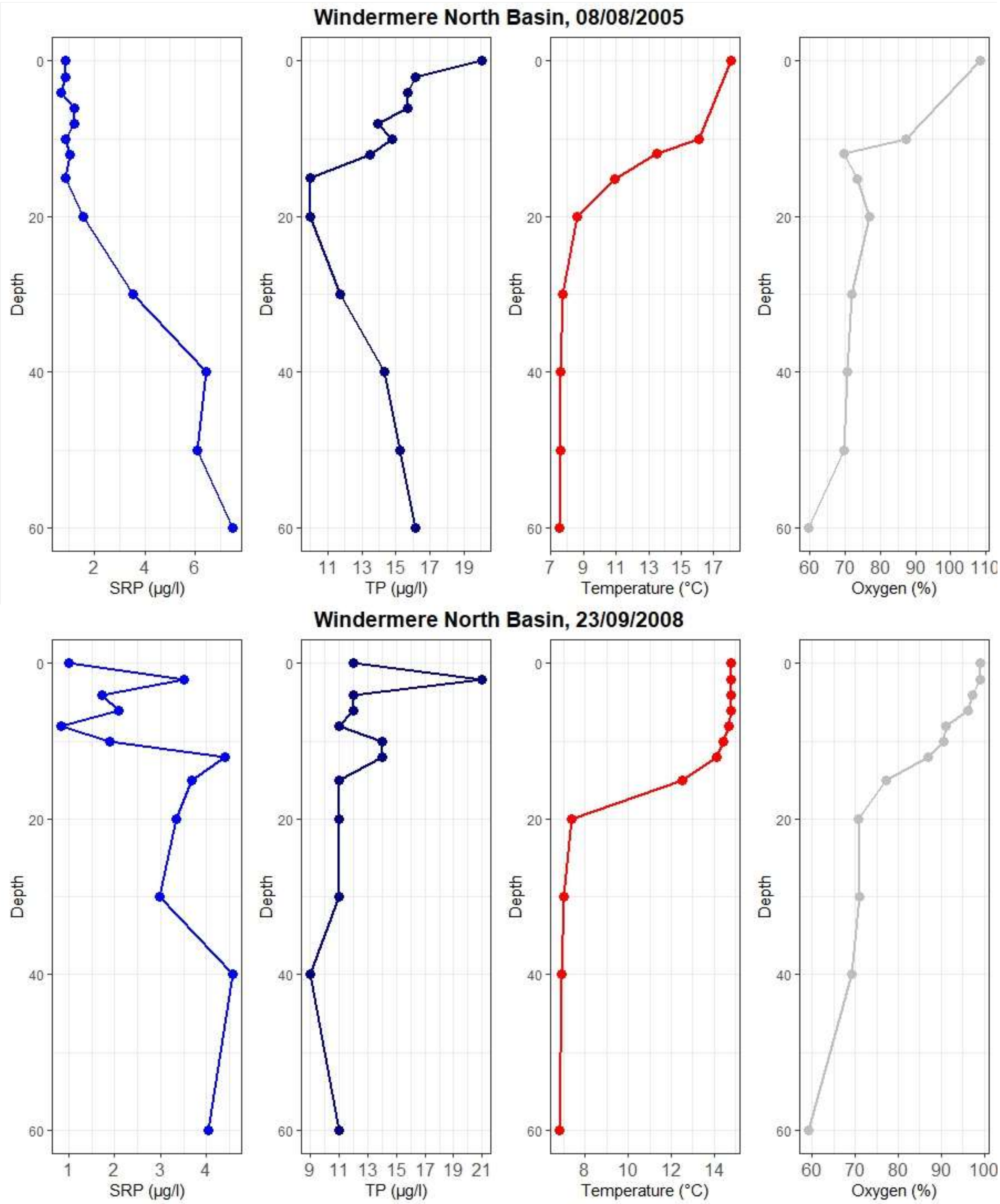


Figure 3.18. Depth profiles for the determinands Soluble Reactive Phosphorus (µg/l), Total Phosphorus (µg/l), Temperature (°C) and Dissolved Oxygen (mg/l) from Windermere North Basin from 1990-2008 at roughly every 5 years and including most recent dataset in 2008 (data for 1994 and 1996 provided as 1995 missing). Measurements taken on a single date in the year (detailed in the plot title) as part of UKCEH long-term lakes monitoring programme.

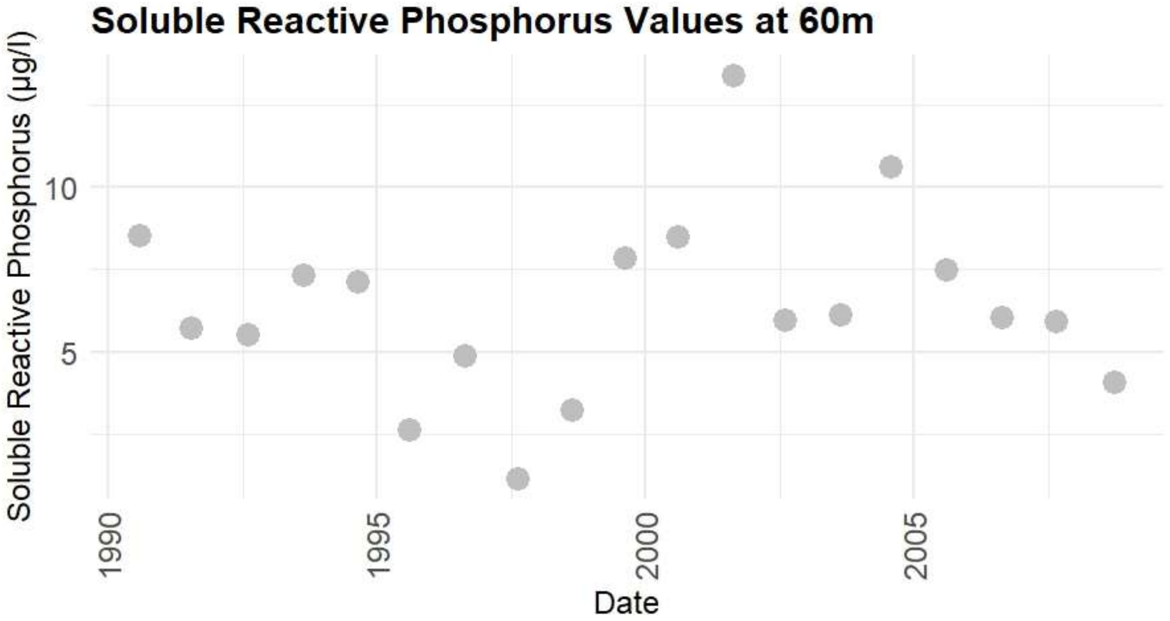


Figure 3.19. Annual Soluble Reactive Phosphorus concentrations (µg/l) of Windermere North Basin from water samples taken from the deepest depth (60m) from 1990-2008.

4.8.4 Assessment of evidence

The Windermere basins had the highest number of publications returned in this rapid review (Table 3) yet none had quantified internal loading. Much of the literature returned was focussed on surface water monitoring and external load mass-balance P estimates conducted before and after tertiary treatment installation, which did not consider internal P supplies. Whilst data from long-term limnological monitoring enabled an assessment of water-column P and oxygen concentrations throughout the depth of the basin, these data were from over a decade ago and only conducted sporadically once a year, thereby not capturing seasonal dynamics. Before tertiary treatment was implemented, P loads to the basin and hypolimnion were much higher as was hypolimnetic oxygen depletion, however anoxia was never recorded in the depth profiles provided in this review. Whilst there is evidence that stratification is being modified in the basin, oxygen concentrations, measured in the seasonal Lakes Tour survey in 2021 remained above 5 mg/l. Updates to P load estimates and quantification of sediment P fractions are required to understand sediment P dynamics and therefore, internal loading risk more accurately here.

4.9 Windermere South Basin

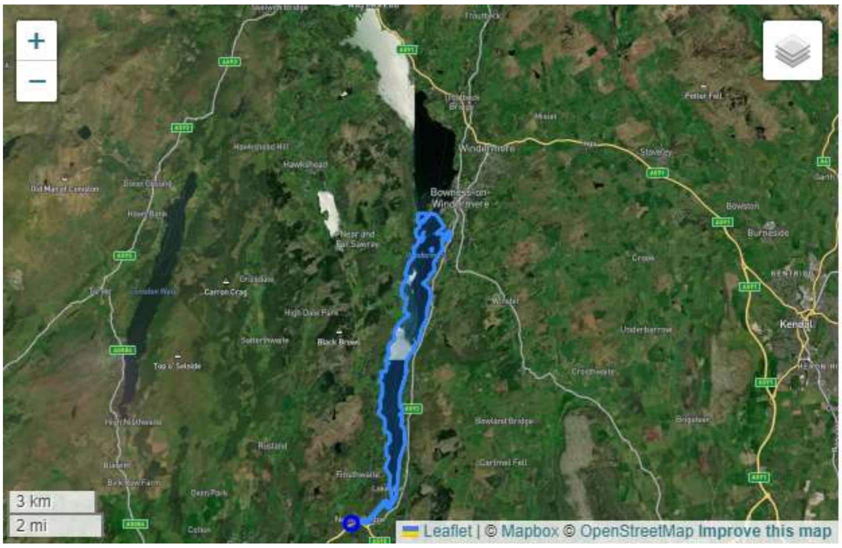


Figure 3.20 Satellite map of Windermere South Basin taken from UK Lakes Portal © UK Centre for Ecology & Hydrology 2023. Original source: Leaflet, ©Mapbox, © OpenStreetMap.

The South Basin of Windermere has a smaller volume and is shallower than its northern counterpart (Fig. 3.20). Its main inflows are the North Basin and Cunsey Beck, which drains the eutrophic Esthwaite Water, with its outflow being the River Leven at its south end (Fielding et al., 2020). The South Basin directly receives treated effluent from Tower Wood WwTW and indirectly from those that feed into the North Basin, as well as Hawkshead, Near Sawrey and Far Sawrey WwTWs whose effluent is released into Esthwaite Water and other tributaries upstream of the South Basin (McGowan et al., 2012), and non mains septic tanks and package treatment plants. From the mid to late 20th century, nutrient enrichment and hypolimnetic anoxia have been recorded in the South Basin (Reynolds & Irish, 2000; McGowan et al., 2012).

4.9.1 Oxygen conditions

Evidence for deep-water anoxia in the South Basin in the 1980s was recorded by both sedimentary analyses and monitoring. Firstly, in geochemical analyses of sediments originating from the 1980s, sediment anoxia is indicated by the pelletisation of sediment which often is due to enhanced benthic activity and the cessation of Fe and Mn laminae and decreasing sedimentary sulphur (Fielding et al., 2020). Monitoring of the lake revealed that anoxia in the basin occurred in 1981, 1983, 1985 and 1988 (Heaney et al., 1989; Reynolds et al., 1996). Hypolimnetic DO reduced by 70-85% from a baseline condition of 33.5 mg l^{-1} determined by Lund et al., (1963) as the basin-wide hypolimnetic DO value (using data collected in the late 1940s in late autumn when oxygen levels were at there most depleted) (Heaney et al., 1989). This reduction was driven by nutrient enrichment (Heaney et al., 1989).

The years with the highest depletions of deep-water DO were correlated with the increased production of the non-buoyant cyanobacterium *Tychonema bourrellyi* (J.W.G. Lund) Anagnostidis & Komárek, 1988, and the attendant decomposition following settlement of its filaments (Heaney et al., 1989; Mills et al., 1990; McGowan et al., 2012). The anoxia of this time was cited as affecting Arctic charr (*Salvelinus alpinus*) behaviour and survival (Reynolds, 1996b). Following the establishment of tertiary treatment in 1992, there were a few years in which some recovery of DO was noted, with concentrations not falling below 4 mg/l in the early 1990s (Reynolds et al., 1997). However, since then worsening DO depletion has been noted, although the decline has occurred at a much slower rate with minima often recorded in autumn and corresponding to *Tychonema bourrellyi* blooms during the 1990s (Heaney et al., 1996). In 2002, DO fell to 0.6 mg/l, the first time it had fallen below 1 mg/l since tertiary treatment, corresponding but not statistically related to the increased hypolimnetic temperatures of this year (Maberly et al., 2003).

Trends in the UKCEH Lakes Tour 2021 temperature-oxygen depth profiles at Windermere South Basin follow similar seasonal behaviour to that of the North Basin in 2021 (Fig. 3.18; 3.21). The biggest difference was that, in autumn, DO concentrations fell below 5 mg/l at 24m depth downwards, whereas in the North Basin concentrations did not drop this low.

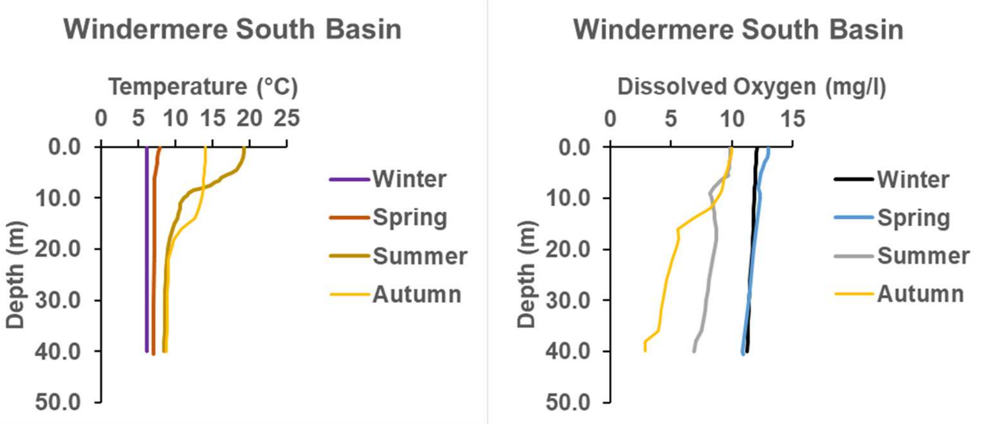


Figure 3.21 The seasonal depth profiles of Temperature (°C) and Dissolved Oxygen (mg/l) concentration for Windermere South Basin taken as part of the Lakes Tour 2021 (UKCEH). Spring data collected 14/04/2021, summer data collected 06/07/2021, autumn data collected 13/10/2021 and winter data collected 14/02/2022.

4.9.2 Sediment P enrichment

Geochemical analyses indicate persistent eutrophication in the South Basin from the 1980s onwards, with δ15N signatures indicative of sewage which is typically isotopically heavier (McGowan et al., 2012; Fielding et al., 2020). Around the same time, sediment traps found biogenic P flux to the sediment was greatest following the spring bloom. This flux was noted as being considerably greater in the South Basin compared to the North Basin (Corry et al., 1990) (see section 3.8.2). Whilst concentrations were not deemed overtly excessive in either basin (compared to Esthwaite Water for example), deeper sediments in both basins had higher concentrations than those in shallow waters (Corry et al., 1990; Corry & Lishman, 1991). The authors could not easily relate the patterns in the sediment P concentrations to biogenic fluxes alone but suggested focussing of shallow-water sediments into deeper areas, with an increased frequency of resuspension of particulate and leachate material from decomposing algae in shallow sediments and interstitial waters as reasoning for the spatial variation in sediment P content (Corry et al., 1990; Corry & Lishman, 1991). This phenomenon of 'sediment focussing' to the deepest overlying water depths is a common characteristic in the redistribution of sediments and elements bound within them in many lakes.

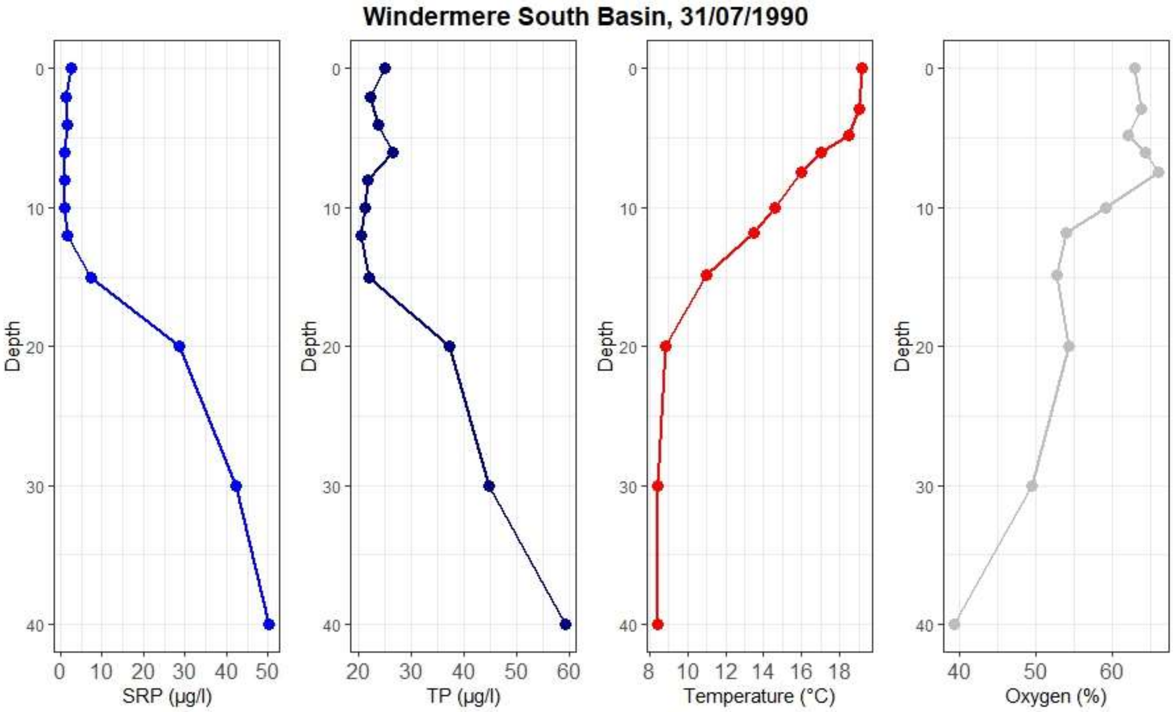
The establishment of tertiary treatment in 1992 at Tower Wood WwTW led to a notable improvement to the P loading of the South Basin, with the annual P loads reduced by half and the SRP fraction being reduced by a third as estimated from comparing data between 1978-1991 and 1993-2007 (Maberly et al., 2008). The P load from Tower Wood fell from an estimated 5.85 to 2.82 Mg y-1 though combined sewer overflows were not included in this analysis (Maberly et al., 2008). Seasonal differences were noted, with summer P loadings greater than winter from both WwTWs at Windermere, though Tower Wood was identified as responsible for 3x the load of Ambleside WwTW (Maberly et al., 2008). Whilst these reductions were commended, WwTWs remained the largest contributor of P to both Windermere basins, estimated to account for 37% of TP and 66% of SRP, with percentages slightly higher for Tower Wood than the averages presented here (Maberly et al., 2008). Updates to these estimates in 2009 were broadly similar, with TP and SRP loadings estimated at 29% and 51% respectively, from WwTWs, whilst inflowing streams contributed the highest TP (71%) and second highest (49%) load (Maberly, 2009). The influence on phytoplankton was immediate, with a reduction in chlorophyll a maxima and cyanobacterial blooms (Reynolds et al., 1997). Monitoring of the P flux to the sediments of the South Basin in the first few years following tertiary treatment in 1992, did not show a reduction in particulate flux but an increase in range from 40-60 µg P cm^2 $month^{-1}$ in 1992 to 20-60 µg P cm^2 $month^{-1}$ in 1996 (Reynolds et al., 1997). Similarly, the AEP content of the sediments did not change during this period with no difference between the north and South Basins though a prominent difference between shallow (<10m) and deeper (>10m) waters (Reynolds et al., 1997). Interestingly, in 1994, poor removal performance was noted following an increase in loading compared to the previous year from 3.94 to 5.74 Mg y^{-1} (Reynolds et al., 1996b). However, since 1995, there has been a decline in the annual maximum water column SRP concentration (Maberly et al., 2006), with research needed to understand if this has translated to the P concentration in the sediments.

4.9.3 Evidence for internal P loading

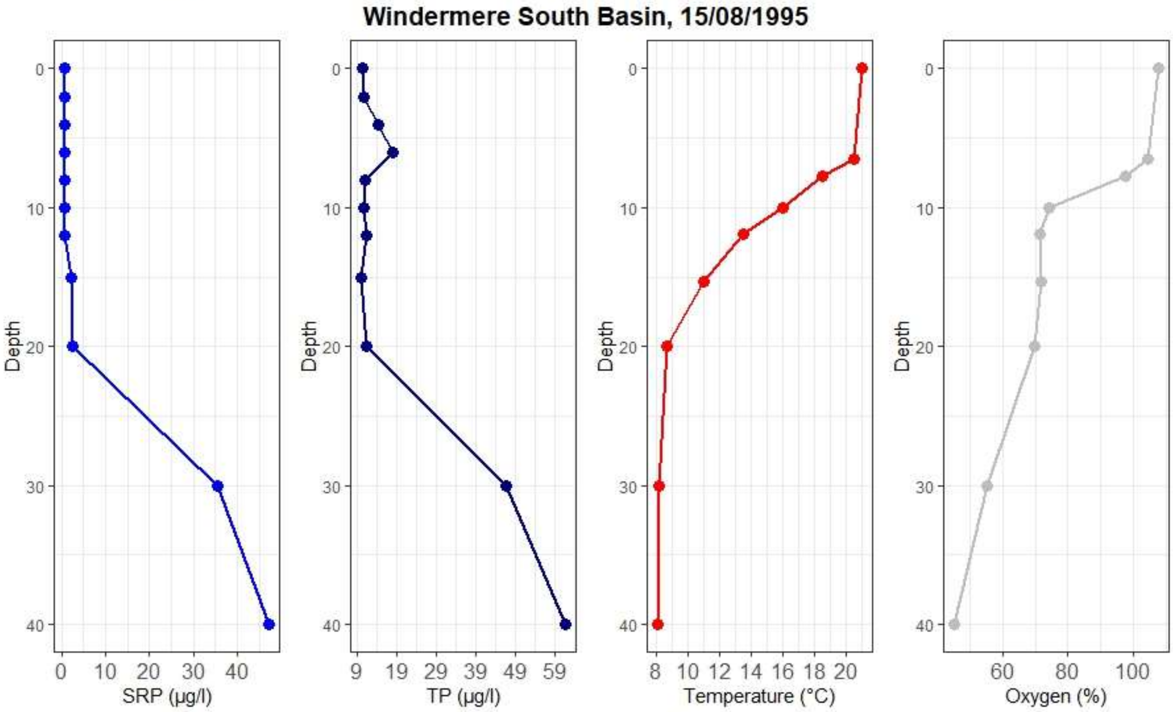
Historical evidence for internal P release stems from monitoring and modelling observations, and sedimentary analyses. In the late 1980s, the South Basin had high SRP concentrations in the hypolimnion (up to 100x that of surface concentrations) at the same time as anoxia occurred in late autumn (Heaney et al., 1996; Corry et al., 1992). The model PROTECH (Phytoplankton RespOnses To Environmental

Change) which simulates *in situ* dynamics of phytoplankton in lakes and reservoirs, noted a discrepancy with model output and the driving data from 1998, in which the observed P data was slightly higher than the modelled (6.8 vs 5.6 mg m^{-3}) (Maberly & Elliott, 2009). Internal P loading was suggested as a potential mechanism to resolve this discrepancy, with observations of anoxia and elevated hypolimnetic SRP in summer used to support the suggestion (UKCEH unpublished) (Maberly & Elliott, 2009). Finally, analyses of sediments indicate historical internal P loading in the South Basin from the presence of Fe oxyhydroxides in the top few cm of sediment of a core collected in 2014, which can indicate redox mobilisation from P recycling (Fielding et al., 2020).

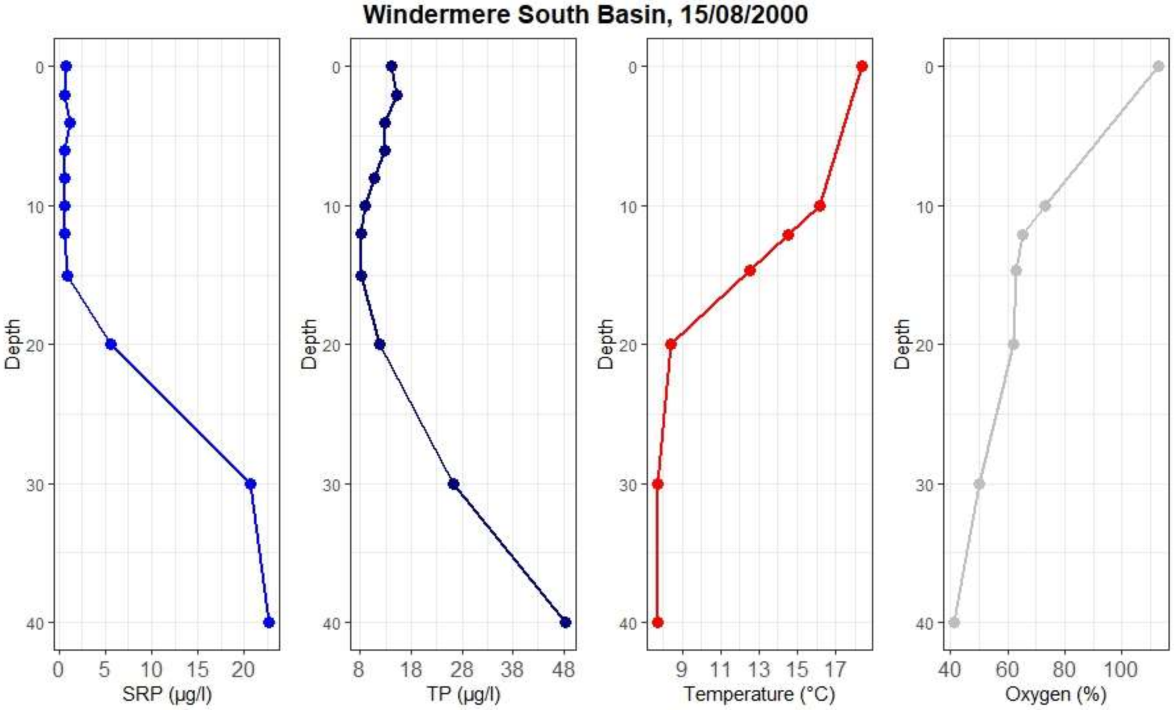
The UKCEH long-term monitoring depth profiles from 1990-2008 in the South Basin confirm these findings, showing TP/SRP values were greatest below ~20m depth, below the thermocline (Fig. 3.22). These values are much higher than those from the North Basin (see Fig. 3.18). Interestingly, the lowest values of TP and SRP occur in 2000 and 2008, whereas the highest TP and SRP measurements are recorded in 2005 with values ~50µg/l and ~80µg/l, respectively. DO concentrations were lowest below the thermocline, with the deepest depth at 40m having the lowest value. In 1990, this was ~4 mg/l but thereafter this remained above 5 mg/l. Much like the North Basin, for most years, there was a drop in concentrations within the thermocline. The accumulation of P within the hypolimnion indicated a potential for internal loading, but the lack of anoxia reduced the associated risk (Zhang et al., 2020). Anoxia in this basin has typically been observed in later months (Sept-Nov) so it is also possible that monitoring missed these anoxic episodes. An alternative source of hypolimnetic P, could be from continued external P loads, converted into liable organic matter via spring and summer phytoplankton growth, providing P to bottom waters and sediments from algal decomposition, with stratification preventing the replenishment of nutrients from bottom to surface waters. In other words, P enrichment of the hypolimnion is driven by organic matter remineralisation rather than sediment P release.

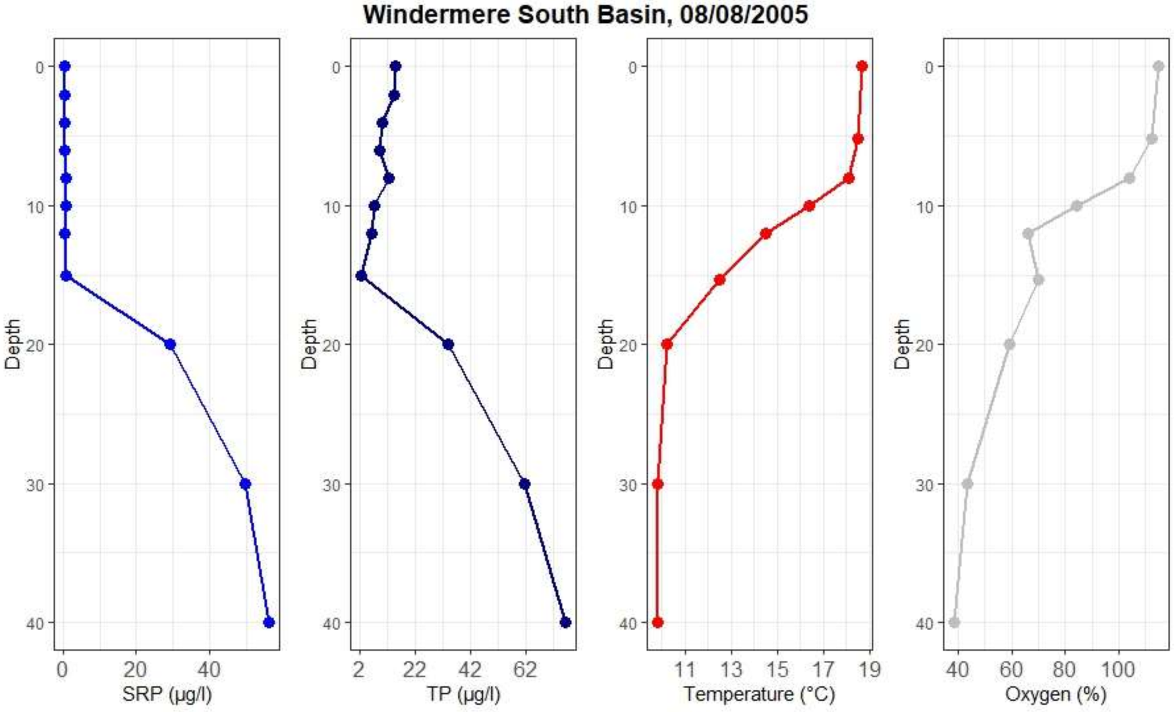


Windermere South Basin, 31/07/1990



Windermere South Basin, 15/08/1995


Windermere South Basin, 15/08/2000
Depth
0
10
20
30
40
SRP (µg/l)
0 5 10 15 20
TP (µg/l)
8 18 28 38 48
Temperature (°C)
9 11 13 15 17
Oxygen (%)
40 60 80 100


Windermere South Basin, 08/08/2005
Depth
0
10
20
30
40
SRP (µg/l)
0 20 40
TP (µg/l)
2 22 42 62
Temperature (°C)
11 13 15 17 19
Oxygen (%)
40 60 80 100

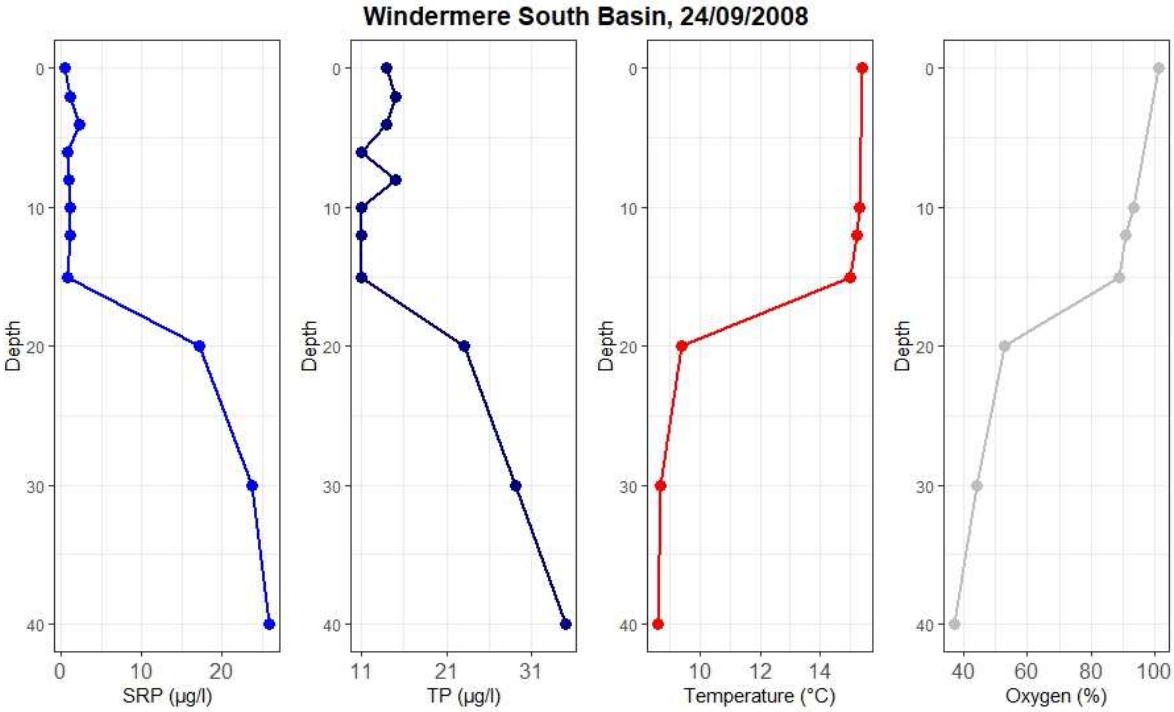


Figure 3.22 Depth profiles for the determinands Soluble Reactive Phosphorus (µg/l), Total Phosphorus (µg/l), Temperature (°C) and Dissolved Oxygen (mg/l) from Windermere South Basin from 1990-2008 at every 5 years and including most recent dataset in 2008. Measurements taken on a single date in the year (detailed in the plot title) as part of UKCEH long-term lakes monitoring programme.

Concentrations of SRP at greatest depth (40m) in the South Basin from 1988-2008 show substantial interannual variation and, in contrast to the North Basin, continually have values above 20 µg/l (Fig. 3.23; Fig. 3.18). In 1998, the values dropped below 10 µg/l but thereafter remain above 20 µg/l. Prior to the mid-1990s and tertiary treatment at Tower Wood WwTW, concentrations were typically above 40 µg/l, whereas after they were typically below, indicating some success of this remediation measure. However, the later years where values again begin to exceed 40 µg/l may demonstrate the role climatic variability in internal P supply and/or dynamics in other P sources, which have been found to shape interannual stratification patterns and nutrient dynamics (Reynolds et al., 1994).

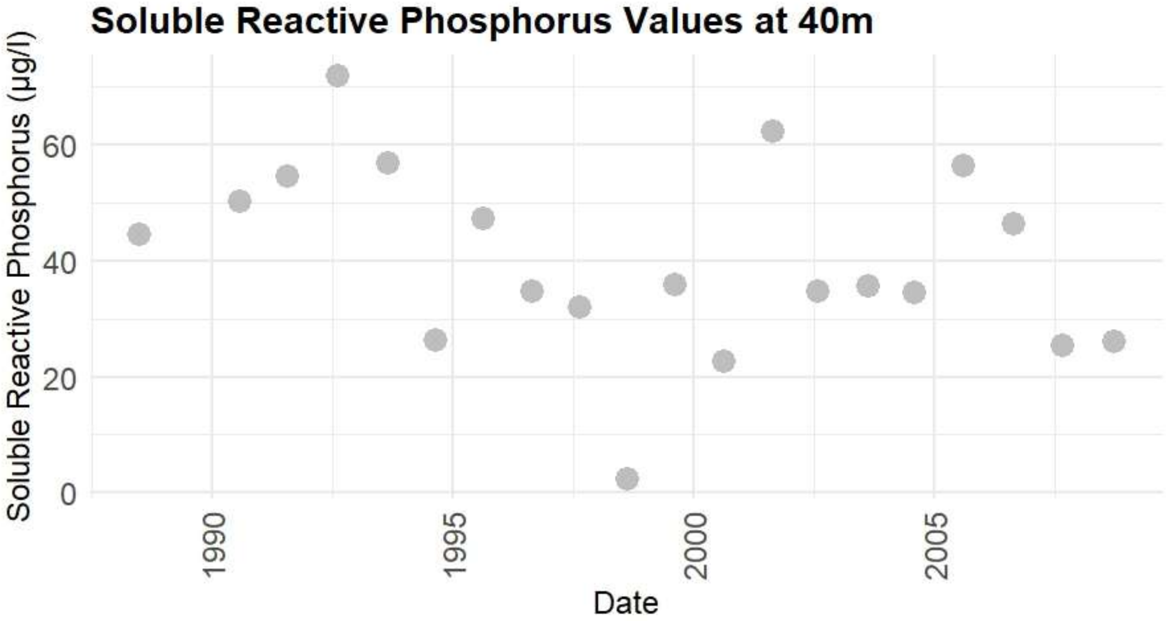


Figure 3.23 Annual Soluble Reactive Phosphorus concentrations (µg/l) of Windermere South Basin from water samples taken from the deepest depth (40m) from 1988-2008.

4.9.4 Assessment of evidence

The literature captured by this review suggests that internal P loading is likely to have been an issue in the 1980s just before the installation of tertiary treatment, supported by geochemical evidence in the sediments and anoxia reported by long-term monitoring. The contribution that this internal P source to the lake P budget was not directly quantified. The success of wastewater remediation is denoted by some recovery of oxygen at depth. However, the presence of mobile P in the sediments and high concentrations of P at depth recorded after the initiation of tertiary treatment, coupled with low autumnal oxygen at the sediment/water interface (~2.5 mg/l) recorded by the UKCEH Lakes Tour 2021, indicates that the lake is still at risk of internal P loading. Although no studies on the deep-water accumulation of P have taken place since 2008 and little is known about whether internal loading contributes significantly to the P budget of the lake or how this may vary seasonally.

5. Conclusions, Implications & Recommendations

This study has considered the evidence for sediment nutrient enrichment and risk of internal loading across eight of the larger lakes of the Windermere catchment. Based on literature searches and use of historical data, we draw the following conclusions:

Historic and contemporary nutrient enrichment

- All basins in the catchment have evidence of historic and current P enrichment of their waters from external sources. This implies that sediment P enrichment is likely across all eight lakes albeit to different magnitudes.
- At sites such as Blelham Tarn, Esthwaite Water and Elterwater, mass-balances have relied more-heavily on estimates and the deduction of internal P loading, following quantification of external supplies and water column nutrient dynamics. In contrast, historic P budgets in the Windermere basins did not include internal sources in their calculations, though sedimentary and monitoring investigations suggest historic internal P loading in the South Basin.

The literature returned in this rapid review points to external catchment sources of P as being the dominant P sources to the lakes of the Windermere catchment. It is therefore recommended that the primary step in reducing the risk of internal P loading is quantifying and managing these external supplies.

Oxygen conditions

- All the smaller, shallower lakes in the catchment (i.e. Blelham Tarn, Esthwaite Water, Elterwater,Grasmere, Loughrigg Tarn and Rydal Water) undergo seasonal anoxia, thereby increasing their risk of redox-mediated internal P release.
- The South basin of Windermere has shown recovery from seasonal anoxia since tertiary treatment was implemented. This implies internal loading reduced following this intervention. However, more recent oxygen data implies conditions have again deteriorated, although anoxia was not recorded during the 2021 Lakes Tour survey.
- Gaps in the seasonal data available for Loughrigg Tarn warrant collection of further seasonal depth-oxygen profiles here, particularly considering the summer anoxia at the sediment/water interface recorded in the UKCEH Lakes Tour 2021.

- Evidence from lakes such as Grasmere and Blelham Tarn, indicate a long-term trend in increasing area and duration of seasonal anoxia (e.g. Foley et al., 2012). This increase in the time period over which internal loading could occur and therefore its importance in the lake nutrient budget suggests that there is a need to monitor the oxygen conditions in all the Windermere catchment lakes, with more routine temperature-oxygen depth profiles recommended.

Sediment P enrichment

- Sediment P concentrations including TP and AEP-fractions have been directly quantified at Elterwater, Esthwaite Water, and the North and South Basins of Windermere.
- In Elterwater's inner basin, mean TP concentrations exceeded 5000 μg g−1 DW with mean mobile AEP concentrations ~3900 μg g−1 DW from sediments collected in 2014 (Mackay et al., 2015, 2020). Compared to earlier assessments by Parker et al., (2003) there has been a shift to a greater proportion of mobile AEP comprising the TP of the inner basin. The values of the inner basin are much greater than those of the middle and outer basins.
- At Esthwaite Water, Anderson (2018) recorded TP concentrations in the central basin of 3034 μg g-1 DW and AEP concentrations of 2628 μg g-1 DW from sediments collected in 2014.
- Sediments retrieved in 1989/1990 from the North and South Basins of Windermere recorded mean AEP from the North Basin at sites >10m = 1577.7 μg g-1 DW, and from the South Basin at sites >10m = 1849.6 μg g-1 DW (Corry et al., 1992).
- These data indicate Elterwater inner basin as having the highest concentrations of TP and AEP, followed by Esthwaite Water. The data from Windermere South Basin and Windermere North Basin suggest the sediments were less enriched, however, these data are now over thirty years old and therefore the values are likely to have changed in this time. The sediment TP data places the sediments of both Elterwater and Esthwaite Water into the eutrophic category of the lake categorisation done by Carey and Rydin.
- Given the seasonal anoxia and smaller size and volume of Elterwater inner basin compared to the other sites, internal P loading may be a major contributor to the lake's P budget. Up-to-date assessments of TP and AEP fractions at Elterwater would help assess whether the diversion of water in 2016 into the inner basin has reduced these concentrations. Indeed, updates to sediment P conditions at all the lakes would be recommended given these data were obtained a decade or more ago.

- Studies investigating sediment P found deep sediments had higher total and mobile P concentrations compared to shallow sediments, even when littoral areas were a source of P themselves. Indeed, considerable inter-basin variability in the sediment P fractions can be a result of several factors including proximity to and the nature of, external P sources (i.e. Anderson, 2018).
- At Blelham Tarn, Grasmere, Loughrigg Tarn and Rydal Water no studies have conducted direct measurements of sediment P. It would therefore be recommended to retrieve sediment cores from these sites and conduct TP/AEP analyses, especially given their shallow depth, eutrophic histories, and susceptibility of hypolimnetic anoxia.

Internal P loading

- Whilst the Windermere catchment lakes remain some of the best studied lakes in the world, internal P loading and its contribution to the current P budget of the lakes remains largely unquantified in all but Esthwaite Water. At Esthwaite Water, a direct quantification of external and internal P budgets found that internal P loading contributed ~14% of the annual P load to the lake (Anderson et al., 2018).
- Historic monitoring data provide evidence for elevation of P in the hypolimnia of Esthwaite Water and Windermere North and South Basins. This hypolimnetic P increase in Esthwaite Water was over 10x the concentrations of the Windermere Basins in the late 2000s. This indicates Esthwaite Water has the highest internal P recycling potential of these three basins. More recent campaign-based measurements, as part of PhD research has also identified elevated hypolimnetic P concentrations at Blelham Tarn and Elterwater.
- The absence of literature returned for Loughrigg Tarn and Rydal Water means that it is not possible to assess the state of sediment nutrient enrichment or the role of internal P loading in these lakes. Further investigation would be needed to determine their risk of internal P loading, with seasonal temperature, oxygen, and nutrient depth-profiles, a useful first step.
- To accurately assess the spatial and temporal external versus internal P sources in the Windermere catchment lakes, mass-balance assessments would be recommended.

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