Lakes Tour 2021

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Executive summary

1. This Lakes Tour 2021/22 report presents results and analysis from a seasonal survey of the limnology of the 20 major lakes and tarns in the English Lake District, undertaken in April, July, October and November 2021 and January and February 2022. This most recent Lakes Tour is a continuation of similar tours carried out in 1984, 1991, 1995, 2000, 2005, 2010 and 2015.
2. In each seasonal sampling campaign, depth-resolved profiles of water temperature and dissolved oxygen concentration were measured, and Secchi depth determined. An integrated surface water sample was analysed for pH, alkalinity, major anions and cations, plant nutrients, phytoplankton chlorophyll *a* and species composition and, during the July sampling, heavy metals and micro-organic pollutants. In addition, a vertical trawl was carried out to quantify the crustacean zooplankton community abundance and species composition.
3. All lakes in the survey thermally stratified; surface water temperature and the temperature difference between the surface and bottom water were both at their maximum during the summer. Oxygen depletion at depth occurred for the more productive lakes during summer and autumn.
4. Secchi depth varied across the lakes from >10 m in the unproductive lakes such as Buttermere, Crummock Water and Wastwater, to <2 m in more productive lakes such as Blelham Tarn and Esthwaite Water. There has been a significant decline in Secchi depth over the long term at some of the unproductive lakes.
5. The general pattern of major ion concentration varies across the lakes as a function of the underlying geology. Higher ionic concentrations occur on the generally softer geologies of the south lakes, whilst lower buffering capacity and higher propensity to acidify are more typical of lakes that are underlain by the more acidic Borrowdale volcanics and igneous intrusions of the western and central lakes. The concentration of major ions in the lakes has been significantly declining over time.
6. Nutrient concentrations varied during the year. Peaks in nutrient concentration tended to occur during the winter period and seasonal draw down for phytoplankton growth was evident for soluble reactive phosphorus (SRP), nitrate (TON) and silica. The highest TP concentrations were measured in Bassenthwaite Lake, Elterwater and Esthwaite Water. Loughrigg Tarn had the highest

concentration of nitrate. Ammonium was only detected in seven lakes above the limit of detection and could be indicative of internal nutrient supply in these systems. Silica concentrations were highest in Bassenthwaite Lake and Blelham Tarn in the winter.

7. Chlorophyll *a* concentration was used as a measure of phytoplankton biomass or abundance. Large seasonal variations of phytoplankton chlorophyll *a* were seen, with peaks generally associated with spring and summer communities. Large phytoplankton blooms occurred in summer samples at Blelham Tarn, Elterwater, Esthwaite Water and Loughrigg Tarn.
8. Long-term trends in the concentrations of nutrients and chlorophyll *a* were largely not significant, although the direction of the long-term trend was negative. Over the short term however, TP concentrations have increased in some lakes. This change needs to be watched since phosphorus availability is a key driver of phytoplankton growth across these lakes. A long-term change in the TP:chlorophyll *a* ratio is also reported, which implies that more phytoplankton growth may be expected for the same amount of phosphorus. A significant long-term decline in nitrate concentration has occurred since 1984.
9. The phytoplankton community across all the lakes was diverse, with representatives from all the major groups. The communities within each lake showed patterns of seasonal succession with varying dominance by different groups or individual taxa in each season. The most diverse period was typically the summer and the least diverse was the winter. There was some indication that cyanobacteria diversity was higher in more productive lakes.
10. Zooplankton communities showed some similarities among lakes, including a dominance of calanoid copepod species in spring, autumn and winter. Cladocera and rotifer abundances were more varied among lakes. Seasonal peaks for different genera including *Ceriodaphnia*, *Daphnia*, *Bosmina* and *Asplanchna* occurred in specific lakes.
11. Heavy metal concentrations were measured in the summer only. Concentrations were generally low, with most being below the limit of detection and these values were similar to those reported in 2015. Ennerdale Water and Loweswater were the lakes where the heavy metal concentrations most frequently exceeded the limit of detection.

12. Four micro-organic compounds were detected at levels above the detection limit at some sites in the summer of 2021. These were Diazinon, 2,4-Dichlorophenoxyacetic acid, MCPA and PAA. Of these, PAA was detected most frequently, occurring at measurable concentrations in 11 lakes.
13. Changes in the number of lakes being classified as being at Good ecological status or above have occurred since the last survey. There has been an overall decline in the number of lakes achieving this level based on TP concentrations, whilst there has been a continued improvement in the number of lakes at Good or better ecological status based on the measured chlorophyll *a* concentration.
14. Suggestions for further work are made to investigate the drivers of change observed in the Secchi depth, the changes to the TP:chlorophyll *a* ratio, the declines observed in minimum oxygen concentration, the indications of increasing nutrient concentrations at some sites, the deteriorating water quality at Esthwaite Water, and knowledge gaps around the fish populations in the lakes.

1 Introduction

The English Lake District has a long history of environmental monitoring dating back to the 1920s. The major lakes of the region have historically been sampled by the Freshwater Biological Association prior to 1989 and more latterly by the Natural Environment Research Council (NERC) research institutes, the Institute of Freshwater Ecology and its successor the Centre for Ecology & Hydrology. The current survey has been led by the newly independent charitable research institute the UK Centre of Ecology and Hydrology, which separated from NERC in 2019. In the early part of the twentieth century, Pearsall (1921) ordered eight of the major lakes according to trophic status, a factor that was related to their surrounding geology and land use. These lakes ranged from the unproductive, e.g. Wastwater, situated in steep catchments of hard volcanic rocks with very shallow soils to the more productive e.g. Esthwaite Water, which lie on softer rocks in fertile valleys with deep alluvial soils. The English Lake District is particularly unusual in having a wide range of lake types in such a small geographic area.

Over the last century a number of surveys of the English Lakes have been carried out (Pearsall 1932; Gorham et al. 1974; Jones et al. 1979; Kadiri and Reynolds 1993). Some of these data were reviewed by George (1992) and Talling (1999). The current form of the ‘Lakes Tour’ comprising twenty major lakes and tarns started in 1984. The Lakes Tour survey has been repeated on a roughly five-yearly interval since that time: 1991, 1995, 2000, 2005 and 2010 (Hall et al. 1992, 1996; Parker et al. 2001; Maberly et al. 2006a, 2011, 2016). Sampling for the survey is done on a seasonal basis, which is of too low a frequency to capture the shorter-term dynamic state of lake environments (hourly to monthly changes), but instead provides a snapshot of change over the year. Despite the low sampling frequency, the Lakes Tour dataset provides a robust and fairly comprehensive picture of how lakes have responded to long-term environmental pressures because of its methodological consistency. It can also be used to identify patterns of water quality changes across the region and provide an indicator of where further investigations of changes at individuals lakes are warranted.

The English Lake District is England’s largest national park. It has a long history as being a tourist destination which dates from the 18th century and it is now a very popular tourist region in the UK. The appeal of the area is a result of a combination of dramatic landscapes, combining mountains, glacial valleys and lakes with the heritage and cultural appeal of several artistic and conservation movements. As a result, the area was designated as a UNESCO World Heritage Site in 2017. Similar to much of the natural environment, human pressures on the area have grown over time, which have impacted on the water quality of the lakes. Inputs of sewage from tourist activities and the local population, combined with changes in the intensity of agriculture, industrial pollutants, climate change and introduction of invasive non-native species places multiple ecological pressures on the lakes.

The current legislation in the UK that covers the protection of ecological quality in lakes originates from the European Commission in 2000. The Water Framework Directive (WFD; 2000/60/EC), which has been enshrined in UK law places a legal duty on the Environment Agency to manage inland, estuarine and coastal water, including lakes, to prevent further deterioration and to improve their ecological quality. More recently, the 25 year Environment Plan and subsequent Environment Act 2021 sets out targets for the improvement of the environment over the longer term. Quality or ecological status is determined partly by water chemistry but more by a range of ecological characteristics including the composition and abundance of phytoplankton. The data from the Lakes Tour have been used to help determine ecological quality boundaries for the implementation of the WFD.

In addition to the range of variables measured as part of the original surveys, the Lakes Tour in 2021/22 included measurements of heavy metals and micro-organic pollutants during the summer sampling period and sample for eDNA analysis were collected.

2 Methodology

2.1 Sites

Twenty lake basins were surveyed, including the two basins of Windermere (North and South), as part of the Lakes Tour 2021/22. Their location and catchments are shown in Figure 1 below and summary characteristics provided in Table 1.

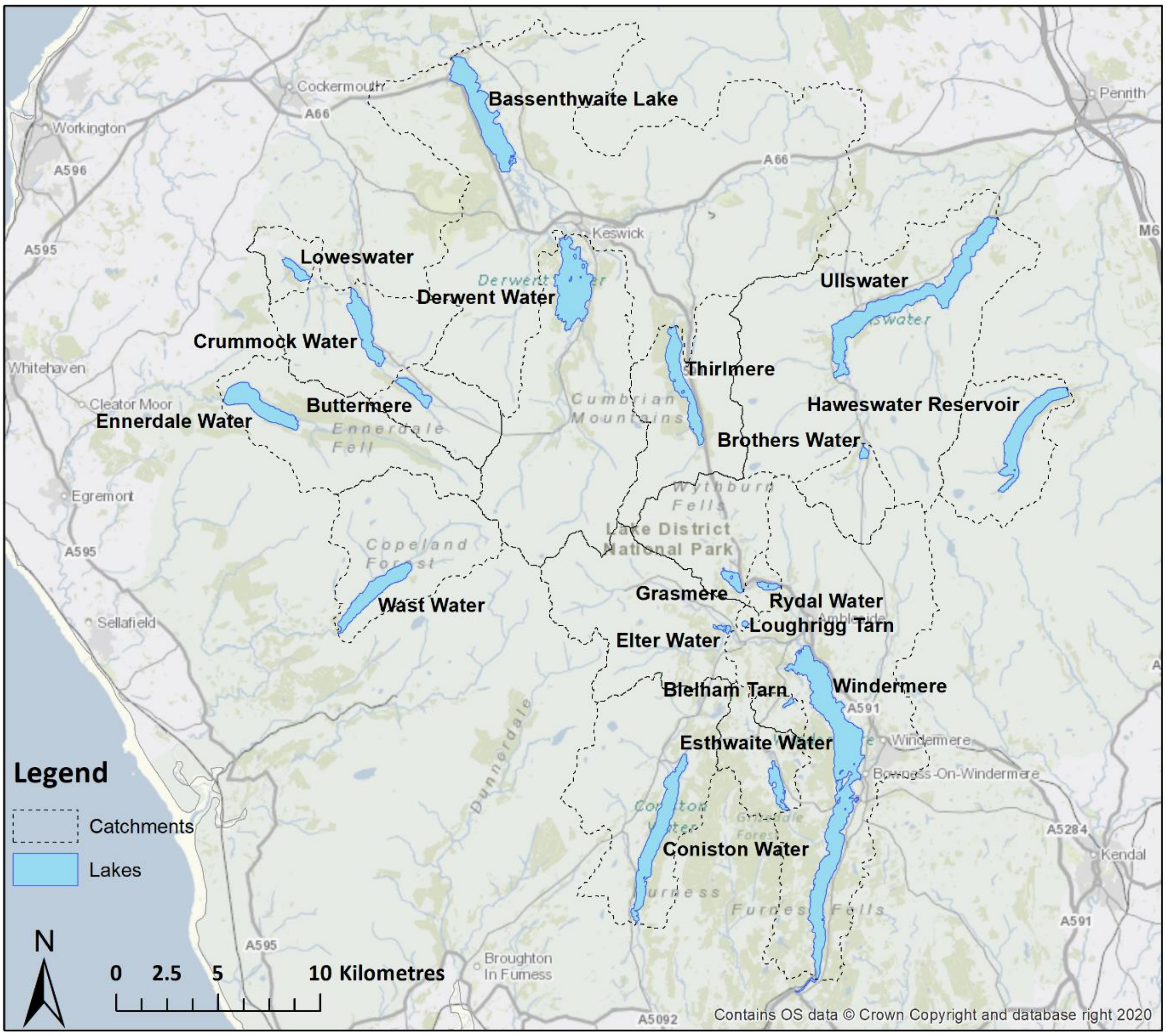


Figure 1 Location of the twenty lakes which make up the Lakes Tour sites and their catchment boundaries

Table 1 Lake and catchment characteristics for the twenty lake basins sampled in the Lakes Tour

Lake	Catchment area (km^2)	Mean catchment altitude (m)	Lake altitude (m)	Lake length (km)	Max. width (km)	Area (km^2)	Volume (m^3 x 10^6)	Mean depth (m)	Max. depth (m)	Approx. mean retention time (days)
Bassenthwaite Lake	360	333	69	6.2	1.10	5.3	27.9	5.3	19.0	30
Blelham Tarn	4.3	105	47	0.67	0.29	0.1	0.7	6.8	14.5	50
Brothers Water	13.2	437	161	0.60	0.40	0.2	1.5	7.2	15.0	21
Buttermere	18.7	377	101	2.0	0.54	0.9	15.2	16.6	28.6	140
Coniston Water	62.5	227	44	8.7	0.73	4.9	113.3	24.1	56.1	340
Crummock Water	62.7	327	98	4.0	0.85	2.5	66.4	26.7	43.9	200
Derwent Water	85.4	354	75	4.6	1.91	5.4	29.0	5.5	22.0	55
Elterwater	1.0	108	74	1.0	0.4	0.03	0.1	3.3	7.0	20
Ennerdale Water	43.5	374	112	3.8	1.10	3.0	53.2	17.8	42.0	200
Esthwaite Water	17.0	148	65	2.5	0.62	1.0	6.7	6.9	15.5	100
Grasmere	30.2	328	62	1.6	0.60	0.6	5.0	7.7	21.5	25
Haweswater	32.3	463	240	6.9	0.90	3.9	76.6	23.4	57.0	500
Loughrigg Tarn	0.95	175	99	0.4	0.3	0.07	0.5	6.9	10.3	117
Loweswater	8.2	243	121	1.8	0.55	0.6	5.4	8.4	16.0	150
Rydal Water	33.8	312	57	1.2	0.36	0.3	1.5	4.4	18.0	9
Thirlmere	53.8	398	179	6.0	0.78	3.3	52.5	16.1	46.0	280
Ullswater	147	393	145	11.8	1.02	8.9	223.0	25.3	63.0	350
Wastwater	42.5	385	61	4.8	0.82	2.9	115.6	40.2	76.0	350
Windermere North Basin	175	231	39	7.0	1.6	8.1	201.8	25.1	64.0	180
Windermere South Basin	250	231	39	9.8	1.0	6.7	112.7	16.8	42.0	100

2.2 Sampling

Location and dates

Where possible, each lake was sampled from approximately the deepest point, and these locations are provided in Table 2. Bad weather on nine occasions meant that it was not possible to launch a boat and a shoreline dip sample had to be taken instead. In previous surveys, the aim was to collect all samples within a two-week period, weather permitting. Owing to staff shortages and the loss of in-kind support during the 2021 survey, this condition was not met. Sampling occurred over 23 days in April, 22 days in July, 39 days in October and November and 30 days in January and February. The date each lake was sampled is given in Table 2. Overall, UKCEH sampled lakes on 74 occasions and the Environment Agency (EA) on 6 occasions.

Water column temperature and oxygen profiles

Vertical temperature and oxygen profiles over the whole lake depth were recorded when samples were collected from the deepest point in the lake. Three different sensors were used as part of the data collection: two Yellow Springs Instruments (YSI) ProODO sensors used by UKCEH, and a YSI WQ 6600 used by the EA. Sensors were calibrated just prior to, or on each sampling day.

Conductivity

Conductivity was measured on the same day as sampling, either in the field or on immediate return to the laboratory with a WTW Cond 197i sensor, for the samples analysed by UKCEH (see Table 3), and with the YSI 650 hand-held to record the data attached to the YSI WQ 6600 sonde for the samples analysed by the EA.

Table 2 Sampling location and dates for the Lakes Tour 2021/22. Sampling teams are designated as superscripts: C=UKCEH and E =EA.

Lake	Sampling location (NGR)	April	July	October/ November	January/ February
Bassenthwaite Lake	NY214295	14-Apr^{C}	01-Jul^{C}	16-Nov^{C}	03-Feb^{C}
Blelham Tarn	NY366006	13-Apr^{C}	07-Jul^{C}	25-Oct^{C}	17-Feb^{C}
Brothers Water	NY403127	07-Apr^{C}	01-Jul^{C}	08-Oct^{C}	16-Feb^{E}
Buttermere	NY188154	08-Apr^{C}	07-Jul^{C}	07-Oct^{C}	20-Jan^{C}
Coniston Water	SD298935	12-Apr^{C}	08-Jul^{C}	19-Oct^{C}	15-Feb^{E}
Crummock Water	NY158192	08-Apr^{C}	07-Jul^{C}	10-Nov^{C}	20-Jan^{C}
Derwent Water	NY267207	14-Apr^{C}	01-Jul^{C}	16-Nov^{C}	03-Feb^{C}
Elterwater	NY329043	13-Apr^{C}	06-Jul^{C}	10-Nov^{C}	08-Feb^{C}
Ennerdale Water	NY103153	15-Apr^{C}	14-Jul^{C}	10-Nov^{C}	09-Feb^{E}
Esthwaite Water	SD358972	13-Apr^{C}	07-Jul^{C}	12-Oct^{C}	14-Feb^{C}
Grasmere	NY340064	12-Apr^{C}	15-Jul^{C}	11-Oct^{C}	02-Feb^{C}
Haweswater	NY478139	20-Apr^{C}	13-Jul^{C}	14-Oct^{C}	10-Feb^{E}
Loughrigg Tarn	NY344044	13-Apr^{C}	06-Jul^{C}	27-Oct^{C}	08-Feb^{C}
Loweswater	NY127215	20-Apr^{C}	08-Jul^{C}	11-Nov^{C}	08-Feb^{E}
Rydal Water	NY358063	13-Apr^{C}	06-Jul^{C}	11-Oct^{C}	02-Feb^{C}
Thirlmere	NY318154	20-Apr^{C}	01-Jul^{C}	08-Oct^{C}	25-Jan^{C}
Ullswater	NY400190	01-Apr^{C}	22-Jul^{C}	04-Nov^{C}	26-Jan^{C}
Wastwater	NY160058	23-Apr^{C}	21-Jul^{C}	03-Nov^{C}	14-Feb^{E}
Windermere North Basin	NY383006	14-Apr^{C}	06-Jul^{C}	13-Oct^{C}	14-Feb^{C}
Windermere South Basin	SD382914	14-Apr^{C}	06-Jul^{C}	13-Oct^{C}	14-Feb^{C}

Table 3 Sensors used for the temperature and oxygen profiles. P1 - YSI ProODO1, P3 -YSI ProODO3, Y – YSI WQ 6600 APEM – profile measured by APEM Ltd.

Lake	Jan/ Feb	April	July	Oct/ Nov
Bassenthwaite Lake		P3	P3	
Blelham Tarn	P3	P1	P3	P1
Brothers Water		P1	P1	P1
Buttermere	P3	P1	P1	P1
Coniston Water	Y	P1	P1	P3
Crummock Water	P1	P1	P1	P3
Derwent Water	P1	P3	P3	P3
Elterwater		P1	P3	P3
Ennerdale Water	Y	P1	P1	P1
Esthwaite Water	P1	P1	P3	P3
Grasmere	P1	P1	P3	
Haweswater	Y	P1	P1	APEM
Loughrigg Tarn		P1	P3	P3
Loweswater	Y	P1	P3	P3
Rydal Water	P1	P1	P3	P1
Thirlmere	P1	P1	P1	
Ullswater	P1	P1	P1	P3
Wastwater	Y	P1	P1	P1
Windermere North Basin	P1	P1	P1	P1
Windermere South Basin	P1	P1	P1	P1

Secchi disc transparency

To measure the water transparency, a metal disc was lowered into the water until it disappeared. The disc was then raised slightly until it reappeared, and that water depth was recorded. Measurements carried out by UKCEH used a white painted metal disc, 30 cm in diameter, while measurements carried out by the EA used a 20 cm disc with black and white quadrants. Tests found reasonable agreement between depths recorded using these two types of disc (R^2 = 0.89 for eight parallel measurements).

Water samples

Water samples were taken as an integrated sample of surface water using a weighted 5 m long plastic tube, or a 7 m long tube for the two basins of Windermere. The tube was lowered until vertical in the water column, the upper end was then sealed, and the tube recovered. Replicate samples were dispensed into a previously rinsed 5 dm^3 plastic bottle. After mixing thoroughly, the water was decanted into the following bottles:

1) Two disposable 500 cm^3 plastic bottles, for nutrient analysis.

2) A 1 dm^3 plastic bottle containing 5 cm^3 of Lugol's iodine for subsequent enumeration and identification of phytoplankton populations (Lund *et al.,* 1958). The iodine was added to preserve the phytoplankton cells and increase their rate of sedimentation during subsequent processing in the laboratory.

3) A small glass bottle with a ground glass stopper was filled to the top and stoppered to ensure there was no air was trapped within the bottle. This sample was used to determine the pH and alkalinity of the lake water.

The remainder of the water sample was used for the determination of phytoplankton chlorophyll *a* concentration.

During the summer sampling campaign, additional sub-samples were obtained to repeat analyses carried in 2010 and 2015 for micro-organics and heavy metals, analysed by the EA: i) an acid-washed 1 dm^3 glass bottle (code PEST P) for general organics; ii) a 1 dm^3 plastic PET bottle (code Gen) for general inorganic; iii) a 250 cm^3 plastic clear PET containing 2 cm^3 of 3 M formic acid (code HERBP) for Volatile Organics; iv) a 125 cm^3 polypropylene (code MET) for total metals analysis and v) a 125 cm^3 polypropylene (code METD) for filtered metals.

Chemical analysis

Nitrate, chloride, sulphate, sodium, calcium, magnesium and potassium concentrations were determined by ion chromatography using a Metrohm ion chromatograph. Ammonia, dissolved reactive silicate, total phosphorus, soluble reactive phosphate, alkalinity and pH were determined as described in Mackereth et al. (1978). All analyses were carried out at UKCEH apart from those for metals and micro-organics, which were analysed by the Environment Agency.

Phytoplankton pigments and populations

The concentration of phytoplankton pigments was determined using the procedure described by Talling (1974). Briefly, a known volume of water was filtered through a Whatman GF/C filter, the pigments extracted in boiling methanol and analysed spectrophotometrically.

Samples for phytoplankton species enumeration were concentrated and identified using light microscopy. A 300 ml sub-sample of the iodine-preserved water sample was concentrated to 5 cm^3 by sedimentation. A known volume of the concentrated sample was transferred to a counting chamber and the phytoplankton were enumerated as described by Lund et al. (1958). Microplankton and nanoplankton were counted at x100 magnification and x400 magnification respectively.

Zooplankton populations

The zooplankton population in each lake was determined using a vertical water column haul, where conditions permitted sampling at the deepest point. A non-closing zooplankton net (mesh size 250 µm, mouth diameter 0.3 m) was lowered to 2/3 the maximum depth of the water column and then hauled steadily to the surface. The contents of the net were emptied into a bottle, and immediately fixed by adding ethanol. In the laboratory the samples were concentrated by filtration and stored in labelled vials in 4% formalin. Unfortunately, due to technical difficulties with preservation, samples collected during the July sampling campaign had to be discarded.

Zooplankton samples from each lake were processed through a FluidImaging FlowCam Macro®, fitted with a 2000µm x 100000µm Flowcell. A Lakes Tour context file was produced within VisualSpreadsheet (VS) to specify the desired filter metrics during imaging which included a minimum capture size diameter of 150 µm. Samples were cyclically connected via peristaltic to the FlowCam and a 110 µm filter mesh was used to catch and concentrate capture organisms. Using a smaller mesh size than the capture organism resolution reduced the risk of capture particle escapes, and thus the likelihood of multiple imaging of the same particle.

During imaging, samples were passed through the FlowCam at a flow rate of 200 millilitres per minute. This flow rate is recommended as optimum by the manufacturers to avoid double imaging and the omission of capture particles all together. The autoimage function on Visual Spreadsheet was used to collect particle images a rate of 9-10 frames per second.

Following data capture, image datasets for each sample were manually manipulated within VS. The sort function was used to systematically remove uninteresting images including blank images, air bubbles, dirt, fibres, carapaces, body fragments and diatoms. Images were manually classified into eight taxonomic libraries: *Asplanchna, Bosmina, Bythotrephes, Calanoida, Ceriodaphnia, Daphnia, Keratella,* and *Cyclopoid.* The final image library dataset consisted of 1,420 images with image numbers in each library ranging between 4 and 679.

Library filters were produced in VS using average field values derived from image libraries such as aspect ratio, diameter and edge gradient and used to run an automated classification on each lake-season image dataset. Each classification was assessed and manual corrections were performed where images had been classified incorrectly. Each classification was re-assessed by a specialist taxonomist for quality control.

3 Present status and long-term change

3.1 Weather during 2021/ 22

The maximum and minimum temperatures during the first half of 2021 were very close to the long term average. However, following a slightly cooler April and May period, temperatures increased in June and remained above the long term average for the rest of the year (Figure 2). Rainfall in 2021 was initially above the long term average for the first quarter of the year. However April, the spring sampling period, was exceptionally dry, with the lowest total for the year and, after a wetter May, the following four months all had rainfall totals below the long term average, including the July summer sampling (Figure 2). This pattern was disrupted by a very wet period during October (autumn sampling in October and November), before rainfall dropped to below average levels for the next three months, with February then characterised by a wetter stormy period, when most of the winter sampling took place.

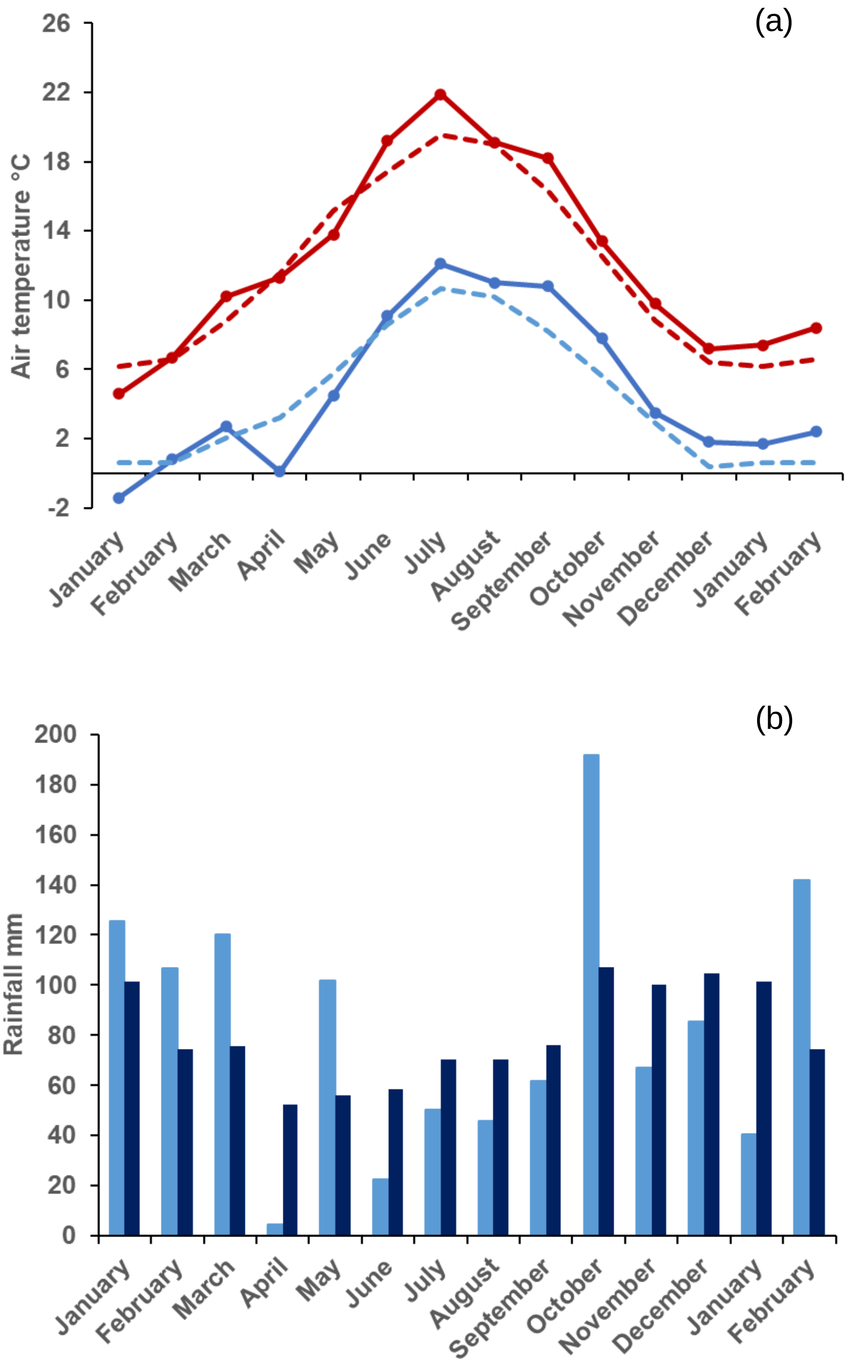


Figure 2 a) maximum (solid red line) and minimum monthly air temperatures (solid blue line) for 2021 - 2022 in comparison to the 30 year (1981 – 2010) average monthly maximum and minimum temperatures (dotted lines) and b) monthly rainfall totals (pale blue bar) for 2021 – 2022 in comparison to the 30 year (1981 – 2010) average monthly rainfall total (dark blue bar) from Newton Rigg Weather Station (https://www.metoffice.gov.uk/research/climate/maps-and-data/historic-station-data).

3.2 Limnology of the lakes in 2021/ 22

Water column profiles of temperature and oxygen concentration

During 2021 and early 2022, the twenty lakes followed a typical evolution of temperature profiles found in temperate lakes (Figure 3), which follows the pattern of seasonal air temperature change. In the winter period, characterised here by measurements taken in January or February 2022, the lakes were isothermal from the surface to the bottom, and therefore fully mixed. The mean winter temperature was 5.8°C during this period. During the spring sampling in April 2021, average temperature was 7.1°C (average surface temperature 8.2°C) and more variation in surface temperatures among lakes was noticeable as increased surface heating occurred. Smaller lakes such as Loughrigg, Loweswater and Rydal Water showed evidence of warming throughout much of their water columns, whilst the lakes with the largest volumes and heat capacities such as Buttermere, Ullswater and Wastwater remained relatively uniform in temperature throughout the water column. It is interesting to note that a relatively large lake, Haweswater, showed evidence for a very sharp temperature change with depth near the surface, which likely relates to rapid heat absorption due to the higher dissolved organic matter (DOM) concentrations at this site.

In July 2021, during the summer sampling, the difference between average water column temperatures and average surface temperature is at its highest; 12.1°C compared to 19.4°C. Temperature differences between the surface and bottom of the lakes are on average 12.4°C in this season, but this ranges from 8.5°C in Bassenthwaite Lake, where temperature stratification is typically weaker and the lake frequently mixes, to 16.1°C in Ullswater, where the surface temperature on the day of sampling was 23.1°C and the temperature at 58 m was 7°C. In the autumn sampling period, carried out in October and November 2021, the average water temperature was 10.1°C across the lakes. The surface waters cooled since the peak in the summer and were now only slightly above the water column average at 11.4°C. Variations in the temperature profiles among lakes were very apparent in this season, with some lakes, such as Derwent Water and Loweswater, then being isothermal and fully mixed, whilst larger or sheltered lakes like Coniston, Windermere, and Blelham Tarn still had distinct temperature gradients differentiating the surface epilimnion from the deeper hypolimnetic waters.

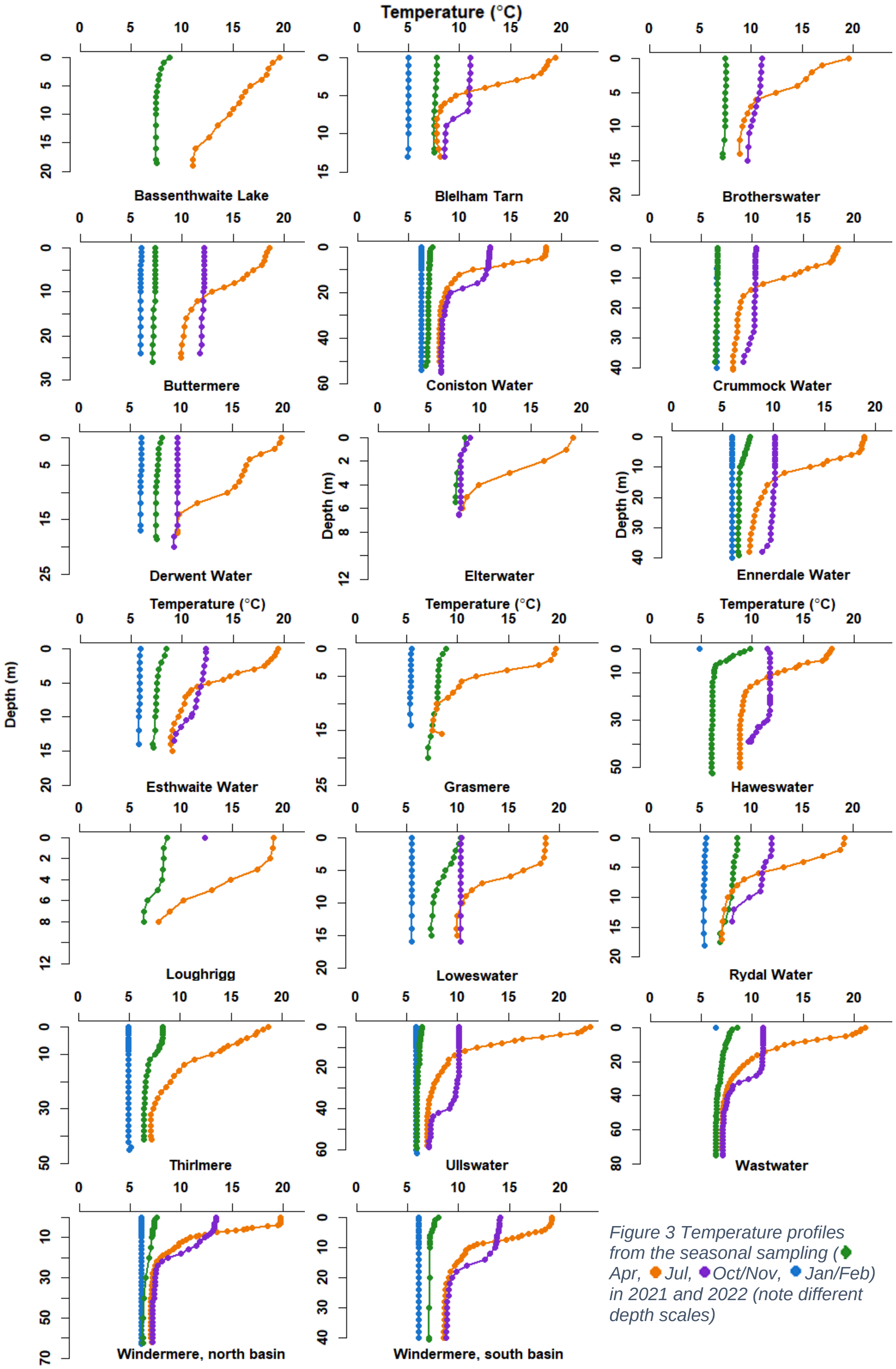


Figure 3 Temperature profiles from the seasonal sampling (● Apr, ● Jul, ● Oct/Nov, ● Jan/Feb) in 2021 and 2022 (note different depth scales)

Oxygen dynamics in the twenty lakes also followed a seasonal pattern, linked to surface heating, temperature stratification development, and the productivity of the system (Figure 4). This typically resulted in relatively uniform high oxygen concentrations with depth for all lakes during the winter isothermal period, with average concentrations of 11.8 g m^{-3}. Uniform oxygen concentrations were also typical during the spring sampling period, although in more productive lakes (e.g. Loughrigg and Loweswater), where thermal stratification had developed, oxygen depletion at depth occurred. In these lakes, deep water concentrations were 5 – 10 g m^{-3} lower at the bottom of the lake compared to the surface.

The contrast in oxygen profiles between productive and less productive lakes became clearer in the summer and autumn periods. Oxygen depletion in deep waters was at its maximum due to the extended period of thermal stratification, which started in the spring, preventing oxygen renewal that would offset oxygen consuming microbial decomposition of organic matter. In the most productive lakes, such as Blelham Tarn and Esthwaite Water, oxygen depleted waters occupied a large proportion of the water column. In contrast, the low productivity lakes such as Ennerdale Water, Crummock Water and Thirlmere, did not have clear changes in oxygen concentration with depth throughout the year. Wastwater usually shows this pattern, although some very low oxygen readings were taken during the autumn sampling in 2021. It’s not clear whether these readings are real or influenced by sediment disturbance, but they should probably be interpreted with caution. The slight reduction in surface oxygen concentrations during the summer at these sites reflected reductions in oxygen solubility as water warms. Where thermal stratification was weak, such as in Bassenthwaite Lake, oxygen depletion was generally limited by frequent mixing of the water column. Sub-surface peaks in oxygen at sites such as Elterwater and Loughrigg may indicate locations of intense photosynthesis produced by sub-surface blooms in phytoplankton.

The minimum oxygen concentration found in each lake during the year is a useful indicator of the state of the lake ecosystem, and whether it is subject to anoxia and other biogeochemical changes that can be detrimental to both habitat and water quality. Table 4 summarises the minimum oxygen concentrations recorded in the deep waters of each lake. Typically, these values were found during the summer sampling in July, but for lakes with thermal stratification that lasted into the late autumn and winter, maximum oxygen depletion occurred in autumn. The minimum oxygen concentrations were lowest in the most productive lakes such as Blelham Tarn and Esthwaite Water, where degradable organic matter, usually from phytoplankton, was highest. The highest minimum concentrations were therefore in unproductive lakes such as Buttermere and Ennerdale Water, where these organic matter inputs are very low.

Table 4 Annual minimum deep water oxygen concentration in 2021. These values relate either to measurements from the summer or autumn sampling periods.

Lake	Minimum oxygen concentration at depth ($g\ m^{-3}$)
Bassenthwaite Lake	3.73
Blelham Tarn	0.18
Brothers Water	1.43
Buttermere	7.81
Coniston Water	3.20
Crummock Water	6.73
Derwent Water	5.39
Elterwater	0.11
Ennerdale Water	7.80
Esthwaite Water	0.04
Grasmere	0.53
Haweswater	7.01
Loughrigg Tarn	0.26
Loweswater	0.43
Rydal Water	0.35
Thirlmere	5.61
Ullswater	5.46
Wastwater	0.24
Windermere North Basin	5.10
Windermere South Basin	2.85

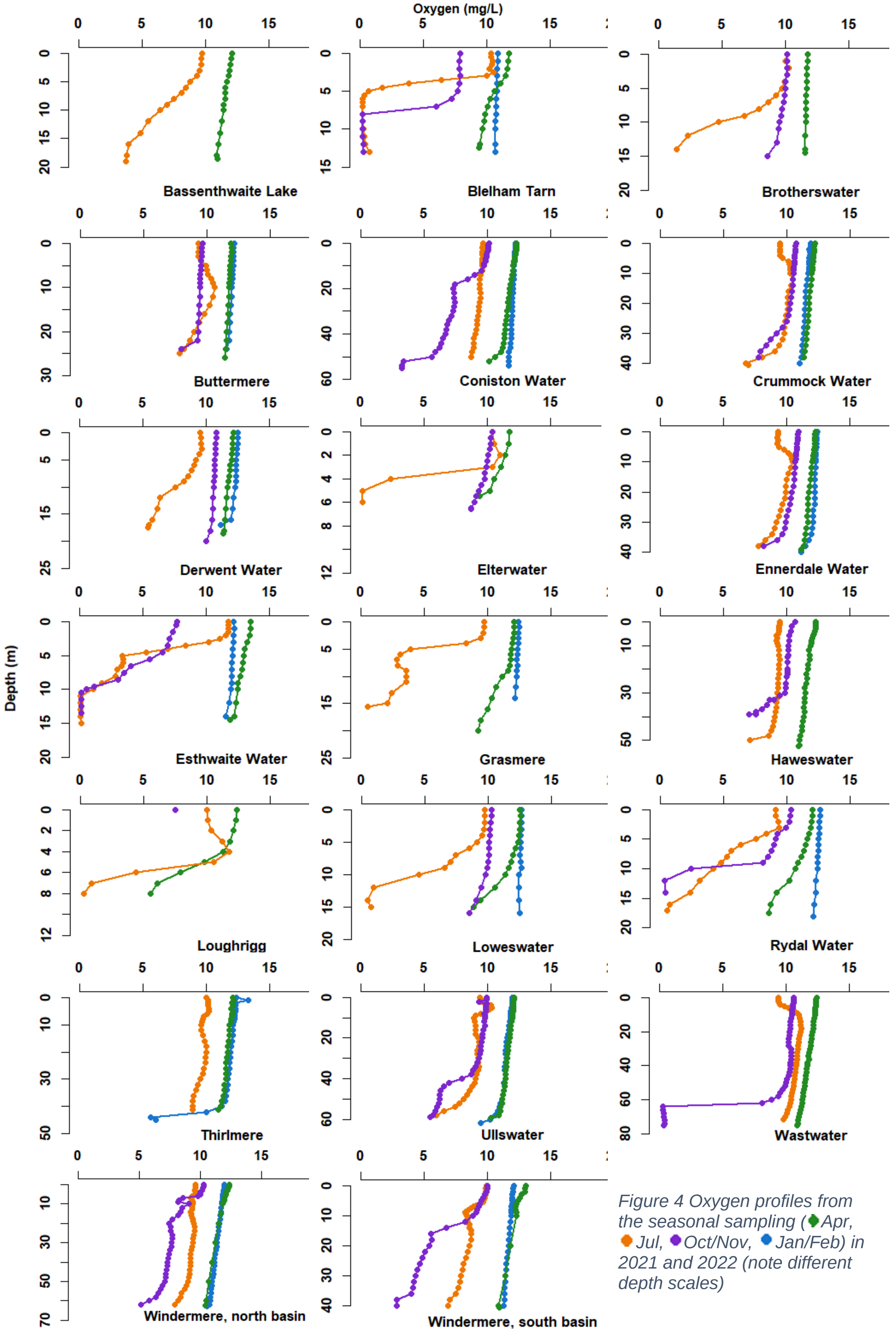


Figure 4 Oxygen profiles from the seasonal sampling (● Apr, ● Jul, ● Oct/Nov, ● Jan/Feb) in 2021 and 2022 (note different depth scales)

Secchi disc transparency

The depth at which a Secchi disc disappears when lowered through the water column is an approximate measure of water transparency. In clear water lakes, which represent most of those sites included in the Lakes Tour, water transparency is largely determined by phytoplankton abundance. Figure 5 shows that in unproductive sites, such as Buttermere, Crummock Water and Wastwater, the water column was highly transparent and the Secchi depth approached or exceeded 10 m. In contrast, productive lakes like Blelham Tarn, Elterwater and Esthwaite Water had very shallow Secchi depths, particularly in the summer, when they fell to <2 m. Seasonal variations in Secchi depth are typically related to phytoplankton abundance, but other factors such as concentrations of suspended sediments and dissolved organic matter (DOM) also affect water transparency, the former likely to be more important during the wetter autumn and winter period, whilst DOM can be important for lakes with highly organic catchment soils, such as Haweswater.

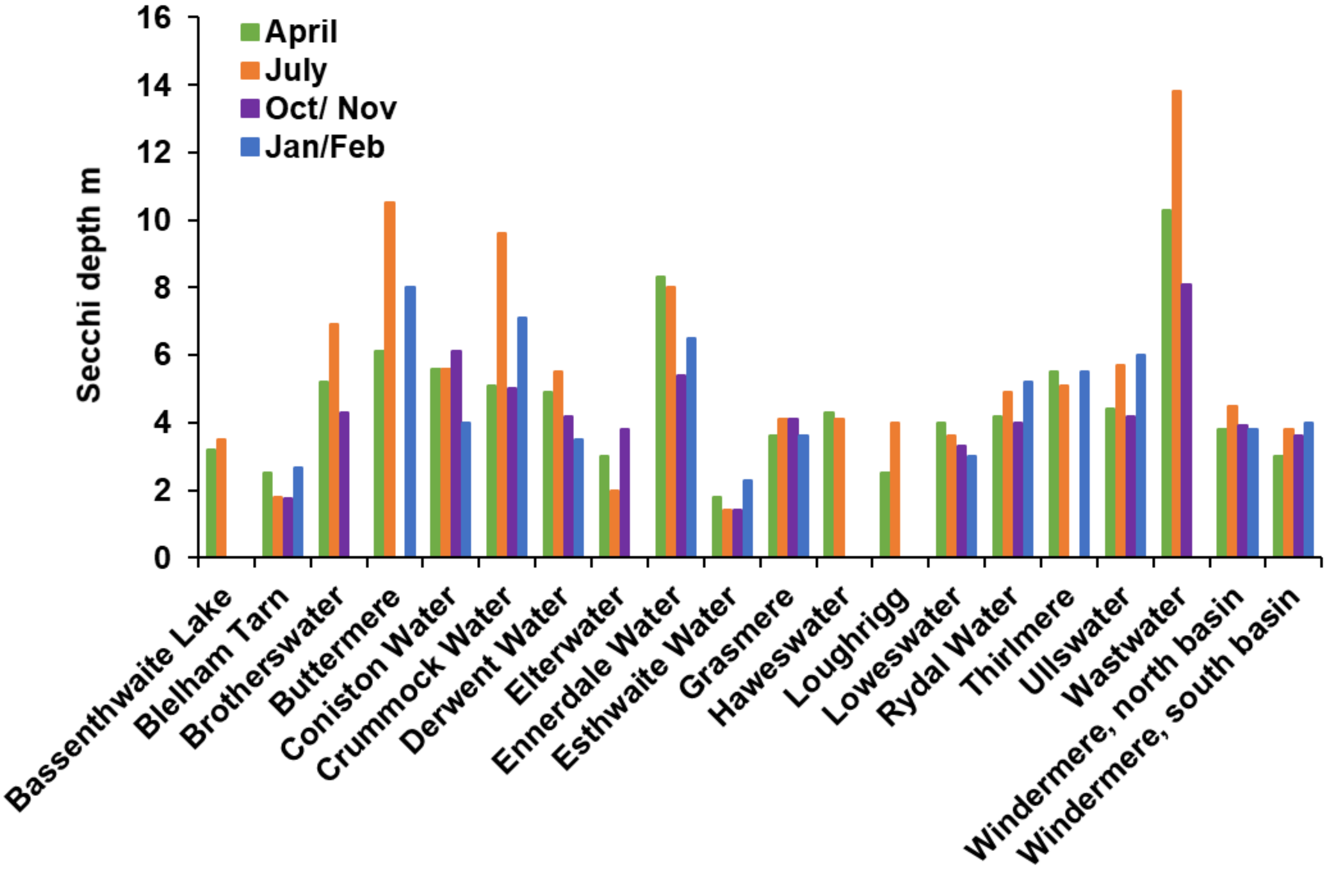


Figure 5 Seasonal changes in Secchi disc transparency in the 20 lake basins during 2021/22.

Major ions

Previous studies have considered the ionic composition of the major lakes and tarns of the English Lake District (Sutcliffe et al. 1982; Sutcliffe 1998). They reveal that there is seasonal variation in the composition of the major ions. This results from variations in inputs from precipitation and differential concentration due to evapo-transpiration changes. However, overall ionic composition is relatively conservative and is therefore presented in Figure 6 as an annual mean concentration.

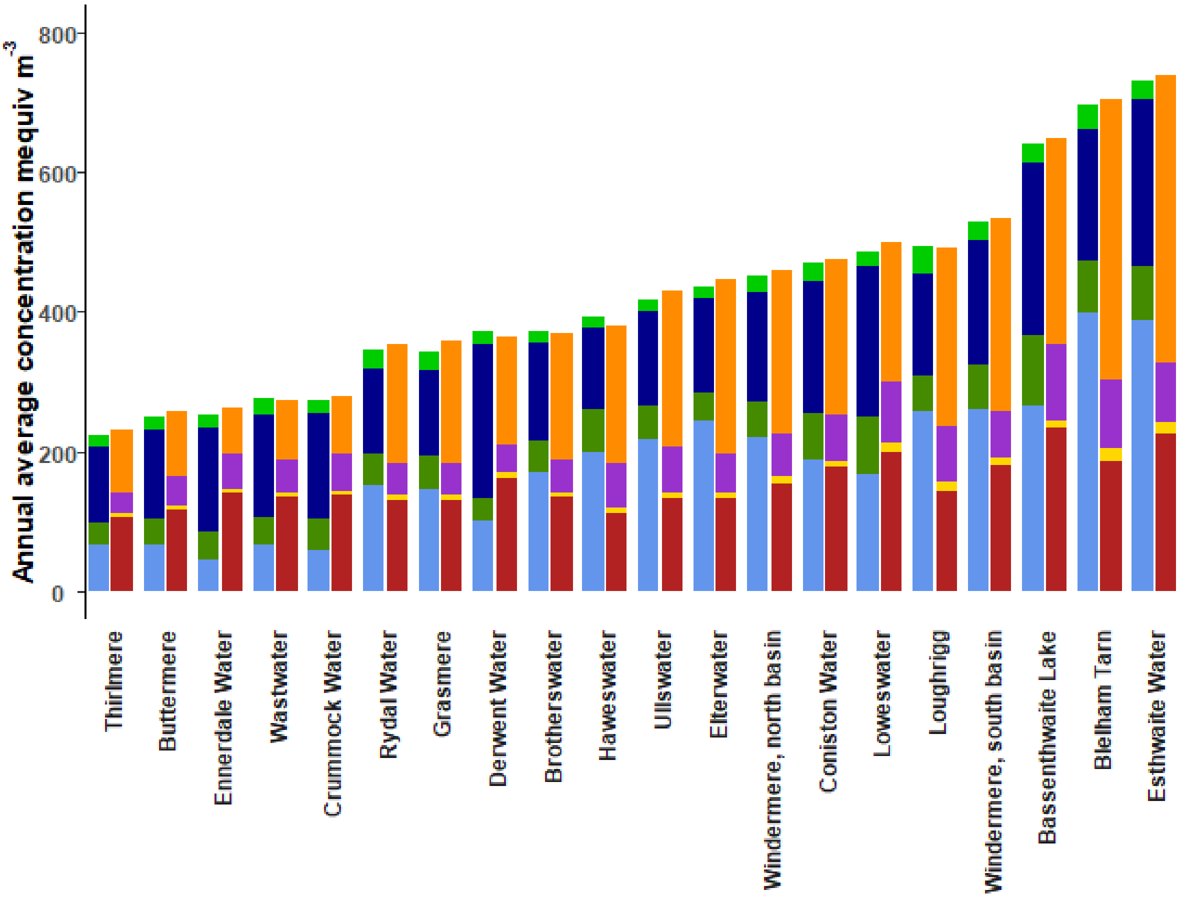


Figure 6 Annual mean concentration of major anions (first column) and cations (second column) for the 20 lake basins in 2015. Lakes are ordered by concentration which reflects the underlying geology and catchment altitude. Anions are: alkalinity (bicarbonate; light blue), chloride (dark blue), nitrate (light green) and sulphate (olive green). Cations are: sodium (red), potassium (yellow), calcium (orange) and magnesium (purple).

In Figure 6, the lakes are ordered by total concentration, which largely reflects the underlying catchment geology and altitude, which is a proxy for precipitation. The lowest ionic concentration was typically found on the more impermeable and acidic rock types of the Borrowdate volcanics and igneous intrusions of the central and western lakes (Thirlmere, Ennerdale Water, Wastwater, Rydal Water, Grasmere, Brotherswater, Haweswater, Ullswater, Elterwater and Loughrigg Tarn). The northern group of lakes is dominated by the underlying geology of the Skiddaw slates series (Buttermere, Crummock Water, Derwent Water, Loweswater and Bassenthwaite Lake), whilst the southern lakes are underlain by softer Silurian slates (Windermere, north basin, Coniston Water, Windermere, south basin, Blelham Tarn and Esthwaite Water).

These geologies influence the dominant anions and cations. For the Borrowdale and Skiddaw series, the dominant anion was chloride, whilst bicarbonate (alkalinity) was more important in lakes on the Silurian slates. Chloride concentrations were relatively consistent across the lakes, whilst alkalinity tended to be lower on the more acidic Borrowdale and Skiddaw series. The balance between calcium and sodium cations also relates to the underlying geology, where calcium is more important in lakes on the Skiddaw slates and sodium more important for lakes on the Borrowdale and Silurian geologies.

Seasonal changes in alkalinity and pH are shown in Figure 7. The lowest alkalinities, <0.1 equivalents m^{-3} occurred in unproductive lakes on more acidic geologies such as Buttermere, Crummock Water, Ennerdale Water and Wastwater (Figure 7a). At these sites there was only a small seasonal variation in alkalinity with the minimum occurring during winter and maximum in autumn. This pattern is likely related to variations in precipitation and dilution in winter, combined with water residence time and evapo-transpiration effects during the summer and autumn. The highest alkalinities occurred in Blelham Tarn and Esthwaite Water, with peaks in more productive lakes occurring during the summer. The variation in pH across the lakes was between 6.2 and 8.0 (Figure 7b). Seasonal peaks in spring and summer are likely to be related to the depletion of carbon dioxide in the lake water that occurs during rapid photosynthesis by phytoplankton. The variation in pH at this time of year is therefore a useful indicator of the presence of high abundances of phytoplankton and the occurrence of algal blooms.

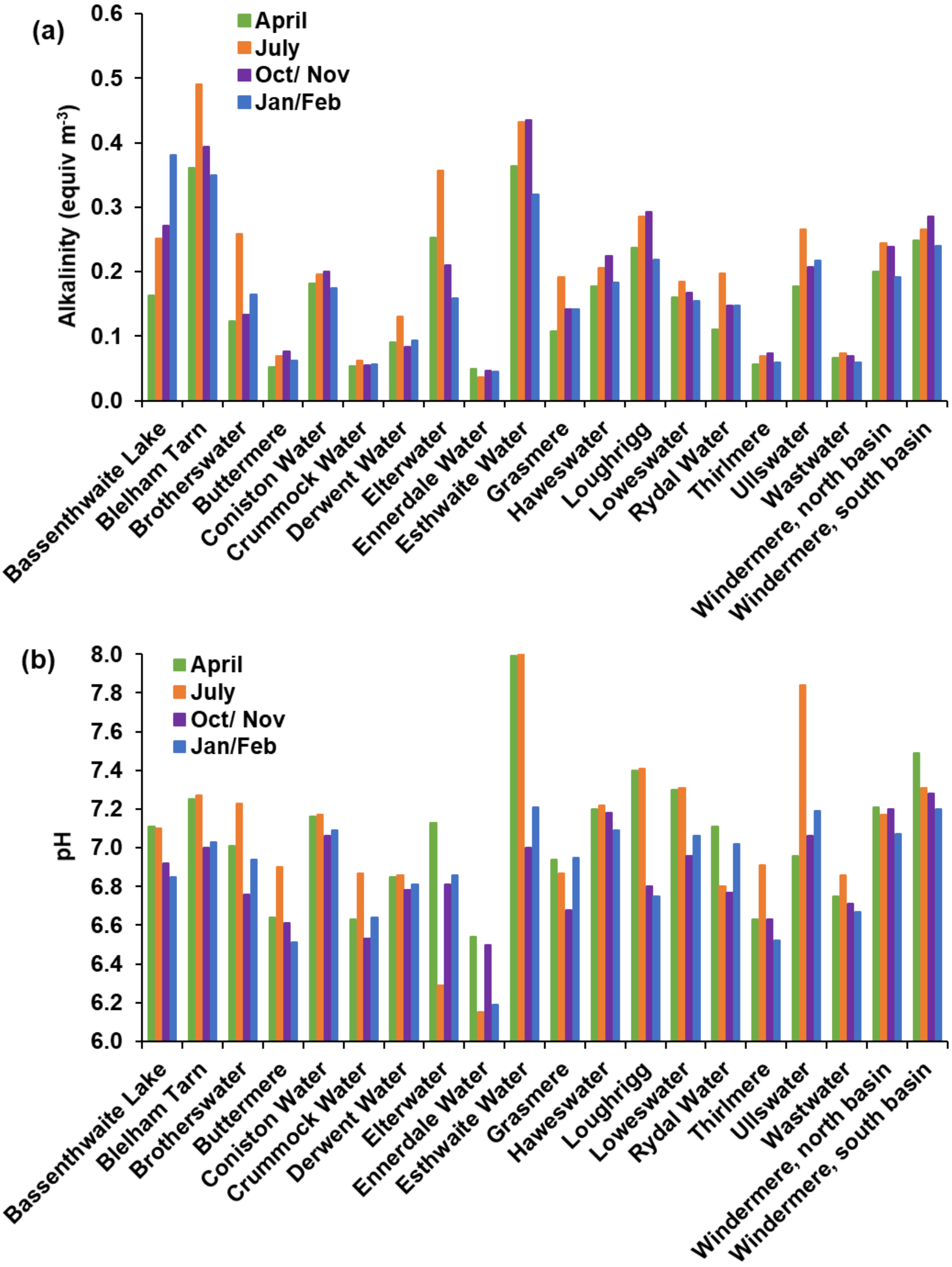


Figure 7 Seasonal changes in a) alkalinity and b) pH in the 20 lake basins during 2021/22.

Nutrient chemistry

The major macronutrients, apart from carbon, which are essential for phytoplankton growth include phosphorus, nitrogen and for some algal groups, the diatoms and chrysophytes, silicon. Concentrations of these nutrients across the twenty lakes are presented below.

The productivity of the major Lakes Tour lakes is primarily controlled by the concentration of phosphorus in the water, which is the nutrient that limits phytoplankton growth most frequently. Total phosphorus (TP) is a measure of both dissolved and particulate forms of phosphorus, which may be composed of organic or inorganic compounds. Although not all of this phosphorus is likely to be ‘bioavailable’ to phytoplankton for growth at any one time, it provides a good proxy for the trophic status of a lake. Across the twenty lakes, TP concentrations ranged from below the limit of detection (5 mg m^{-3}) at Ennerdale Water and Wastwater to the highest concentrations (>30 mg m^{-3}) at Bassenthwaite Lake, Elterwater and Esthwaite Water (Figure 8). Seasonal variations in TP concentrations within a lake were typically not large, but seasonal peaks occurred during the winter for most lakes, and concentrations tended to be lower in autumn (Figure 9). This pattern of winter peaks may be indicative of catchment nutrient sources, whilst peaks occurring during the summer or autumn could indicate an internal nutrient supply.

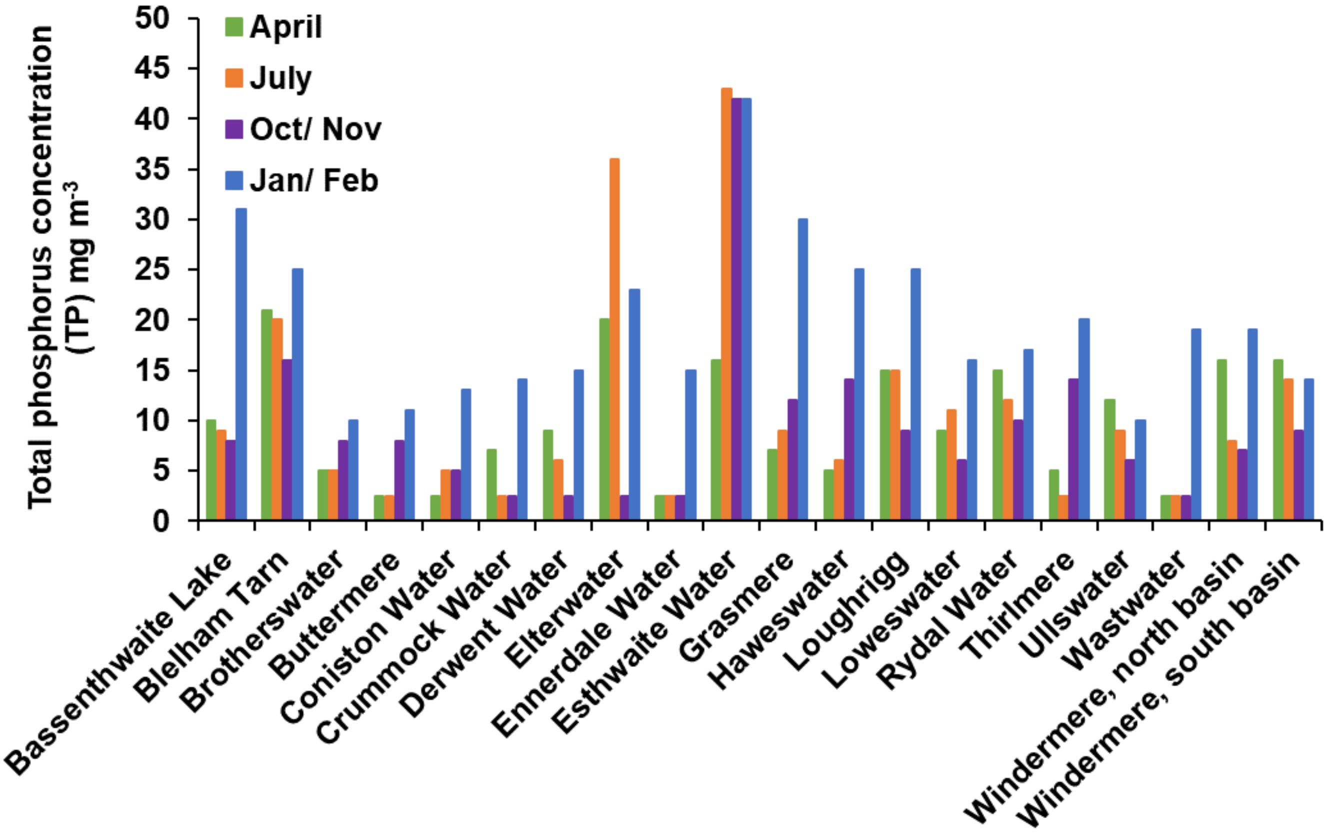


Figure 8 Seasonal changes in the concentration of total phosphorus in the 20 lake basins during 2021/22.

Soluble reactive phosphorus (SRP) is an analytically determined phosphorus fraction that approximates the dissolved inorganic phosphorus in the water column. This fraction is considered to be the most bioavailable for phytoplankton growth and is readily taken up into algal biomass or adsorbed to other inorganic particles. The seasonal pattern in SRP concentrations largely reflects the demand for phytoplankton growth during the growing season, which results in a seasonal minimum in the summer and peaks in concentration during the winter (Figure 9b), when phytoplankton growth is limited by light and temperature.

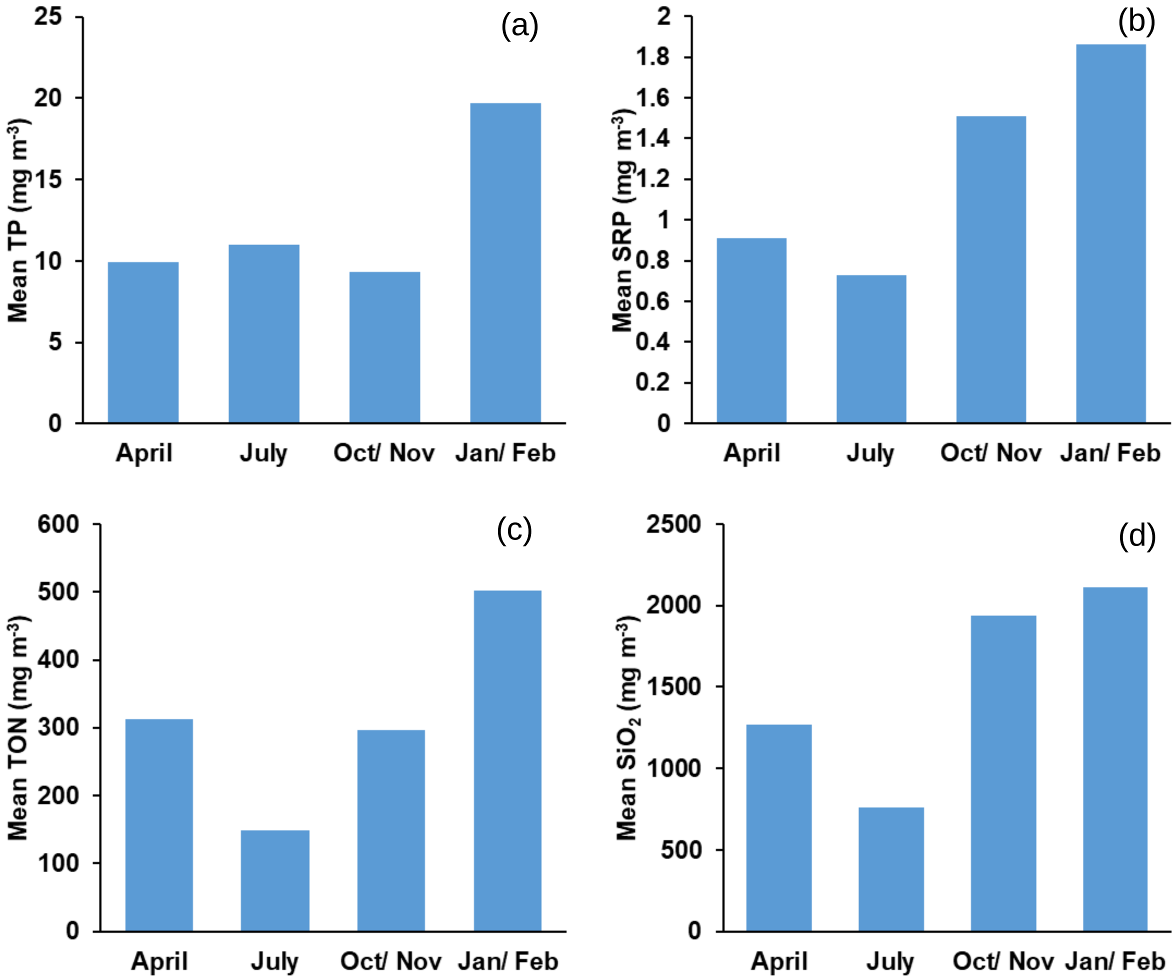


Figure 9 Mean seasonal concentrations of: a) total phosphorus, b) soluble reactive phosphorus, c) nitrate-nitrogen and d) silica in the 20 lake basins during 2021/22.

Typically, phosphorus is considered to be limiting to phytoplankton growth when the concentration drops below around three micrograms per cubic metre (Reynolds 2006). Across most lake sites, SRP concentrations were frequently below this level, but it is interesting to note the occasions when concentrations exceed this and peaked in some lakes (Figure 10). In particular, the autumn peaks at Esthwaite Water, Grasmere and Loughrigg Tarn may be indicative of internal supply of phosphorus as the lakes overturn at the end of the seasonal thermal stratification period. This phosphorus released at higher rates from the sediments under conditions of water column and sediment anoxia, represents an alternative bioavailable nutrient pool for phytoplankton growth in lakes which have been subject to long term nutrient enrichment.

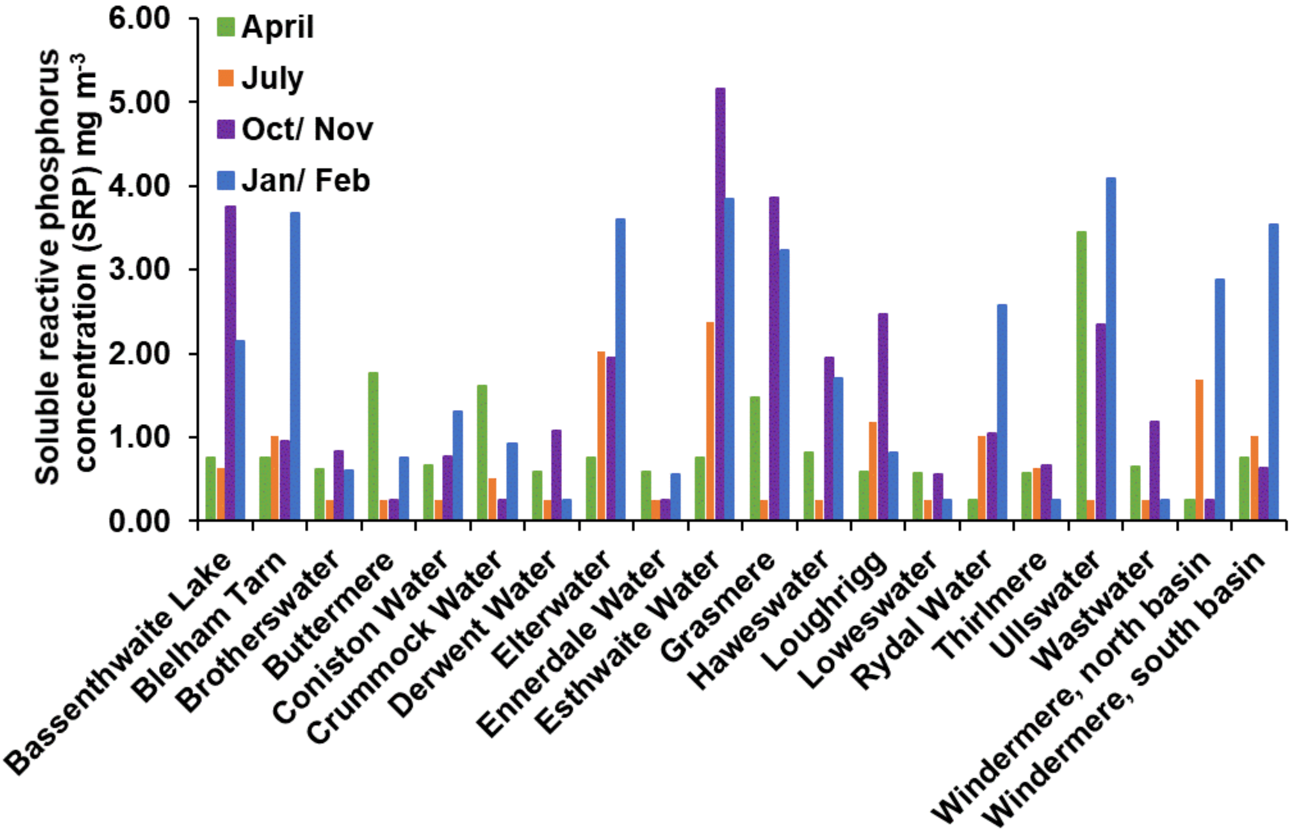


Figure 10 Seasonal changes in the concentration of soluble reactive phosphorus in the 20 lake basins during 2021/22.

Total oxidised nitrogen (TON) is composed of nitrate and nitrite. In freshwater lakes, the concentrations of nitrite are very low to zero and therefore TON essentially represents the nitrate concentration in the water. Nitrate is a dissolved inorganic species of nitrogen and is usually the dominant dissolved inorganic nitrogen species available to phytoplankton. The average seasonal pattern in TON concentration follows a unimodal shape with a seasonal minimum in summer and peak during the winter (Figure 9c). As with SRP, this pattern largely tracks the drawdown of the nutrient during the summer growing season, and replenishment of the nutrient through catchment transfers under higher precipitation and river flows over the winter. Summer drawdown of nitrate can be particularly pronounced in lakes with higher phytoplankton abundance, such as Elterwater, Esthwaite Water and Grasmere (Figure 11), resulting in concentrations below the detection limit and potentially limiting to phytoplankton growth. These conditions push these lakes into a state of co-limitation by both phosphorus and nitrogen. TON concentrations were lowest in Elterwater during the Lakes Tour 2021/22 sampling (average 189.6 mg m^{-3}) and highest in Loughrigg Tarn, average 551.2 mg m^{-3}. Differences in TON concentrations among lakes were lower than for TP or SRP.

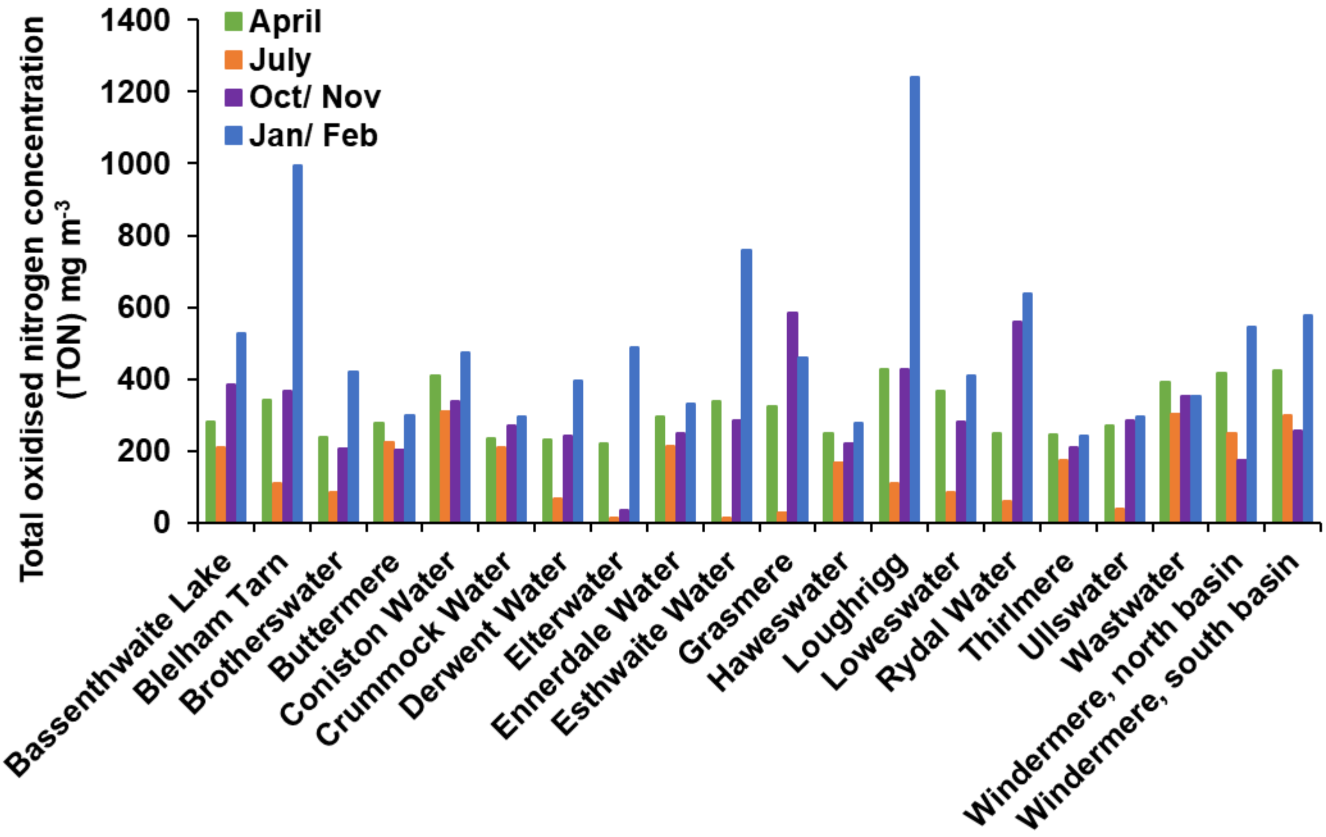


Figure 11 Seasonal changes in the concentration of total oxidised nitrogen in the 20 lake basins during 2021/22.

Ammonium nitrogen is another dissolved inorganic form of nitrogen found in fresh waters. It is in a more reduced form than nitrate and is often considered to be preferred by phytoplankton as a resource (Glibert et al. 2016). This preference has been found to be dependent on the phytoplankton group, with cyanobacteria increases associated with increases in ammonium concentration. Across most of the twenty lakes, ammonium concentrations were below the limit of detection for the method (33 mg m^{-3}). Only eight values were above this level across all lakes and seasons (Figure 12). These higher concentrations tended to occur in autumn, particularly in more productive lakes such as Esthwaite Water and Loughrigg Tarn that are subject to hypolimnetic anoxia and subsequent internal nutrient release.

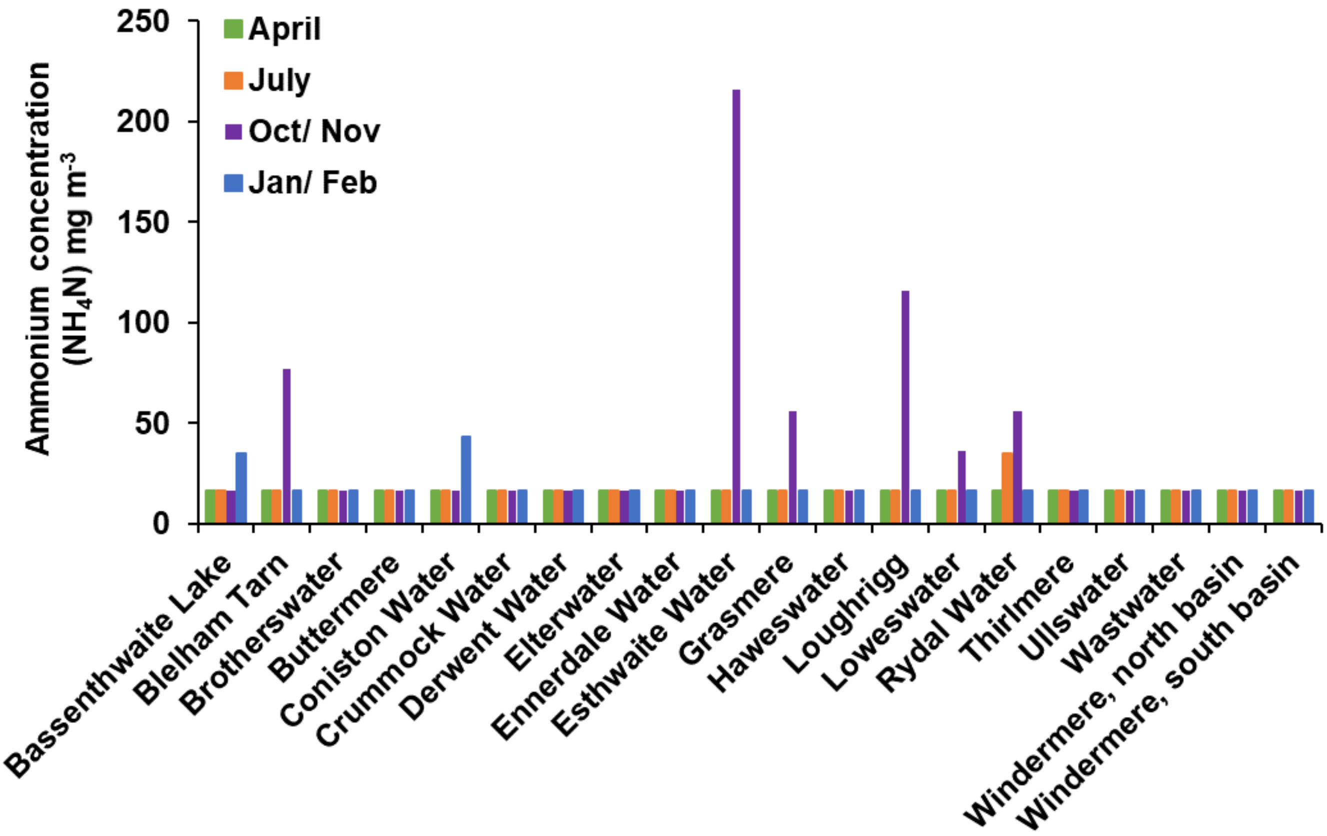


Figure 12 Seasonal changes in the concentration of ammonium-nitrogen in the 20 lake basins during 2021/22. Note, most samples were below the detection limit.

Dissolved silica is a key nutrient resource for two different phytoplankton groups, being required by both chrysophytes and diatoms in their cell walls and scales. The average seasonal pattern in silica concentrations was similar to that for SRP and TON, although more acute depletion occurred during spring and summer, when diatoms bloom. Strong replenishment from the catchment in autumn and winter may reflect these seasons being particularly wet during the 2021/22 survey (Figure 9). The highest seasonal concentrations occurred in Bassenthwaite Lake and Blelham Tarn during the winter, whilst really marked drawdown of silica occurred in Esthwaite Water, Loughrigg Tarn and Loweswater during the spring (Figure 13). Eight of the lakes had seasons where silica concentrations dropped below 500 mg m^{-3}, which is the concentration considered limiting for diatom growth (Lund 1950).

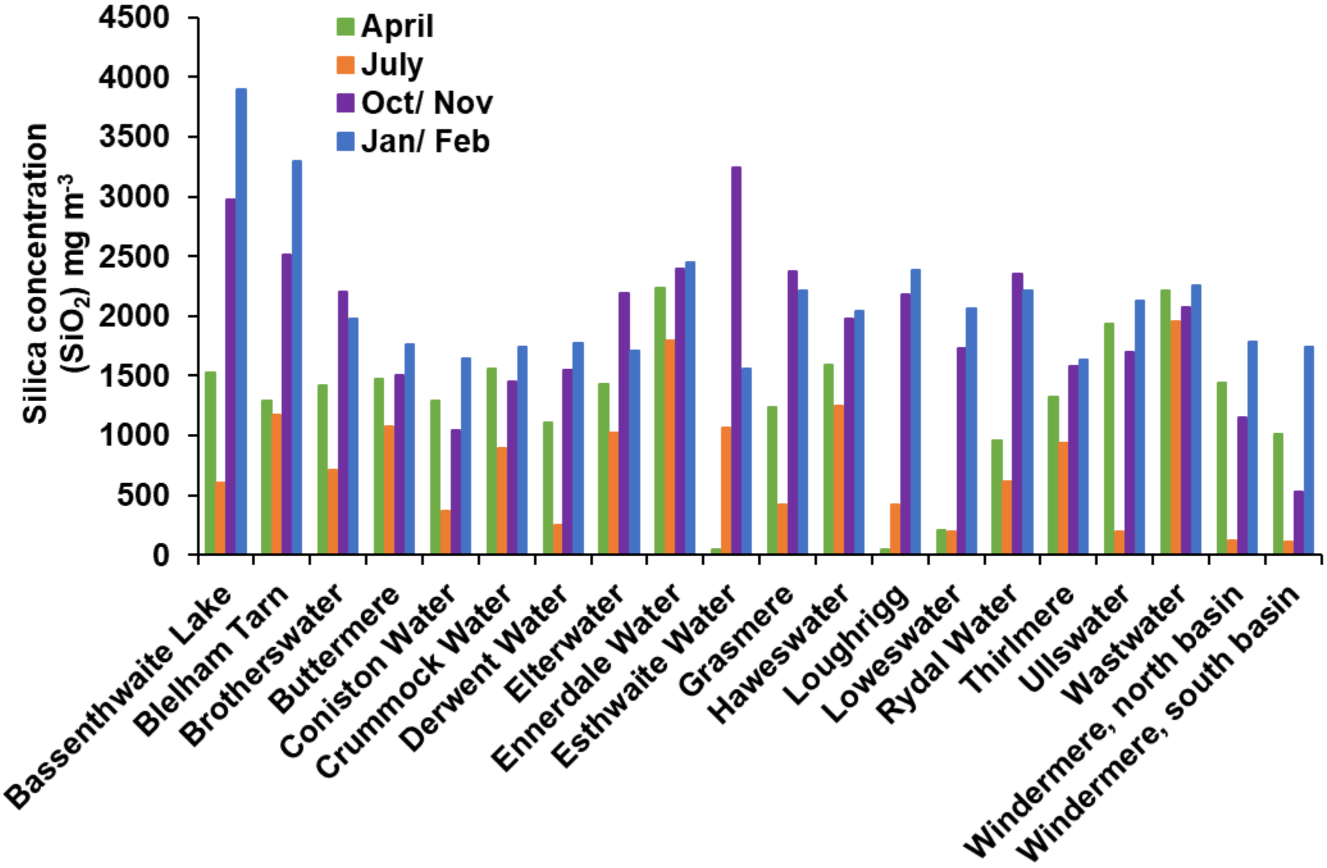


Figure 13 Seasonal changes in the concentration of silica in the 20 lake basins during 2021/22.

Phytoplankton chlorophyll a concentration

Chlorophyll *a* is the photosynthetic pigment present in all phytoplankton, and its concentration can be used as an approximation of the amount or abundance of phytoplankton that is present in a water sample. Annual average chlorophyll *a* concentration ranged from <1 mg m^{-3} in Wastwater to 21.6 mg m^{-3} in Elterwater, with large seasonal variation in concentration evident across the lakes (Figure 14). The seasonal pattern of chlorophyll *a* concentration typically included peaks in growth in the spring and summer periods, usually dominated by different phytoplankton groups such as diatoms in the spring and green algae and cyanobacteria in summer. The data from 2021/22 clearly revealed these seasonal peaks in several lakes, but in addition, very high concentrations of chlorophyll *a*, indicative of phytoplankton blooms occurred in summer samples at Blelham Tarn, Elterwater and Esthwaite Water. The very low productivity lakes showed very little seasonal variation in growth, although there is some evidence for the highest concentrations in Buttermere, Crummock Water, Ennerdale Water and Wastwater to occur in spring. Phytoplankton peaks were also present in autumn in Coniston Water and both basins of Windermere, which may relate to their continued stratification at this time enabling sufficient light into the lake to enable growth to occur. In general, chlorophyll *a* concentrations were lowest in winter when unfavourable conditions of light and temperature limit phytoplankton growth. In addition, for lakes with shorter residence times (<100 days as an annual average), higher flushing at this time of year will wash out phytoplankton cells at higher rates that they can replicate. However, two lakes, Loughrigg Tarn and Loweswater also had chlorophyll *a* peaks during the winter period. The exact cause of this is unknown but could relate to the relatively long residence time of these small water bodies.

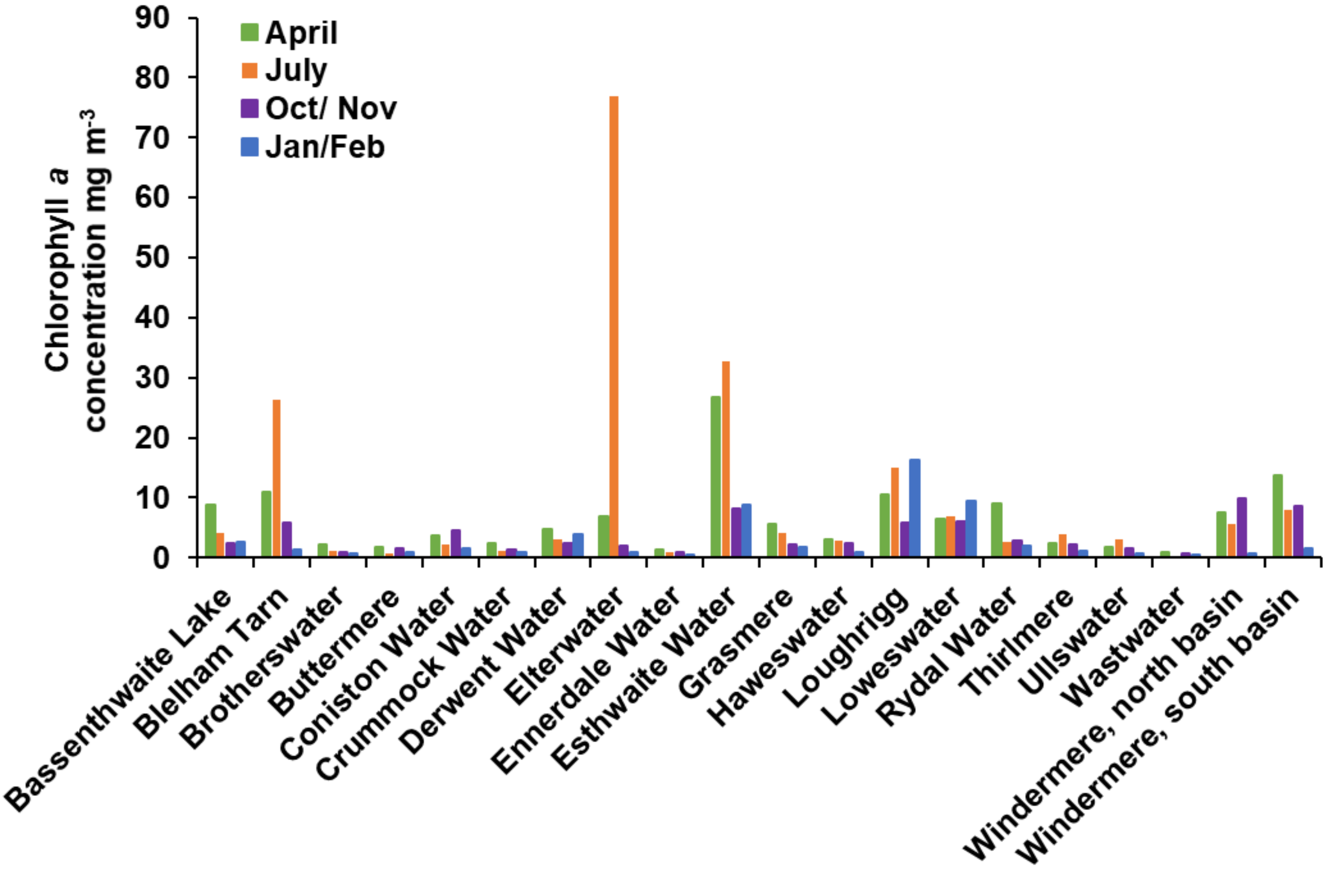


Figure 14 Seasonal changes in the concentration of phytoplankton chlorophyll a in the 20 lake basins during 2021/22.

Phytoplankton species composition

The phytoplankton form the base of the pelagic food web and are an essential component of the ecosystem. They are also sensitive to internal and external drivers of change and a key biological quality element used by the Water Framework Directive to assess the ecological status of a lake.

Across the 80 samples, at total of 188 taxa were recorded: 12 charophytes, 65 chlorophytes, 25 cyanobacteria, 8 chrysophytes, 8 cryptophytes, 34 diatoms, 8 dinoflagellates, 2 euglenophytes, 2 haptophytes and 17 ochrophytes. The number of taxa recorded varied between lakes, with 30 to 65 taxa typically recorded over the four seasons (Figure 15). The most commonly recorded genera were *Cyptomonas*, *Rhodomonas*, *Asterionella* and *Chrysochromulina*. The lowest number of taxa were recorded in the winter samples (January and February), 91, and the highest number of taxa were recorded in summer, 141. Spring and autumn had similar numbers of taxa present, 116 and 118 taxa, respectively. The more productive lakes such as Esthwaite Water, Loughrigg Tarn and Loweswater, tended to have a higher proportion of the diversity made up of cyanobacteria taxa. Although the number of taxa doesn't necessarily equate to a larger biovolumes, the pattern of increasing abundance of cyanobacteria with increasing nutrient concentrations is a consistent relationship found across a number of lake surveys (Jeppesen et al. 2000; Verspagen et al. 2022).

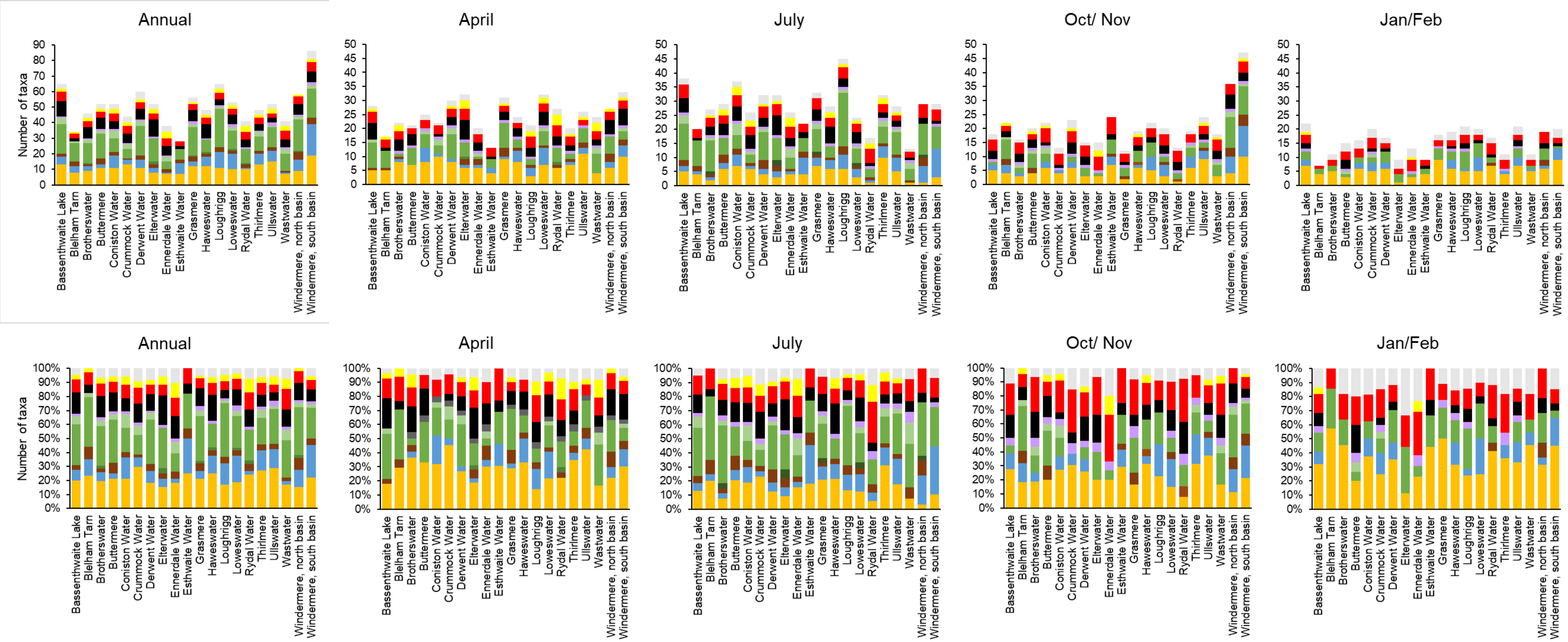


Figure 15 Composition of the major groups of phytoplankton in terms of number of taxa (top row) and percentage number of taxa (bottom row) in the 20 lake basins during 2015. Diatoms (gold); cyanobacteria (blue); dinoflagellates (brown); euglenophytes (dark green); chlorophytes (green); charophytes (pale green); haptophytes (lilac); ochrophytes (black); cryptophytes (red); chrysophytes (yellow); unknown (pale grey).

Zooplankton species composition

FlowCam Macro image analysis yielded information on the abundance of two rotifer genera (*Asplanchna, Keratella*), eight cladoceran genera (*Daphnia, Bosmina, Bythotrephes, Ceriodaphnia, Diaphanosoma, Daphnia, Holopedium, Sida*), and two copepod groups (calanoids, cyclopoids). Combining all taxa, total zooplankton abundance varied up to a maximum of 1853 individuals m^{-3} of lake water (Figure 16).

In the spring survey, the highest abundances were recorded in Crummock Water, Derwent Water, Loughrigg Tarn, and Loweswater (Figure 17a). Calanoid copepods numerically dominated these communities. Unfortunately, most of the summer samples were lost to degradation, but the remaining samples revealed that communities in Coniston Water and Ullswater were numerically dominated by cyclopoid copepods at this time of year (Figure 17b). In the autumn survey, adverse weather prevented the safe collection of net tows at Bassenthwaite Lake, Coniston Water, Haweswater, Loughrigg Tarn, and Thirlmere (Figure 17c). As was the case in the spring, calanoid copepods were dominant in several lake communities (Brotherswater, Derwent Water, Loweswater, Windermere, Rydal Water, Ullswater, Wastwater) during the autumn. Other taxa showed dominance, each in a small number of the lakes (the small cladoceran *Ceriodaphnia* in Loweswater and Rydal Water, the large cladoceran *Daphnia* in Brotherswater, the rotifer *Asplanchna* in Esthwaite Water, and the small cladoceran *Bosmina* in Grasmere). In winter, calanoid copepods remained dominant in several lakes: Buttermere, Coniston Water, Crummock Water, Derwent Water, Loweswater, Windermere, Thirlmere, and Ullswater (Figure 17d).

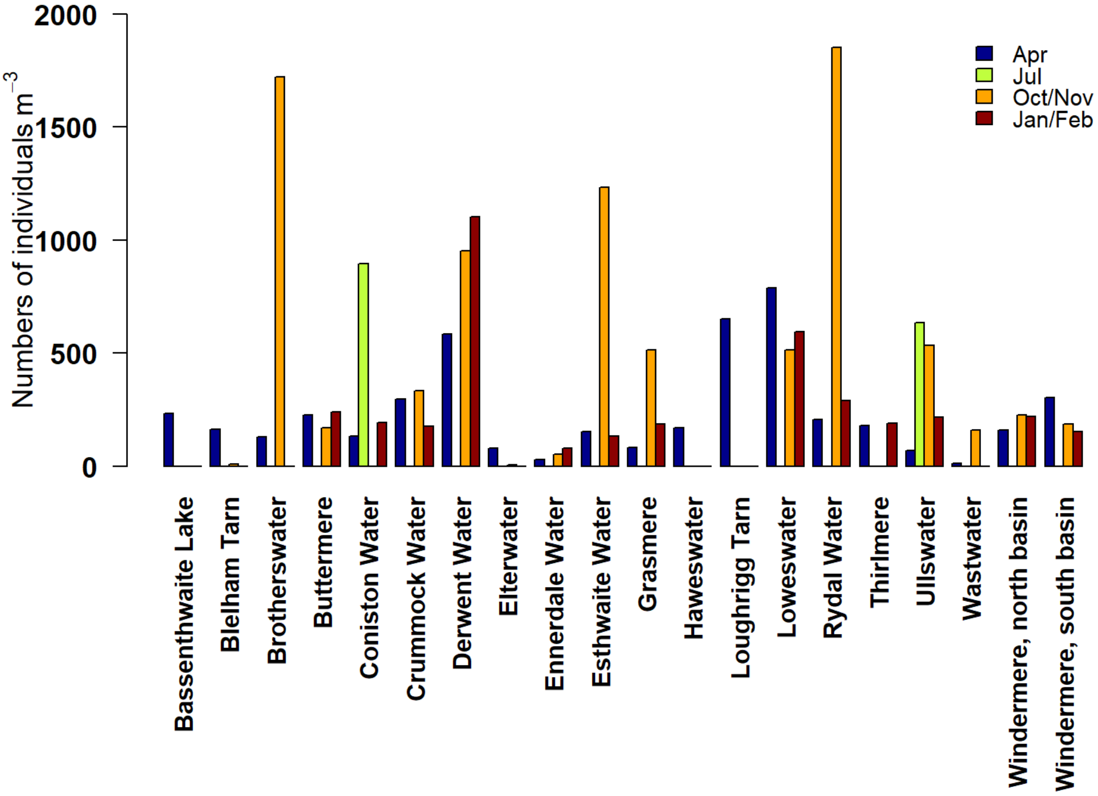
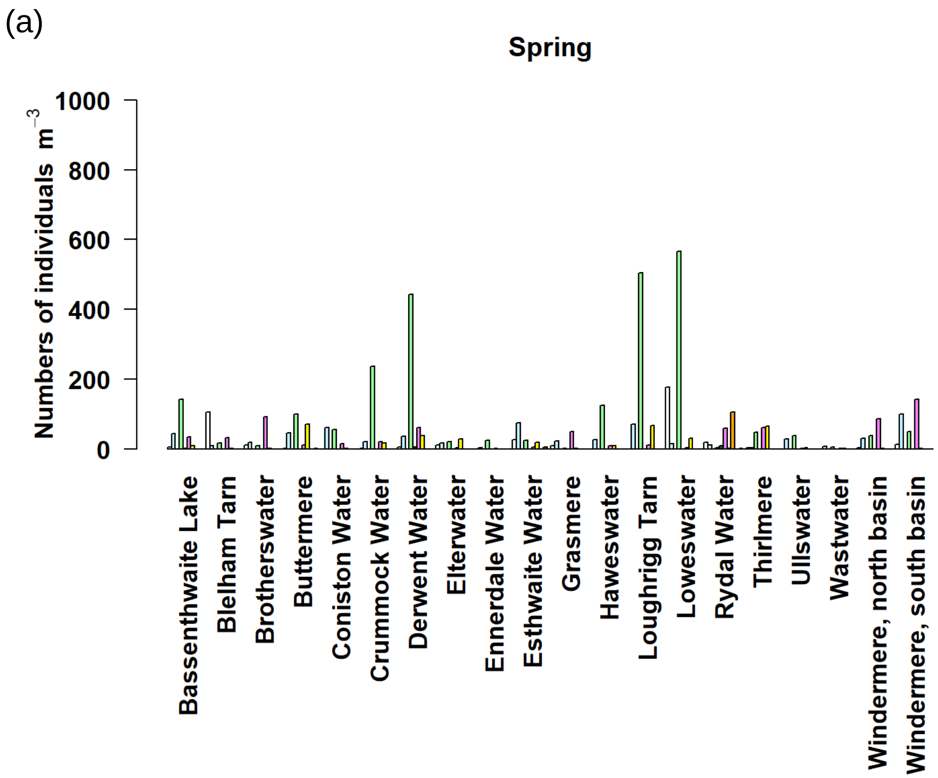
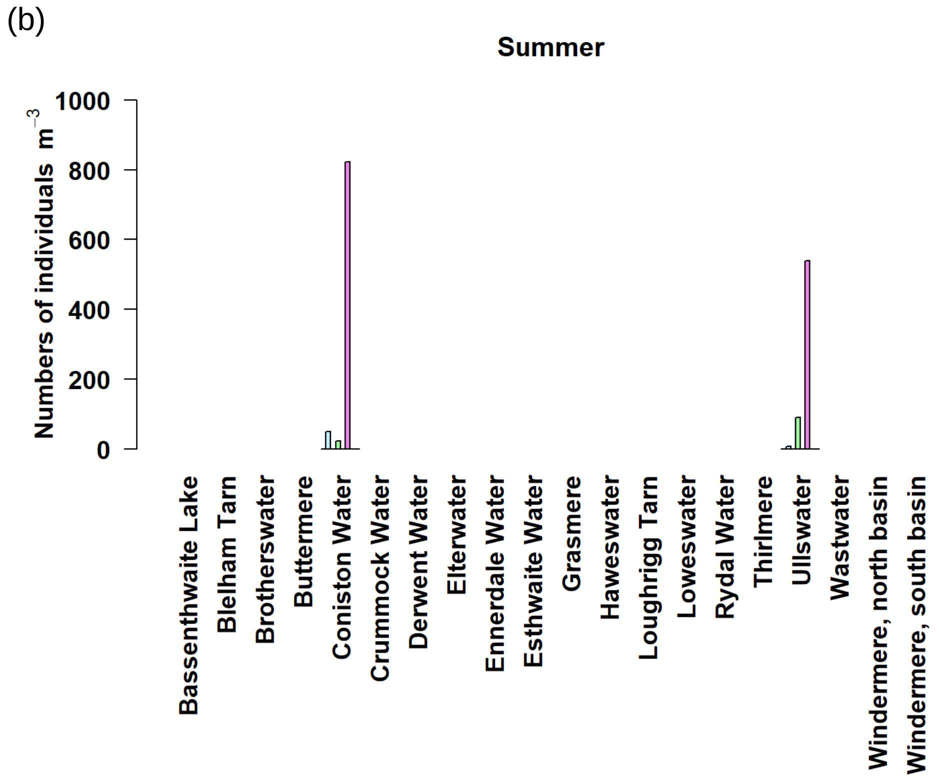


Figure 16 Seasonal changes in the total abundance of zooplankton in the 20 lake basins during 2021/22.


(a)
Spring
Numbers of individuals m^{-3}
1000
800
600
400
200
0
Bassenthwaite Lake
Blelham Tarn
Brotherswater
Buttermere
Coniston Water
Crummock Water
Derwent Water
Elterwater
Ennerdale Water
Esthwaite Water
Grasmere
Haweswater
Loughrigg Tarn
Loweswater
Rydal Water
Thirlmere
Ullswater
Wastwater
Windermere, north basin
Windermere, south basin


(b)
Summer
Numbers of individuals m^{-3}
1000
800
600
400
200
0
Bassenthwaite Lake
Blelham Tarn
Brotherswater
Buttermere
Coniston Water
Crummock Water
Derwent Water
Elterwater
Ennerdale Water
Esthwaite Water
Grasmere
Haweswater
Loughrigg Tarn
Loweswater
Rydal Water
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Wastwater
Windermere, north basin
Windermere, south basin

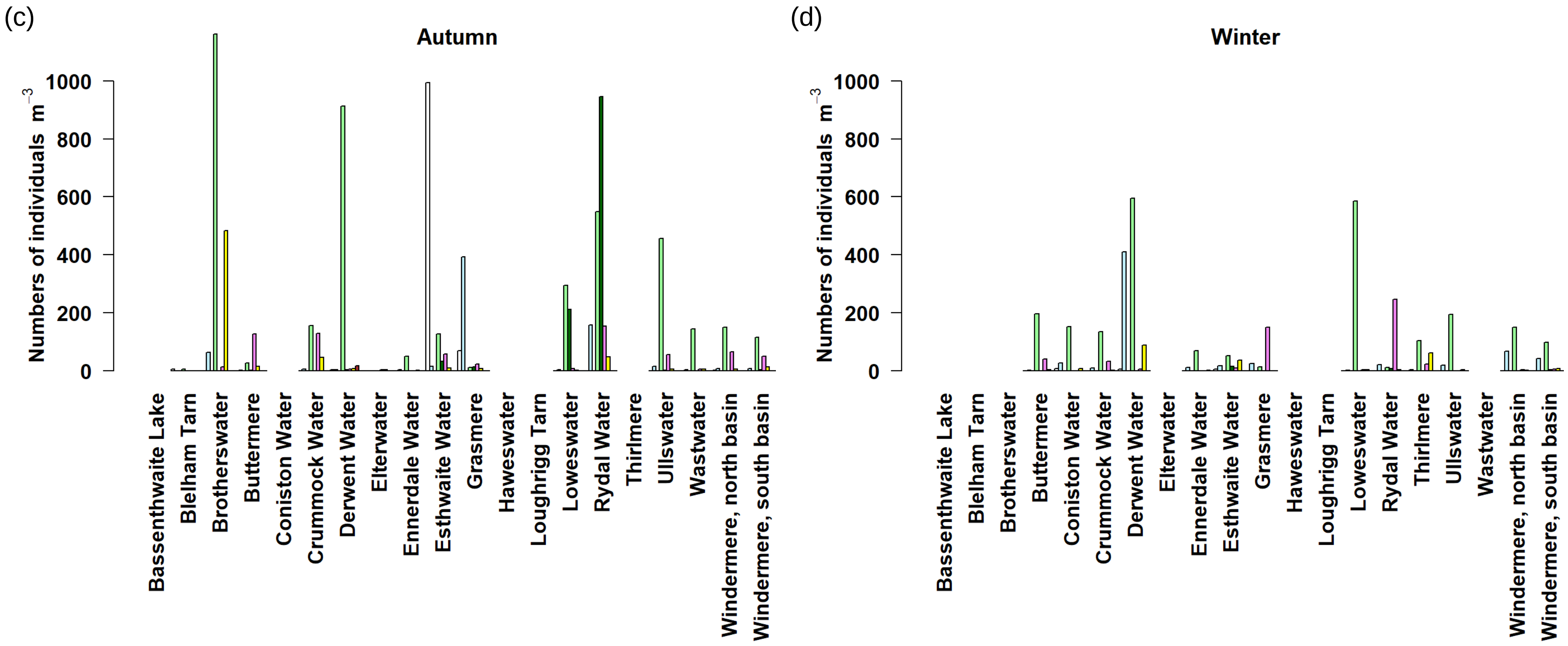


Figure 17 Zooplankton community composition in a) spring, b) summer, c) autumn and d) winter for the 20 lake basins

Heavy metals

Heavy metal concentrations have been measured in the Lakes Tour since 2010. In the previous two surveys samples were collected in each season. However, in 2021/22, samples were only collected during July due to logistical and resource limitations. Since the corresponding data only represent one point in time, no attempt has been made to compare concentrations to Environmental Quality Standards (UKTAG 2015). The data provide a snapshot of current metal concentrations across the lakes, and serve as a baseline for future studies. Where relevant, the annual results from 2015 and 2010 are compared to the data from July 2021.

Aluminium

Concentrations of filtered aluminium ranged from below the limit of detection of 10 mg m-3 in six of the lakes, to 22 mg m-3 in Ennerdale Water and Thirlmere (Figure 18, Table 5). A high concentration of 170 mg m^{-3} was recorded at Elterwater, but since this isn't reflected in the total aluminium concentration, it's likely to be a contamination issue with the sample. Total aluminium concentrations varied between 11 mg m^{-3} at Loughrigg Tarn to 53 mg m^{-3} in Crummock Water. Concentrations of filtered aluminium were generally similar to the annual values recorded in 2015, although total aluminium values were lower. This may reflect the fact that the summer sampling could miss catchment sources of metals that would be mobilised during the wetter months.

Cadmium

All filtered and total samples for cadmium, were below the limit of detection of 0.1 mg m-3, except for samples from Loweswater (Figure 18, Table 5). In this lake, concentrations were 0.12 mg m-3 filtered and 0.21 mg m-3 total, and therefore only just above the detection limit in both cases. These results are similar to the findings from 2015.

Chromium

All filtered and total samples for chromium were below the detection limit of 0.5 mg m-3, except for the filtered chromium sample at Elterwater (Figure 18, Table 5). As discussed above, this is likely to be a spurious result caused by contamination of the sample. These results are similar to the findings from 2015.

Copper

Concentrations of filtered copper ranged from below the limit of detection (1 mg m^{-3}) in 11 lakes to 3.1 and 3.4 mg m^{-3} in Coniston Water and Loweswater, respectively (Figure 18, Table 5). Coniston Water has known copper mines in its catchment, the source of copper in Loweswater is less clear, but copper veins within the Skiddaw slates series have been mined for centuries. Total copper concentration was not analysed for these samples.

Nickel

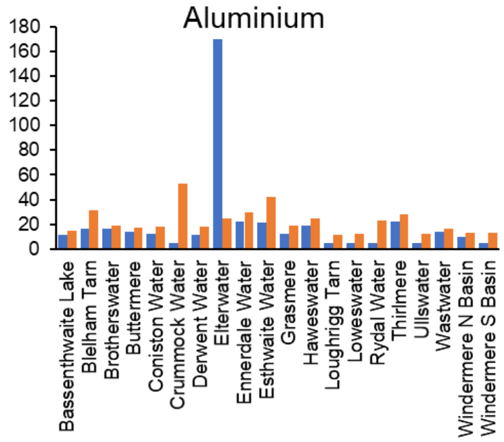
Nickel was below the detection limit (1 mg m^{-3}) in all samples, apart from the total nickel value at Elterwater, which may represent a contamination issue (Figure 18, Table 5). These results are similar to the findings from 2015.

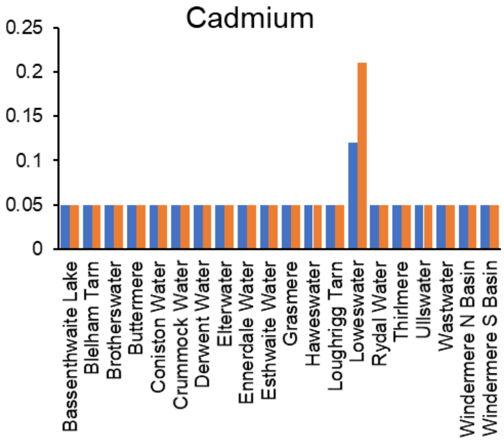
Lead

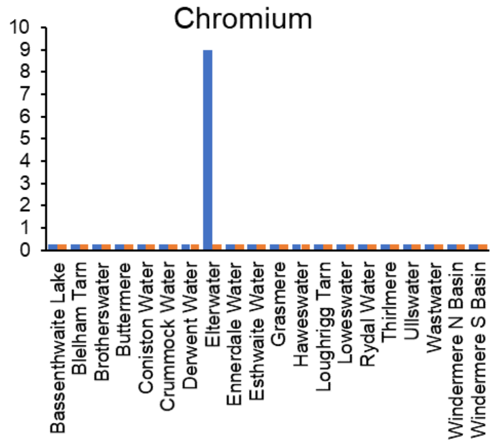
Filterable lead was below the limit of detection (2 mg m^{-3}) in all lakes, except for the sample from Elterwater, which is considered suspect (Figure 18, Table 5). Total lead concentrations were also generally below the detection limit, apart from the samples from Bassenthwaite Lake, Buttermere, Derwent Water, Ennerdale Water and Grasmere. Ennerdale Water had the highest total lead concentration of 5.2 mg m^{-3}.

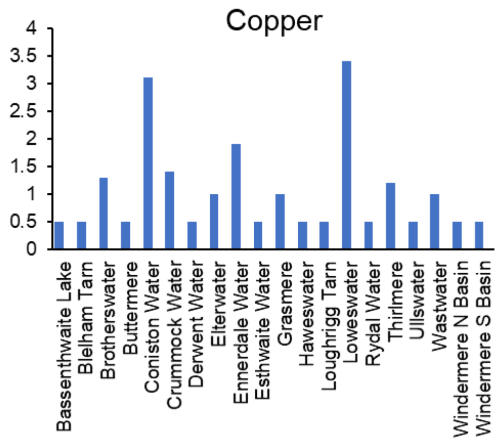
Zinc

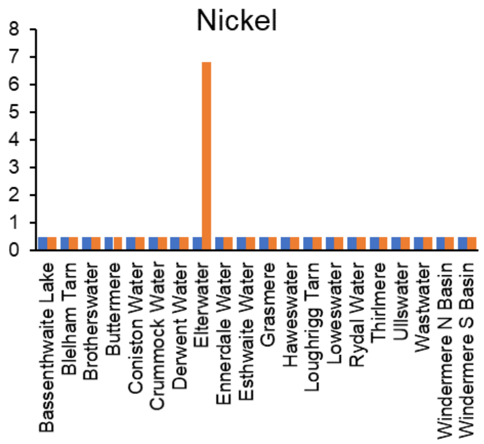
Concentrations of both filterable and total zinc were below the detection limit of 5 mg m^{-3} for most lakes (Figure 18, Table 5). The only exceptions to this were for Bassenthwaite Lake and Ullswater, where total zinc concentrations were 7.3 and 5.5 mg m^{-3}, respectively. These values are all generally lower than those measured in 2015.

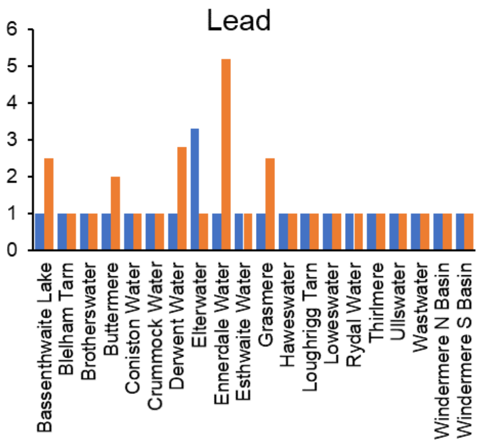












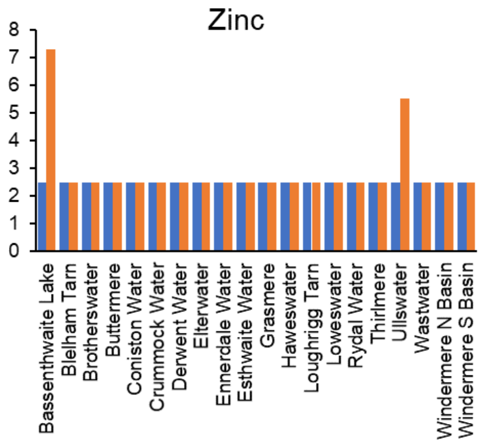


Figure 18 Metal concentrations (mg m^{-3}) in the 20 lakes in July 2021. Note that values less than the limit of detection (see Table 5) have been given a value of half the detection limit. Values refer to filtered (blue) and total (orange).

Table 5 Heavy metals concentration (mg m^{-3}) in the Lakes Tour samples in July 2021. The 4-figure number below each determinand is the EA method code. Filt = Filtered, Tot = Total.

		Aluminium		Cadmium		Chromium		Copper		Nickel		Lead		Zinc	
		Filt	Tot	Filt	Tot	Filt	Tot	Filt	Tot	Filt	Tot	Filt	Tot	Filt	Tot
Site	Date	6037	6057	0106	0108	3409	3164	6450	6452	6462	3410	0052	0050	3408	6455
Bassenthwaite Lake	01/07/2021	11	15	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	2.5	< 5	7.3
Blelham Tarn	07/07/2021	16	31	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5
Brotherswater	01/07/2021	16	19	< .1	< .1	< .5	< .5	1.3		< 1	< 1	< 2	< 2	< 5	< 5
Buttermere	07/07/2021	14	17	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	2	< 5	< 5
Coniston Water	08/07/2021	12	18	< .1	< .1	< .5	< .5	3.1		< 1	< 1	< 2	< 2	< 5	< 5
Crummock Water	07/07/2021	< 10	53	< .1	< .1	< .5	< .5	1.4		< 1	< 1	< 2	< 2	< 5	< 5
Derwent Water	01/07/2021	11	18	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	2.8	< 5	< 5
Elterwater	06/07/2021	170	25	< .1	< .1	9	< .5	1		< 1	6.8	3.3	< 2	< 5	< 5
Ennerdale Water	14/07/2021	22	30	< .1	< .1	< .5	< .5	1.9		< 1	< 1	< 2	5.2	< 5	< 5
Esthwaite Water	07/07/2021	21	42	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5
Grasmere	15/07/2021	12	19	< .1	< .1	< .5	< .5	1		< 1	< 1	< 2	2.5	< 5	< 5
Haweswater	13/07/2021	19	25	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5
Loughrigg Tarn	06/07/2021	< 10	11	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5
Loweswater	08/07/2021	< 10	12	0.12	0.21	< .5	< .5	3.4		< 1	< 1	< 2	< 2	< 5	< 5
Rydal Water	06/07/2021	< 10	23	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5
Thirlmere	01/07/2021	22	28	< .1	< .1	< .5	< .5	1.2		< 1	< 1	< 2	< 2	< 5	< 5
Ullswater	22/07/2021	< 10	12	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	5.5
Wastwater	21/07/2021	14	16	< .1	< .1	< .5	< .5	1		< 1	< 1	< 2	< 2	< 5	< 5
Windermere N Basin	06/07/2021	10	13	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5
Windermere S Basin	06/07/2021	< 10	13	< .1	< .1	< .5	< .5	< 1		< 1	< 1	< 2	< 2	< 5	< 5

Micro-organic pollutants

Micro-organic pollutants have been analysed in Lakes Tour samples since 2010. In the 2021/22 Lakes Tour, samples were only analysed from the summer samples, collected in July 2021. The 69 compounds analysed, and their limits of detection are provided in Table 6. Only four compounds had concentrations that exceeded the limit of detection, they are discussed in the following section.

Phenoxy acetic acid (PAA)

This compound forms the part-structure of many phenoxy herbicides including MCPA and 2,4-D. It has been the most widely detected compound across the previous Lakes Tours. The maximum concentration was 0.079 mg m^{-3} measured in Windermere, south basin (Table 6 and Table 7). This site was also had the highest concentration measured in the 2015 Lakes Tour. Concentrations measured in 2021 were generally lower than in 2010 and 2015, although sampling only occurred during the summer in 2021 and this is likely to result in an underestimate of concentrations, which will be linked to catchment activities and runoff during wetter periods of the year.

4-Chloro-2-methylphenoxyacetic acid (MCPA)

MCPA is a widely used herbicide targeting annual and perennial broadleaf weeds in agricultural and domestic settings. It was detected in three lakes, Bassenthwaite Lake, Blelham Tarn and Esthwaite Water, above the limit of detection (Table 6 and Table 7). The maximum recorded concentration of 0.024 mg m^{-3}, in Blelham Tarn, is around 500 times lower than the maximum allowable concentration, and concentrations were again typically lower than the 2015 average.

3,6-dichloro-2-pyridinecarboxylic acid (Clopyralid)

Clopyralid is a selective herbicide used for control of broadleaf weeds, especially thistles and clovers. It was detected on four occasions in 2010 but was not detected in 2015 or 2021 (Table 6).

Table 6 Micro-organic compounds (mg m^{-3}) analysed in July 2021, their EA methods code, the limit(s) of detection (LOD), the number of values above the LOD, the maximum concentration recorded, and allowable mean concentration from UKTAG Annex V111 substances. Values in parentheses are results from 2010 and 2015.

EA Code	Description	LOD	Number > LOD	Max concentration	Allowable concentration
0723	Diazinon	0.001	2 (27,38)	0.0031	0.01
3545	2,4-Dichlorophenoxyacetic acid (2,4-D)	0.005	3 (1,2)	0.016	0.3
3548	4-Chloro-2-methylphenoxyacetic acid (MCPA)	0.005	3 (8,11)	0.024	12-80*
6671	Phenoxyacetic acid (PAA)	0.01	11(50,39)	0.079	-
0503	Chlorfenvinphos	0.01	0	<LOD	-
0507	Dichlorvos	0.004	0	<LOD	-
0535	Malathion	0.002	0	<LOD	-
0543	Parathion-ethyl :- {Parathion}	0.004	0	<LOD	-
0547	Phorate				-
1118	Fenthion	0.008	0	<LOD	-
1119	Parathion-methyl	0.005	0	<LOD	-
3001	Simazine	0.003	0	<LOD	-
3002	Atrazine	0.003	0	<LOD	-
3009	Terbutryn	0.004	0	<LOD	-
3546	2,4,5-T :- {2,4,5-Trichlorophenoxyacetic acid}	0.005	0	<LOD	-
3547	4-Chlorophenoxyacetic acid		(2,0)		-
3549	Mecoprop	0.005	0 (3,0)	<LOD	18
3550	Dicamba	0.01	0	<LOD	-
3551	Dichlorprop :- {2,4-DP}	0.005	0	<LOD	-
3552	Fenoprop	0.005	0	<LOD	-
3555	Triclopyr	0.005	0 (1,1)	<LOD	-
3790	MCPB :- {4-Chloro-2-methylphenoxybutyric	0.005	0 (1,0)	<LOD	-
3791	2,4-DB :- {4-(2,4-dichlorophenoxy)butyric acid}	0.005	0 (1,0)	<LOD	-
3792	Benazolin	0.005	0	<LOD	-
4064	Fluroxypyr	0.005	0	<LOD	-
4065	Bentazone	0.003	0 (1,0)	<LOD	500
5563	Prometryn	0.005	0	<LOD	-
6447	Dimethoate	0.006	0	<LOD	-
6448	Propyzamide	0.005	0 (1,0)	<LOD	100
6449	Bromoxynil	0.005	0 (1,0)	<LOD	100
6487	Triazophos	0.005	0	<LOD	-
6620	Clopyralid	0.005	0 (4,0)	<LOD	-
6628	Cyanazine	0.006	0	<LOD	-
6635	Desmetryne	0.005	0	<LOD	-
6640	Fenchlorphos :- {Ronnel}	0.005	0	<LOD	-
6649	Iprodione	0.008	0	<LOD	-
6672	Phenoxybutyric acid :- {PBA}	0.005	0	<LOD	-
6673	Phenoxypropionic acid :- {PPA}				-
6776	Fenpropimorph	0.007	0	<LOD	-
6976	Napropamide	0.005	0	<LOD	-
7071	Prochloraz				-
7154	Ethofumesate	0.005	0	<LOD	-
7159	Fonofos	0.001	0	<LOD	-
7181	Chlorpyrifos-methyl	0.001	0	<LOD	-
7726	2,3,6-TBA :- {2,3,6-Trichlorobenzoic acid}	0.02	0 (1,0)	<LOD	-
8804	Atrazine-desethyl :- {Atrazine-de-ethyl}	0.02	0	<LOD	-
8997	Atrazine-desisopropyl :- {Atrazine de-	0.02	0	<LOD	-
8998	Pirimiphos-ethyl	0.005	0	<LOD	-
8999	Irgarol 1051	0.005	0	<LOD	-
9000	Iodofenphos	0.001	0 (1,0)	<LOD	-
9002	Metazachlor	0.005	0	<LOD	-
9068	Ioxynil	0.005	0	<LOD	-
9338	Bendiocarb	0.005	0	<LOD	-
9474	Coumaphos	0.005	0	<LOD	-
9479	Mevinphos	0.008	0	<LOD	-
9519	Carbophenothion	0.005	0	<LOD	-
9586	Propetamphos	0.005	0	<LOD	-
9606	Bupirimate	0.005	0	<LOD	-
9634	Propazine	0.002	0	<LOD	-
9715	Azinphos-methyl	0.003	0	<LOD	-
9716	Fenitrothion	0.001	0	<LOD	-
9851	Pirimiphos-methyl	0.003	0	<LOD	-
9860	Metalaxyl	0.008	0	<LOD	-
9863	Azinphos-ethyl	0.006	0	<LOD	-
9883	Picloram	0.005	0 (1,0)	<LOD	-
9911	Trietazine	0.002	0	<LOD	-
9959	Pirimicarb	0.004	0	<LOD	-
9978	Chlorpyrifos-ethyl	0.002	0	<LOD	-
9979	Ethion	0.005	0	<LOD	-

* Lower value if pH<7, higher value if pH>7.

Diazinon

Diazinon (O,O-Diethyl O-[4-methyl-6-(propan-2-yl)pyrimidin-2-yl] phosphorothioate) is a contact organophosphorus acaricide or insecticide. It was detected in two of the 20 lakes, Bassenthwaite Lake and Derwent Water, at concentrations of 0.002 and 0.003 mg m^{-3}, respectively (Table 6 and Table 7). These values are lower than the average concentration of Diazinon found during the 2015 survey, which measured concentrations in four, seasonal samples at each lake. It is interesting to note that these lakes are connected, which may indicate a common source or sources for the compound. In both 2010 and 2015, Diazonin was reported in 16 of the twenty lakes, where it was found on all four sampling occasions in Buttermere, Crummock Water, Ullswater and Windermere, north basin.

Mecoprop

Methylchlorophenoxypropionic acid (MCPP) is a common general use herbicide found in many household weed killers and "weed-and-feed" type lawn fertilizers. It was detected three times in 2010 but was not detected in 2015 or 2021 (Table 6).

4-CAA

4-Chlorophenoxyacetic acid (4-CAA) is an artificial plant hormone (an analogue of auxin) and is presumably active as a herbicide. It was detected twice in 2010 but was not detected in 2015 or 2021 (Table 6).

2,4-D (2,4-Dichlorophenoxyacetic acid)

2,4-D is commonly used phenoxy herbicide used to control broadleaf weeds. In July 2021, it was above the limit of detection at Grasmere, Rydal Water and Windermere, north basin (Table 6 and Table 7). The concentration of the compound was 0.01, 0.016 and 0.005 in those three lakes. Again, it is interesting to note that these lakes are all connected. It was detected once in the Lakes Tour 2010 and twice in 2015, at Esthwaite Water and Blelham Tarn.

Triclopyr

Is a herbicide designed to kill broadleaved weeds rather than grasses. It was detected at Blelham Tarn in 2015. However, it was not detected in 2021 or in 2010 (Table 6).

Table 7 Mean concentration of the four detectable micro-organic compounds in in the twenty lakes in July 2021 (mg m^{-3}).

EA Code	0723	3545	3548	6671
Lake	Diazinon	2,4-Dichlorophenoxyacetic acid (2,4-D)	4-Chloro-2-methylphenoxyacetic acid (MCPA)	Phenoxyacetic acid (PAA)
Bassenthwaite Lake	0.0019	-	0.0085	0.028
Blelham Tarn	-	-	0.024	0.011
Brotherswater	-	-	-	0.022
Buttermere	-	-	-	-
Coniston Water	-	-	-	-
Crummock Water	-	-	-	-
Derwent Water	0.0031	-	-	0.027
Elterwater	-	-	-	0.012
Ennerdale Water	-	-	-	-
Esthwaite Water	-	-	0.011	0.022
Grasmere	-	0.01	-	0.011
Haweswater	-	-	-	-
Loughrigg Tarn	-	-	-	0.03
Loweswater	-	-	-	-
Rydal Water	-	0.016	-	0.024
Thirlmere	-	-	-	-
Ullswater	-	-	-	-
Wastwater	-	-	-	-
Windermere N Basin	-	0.0054	-	0.11
Windermere S Basin	-	-	-	0.079

3.3 Current status of the Lakes Tour lakes and evidence for change

Classification boundaries and statistical trends

This section provides an assessment of the current status of each lake basin surveyed in 2021/22. In addition to a general assessment, each lake is categorised according to trophic status and likely ecological status, based upon measured total phosphorus and chlorophyll *a* concentrations, using the criteria of the Water Framework Directive (UKTAG 2015). The Organisation for Economic Co-operation and Development (OECD) developed five trophic categories as part of its work on the Eutrophication of Waters in the 1980s (Organisation for Economic Co-operation and Development 1982), which linked phosphorus concentrations with algal biomass, measured as chlorophyll *a* concentration, and water clarity, measured as the Secchi disc depth. These are defined in Table 8.

Table 8 OECD (1982) boundaries for lake trophic status.

Trophic category	Mean annual TP (mg m^{-3})	Mean annual Chl *a* (mg m^{-3})	Max Chl *a* (mg m^{-3})	Mean annual Secchi (m)	Min Secchi (m)
Ultra-oligotrophic	≤ 4	≤ 1	≤ 2.5	≥ 12	≥ 6
Oligotrophic	4 < 10	1 < 2.5	2.5 < 8	12 > 6	6 > 3
Mesotrophic	10 < 35	2.5 < 8	8 < 25	6 > 3	$3 \leq 1.5$
Eutrophic	35 < 100	8 < 25	25 < 75	3 > 1.5	$1.5 \leq 0.7$
Hypertrophic	≥ 100	≥ 25	≥ 75	≤ 1.5	≤ 0.7

The current legislative framework for the classification of lakes in England is still provided by the European Union Water Framework Directive (WFD; 2000/60/EC). The original targets for the Directive were for lakes and surface waters to be maintained or returned to Good Ecological Status by 2015 or 2027 at the latest. The boundaries for ecological status of different Biological Quality Elements or Supporting elements are set depending on the type of lake. Two features are relevant for lake type: alkalinity and mean depth. Low alkalinity lakes have an annual mean alkalinity less than 200 mequiv m^{-3}, moderate alkalinity 200 to less than 1000 mequiv m^{-3} and high alkalinity more than 1000 mequiv m^{-3} (does not apply to any of the major Lake District lakes). The depth categories relate to mean depth and are very shallow, less than 3 m;

shallow, 3 to 15 m; and deep, more than 15 m. Table 9Table 10 gives the WFD categories for each of the 20 lakes for total phosphorus and chlorophyll *a* indicators.

*Table 9 Site-specific annual mean total phosphorus concentrations (mg m^{-3}) for different lake types (LAS: low alkalinity shallow; LAD: low alkalinity deep; LAVS low alkalinity very shallow; MAS medium alkalinity shallow; MAD: medium alkalinity deep). Ecological quality designated as reference state (Ref) and boundaries for High:Good (H:G), Good:Moderate (G:M), Moderate:Poor (M:P) and Poor:Bad (P:B).*not a WFD waterbody*

Lake	Type	Ref	H:G	G:M	M:P	P:B
Bassenthwaite Lake	MAS	<7.5	10.0	15.0	30.0	60.0
Blelham Tarn	MAS	<9.0	11.9	17.7	35.4	71.0
Brothers Water	LAS	<6.2	8.3	12.5	25.1	50.2
Buttermere	LAD	<3.9	5.2	8.2	16.3	32.7
Coniston Water	LAD	<5.1	6.9	11.0	22.0	44.1
Crummock Water	LAD	<3.5	5.0	8.0	16.0	32.0
Derwent Water	LAS	<6.2	8.2	12.4	24.8	49.5
Elterwater	LAVS	<7.9	12.0	17.9	35.8	71.7
Ennerdale Water	LAD	<3.7	5.0	8.0	16.0	32.0
Esthwaite Water	MAS	<8.3	11.0	16.4	32.8	65.7
Grasmere	LAS	<6.2	8.2	12.5	25.0	50.0
Haweswater	MAD	<4.4	6.1	9.6	19.2	38.4
Loughrigg Tarn*	MAS	<8.0	11.0	16.0	32.0	64.0
Loweswater	LAS	<6.0	8.1	12.2	24.4	48.9
Rydal Water*	LAS	<5.0	7.0	10.0	20.0	40.0
Thirlmere	LAD	<4.0	5.4	8.3	16.7	33.4
Ullswater	MAD	<4.9	6.7	10.6	21.3	42.5
Wastwater	LAD	<3.4	5.0	8.0	16.0	32.0
Windermere North Basin	MAD	<5.4	7.3	11.6	23.2	46.4
Windermere South Basin	MAD	<6.1	8.3	12.8	25.6	51.1

*Table 10 Site-specific annual geometric mean concentrations of phytoplankton chlorophyll a (mg m^{-3}) at reference state (Ref) and the High:Good (H:G), Good:Moderate (G:M), Moderate:Poor (M:P) and Poor:Bad (P:B) boundaries. *not a WFD waterbody*

Lake	Ref	H:G	G:M	M:P	P:B
Bassenthwaite Lake	<2.6	5.3	8.0	15.5	52.6
Blelham Tarn	<2.8	5.6	8.5	16.4	55.8
Brothers Water	<2.2	3.5	7.6	14.8	44.2
Buttermere	<1.5	2.4	4.6	9.0	30.6
Coniston Water	<1.8	2.7	5.3	10.3	35.1
Crummock Water	<1.4	2.2	4.3	8.4	28.4
Derwent Water	<2.2	3.5	7.6	14.8	44.2
Elterwater	<3.4	5.3	11.2	22.4	67.2
Ennerdale Water	<1.5	2.3	4.5	8.8	29.9
Esthwaite Water	<2.7	5.4	8.2	16.0	54.3
Grasmere	<2.2	3.4	7.4	14.4	43.1
Haweswater	<1.8	2.8	5.4	10.4	35.4
Loughrigg Tarn*	<3.1	6.1	9.3	18.6	56.2
Loweswater	<2.2	3.4	7.6	14.7	44.0
Rydal Water*	<1.8	3.6	6.3	12.6	38.1
Thirlmere	<1.7	3.3	5.0	10.0	30.4
Ullswater	<1.8	3.7	5.6	10.8	36.7
Wastwater	<1.4	2.1	4.2	8.1	27.4
Windermere North Basin	<1.8	3.6	5.5	10.6	36.0
Windermere South Basin	<2.0	4.0	6.0	11.7	39.6

Summary statistics of the data collected as part of the Lakes Tour surveys were compared to the boundary values in Table 9Table 10, specifically mean annual concentrations of total phosphorus and chlorophyll *a* . The latter was calculated from the annual geometric mean, which is the exponent of the mean of the natural log of the data, corrected for the effect of the geometric calculation using the following formula:

$$Observed\ Chla = GM_{chlorophyll} \times e^{0.5 \times (2.323 \times SD_g)^2}$$

Where: $GM_{chlorophyll}$ is the geometric mean of the measured chlorophyll concentrations; and SD_g is the standard deviation from a population of UK lakes which, for the lakes considered here (alkalinity < 1 mequiv m^{-3}), has a value of 0.345 (UKTAG 2008). Note that the methodology requires monthly values for TP and chlorophyll *a,* while four seasonal samples were available for analysis here. We recognise that this may introduce some inaccuracy in classification. Further, in formal WFD assessments, these values are calculated as three-year means rather than as an annual mean, and so results may differ from what would be obtained through formal assessment and are only indicative.

For each lake, records from the 2021/22 Lakes Tour are assessed for the current status and also compared to previous surveys. Where possible, this covers all seven Tours back to 1984, to assess the extent of any change in these lakes. A statistical assessment of change over time is made using a trend analysis called Sen’s slope estimator. This is a non-parametric method which computes the linear rate of change in time series data. The advantage of this method is that it is robust to temporal autocorrelation, a common artefact of time series data, and can be applied to only small numbers of observations. The major changes are reported on a lake-by-lake basis. Although results for SRP and NH_4-N are presented, they are not analysed in detail as many of the concentrations were below the detection limit. A summary of these analyses is presented below in Table 11, and then discussed for each lake in the context of their current state.

Table 11 Sen's slope coefficients for annual mean concentrations in parameters between 1984 and 2021/22. Significant slopes ($P<0.05$) are green to indicate significant decreases, or orange to indicate significant increases. NB: 1) a negative slope of H+ is an increase in pH, 2) a negative slope of SD = Secchi Depth is shallower.

Lake	TP	SRP	NO_3-N	NH_4-N	SiO_2	Chla	SD	H^+	Alk	SO_4	Cl	Ca	Mg	Na	K	Cond
Bassenthwaite Lake	-1.40	-0.03	-14.41	3.42	0.02	-0.80	0.14	5.00E-09	13.96	-7.13	-19.23	-4.49	-2.24	-6.66	-0.86	-1.88
Blelham Tarn	-1.90	-0.19	-79.04	-4.63	0.02	0.70	0.01	8.24E-09	0.25	-14.00	-21.10	-25.21	-5.54	-14.95	-1.75	-6.20
Brotherswater	-0.10	-0.27	-9.78	0.08	-0.01	-0.04	-0.11	-2.97E-09	8.22	-8.67	-15.77	-7.76	-2.73	-8.66	-0.54	-3.52
Buttermere	0.02	0.04	8.79	2.00	-0.05	0.00	-0.34	-2.02E-08	3.60	-5.91	-11.80	-6.24	-3.23	-9.46	-0.43	-3.10
Coniston Water	0.10	0.00	-9.21	2.58	0.05	-0.11	-0.18	-2.70E-09	4.76	-12.12	-13.84	-11.76	-3.53	-7.44	-0.71	-4.59
Crummock Water	-0.01	0.04	4.87	2.20	0.01	-0.06	-0.24	-2.24E-08	2.76	-7.29	-13.07	-6.52	-3.72	-7.86	-0.53	-2.73
Derwentwater	0.01	0.02	-12.08	1.63	-0.05	0.15	0.11	-6.05E-09	4.73	-8.25	-16.04	-9.87	-3.58	-12.17	-0.59	-3.44
Elterwater	-2.30	-0.33	-9.51	-15.54	0.00	1.18	0.07	1.27E-08	4.14	-10.61	-19.73	-8.29	-0.76	-11.21	-1.09	-3.16
Ennerdale Water	0.22	-0.06	-21.21	2.25	-0.06	0.03	-0.74	-1.09E-08	3.81	-7.52	-12.12	-6.38	-4.52	-9.75	-0.41	-3.06
Esthwaite Water	-0.46	-0.53	-67.49	-2.25	0.05	-1.01	0.10	-4.79E-09	6.72	-15.95	-20.63	-16.43	-4.70	-7.63	-1.96	-5.03
Grasmere	-1.04	-0.08	9.79	-0.85	0.01	0.09	0.00	5.26E-09	4.45	-8.29	-22.69	-10.18	-3.24	-15.22	-0.76	-3.90
Haweswater	0.36	0.02	-13.99	1.38	0.02	-0.15	-0.05	-3.92E-09	5.53	-9.14	-15.04	-7.37	-3.80	-10.14	-0.83	-3.60
Loughrigg Tarn	-1.87	-0.86	32.28	-3.94	0.00	-1.12	0.15	5.95E-09	1.38	-12.41	-19.55	-17.84	-3.58	-10.53	-0.75	-4.81
Loweswater	-0.17	-0.03	-37.46	2.73	0.02	0.17	-0.05	-2.08E-09	1.47	-10.49	-19.01	-15.51	-5.01	-10.26	-0.74	-4.69
Rydal Water	-0.87	-0.42	5.67	2.38	-0.02	-0.21	-0.09	-6.30E-09	8.35	-9.10	-24.17	-10.73	-3.66	-14.66	-0.55	-4.69
Thirlmere	0.52	-0.06	-7.23	1.21	-0.06	0.22	-0.29	-2.52E-08	3.88	-9.10	-15.27	-8.62	-3.12	-9.76	-0.48	-3.74
Ullswater	-0.20	0.18	-10.39	2.00	0.13	-0.76	-0.16	-2.41E-09	1.92	-8.95	-13.39	-9.89	-3.14	-7.37	-0.51	-2.83
Wastwater	0.45	0.00	-4.38	2.05	0.00	-0.04	-0.63	-1.34E-08	3.90	-7.18	-9.38	-5.40	-2.98	-6.65	-0.44	-2.99
Windermere North Basin	-0.56	-0.21	-12.88	0.50	-0.01	0.38	-0.13	1.92E-09	7.65	-10.90	-15.91	-8.57	-2.50	-10.31	-0.60	-3.74
Windermere South Basin	-2.51	-1.21	0.79	-0.50	0.01	-0.05	-0.11	6.66E-10	6.04	-10.44	-17.86	-10.11	-2.70	-8.56	-0.46	-3.42

Bassenthwaite Lake

Bassenthwaite Lake from Winlatter Pass. (Photo: M.M. De Ville).

Bassenthwaite Lake is a large shallow lake in the northwest of the English Lake District (Figure 1). The shallow nature of the lake, combined with the large catchment area result in a relatively short water residence time (mean, ~ 30 days), a feature that plays an important role in determining its status and function. Upstream, both Derwent Water and Thirlmere are within the Bassenthwaite catchment. Key water quality variables in 2021/22 are provided in Table 12. A review of Bassenthwaite Lake was published in 2006 (Thackeray et al. 2006).

Table 12 Summary of limnological conditions and trophic and Water Framework Directive classifications of Bassenthwaite Lake in 2021/22

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	267		
Mean pH (geometric mean)	7.0		
Mean total phosphorus (mg m^{-3})	14.5	Mesotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	1.8		
Mean nitrate-nitrogen (mg m^{-3})	351		
Mean silica (mg m^{-3})	2251		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	4.5	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	8.8	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	5.3		High/Good
Mean Secchi depth (m)	3.4	Mesotrophic	
Minimum Secchi depth (m)	3.2	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	3.7		

The water quality in Bassenthwaite Lake has continued to improve since the last survey in 2015, in terms of the chlorophyll *a* concentration and Secchi depth. However, mean total phosphorus concentrations were higher than in the previous survey. The lake is classed as mesotrophic on most measures, and improvements in the light climate have resulted in the lake being oligotrophic for the minimum Secchi depth measured. As mentioned in the previous report, this measure may relate more to suspended sediment particles than phytoplankton concentrations, but the chlorophyll *a* concentration has continued to decline from its peak in 2000. The lake is categorised as being at a good ecological state for TP and on the border between good and high for chlorophyll *a* concentration according to the WFD classification boundaries.

There are no statistically significant changes in the concentrations of the macro nutrients in Bassenthwaite Lake since 1984 (Table 11) and the most recent change in TP has been a slight increase in concentration since 2015, which may be of concern if other indicators worsen (Figure 19). Alkalinity is the only major ion to show a significant increase over the time series, whilst sulphate and potassium concentrations have both declined (Table 11).

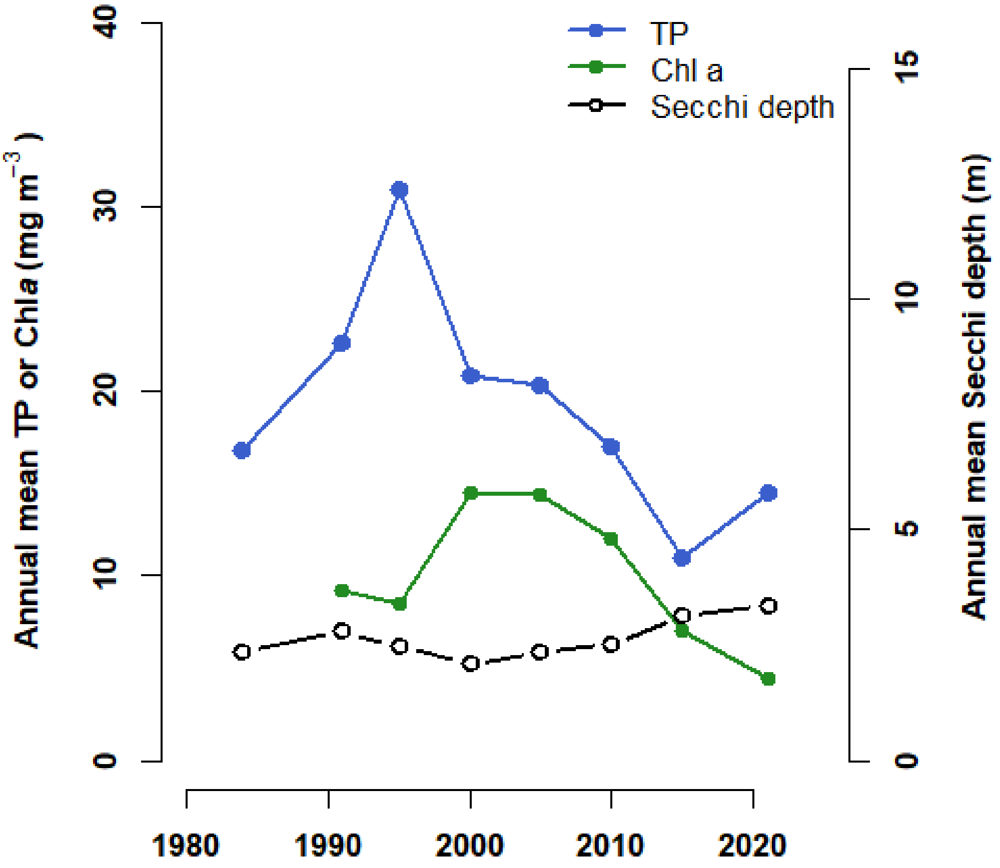


Figure 19 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Bassenthwaite Lake.

Blelham Tarn

Blelham Tarn (Photo: S.C. Maberly)

Blelham Tarn is a small lake whose outflow drains into the north basin of Windermere (Figure 1). In 2021/22 the lake had the highest annual mean alkalinity, and second highest calcium, magnesium, potassium concentrations of the twenty lakes (Table 13). The chlorophyll *a* and Secchi disc depth have both improved since 2015 and the lake had only the 4th highest annual chlorophyll *a* concentration and second shallowest Secchi depth.

Table 13 Summary of limnological conditions and trophic and Water Framework Directive classifications at Blelham Tarn in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	399		
Mean pH (geometric mean)	7.1		
Mean total phosphorus (mg m^{-3})	21	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.6		
Mean nitrate-nitrogen (mg m^{-3})	454		
Mean silica (mg m^{-3})	2068		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	11.1	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	26.3	Eutrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	9.6		Moderate
Mean Secchi depth (m)	2.2	Eutrophic	
Minimum Secchi depth (m)	1.8	Mesotrophic	
Minimum oxygen concentration (g m^{-3})	0.2		

According to the OECD classification, Blelham Tarn remains on the meso-eutrophic boundary and, despite reductions in total phosphorus and chlorophyll *a* concentrations and a slight improvement in the mean Secchi depth compared to 2015, no status class boundaries have changed over the last five years. The lake experiences severe oxygen depletion with depth during the summer and complete anoxia occurs up to five metres, severely restricting oxygenated habitat in the lake. The ecological state of the lake based on the total phosphorus and chlorophyll *a* concentration indicators remains at Moderate, and it would fail oxygen concentration targets.

Interestingly, the statistically significant increase in chlorophyll *a* reported in the 2015 Lakes Tour report has been reversed in the 2021/22 data and concentrations of chlorophyll *a* in the Tarn are at their lowest since this measure started in the 1991 Lakes Tour (Figure 20). Nitrate concentrations have experienced a statistically significant reduction since 1984 and TP concentrations are slightly lower than those measured in 2015 (Table 11). Significant reductions also occurred in sulphate, calcium, potassium and conductivity, whilst there has been a significant reduction in pH.

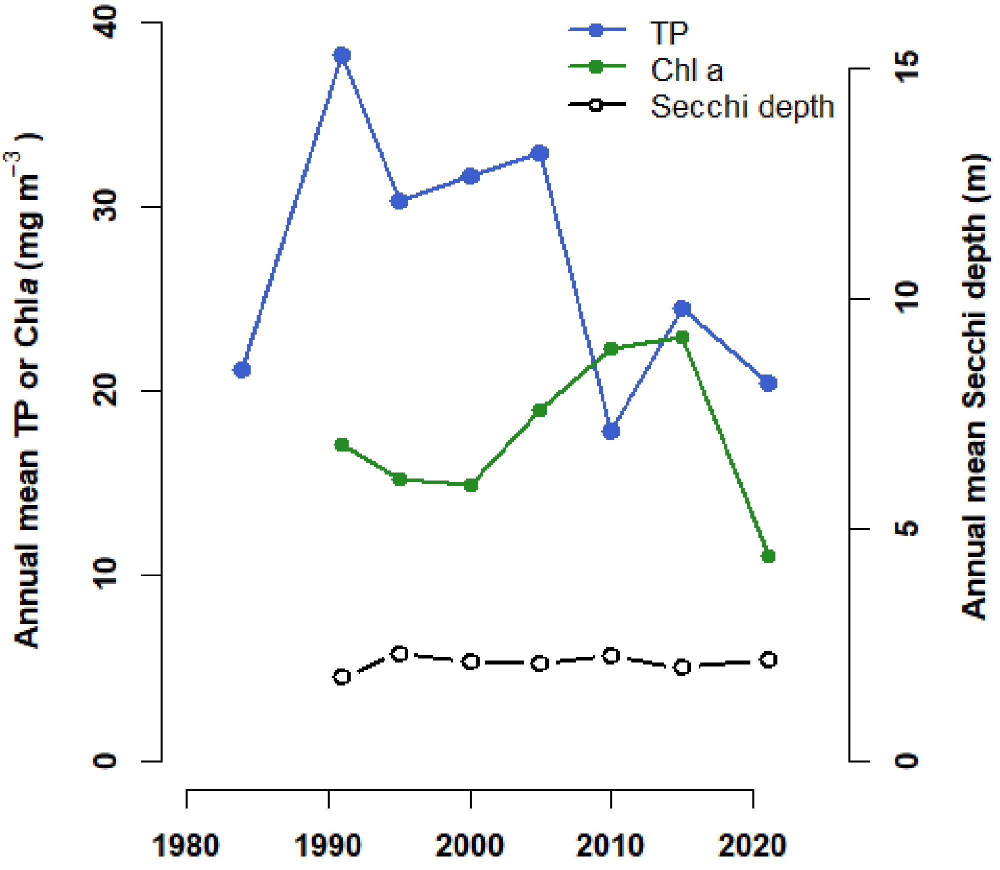


Figure 20 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Blelham Tarn.

Blelham Tarn is studied fortnightly as part of the UKCEH long-term monitoring programme (https://uk-scape.ceh.ac.uk/our-science/projects/cumbrian-lakes-monitoring-platform) that was started by the Freshwater Biological Association in 1945 and continued by UKCEH since 1989. There is a UKCEH Automatic Water Quality Monitoring Station on the lake which also forms part of the monitoring programme, and provides high temporal resolution data on lake condition.

Brothers Water


Brothers Water from Kirkstone Pass (Photo: M.M. De Ville).

Brothers Water is a small lake whose outflow drains into the southern part of Ullswater, forming the south westerly edge of the large River Eden catchment (Figure 1). It has the second highest altitude catchment (Table 1). In 2021/22 it had the fourth lowest chlorophyll *a* concentration and fifth deepest Secchi depth and had a circum-neutral pH (Table 14).

Table 14 Summary of limnological conditions and trophic and Water Framework Directive classifications at Brothers Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	170		
Mean pH (geometric mean)	7.0		
Mean total phosphorus (mg m^{-3})	7.0	Oligotrophic	High
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	238		
Mean silica (mg m^{-3})	1578		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	1.2	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	2.2	Ultra-oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	1.6		High
Mean Secchi depth (m)	5.5	Mesotrophic	
Minimum Secchi depth (m)	4.3	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	1.4		

Brothers Water is largely oligotrophic in its classification, having low TP and chlorophyll *a* concentrations. Interestingly for this trophic status, the lake is subject to oxygen depletion at depth during the summer. A previous study by Mackay et al. (Mackay et al. 2015a) investigated the potential causes of this issue and concluded that the unusual bathymetry of the lake was not a major contributor to enhanced oxygen depletion. External sources of labile organic matter, in addition to in-lake phytoplankton production could not be ruled out, and there was an indication that organic carbon accumulation was higher than expected in this lake. For both WFD indicators, the lake is classified as being at High ecological status (Table 14), although it would fail oxygen concentration targets.

There have been no statistically significant changes in the concentration of the major nutrients at Brothers Water (Table 11). However, statistically significant declines in sulphate, magnesium, potassium and conductivity have occurred in the lake. There have been no significant changes in chlorophyll *a* concentration and Secchi depth (Figure 21).

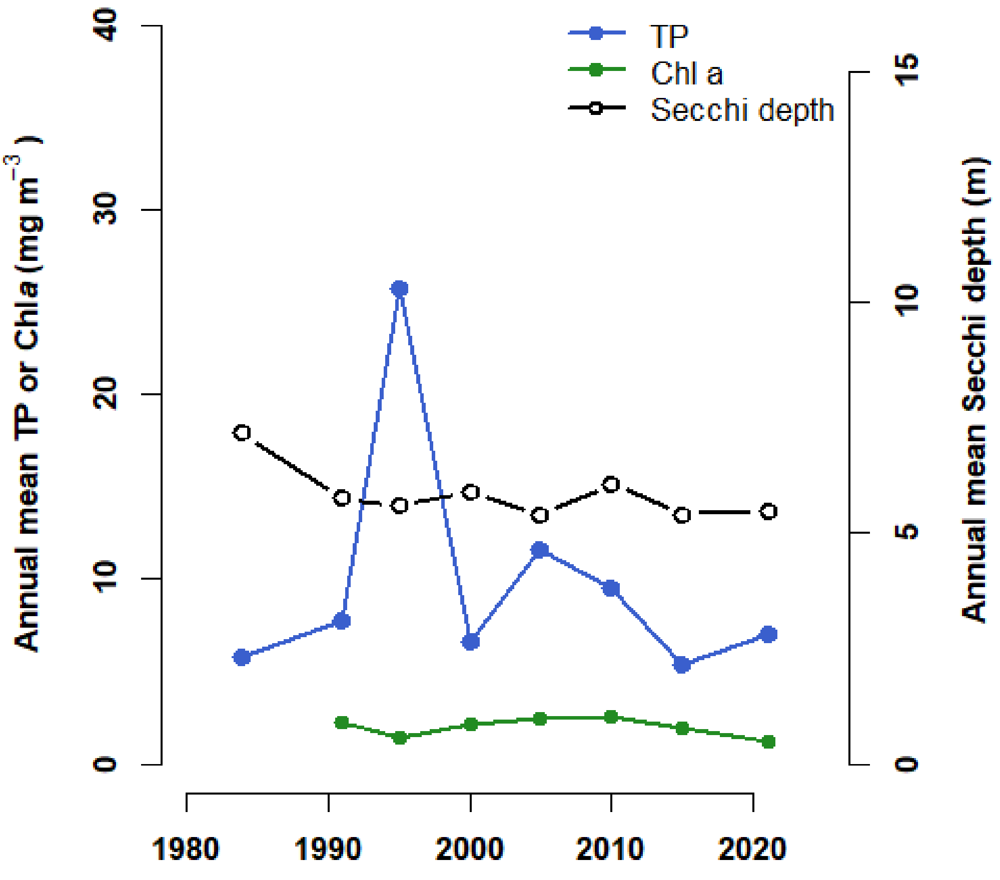


Figure 21 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Brothers Water.

Buttermere

Buttermere is a moderate-sized lake in the northwest of the English Lake District. The outflow from Buttermere drains into Crummock Water (Figure 1). It has the fourth lowest alkalinity of the twenty lakes and the second lowest pH.

Buttermere (Photo R. Groben).

Table 15 Summary of limnological conditions and trophic and Water Framework Directive classifications at Buttermere in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	65		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	6.0	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.8		
Mean nitrate-nitrogen (mg m^{-3})	252		
Mean silica (mg m^{-3})	1453		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	1.2	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	1.8	Ultra-oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	1.5		High
Mean Secchi depth (m)	8.2	Oligotrophic	
Minimum Secchi depth (m)	6.1	Ultra-oligotrophic	
Minimum oxygen concentration (g m^{-3})	7.8		

The lake has low annual mean concentrations of total phosphorus and phytoplankton chlorophyll *a*, and a relatively deep Secchi depth resulting in a classification of oligo – ultra oligotrophic according to the OCED scheme (Table 15). According to the WFD classification, Buttermere is in good ecological status for total phosphorus and high ecological status for chlorophyll *a* concentration. The lake experiences very little oxygen depletion in the deepest water depths during the summer.

The Secchi depth in Buttermere varies by several meters during the year, but is lowest in spring time, which also coincides with the highest chlorophyll *a* concentration. Over time the annual Secchi depth has reduced from around 10 m in the 1990s to a minimum of 6.7 m in 2015 (Figure 22). The transparency has improved on this value in 2021/22 and is around 8 m (Table 15). The lake has seen a statistically significant increase in alkalinity and concomitant reduction in sulphate, calcium, magnesium, sodium and conductivity (Table 11).

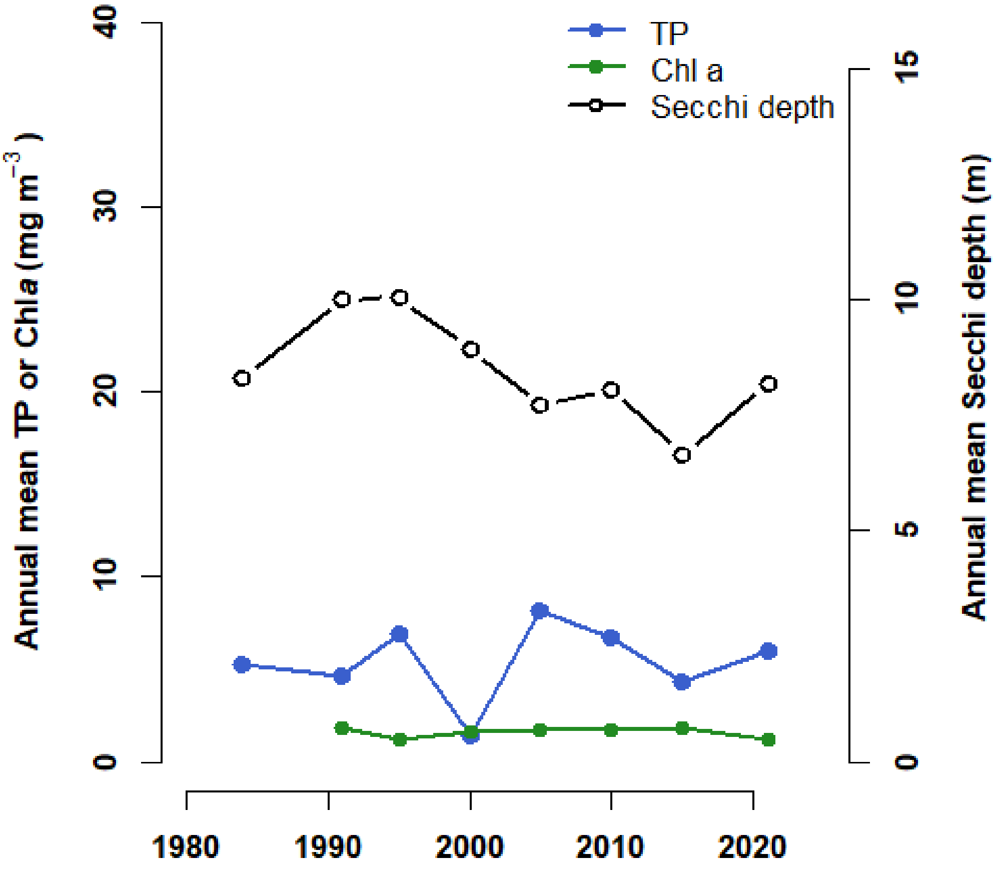


Figure 22 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Buttermere.

Coniston Water

Coniston Water is the fifth largest lake by area in the twenty lakes that make up the Lakes Tour, and is the fourth largest in terms of volume (Table 1). The lake is situated in the southwest of the English Lake District (Figure 1).

Coniston Water (Photo I.J. Winfield).

Table 16 Summary of limnological conditions and trophic and Water Framework Directive classifications at Coniston Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	188		
Mean pH (geometric mean)	7.1		
Mean total phosphorus (mg m^{-3})	6.4	Oligotrophic	High
Mean soluble reactive phosphorus (mg m^{-3})	0.7		
Mean nitrate-nitrogen (mg m^{-3})	383		
Mean silica (mg m^{-3})	1087		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	3.0	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	4.6	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	3.8		Good
Mean Secchi depth (m)	5.3	Mesotrophic	
Minimum Secchi depth (m)	4.0	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	3.2		

The various indicators in the OECD classification system indicate that Coniston Water is oligo-mesotrophic and that the lake experiences slight oxygen depletion with depth (Table 16), maintaining the same classification as in 2015. The ecological status of the lake according to the WFD indicators of TP and chlorophyll *a* are high and good, respectively. A review of the ecology of the lake was carried out around 20 years ago by Dent et al. (2001) and Maberly et al. (2003).

The nutrient chemistry of Coniston Water remains relatively stable. There have been no significant changes in nutrients, phytoplankton chlorophyll *a,* or Secchi depth since around 2000. However, there is some indication of a downward trajectory in TP and chlorophyll *a* in the lake since the previous survey in 2015, with chlorophyll *a* concentrations at their lowest since the Tour started measurements in 1991 (Figure 23). Similar to all the other lakes, significant reductions in sulphate have occurred in Coniston Water, along with reductions calcium, magnesium, sodium, potassium and conductivity (Table 11).

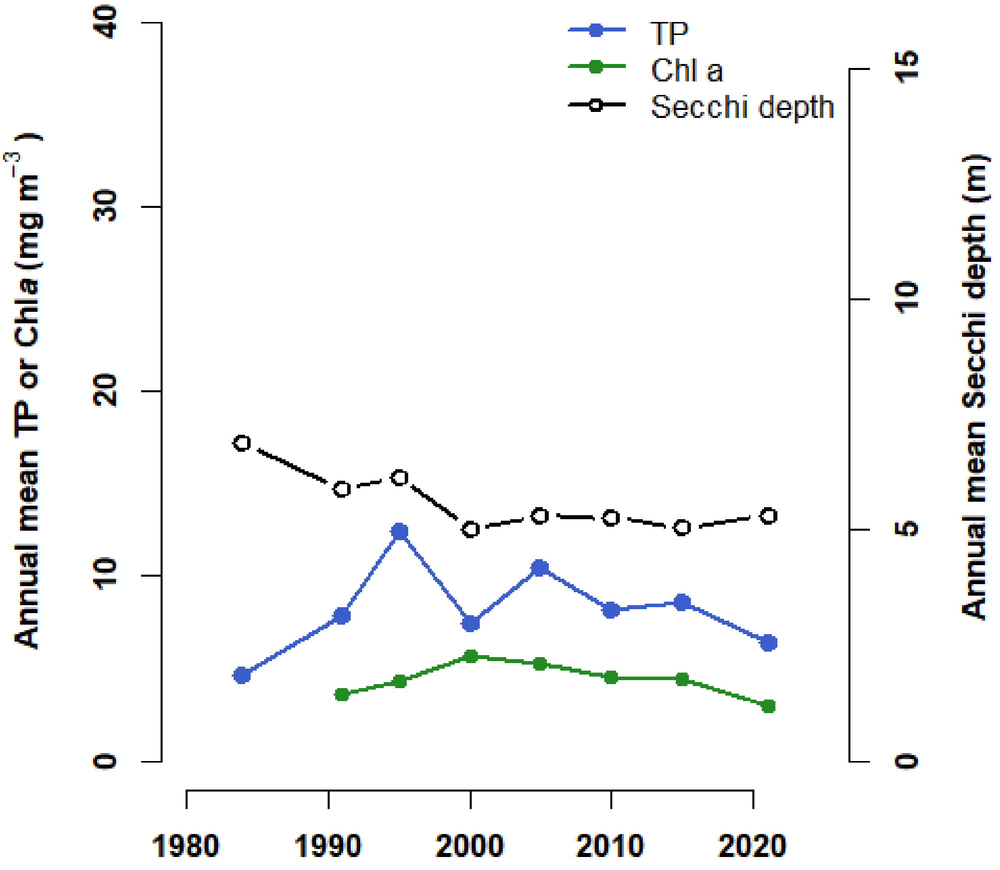


Figure 23 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Coniston Water.

The Coniston-Crake Catchment Partnership was set up to promote good water quality in Coniston Water (https://scrt.co.uk/our-area/coniston-and-crake/).

Crummock Water

Crummock Water is situated in the northwest of the English Lake District (Figure 1). Within its catchment are the lakes of Buttermere to the southeast and Loweswater to the northwest. In 2021/22 it had the second lowest alkalinity of the twenty lakes and third lowest pH.

Crummock Water, looking north-west. (Photo: M.M. De Ville).

Table 17 Summary of limnological conditions and trophic and Water Framework Directive classifications at Crummock Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	57		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	6.5	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.8		
Mean nitrate-nitrogen (mg m^{-3})	252		
Mean silica (mg m^{-3})	1410		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	1.5	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	2.3	Ultra-oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	1.9		High
Mean Secchi depth (m)	6.7	Oligotrophic	
Minimum Secchi depth (m)	5.0	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	6.7		

The trophic status of Buttermere is oligotrophic on all measures, except for maximum chlorophyll *a* concentration, where it is ultra-oligotrophic (). It had the fourth lowest TP concentration and fifth lowest chlorophyll *a* concentration of all the lakes. The minimum oxygen concentration is higher than the concerningly low value recorded in 2015 (3.6

g m^{-3}) and more similar to that from 2010 (6.2 g m^{-3}). The ecological status classes are good for TP, reduced from high in 2015 and high for phytoplankton chlorophyll *a*, increased from good in 2015.

There have been no significant changes in the nutrient or chlorophyll *a* concentrations in the lake over time, however Secchi depth has significantly declined since 1984. This is suggestive of other causes of change in the water transparency at the site, other than phytoplankton abundance. Similar significant reductions in the major ions have occurred in the lake to others in the survey.

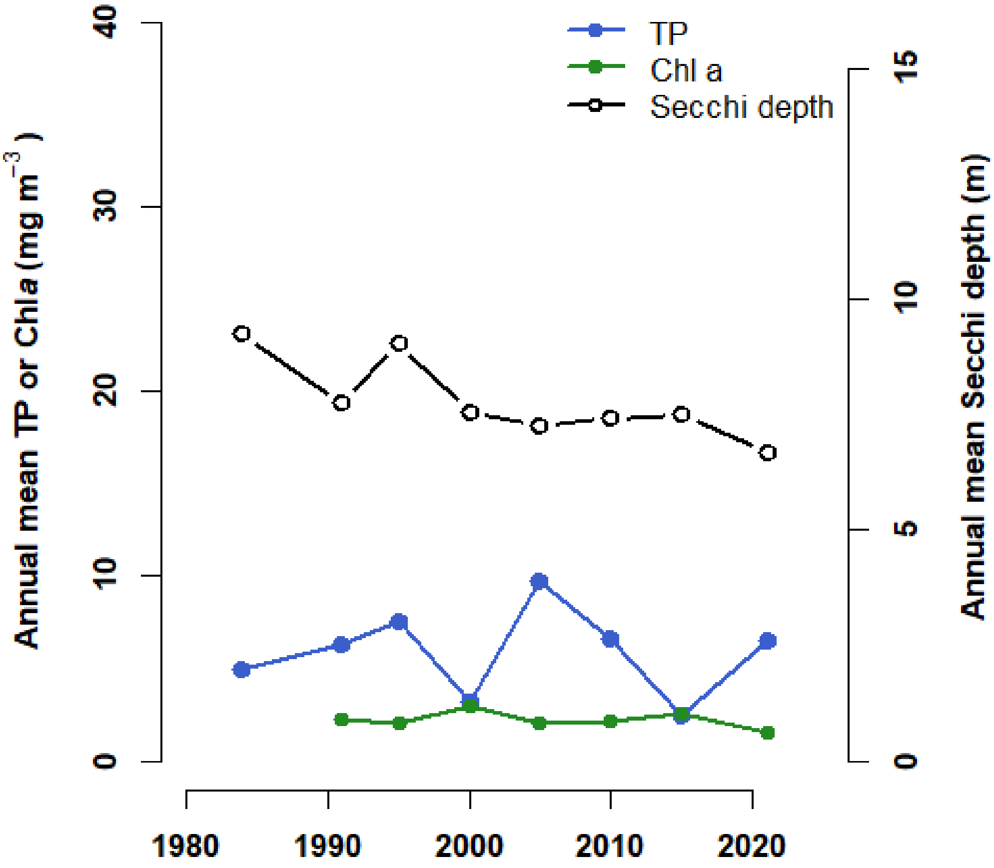
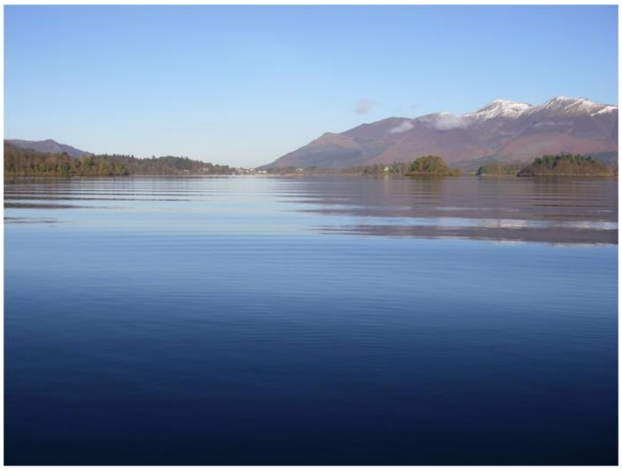


Figure 24 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Crummock Water.

Derwent Water

Derwent Water is located at the north of the English Lake District and it lies within the catchment of Bassenthwaite Lake (Figure 1). Much of the lake is shallow, with a relatively low mean depth, however there are two deep water areas with a maximum depth of 22m (Table 1). In 2021/22, Derwent Water had the lowest concentration of sulphate and the third highest concentration of chloride.



Derwent Water (Photo: M.M. De Ville).

Table 18 Summary of limnological conditions and trophic and Water Framework Directive classifications at Derwent Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	100		
Mean pH (geometric mean)	6.8		
Mean total phosphorus (mg m^{-3})	8.1	Oligotrophic	High
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	233		
Mean silica (mg m^{-3})	1169		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	3.5	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	4.8	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	4.7		Good
Mean Secchi depth (m)	8.1	Oligotrophic	
Minimum Secchi depth (m)	3.5	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	5.4		

The lake has improved in its OECD classification since 2015, now being oligotrophic for both total phosphorus concentration and Secchi depth, although the lake remains mesotrophic for annual mean phytoplankton chlorophyll *a* (Table 18). The lake is at good ecological status for chlorophyll *a* concentration and high ecological status for total phosphorus under the WFD classification scheme.

There have been no statistically significant long-term changes in nutrient concentrations or phytoplankton in Derwent Water (Table 11), although there appears to be a slight, but consistent reduction in TP and chlorophyll *a* concentration since 2005 (Figure 25). The annual Secchi depth was much deeper in 2021/22 than in previous surveys. The only significant changes in water chemistry in the lake have been an increase in alkalinity and reduction in the other major ions.

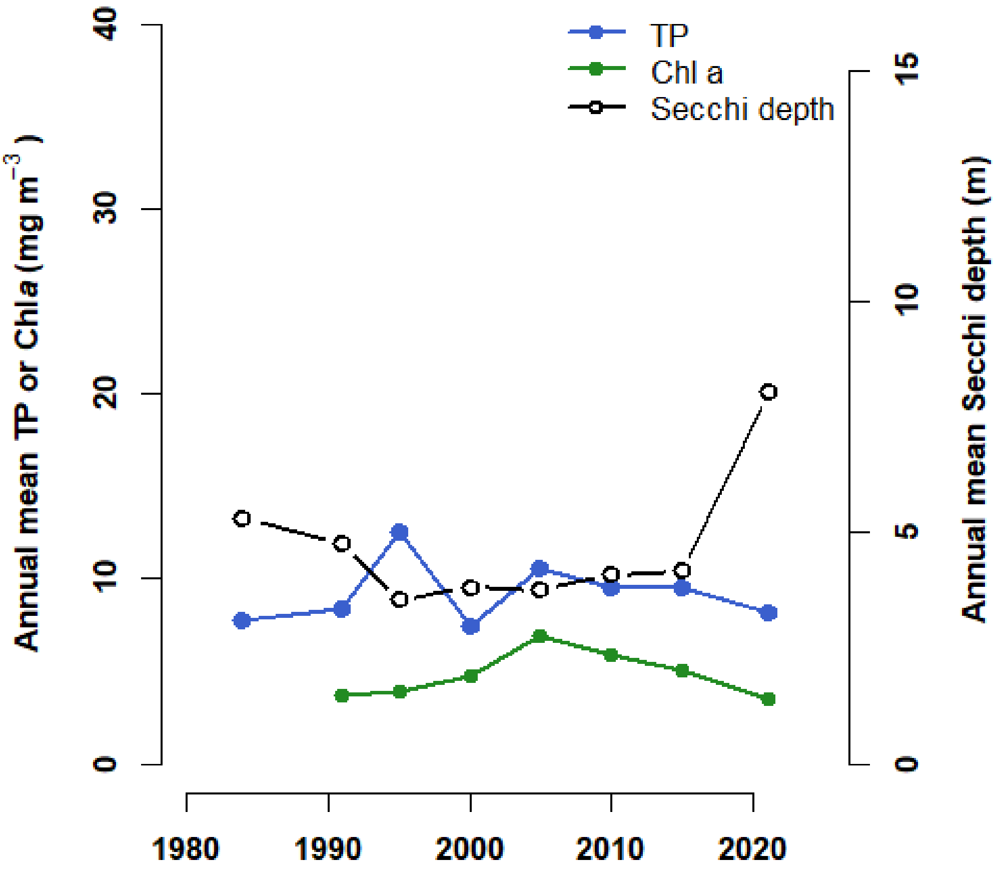


Figure 25 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Derwent Water.

A nutrient budget and modelling study was carried out on Derwent Water in 2006 (Maberly et al. 2006b). This study indicated that annual total phosphorus loads to the lake were 1839 – 2290 kg yr-1 and around a third of this came from sewage.

Elterwater

The inner basin of Elterwater is the smallest of the twenty lakes included in the Lakes Tour in terms of area and also has the second shortest mean retention time (20 days). In 2021/22 it had the third highest concentration of TP but lowest concentration of nitrate and the highest concentration of chlorophyll *a*.

Elterwater viewed from Loughrigg Fell (Photo: M.M. De Ville).

Table 19 Summary of limnological conditions and trophic and Water Framework Directive classifications at Elterwater in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	245		
Mean pH (geometric mean)	6.8		
Mean total phosphorus (mg m^{-3})	20.4	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.1		
Mean nitrate-nitrogen (mg m^{-3})	189.6		
Mean silica (mg m^{-3})	1588		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	21.6	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	76.9	Hypertrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	7.4		Good
Mean Secchi depth (m)	2.9	Eutrophic	
Minimum Secchi depth (m)	2.0	Mesotrophic	
Minimum oxygen concentration (g m^{-3})	0.1		

Elterwater varies in its OECD classification between mesotrophic for TP and minimum Secchi depth and hypertrophic for the maximum phytoplankton chlorophyll *a* concentration. Therefore, as in 2015, the lake is most appropriately classified as eutrophic, also evidenced by the complete oxygen depletion at depth (Table 19).

According to the WFD classification the lake is in ecologically moderate status for TP and good status for chlorophyll *a*.

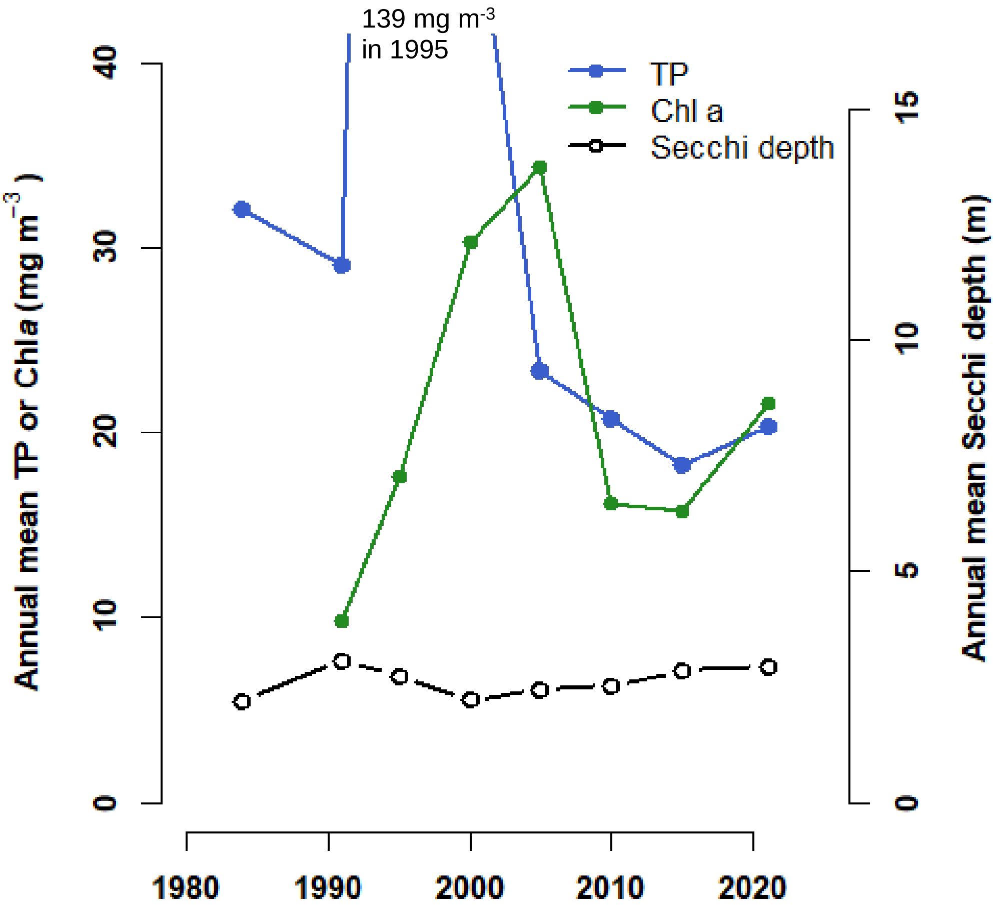


Figure 26 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Elterwater. A high mean TP concentration in 1995 of 139 mg m^{-3} is not plotted for clarity.

There has been a statistically significant decline in TP concentrations in the lake since 1984 and reductions in sulphate and potassium concentrations (Table 11). The steep decline between 2005 and 2015 has been somewhat arrested in the most recent data, but concentrations of TP remain significantly lower than earlier in the timeseries. Of slightly more concern is the recent increase in phytoplankton chlorophyll *a* reported for 2021/22, which was largely driven by a large peak during the summer sampling in July, although the Secchi depth remains largely unchanged from 2015.

Elterwater is currently undergoing active restoration activities and regular monitoring by South Cumbria Rivers Trust. UKCEH have carried out repeated sediment nutrient surveys on the lake (Mackay et al. 2015b; Mackay 2020) and supervised a PhD project to investigate the impact of the main restoration measure employed: management of lake residence type (Olsson et al. 2022a, b).

Ennerdale Water

Ennerdale Water (Photo: S.C. Maberly).

Ennerdale Water, a moderate sized lake, is the most westerly lake in the Lakes Tour (Figure 1). In 2021/22 it had the lowest alkalinity and TP concentration of all the lakes studied, the second lowest chlorophyll *a* concentration and the third deepest Secchi (Table 20). These both represent an improvement in these rankings since 2015.

Table 20 Summary of limnological conditions and trophic and Water Framework Directive classifications at Ennerdale Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	44		
Mean pH (geometric mean)	6.3		
Mean total phosphorus (mg m^{-3})	5.6	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	<0.5		
Mean nitrate-nitrogen (mg m^{-3})	271.8		
Mean silica (mg m^{-3})	2219		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	0.9	Ultra-oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	1.2	Ultra-oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	1.2		High
Mean Secchi depth (m)	7.1	Oligotrophic	
Minimum Secchi depth (m)	5.4	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	7.8		

Ennerdale Water is classified as oligotrophic for TP and Secchi depth and ultra-oligotrophic for phytoplankton chlorophyll *a*. The lake is at good ecological status for TP and high ecological status for chlorophyll *a* concentration (Table 20).

As noted in the 2015 Lakes Tour (Maberly et al. 2016), the phytoplankton chlorophyll *a* concentration has continued to decline slightly over time from 2.4 mg m^{-3} in 2010 to 1.7 mg m^{-3} in 2015 and 1.2 mg m^{-3} in 2021/22. Secchi depth had also improved since the 2010 minimum, but water transparency has significantly declined in the lake since 1984 (Figure 27, Table 11). The lake has also seen a statistically significant decline in nitrate concentration.

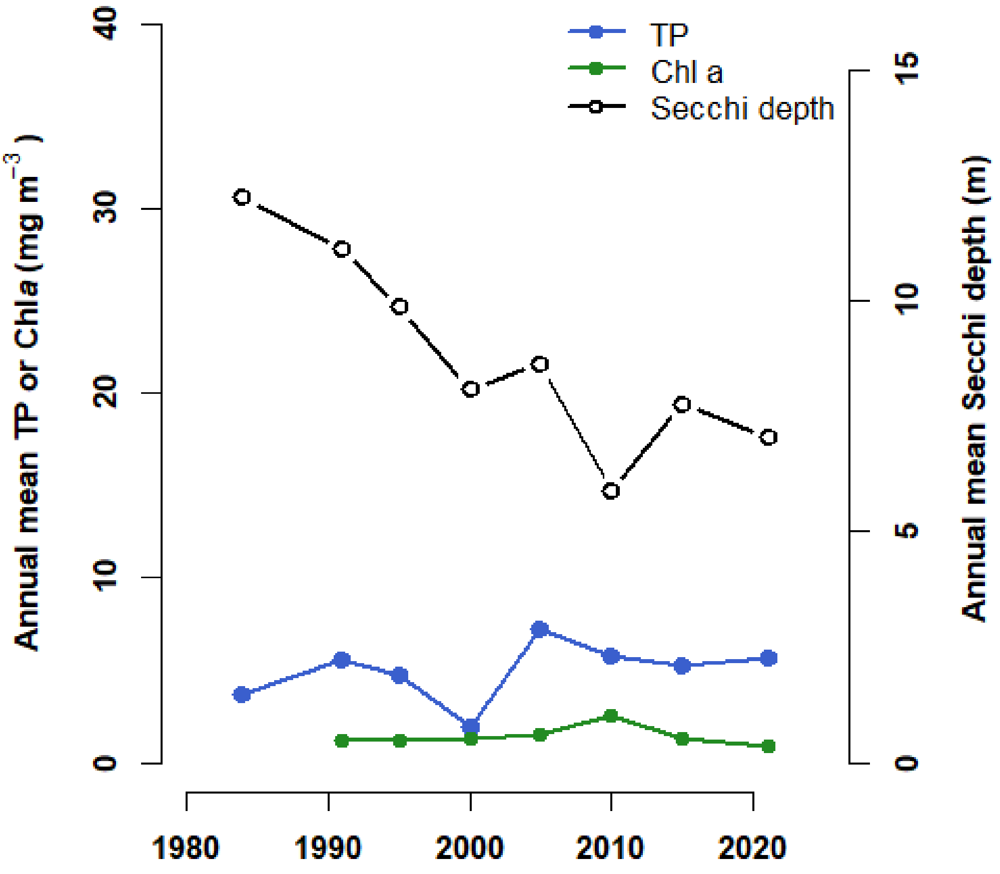


Figure 27 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Ennerdale Water.

Maberly et al. (2016) demonstrated a relationship between Secchi depth and chlorophyll *a* concentration suggesting that at low concentrations only a small change in chlorophyll *a* concentration can result in a large change in Secchi depth, and that this will be contributing to changing transparency in unproductive lakes. However, unmeasured increases in DOC concentration in response to the reductions in sulphate deposition (Monteith et al. 2007) may also be contributing to the transparency changes seen in such systems.

Ennerdale water has experienced a statistically significant decline in nitrate concentration over time and an increase in alkalinity. Other major ions, including sulphate have significantly declined.

UKCEH carried out a number of studies for United Utilities in 2015 and 2016, including a detailed fortnightly limnological survey of Ennerdale Water in 2015 (Mackay et al. 2016a), and a baseline assessment of environmental requirements and nutrient and sediment sources in the Ennerdale Water and upper River Ehen catchments (Mackay et al. 2016b).

Esthwaite Water

Esthwaite Water is a small lake in the south of the English Lake District (Figure 1). It's outflow, Cunsey Beck, drains into the south basin of Windermere. It was classified as the most productive lake in the English Lake District when Pearsall made his original classification of eleven lakes in the 1920s (Pearsall 1921). In 2021/22, the lake had the highest pH and TP, second highest chlorophyll *a* concentration and shallowest Secchi depth of all twenty lakes (Table 21). These values represent a marked deterioration in water quality on the 2015 survey.

Esthwaite Water looking north. (Photo: Freshwater Biological Association).

Table 21 Summary of limnological conditions and trophic and Water Framework Directive classifications at Esthwaite Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	388		
Mean pH (geometric mean)	7.7		
Mean total phosphorus (mg m^{-3})	35.8	Eutrophic	Poor
Mean soluble reactive phosphorus (mg m^{-3})	3.0		
Mean nitrate-nitrogen (mg m^{-3})	350		
Mean silica (mg m^{-3})	1477		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	19.1	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	32.7	Eutrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	21.9		Poor
Mean Secchi depth (m)	1.7	Eutrophic	
Minimum Secchi depth (m)	1.4	Eutrophic	
Minimum oxygen concentration (g m^{-3})	0.0		

Following years of improvements in water quality in the lake, documented in Maberly et al. (2016), large increases in TP and chlorophyll *a*, and a deterioration in Secchi depth have occurred since the last survey (Figure 28). The result is that the lake is classified as eutrophic in all categories according to the OECD scheme, a decline from mesotrophic for TP, maximum chlorophyll *a*, and minimum Secchi depth (Table 21). The lake is also now classified as being of poor ecological status according to the WFD classification for TP and chlorophyll *a* concentration. The causes of this change are currently unclear, as the lake has been subject to a number of restoration initiatives including the closure of the fish-farm and upgrades to the wastewater handing and treatment facilities serving the population around Hawkshead in the past.

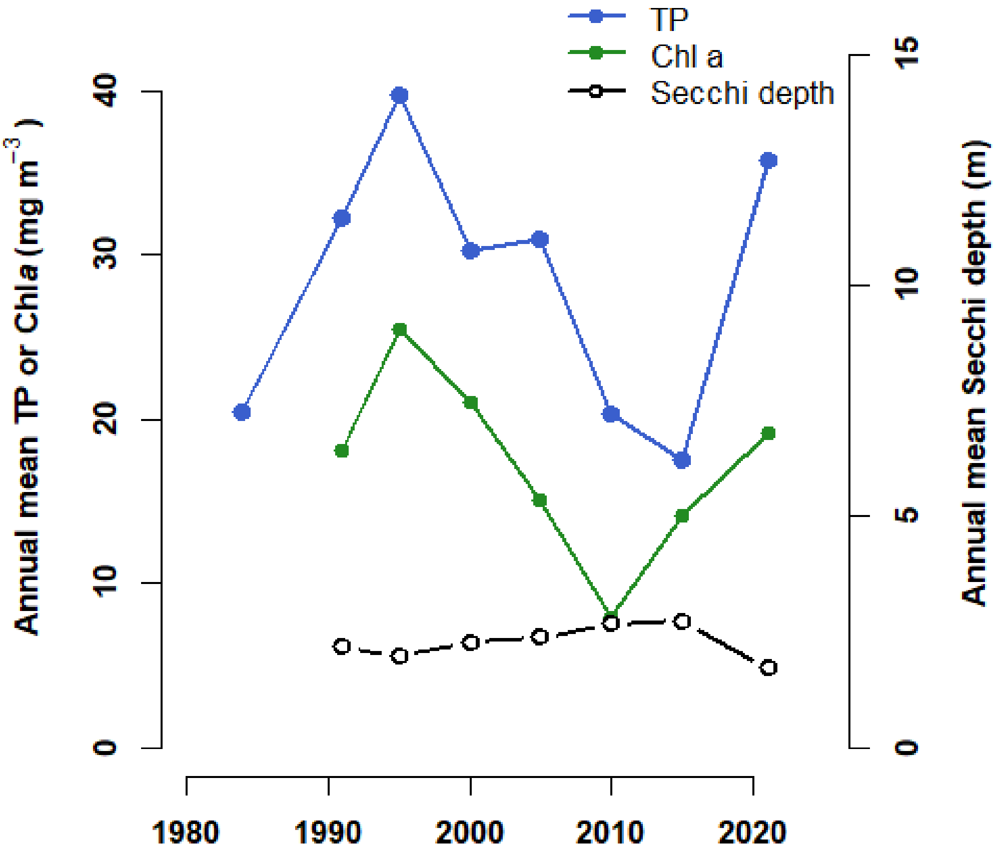


Figure 28 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Esthwaite Water.

There has been a significant decline in nitrate concentration in the lake since 1984 (Table 11) and declines in concentrations of the major ions sulphate, magnesium, and potassium, similar to the pattern seen across the other lakes.

Esthwaite Water is studied fortnightly as part of the UKCEH long-term monitoring programme (https://uk-scape.ceh.ac.uk/our-science/projects/cumbrian-lakes-monitoring-platform) that was started by the Freshwater Biological Association in 1945 and continued by UKCEH since 1989. There is a UKCEH Automatic Water Quality Monitoring Station on the lake which also forms part of the monitoring programme and a greenhouse gas flux tower was added to the site in 2022 as part of the GHGAqua project (https://www.ceh.ac.uk/our-science/projects/ghg-aqua).

Grasmere

Grasmere is a relatively small lake at the northern end of the Windermere catchment (Figure 1). The lake has a short retention time (mean 25 days), which has a profound influence on its limnology (Reynolds et al. 2012).

Grasmere from Loughrigg Terrace. (Photo: M.M. De Ville).

Table 22 Summary of limnological conditions and trophic and Water Framework Directive classifications at Grasmere in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	145.8		
Mean pH (geometric mean)	6.9		
Mean total phosphorus (mg m^{-3})	14.5	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.2		
Mean nitrate-nitrogen (mg m^{-3})	349.5		
Mean silica (mg m^{-3})	1562		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	3.4	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	5.7	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	4.2		Good
Mean Secchi depth (m)	3.9	Mesotrophic	
Minimum Secchi depth (m)	3.6	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	0.5		

In 2021/22 the lake condition had improved relative to the previous survey in 2015, with reductions in TP, mean and maximum chlorophyll *a* concentration and slight improvements to the Secchi depth measures (Table 22). The lake is closer to the oligo-mesotrophic boundary than the meso-eutrophic boundary, as was the case in 2015. However, the lake suffers from pronounced oxygen depletion at depth. According to the WFD classifications, the lake is of moderate ecological status for TP and good ecological status for chlorophyll *a*, which is unchanged from 2015.

Over the long term, the lake has shown a general downward trend in TP concentration (Figure 29), although this isn't statistically significant. There has also been a marked reduction in chlorophyll *a* concentration since 2010 (13.1 to 3.4 mg m^{-3}), but very little change in Secchi depth.

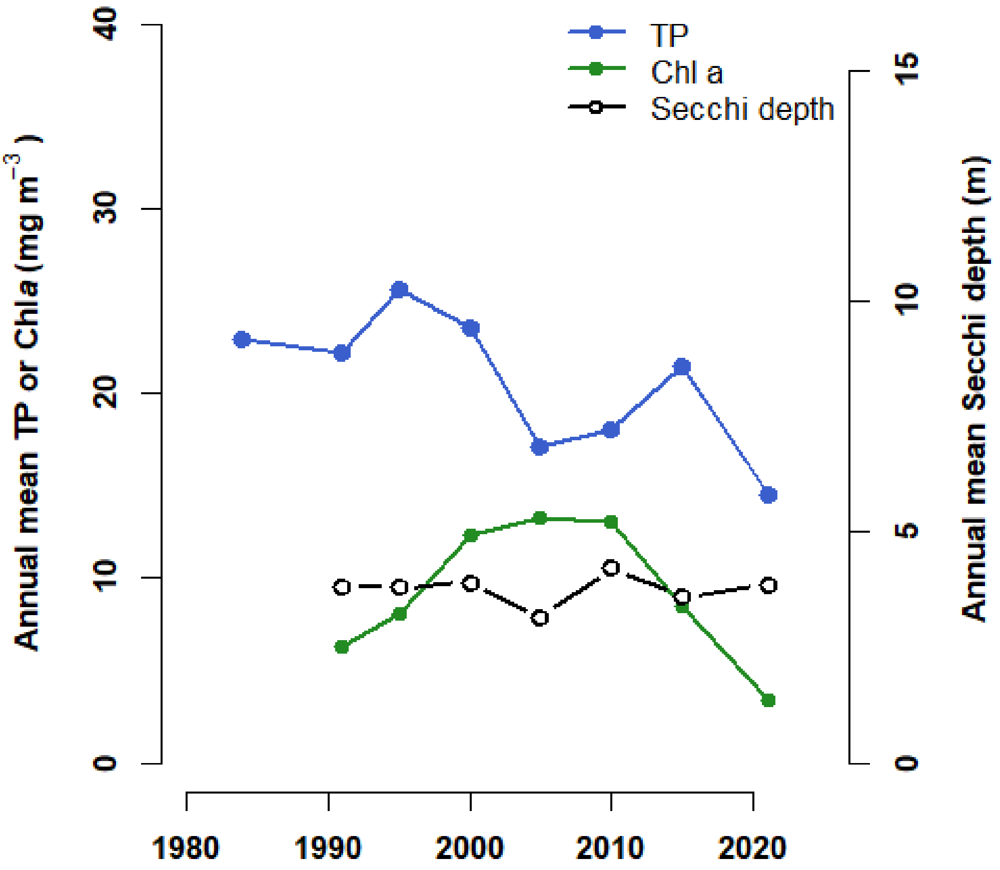


Figure 29 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Grasmere.

The most recent review of the conditions in Grasmere was carried out by Reynolds et al. (Reynolds et al. 2001).

Haweswater

Haweswater is situated in the eastern fells of the English Lake District (Figure 1). It is the fifth largest lake in terms of volume and fourth deepest. It is an important water source for the northwest of England and the original lake level was raised in the 1930s by the construction of a dam at the north-eastern end of the lake. In 2021/22 the lake had the second lowest concentrations of chloride and sodium of the twenty lakes.

Haweswater (Photo: M.M. De Ville).

Table 23 Summary of limnological conditions and trophic and Water Framework Directive classifications at Haweswater in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	198		
Mean pH (geometric mean)	7.2		
Mean total phosphorus (mg m^{-3})	12.5	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.2		
Mean nitrate-nitrogen (mg m^{-3})	229.0		
Mean silica (mg m^{-3})	1712		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	2.3	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	3.1	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.8		High/Good
Mean Secchi depth (m)	4.2	Mesotrophic	
Minimum Secchi depth (m)	4.1	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	7.0		

Haweswater is on the meso-oligotrophic boundary in 2021/22 (Table 23), which represents a slight decline from 2015. This is largely a result of an almost doubling of the TP concentration in the lake since the previous survey. This increase places the lake at moderate ecological status according to the WFD classification, a decline from good in 2015, although it remains at high/ good ecological status for chlorophyll *a* concentration.

There has been a statistically significant decline in nitrate concentrations in the lake since 1984, alongside reductions in the other major ions, as reported for the other lakes in the survey (Table 11). There have been no statistically significant changes in chlorophyll *a* concentration or Secchi depth in the lake over time (Figure 30).

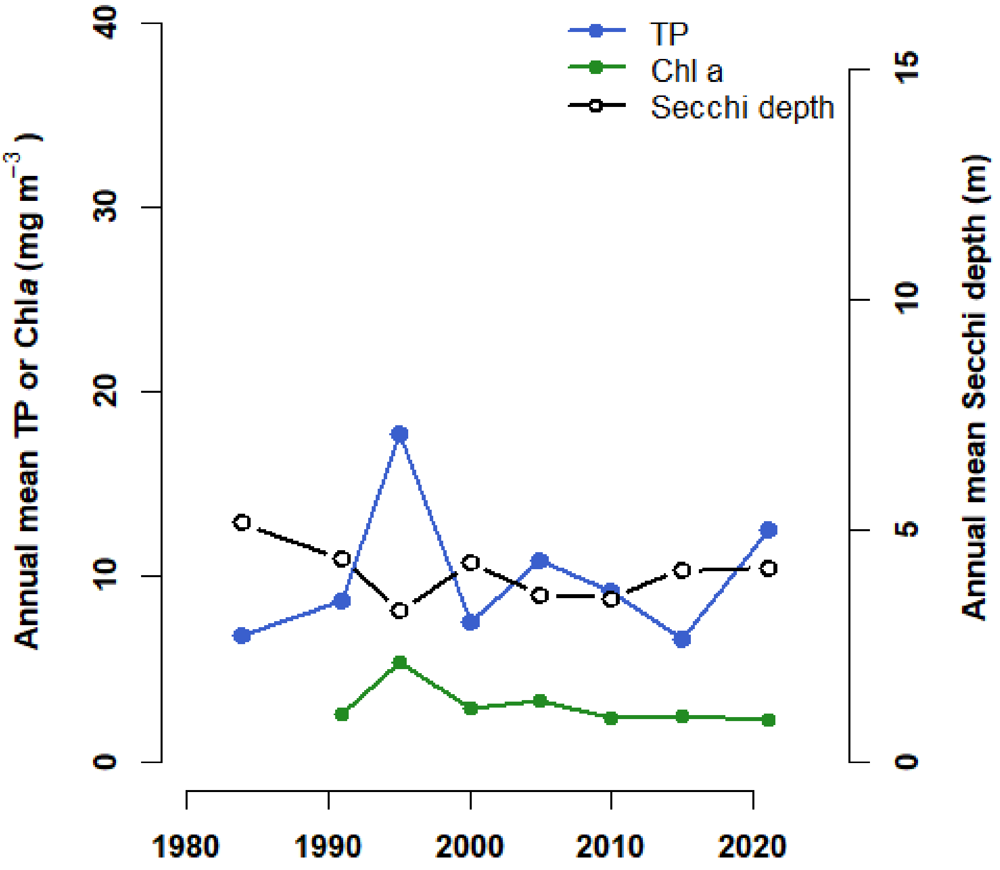


Figure 30 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Haweswater.

Loughrigg Tarn

Loughrigg Tarn. (Photo: M.M. De Ville).

Loughrigg Tarn is a small lake in the centre of the Windermere catchment (Figure 1). It is the second smallest lake in the Lakes Tour survey in terms of area and volume. However, it has a relatively long retention time (mean 117 days), which can negatively impact on the lake status. In 2021/22 it had the highest nitrate concentration of the twenty lakes and the third highest chlorophyll *a* concentration.

Table 24 Summary of limnological conditions and trophic and Water Framework Directive classifications at Loughrigg Tarn in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	258		
Mean pH (geometric mean)	7.1		
Mean total phosphorus (mg m^{-3})	16.0	Mesotrophic	Good/Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.3		
Mean nitrate-nitrogen (mg m^{-3})	551		
Mean silica (mg m^{-3})	1258		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	11.9	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	16.3	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	15.2		Moderate
Mean Secchi depth (m)	3.3	Mesotrophic	
Minimum Secchi depth (m)	2.5	Mesotrophic	
Minimum oxygen concentration (g m^{-3})	0.3		

Loughrigg Tarn is classified as meso-eutrophic based on the OECD classification scheme, and the lake suffers from pronounced oxygen depletion at depth. Loughrigg Tarn has also shown signs of a slight deterioration in TP conditions since 2015 (Table

24, Figure 31). According to the WFD classification the lake is on the boundary between good and moderate ecological status for TP and is of moderate ecological status for chlorophyll *a* concentration.

The relatively long retention time of Loughrigg Tarn is likely to increase phytoplankton growth potential and lead to the retention of nutrients, factors that will likely delay improvements in water quality. The long-term reduction in TP seen since 1991 has been somewhat arrested in the most recent survey, although this and a reduction in SRP are still statistically significant (Table 11, Figure 31). No real change in chlorophyll *a* or Secchi depth have occurred since 2015. Other changes in nutrients are not statistically significant, although it is interesting to note that the lake has a positive increase, but non-significant trend in its nitrate concentration. This latter increase should be watched in future, and consequent impacts on the phytoplankton community considered. Significant reductions in most of the major ions including sulphate have occurred over the long-term record, similar to many of the other lakes in the survey (Table 11).

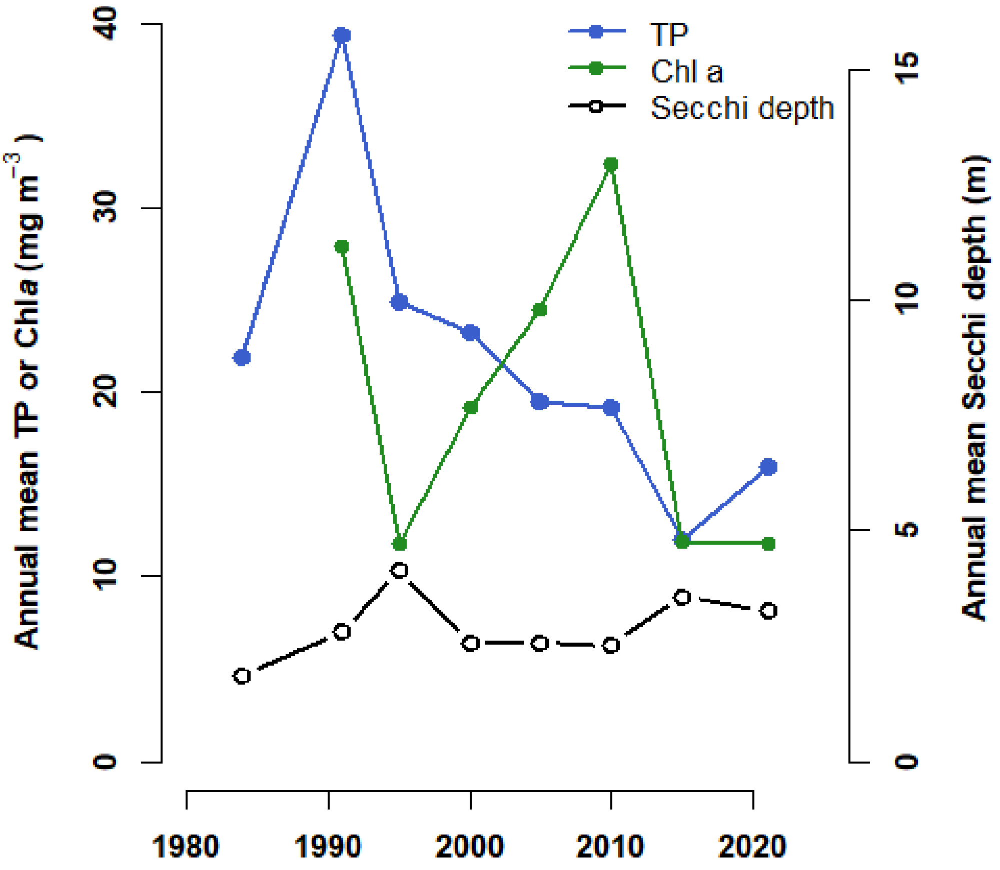


Figure 31 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Loughrigg Tarn.

Loweswater

Loweswater. (Photo M.M. De Ville).

Loweswater is a small lake in the northwest of the English Lake District, the outflow of which drains into Crummock Water (Figure 1). It has a relatively long retention time for a lake of its size (mean 150 days) and this can have an impact on water quality in the lake. In 2021/22 it had the second highest concentration of sulphate and third highest concentration of magnesium.

Table 25 Summary of limnological conditions and trophic and Water Framework Directive classifications at Loweswater in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	166.5		
Mean pH (geometric mean)	7.2		
Mean total phosphorus (mg m^{-3})	10.5	Mesotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	<0.5		
Mean nitrate-nitrogen (mg m^{-3})	286.3		
Mean silica (mg m^{-3})	1050		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	7.2	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	9.4	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	9.9		Moderate
Mean Secchi depth (m)	3.5	Mesotrophic	
Minimum Secchi depth (m)	3.0	Meso-oligotrophic	
Minimum oxygen concentration (g m^{-3})	0.4		

Loweswater is classified as mesotrophic according to the OECD classification, which reflects a slight reduction in chlorophyll *a* concentration since 2015 (*Table 25*). TP was slightly higher in 2021/22, but not sufficiently so to change the categorisation. The lake remains at good ecological status for TP and moderate ecological status for chlorophyll *a* concentration, according to the WFD classification.

Loweswater has continued to experience a declining trend in chlorophyll *a* concentration, which started in 2005, although there have been no further improvements in the Secchi depth since 2015, and TP concentrations increased slightly (Figure 32). The only statistically significant long-term trend in the nutrient data has been a decline in nitrate concentrations (Table 11). Significant declines in sulphate, calcium, magnesium and sodium have also occurred.

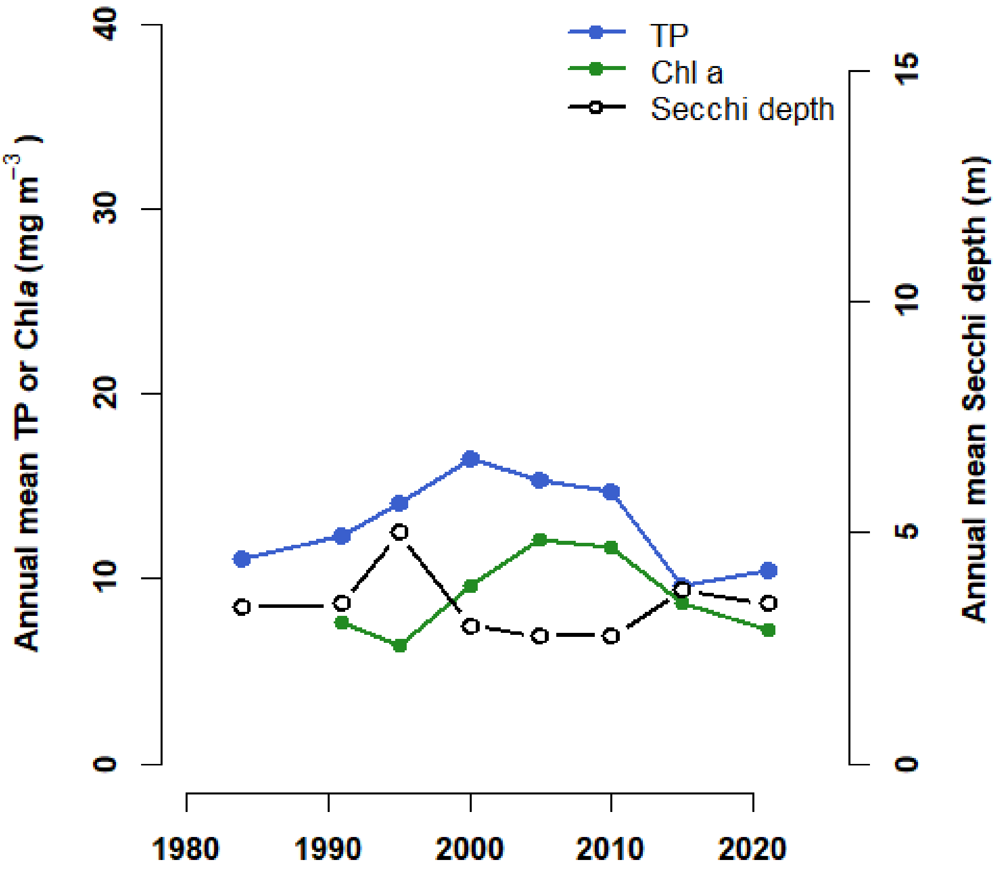


Figure 32 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Loweswater.

Loweswater was the subject of a community-led catchment management project by CEH and Lancaster University. The results of a 12-month study of Loweswater are given in Maberly et al. (2006c). Subsequently, the local community have been funded by a Defra Catchment Restoration Fund to continue the work of improving water quality in the lake (http://westcumbriariverstrust.org/projects/the-loweswater-care-programme).

Rydal Water

Rydal Water is a small lake that receives water from Grasmere, less than 1 km upstream (Figure 1). These lakes are connected in a chain that forms part of the larger Windermere catchment. Rydal Water has the shortest mean retention time of any of the lakes in the Lakes Tour (Table 1), which may benefit water quality.

Rydal Water. (Photo: I.J. Winfield).

Table 26 Summary of limnological conditions and trophic and Water Framework Directive classifications at Rydal Water in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	150.5		
Mean pH (geometric mean)	6.9		
Mean total phosphorus (mg m^{-3})	13.5	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.3		
Mean nitrate-nitrogen (mg m^{-3})	376.5		
Mean silica (mg m^{-3})	1536		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	4.1	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	9.1	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	4.7		Good
Mean Secchi depth (m)	4.6	Mesotrophic	
Minimum Secchi depth (m)	4.0	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	0.4		

Rydal Water is largely mesotrophic according to the OECD classification and these categories haven’t changed since the 2015 Lakes Tour (Table 26). The WFD classification also remains the same, being in moderate ecological state for TP and good ecological state for chlorophyll *a*. The short retention time (mean 9 days) may suppress the accumulation of a larger biomass of phytoplankton in this lake.

Rydal Water continues to show a downward trend in phytoplankton chlorophyll *a* concentration, from the peak in 2005, and the concentration is now lower than at any other time in the record. There has been some improvement in the Secchi depth, with levels now similar to those recorded in 1984 (Figure 33). TP concentrations have however remained largely unchanged since 2010. The short retention time of this lake will make it sensitive to changes in rainfall, which will lead to greater inter-annual variability in the lake. Identifying the causes of changes in Rydal Water is more difficult than in many of the other lakes because it is highly influenced by changes in the larger Grasmere immediately upstream. The only significant chemical changes in the lake have been in the form of the widespread reduction in the major ions reported for the other lakes (Table 11).

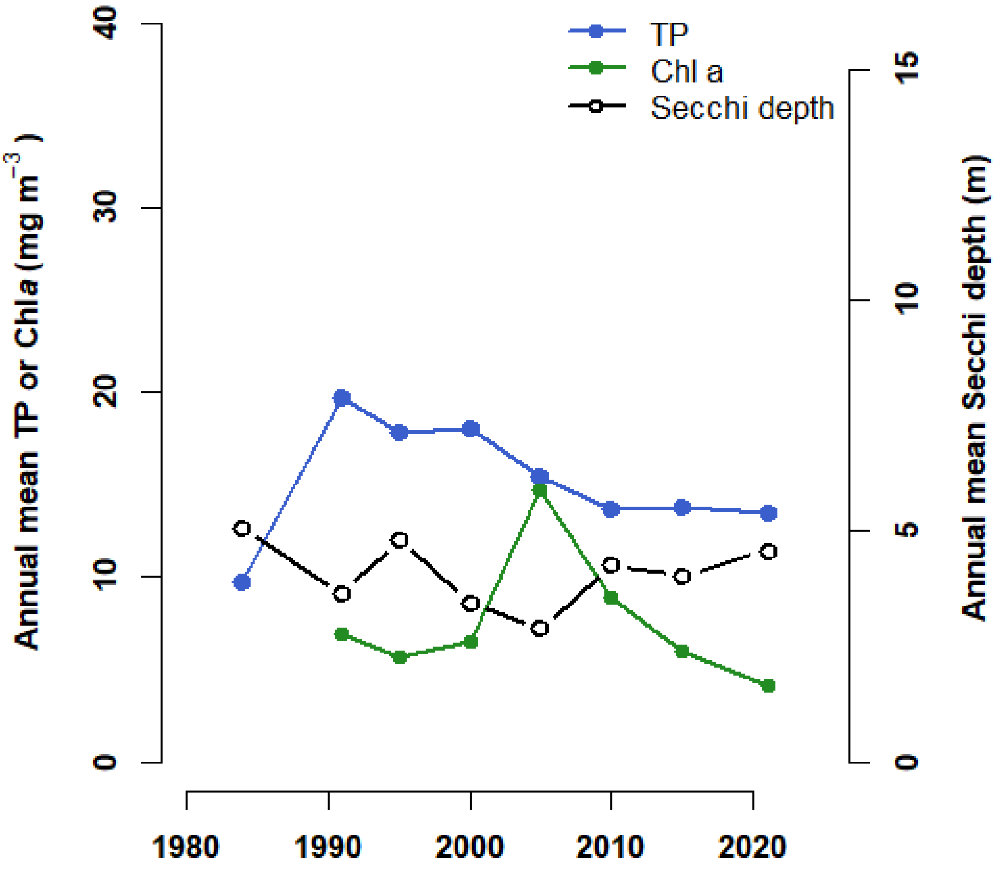


Figure 33 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Rydal Water.

Thirlmere

Thirlmere (Photo: M.M. De Ville).

Thirlmere is a moderate sized lake in the central English Lake District and forms one of the southern boundaries of the large Bassenthwaite Lake catchment (Figure 1). It is an important water supply resource for the northwest of England and is subject to large variations in its water level. As an annual mean in 2021/22, Thirlmere had the lowest concentration of chloride, magnesium, sodium and potassium and second lowest concentration of sulphate of all the lakes.

Table 27 Summary of limnological conditions and trophic and Water Framework Directive classifications at Thirlmere in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	64.8		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	10.4	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	0.5		
Mean nitrate-nitrogen (mg m^{-3})	218.3		
Mean silica (mg m^{-3})	1370		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	2.4	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	3.9	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	3.0		High
Mean Secchi depth (m)	5.4	Mesotrophic	
Minimum Secchi depth (m)	5.1	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	5.6		

Thirlmere remains on the oligo-mesotrophic boundary, with slight oxygen depletion at depth (Table 27). The lake has deteriorated slightly in terms of TP concentration relative to 2015 but remains unchanged with respect of the phytoplankton chlorophyll *a* concentration. The lake changed from good to moderate ecological status for TP but remains at high for chlorophyll *a* concentration according to the WFD categories.

Over the long-term, the lake has seen a significant decline in Secchi depth, and an increase in chlorophyll *a* concentration (Figure 34,Table 11). TP concentrations have slightly increased in the lake and are now at their highest level since the start of the Lakes Tour series in 1984, although this change is not statistically significant. In contrast, there has been a significant decline in nitrate concentrations and an increase in alkalinity, combined with significant declines of the other major ions.

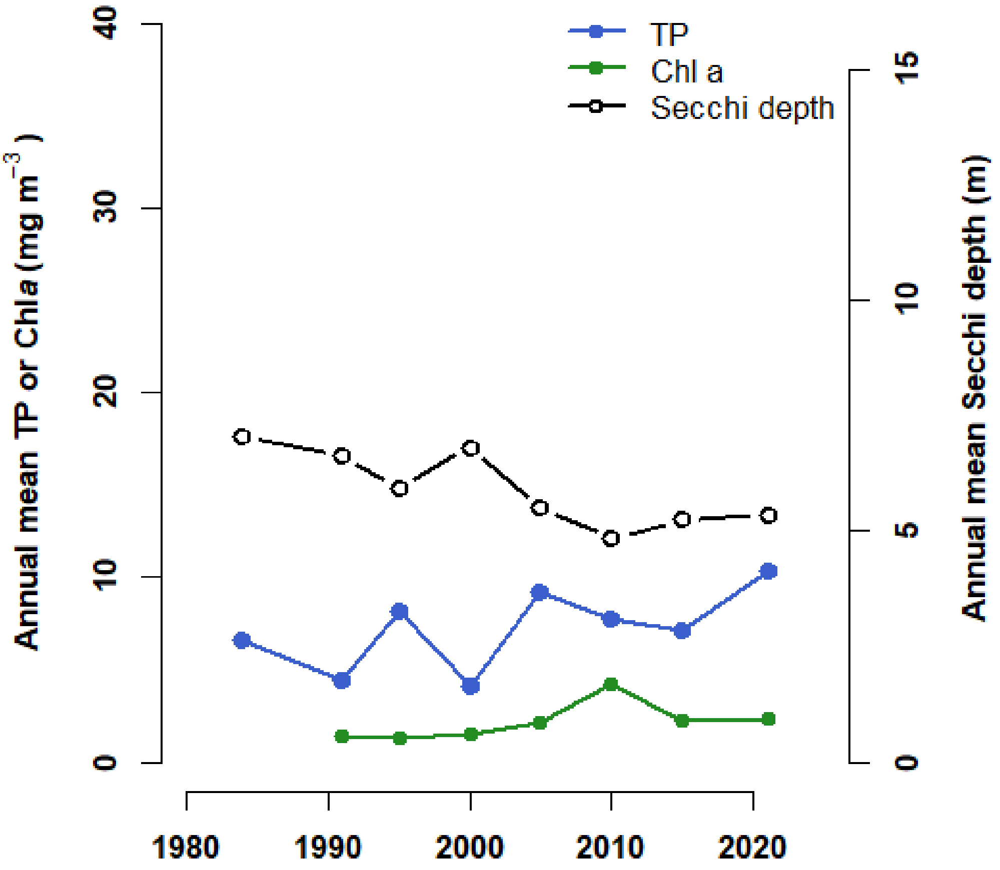


Figure 34 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Thirlmere.

The Thirlmere catchment is currently subject to a number of restoration initiatives and changes in land management practice, following Storm Desmond in 2015. UKCEH carries out high frequency monitoring of several of the lake sub-catchments as part of a programme to improve understanding of sources of DOC and turbidity to the lake (Mackay et al. 2022).

Ullswater

Ullswater is the second largest lake in the English Lake District, after Windermere, in terms of area and volume. It is situated in the northeast of the English Lake District and forms part of the large River Eden catchment (Figure 1).

Ullswater (Photo I.J. Winfield).

Table 28 Summary of limnological conditions and trophic and Water Framework Directive classifications at Ullswater in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	216.8		
Mean pH (geometric mean)	7.3		
Mean total phosphorus (mg m^{-3})	9.3	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	2.6		
Mean nitrate-nitrogen (mg m^{-3})	222.5		
Mean silica (mg m^{-3})	1486		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	1.8	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	3.1	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.2		High
Mean Secchi depth (m)	5.1	Mesotrophic	
Minimum Secchi depth (m)	4.2	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	5.5		

Ullswater is largely oligotrophic according to the 2021/22 data, which reflects a reduction in chlorophyll *a* concentrations since the 2015 Lakes Tour, although the mean Secchi depth is very similar to the previous average. The lake is now at high ecological status for chlorophyll *a* and good ecological status for TP according to the WFD classification. It experiences some oxygen depletion at depth.

There is a significant long-term decline in the chlorophyll *a* concentration at Ullswater, despite relatively little change in the TP concentration, which is similar to the values of the first survey in 1984. Secchi depth also shows no long-term change, with values stable since around 1995. The same pattern of reductions in many of the major ions is also present in Ullswater.

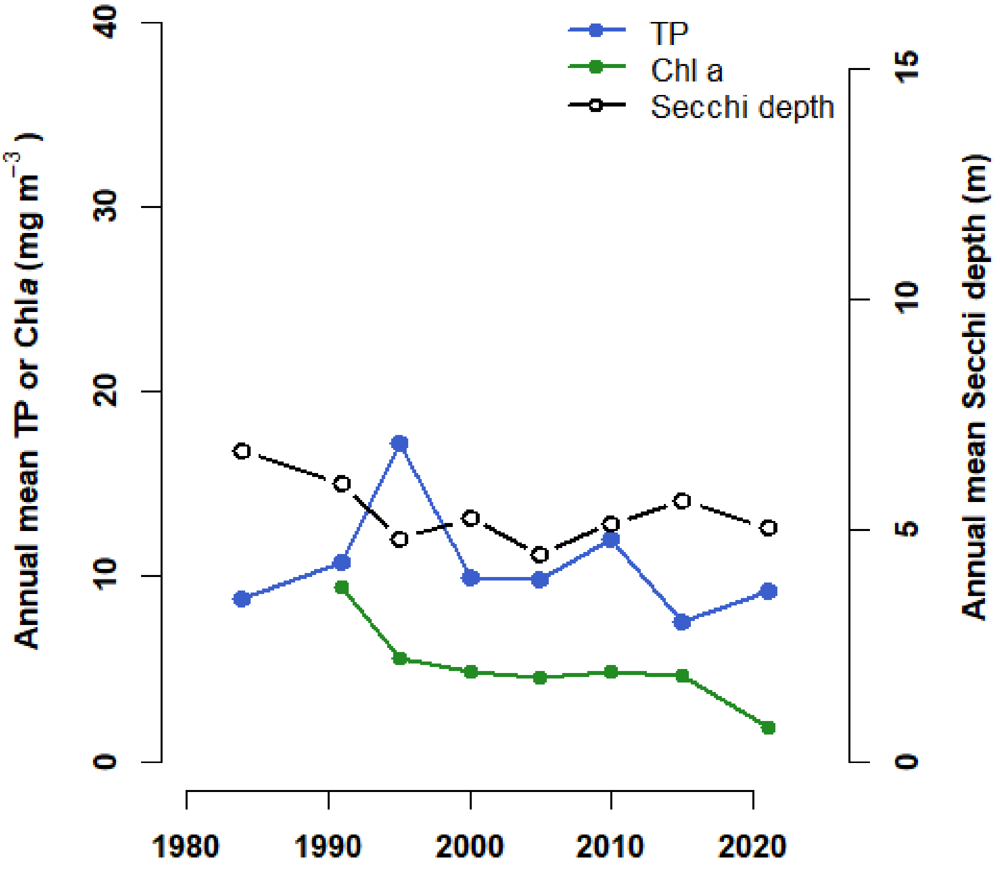


Figure 35 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Ullswater.

A nutrient budget and modelling study was carried out for Ullswater in 2006 (Maberly et al. 2006b) and more recently, Gasca et al. (2015) modelled a new nutrient budget for the lake.

Wastwater

Wastwater is the third largest lake in the English Lake District in terms of volume, but only the tenth largest in terms of area. The depth of the lake, explains this discrepancy, as it has the largest mean and maximum depths (40 m and 76m, respectively). In 2021/22 the lake had the deepest Secchi depth and second highest silica concentration of all twenty lakes.

Wastwater. (Photo: I.J. Winfield).

Table 29 Summary of limnological conditions and trophic and Water Framework Directive classifications at Wastwater in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	67.3		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	6.6	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	350.5		
Mean silica (mg m^{-3})	2124		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	0.6	Ultra-oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	0.9	Ultra-oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	0.6		High
Mean Secchi depth (m)	10.7	Oligotrophic	
Minimum Secchi depth (m)	8.1	Ultra-oligotrophic	
Minimum oxygen concentration (g m^{-3})	0.2		

Wastwater remains the epitome of an unproductive lake in this region, the same position as it held 100 years ago when Pearsall carried out his first surveys of the large lakes (Pearsall 1921). The lake remains ultra-oligotrophic according to most elements of the OECD classification scheme and at high ecological status for chlorophyll *a.* A slight increase in TP concentration has resulted in only good ecological status for this indicator according to the WFD classification (Table 29). The very low minimum oxygen concentration measured is likely to be erroneous (see section 3.2 above).

Chlorophyll *a* concentrations in the lake appear to be very stable over time, however the most recent data suggest that a slight increase in TP occurred since the last survey (Figure 36). There has been a significant decline in the Secchi depth over time, although a slight improvement is noticeable on the 2015 result. As with many of the other lakes in the Lakes Tour, there has been a significant decline in several of the major ions over time (Table 11).

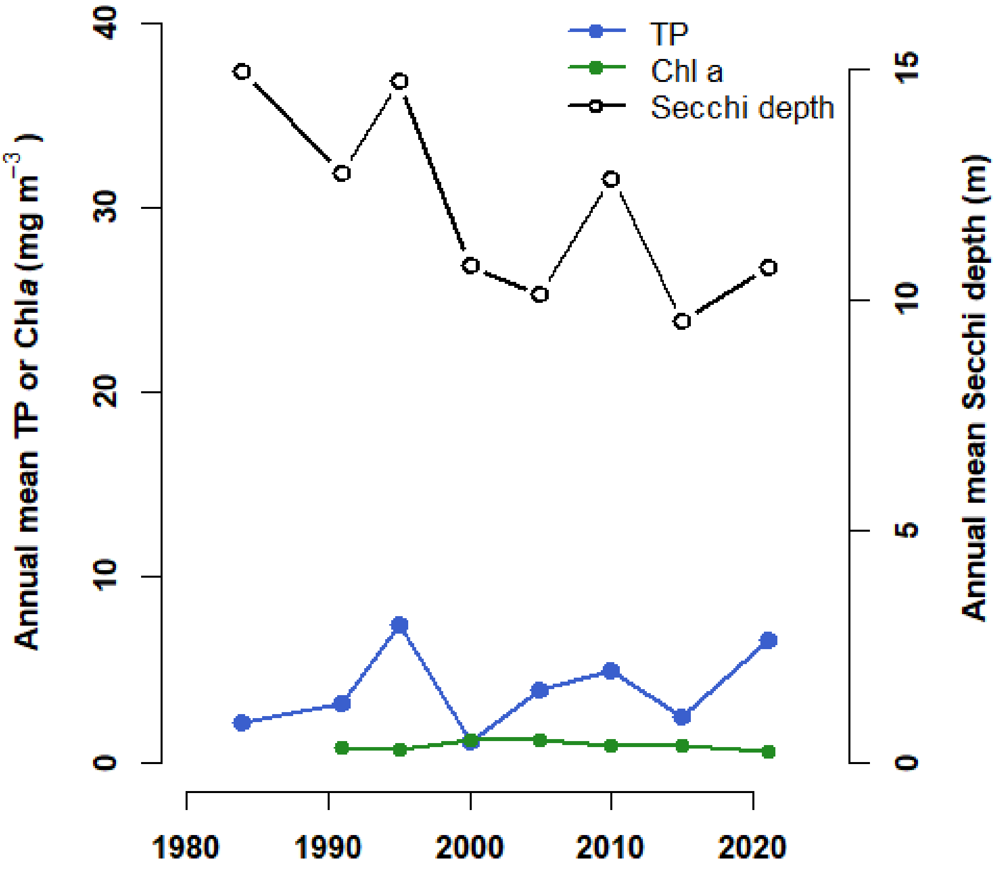


Figure 36 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Wastwater.

Windermere, north basin

Windermere is the largest lake in the English Lake District and the largest natural lake in England by area. Limnologically it is divided by shallow water and islands into a larger and deeper north basin and a slightly smaller and shallower south basin. The north basin has the second largest maximum and mean depth, area and volume of the twenty lakes.

The North Basin of Windermere (Photo: M.M. De Ville).

Table 30 Summary of limnological conditions and trophic and Water Framework Directive classifications at the North Basin of Windermere in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	219.0		
Mean pH (geometric mean)	7.2		
Mean total phosphorus (mg m^{-3})	12.5	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.3		
Mean nitrate-nitrogen (mg m^{-3})	346.8		
Mean silica (mg m^{-3})	1125		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	5.9	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	9.8	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	5.7		Moderate
Mean Secchi depth (m)	4.0	Mesotrophic	
Minimum Secchi depth (m)	3.8	Oligotrophic	
Minimum oxygen concentration (g m^{-3})	5.1		

The north basin of Windermere is mesotrophic and it experiences some oxygen depletion at depth. The lake is classified as being at moderate ecological status for both TP and chlorophyll *a* concentration, according to the WFD classification and although the absolute values are similar to those reported in 2015, change has been sufficient to shift the lake into a lower status class.

There have been no significant long-term changes in the nutrients, chlorophyll *a* concentration or Secchi depth since the first Lakes Tour surveys in 1984 and 1991, but slight declines in TP and Secchi depth are evident, while chlorophyll *a* concentration is below the peak that occurred in 2010 and remains at a similar level to 2015. Similar to nearly all the lakes in the Lakes Tour, Windermere, north basin has experienced a decline in many of the major ions.

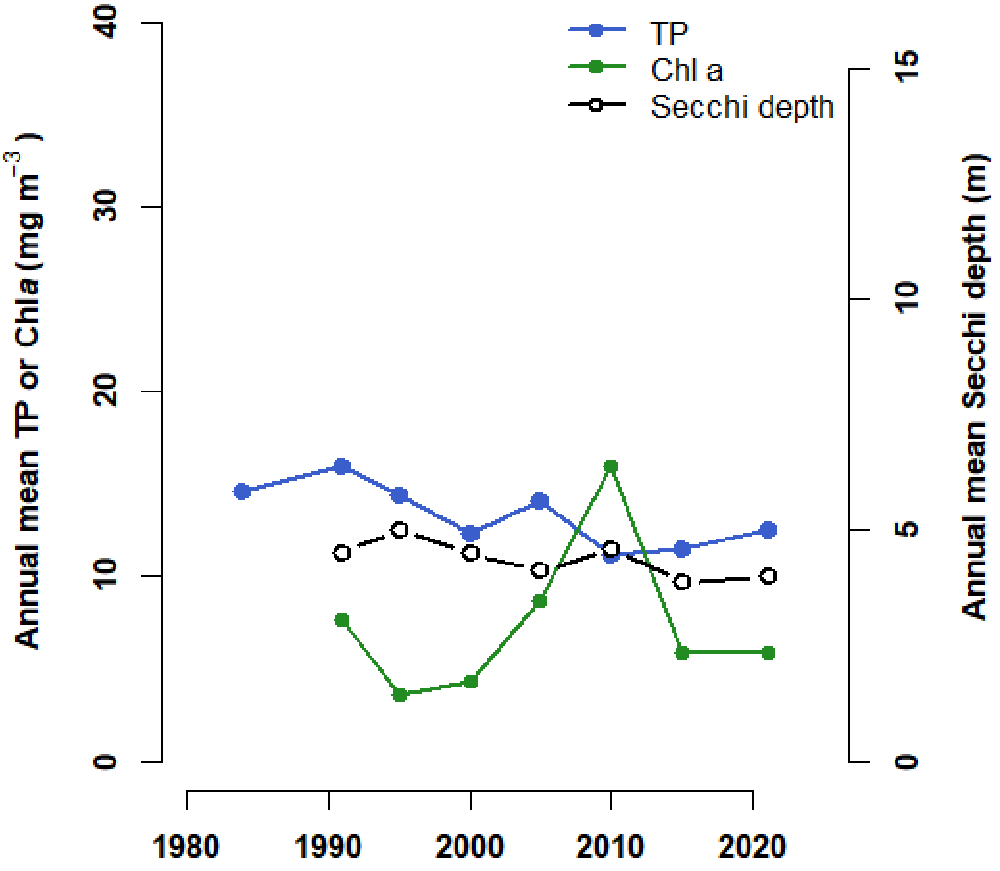


Figure 37 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in the North Basin of Windermere.

In addition to the Lakes Tour records, Windermere north basin is studied fortnightly as part of the UKCEH long-term monitoring programme that was started by the Freshwater Biological Association in 1945 and continued by CEH since 1989 (https://uk-scape.ceh.ac.uk/our-science/projects/cumbrian-lakes-monitoring-platform). Previous nutrient budget studies and assessment of long-term change were carried out in the 2000s by Maberly (2008, 2009) and Maberly et al. (2008) respectively.

Windermere, south basin

Windermere, south basin is around half the volume and 80% of the surface area of the north basin (Table 1). In addition to its connection with the north basin, it receives water from Esthwaite Water via Cunsey Beck.

South Basin of Windermere. (Photo: M.M. De Ville).

Table 31 Summary of limnological conditions and trophic and Water Framework Directive classifications at the South Basin of Windermere in 2021/22.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	260.0		
Mean pH (geometric mean)	7.3		
Mean total phosphorus (mg m^{-3})	13.3	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.5		
Mean nitrate-nitrogen (mg m^{-3})	389.8		
Mean silica (mg m^{-3})	849		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	8.0	Meso-eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	13.7	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	5.7		Good
Mean Secchi depth (m)	3.6	Mesotrophic	
Minimum Secchi depth (m)	3.0	Mesotrophic	
Minimum oxygen concentration (g m^{-3})	2.9		

Windermere, south basin is slightly more productive than the north basin, although the two basins have become increasingly similar in their condition over time. The lake is largely classified as mesotrophic for most indicators, but mean phytoplankton chlorophyll *a* concentration was on the meso-eutrophic boundary in 2021/22, which represents a deterioration on 2015 (Table 31). However, the WFD classification of the lake for chlorophyll *a* has improved from moderate to good ecological status since 2015, whilst the lake remains at moderate ecological status for TP.

Over the longer term, TP and SRP have significantly reduced in the south basin since the early years of the Lakes Tour surveys (Table 11, Figure 38). While there has been some reduction in the chlorophyll *a* concentration over this time, the change was not significant and has plateaued and potentially increased slightly since 2010. The Secchi depth shows a close relationship with the chlorophyll *a* concentration in this lake, with declines associated with increases in phytoplankton biomass. The only other statistically significant change in Windermere, south basin has been a reduction in sulphate, calcium, and magnesium concentrations (Table 11).

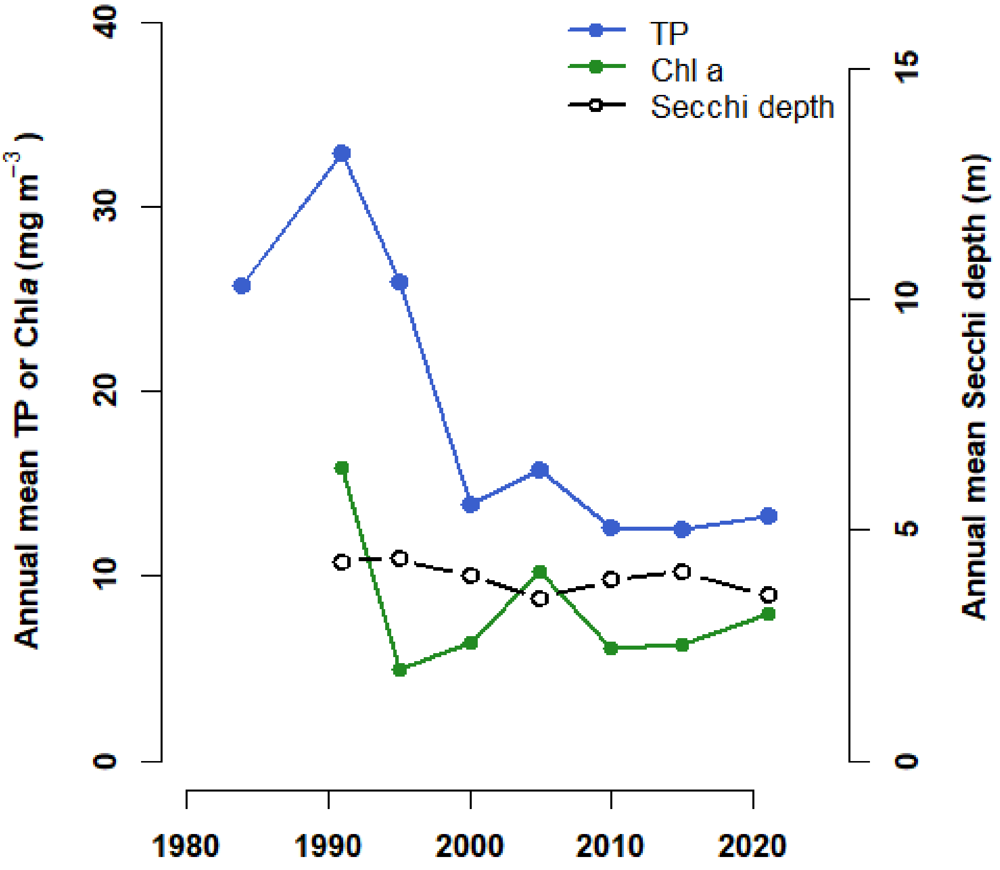


Figure 38 Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Windermere, south basin.

Summary of the lakes in 2021/22

The annual mean values, including oxygen minimum at depth are summarised in Table 32 for all twenty lakes in 2021/22.

Table 32 Annual mean (oxygen minimum at depth) for the 20 lakes of the Lakes Tour in 2015. Note: pH was calculated as the geometric mean.

Lake	TP (mg m^{-3})	SRP (mg m^{-3})	NO_3-N (mg m^{-3})	SiO_2 (g m^{-3})	Chl *a* (mg m^{-3})	Secchi (m)	Min O_2 (g m^{-3})	pH	Alk (mequiv m^{-3})	Cl (mequiv m^{-3})	SO_4 (mequiv m^{-3})	Na (mequiv m^{-3})	K (mequiv m^{-3})	Ca (mequiv m^{-3})	Mg (mequiv m^{-3})
Bassenthwaite Lake	14.5	1.8	351.0	2.3	4.5	3.4	3.7	7.0	266.5	246.7	100.6	233.7	11.5	294.8	108.1
Blelham Tarn	20.5	1.6	453.8	2.1	11.1	2.2	0.2	7.1	398.5	190.3	73.5	185.9	17.0	402.8	99.3
Brothers Water	7.0	0.6	237.8	1.6	1.2	5.5	1.4	7.0	170.3	139.6	45.8	134.5	5.3	180.3	49.4
Buttermere	6.0	0.8	251.5	1.5	1.2	8.2	7.8	6.7	65.0	127.0	38.7	116.5	4.7	90.8	44.2
Coniston Water	6.4	0.7	382.8	1.1	3.0	5.3	3.2	7.1	188.3	189.3	65.3	176.3	10.5	222.2	65.3
Crummock Water	6.5	0.8	252.3	1.4	1.5	6.7	6.7	6.7	57.0	152.0	45.7	137.2	6.6	83.6	51.7
Derwent Water	8.1	0.7	233.3	1.2	3.5	8.1	5.4	6.8	99.5	222.0	32.6	162.1	6.7	155.2	40.4
Elterwater	20.4	2.1	189.6	1.6	21.6	2.9	0.1	6.8	244.5	137.4	38.9	132.4	6.9	248.4	57.6
Ennerdale Water	5.6	0.4	271.8	2.2	0.9	7.1	7.8	6.3	44.3	149.5	39.9	140.3	6.4	65.6	49.3
Esthwaite Water	35.8	3.0	349.6	1.5	19.1	1.7	0.0	7.7	387.8	238.4	78.2	224.3	17.1	409.9	85.9
Grasmere	14.5	2.2	349.5	1.6	3.4	3.9	0.5	6.9	145.8	123.6	47.1	129.7	7.3	174.9	46.5
Haweswater	12.5	1.2	229.3	1.7	2.3	4.2	7.0	7.2	198.0	115.2	62.4	112.3	6.9	197.6	63.7
Loughrigg Tarn	16.0	1.3	551.3	1.3	11.9	3.3	0.3	7.1	258.3	147.0	49.6	143.6	11.7	255.9	79.5
Loweswater	10.5	0.3	286.3	1.0	7.2	3.5	0.4	7.2	166.5	217.3	81.6	198.7	13.7	197.6	88.2
Rydal Water	13.5	1.3	376.5	1.5	4.1	4.6	0.4	6.9	150.5	123.1	45.2	129.3	7.1	169.5	46.8
Thirlmere	10.4	0.5	218.3	1.4	2.4	5.4	5.6	6.7	64.8	108.6	34.1	106.1	4.0	90.6	31.1
Ullswater	9.3	2.6	222.5	1.5	1.8	5.1	5.5	7.3	216.8	135.4	48.6	131.6	8.7	221.1	67.8
Wastwater	6.6	0.6	350.5	2.1	0.6	10.7	0.2	6.7	67.3	145.0	39.3	134.0	5.9	86.2	47.6
Windermere N	12.5	1.3	346.8	1.1	5.9	4.0	5.1	7.2	219.0	157.9	51.0	153.8	9.9	234.3	60.4
Windermere S Basin	13.3	1.5	389.8	0.8	8.0	3.6	2.9	7.3	260.0	178.1	62.8	179.7	12.0	274.0	66.8

4 Patterns of response across all the lakes

4.1 Long-term change

The Lakes Tour survey has been collecting data on water quality across twenty major lakes and tarns in the English Lake District for nearly 40 years. As a five-yearly survey, it can only provide a series of snapshots through time but, over the long term, some significant trends and patterns are emerging from the data, indicative of various drivers of water quality in the lakes.

The first of these, the significant decline in the concentration of several the major ions, has been consistently highlighted in the individual lake summaries in Section 3. These patterns are shown as a combined figure for all the lakes in Figure 36. As is clear from the figure, declines in mean concentrations of nitrate, sulphate, chloride, calcium, magnesium, sodium, potassium and conductivity have occurred and, when tested, were all statistically significant.

Examining more closely patterns in nutrients and lake productivity, there is also an indication of an overall negative trend for total phosphorus, soluble reactive phosphorus and chlorophyll *a* concentrations, but these trends are not statistically significant (Figure 36). As mentioned above, nitrate is the only nutrient with a significant negative trend, and this is likely to be driven by several factors (see next section). Another apparent trend, which is not significant across all lakes, is the reduction in Secchi depth. Reduced transparency is frequently associated with increases in productivity and turbidity. However, this is generally counter to patterns in the other correlates of lake productivity considered here. This could suggest an alternative driver of Secchi depth, particularly given the pattern of larger changes occurring at relatively unproductive sites (see individual lake summaries above). The average concentrations for TP, SRP, NO_3-N and chlorophyll *a* are now below those values recorded at the start of the survey in 1984 or 1991, whilst silica is at its highest concentration since 1984 and Secchi remains lower than at the start of the time series.

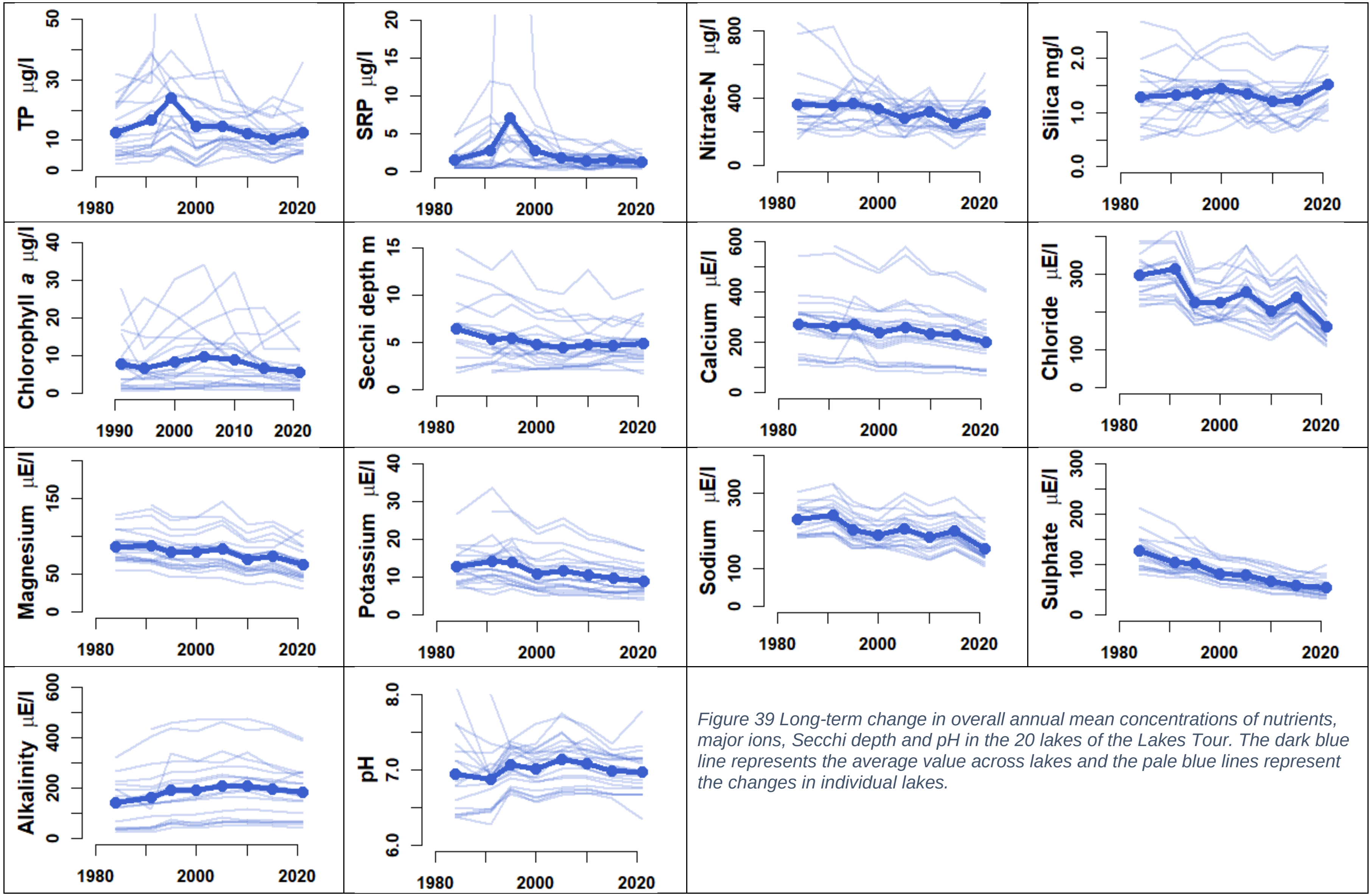


Figure 39 Long-term change in overall annual mean concentrations of nutrients, major ions, Secchi depth and pH in the 20 lakes of the Lakes Tour. The dark blue line represents the average value across lakes and the pale blue lines represent the changes in individual lakes.

4.2 Drivers of responses

Monitoring data are essential if we are to identify patterns and trends in how lake ecosystems have changed over time. Where trends are relatively strong and distinct it may also be possible to at least partially attribute the drivers of the responses seen. This section provides some simple analyses of the patterns and trends discussed above, to make tentative suggestions of possible underlying causes.

Changes in the concentration of major ions

The most coherent pattern of change across the varied lakes included in the Lakes Tour survey is the decline in major ion concentrations. This coherence is indicative of a driver that has a regional scale influence on water chemistry. There are a number of factors that may have contributed to this pattern, although the one likely to have had the largest effect over this period is the well-established reduction in industrial pollutant deposition, principally sulphur dioxide and nitrogen oxides in rainwater. This has occurred since the signing of the UNECE Convention on Long-range Transboundary Air Pollution in 1979, which was the first international treaty to deal with air pollution at a regional level and instigated legislative action at national and EU level to bring down these emissions. The reduction in the deposition of sulphur and hydrochloric acid onto catchment soils has both reduced the concentrations of these ions in the waters but also altered the cycling and leaching of anions, such as labile aluminium and other cations that are naturally present in soil. Therefore, in this dataset we have seen not only a significant decline in anion concentration, but also a reduction in cation concentration. Interestingly the more variable, but still negative, observed change in chloride concentrations is likely to relate to the influence of marine chloride deposition, which can be elevated under more stormy conditions.

In lakes that are sensitive to acid deposition, we would expect such changes to drive up alkalinity and pH. Both measures have indeed tended to increase over this period (see reports on the upland waters monitoring network, https://uwmn.uk/). In the case of the Lakes Tour lakes, other factors such as phytoplankton productivity also influence alkalinity and pH conditions at some sites. As a result, we see a more mixed response among lakes when these lakes are combined into a single trend. Despite this, there is a significant negative correlation between sulphate concentrations and alkalinity, suggestive that the concentration of sulphate is a key driver in the changes in alkalinity seen in this dataset (Figure 37).

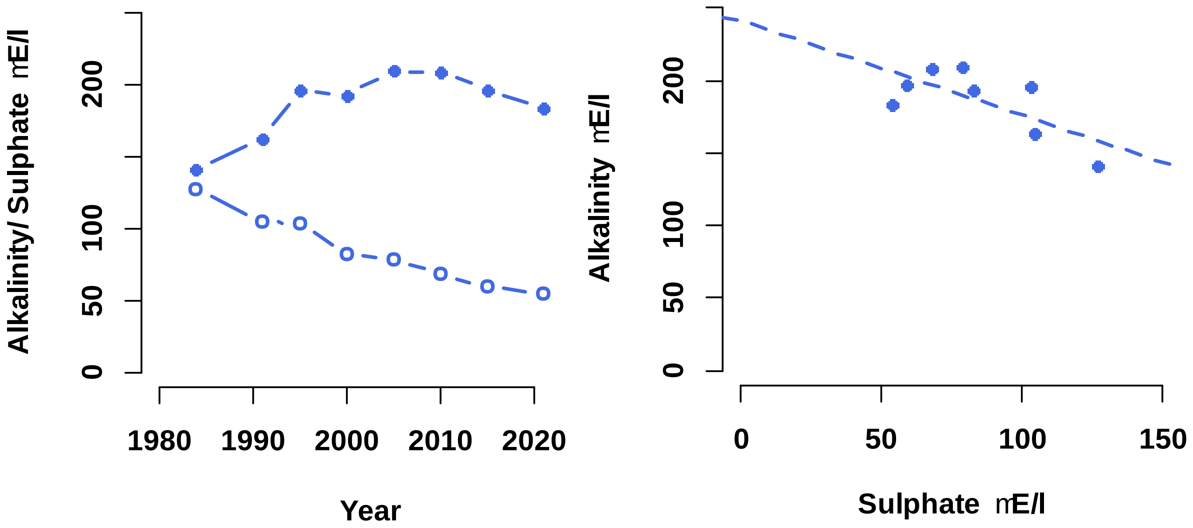


Figure 37 Relationship between annual mean alkalinity and concentration of sulphate for the 20 lakes in the Lakes Tour as (a) a time-series, and (b) a scatter-plot. In panel (a), sulphate concentrations are indicated by open circles and alkalinity by filled circles.

The significant decline in nitrate concentrations across the Lakes Tour lakes is more difficult to assign to one specific factor and it is likely that this pattern is a result of several underlying causes, which are coincident in time. As with the other major ions, changes in deposition of acidifying pollutants are likely to be contributing to the reduction seen. This effect maybe a direct one, where emissions of nitrous oxides have declined over time, but also an indirect one, as some evidence suggests that catchments recovering from acidification can retain, cycle and denitrify nitrogen more effectively, resulting in less nitrate being leached to fresh waters, particularly where catchments have significant forestry cover (Oulehle et al. 2011, 2017).

In addition to changes in acid deposition influencing nitrate concentrations, the use of fertilizers to boost crop productivity in lake catchments can also affect both nitrate runoff and concentrations measured in lake water. Across England and Wales, the use of nitrogen fertilizer peaked in the late 1980s, then declined until 2010, after which time the use has been fairly stable (Figure 38; Agricultural Industries Confederation report based on the British Survey of Fertilizer Practice https://www.agindustries.org.uk/resource/fertiliser-consumption-in-the-uk.html). Although Cumbria specific data were not available, it is likely that these national changes in nitrogen fertilizer use are also indicative of a declining trend in use at this regional level. The extent to which the application of animal manures to crop lands influences the nitrate signal is however unknown, and there is some site-specific evidence for increases in nitrate concentration (e.g. Loughrigg Tarn, see section three). The mixture of land uses, including improved grassland and some other crops in the Lakes Tour lake catchments is suggestive that this may have some influence for particular lakes, although more detailed analysis would be needed to identify the relative roles of changes to atmospheric deposition or direct catchment application for particular lakes. How these changes may be influencing lake productivity or phytoplankton community composition remains poorly understood.

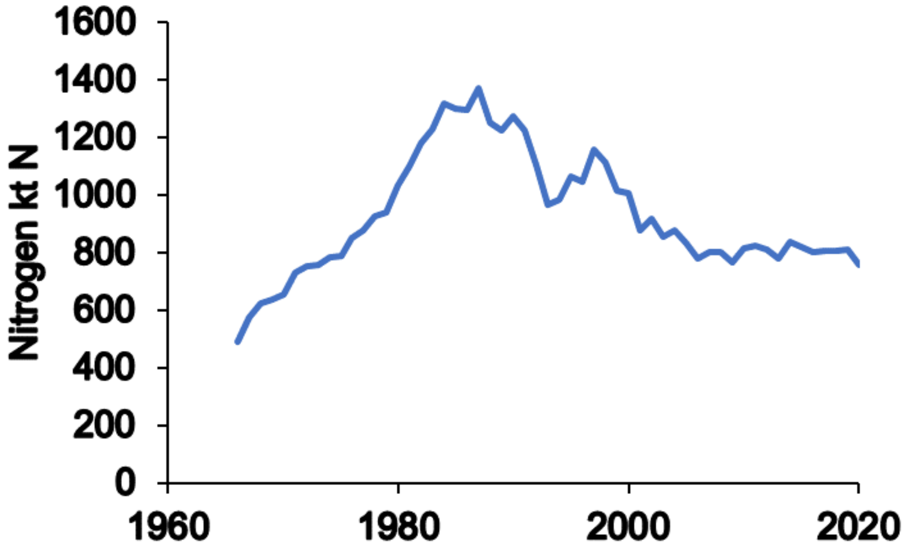


Figure 38 England and Wales nitrogen fertilizer use 1966 to 2020. Data source: Agricultural Industries Confederation report based on the British Survey of Fertilizer Practice accessed 20/12/2022.

Changes in the relationship between phosphorus and chlorophyll *a*

Identified in previous Lakes Tour reports as the key driver of lake productivity, the relationship between total phosphorus and chlorophyll *a* concentration is still a clear pattern in the dataset (Figure 39). This relationship shows that, on average, as phosphorus concentrations increase, so too does the amount of phytoplankton that a lake can support. It is important to note that this is however a log-log relationship which minimises the variation in these data, this variation is important for understanding lake-specific drivers of chlorophyll *a* concentration which could relate to physical conditions (e.g. temperature, light, rainfall, other weather effects) and other chemical and biological influences (e.g. other nutrient concentrations, grazing pressure, inter-specific competition, other growth and loss processes).

Although this pattern has held throughout the time period covered by the Lakes Tour surveys, there appear to be some changes in how sensitively chlorophyll *a* concentration responds to TP. The green and yellow lines on Figure 39 represent the linear regression of this relationship for the data from 1991, the first time chlorophyll *a* was measured in the Lakes Tour, and 2021/22, respectively. What can be seen from these lines is that, although the intercept (point on the y axis where the line crosses) is broadly the same for both years, the slopes differ, with the most recent Lakes Tour data having a larger value for the slope coefficient. In 1991 this slope coefficient was 0.96, whilst in 2021/22 the slope was 1.13. The implication of the increase in slope is that more chlorophyll *a* is now being produced per unit TP. This effect is important to understand, particularly at the lake specific level when considering nutrient management targets. The underlying driver of this change, however, remains to be determined. Specifically, it would be important to determine whether it can be accounted for by site-specific differences or is the result of regional factors such as climate change.

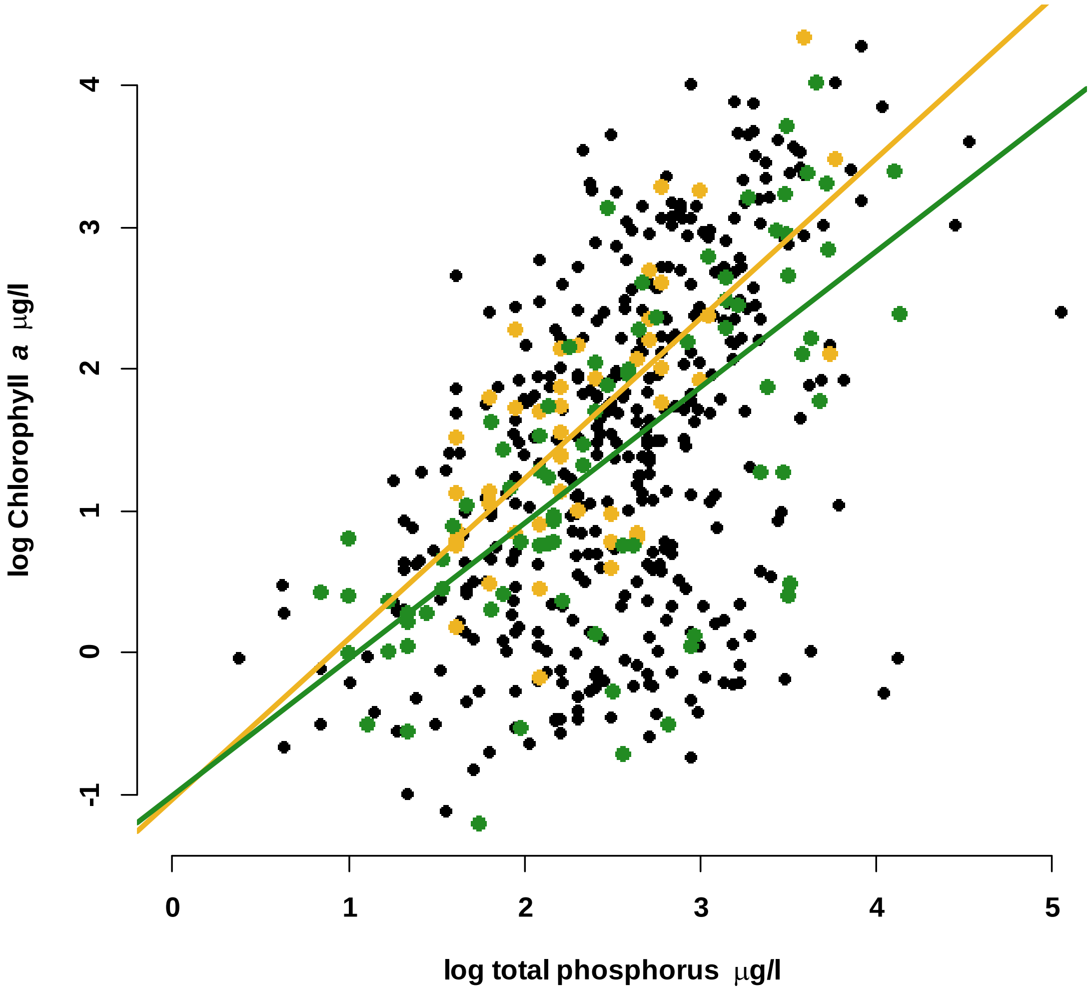


Figure 39 Relationship between concentration of phytoplankton chlorophyll a and total phosphorus for all lakes and Lakes Tour sampling campaigns. Dark green dots and line are 1991 data, yellow dots and line are 2021/22 data.

Changes in Secchi depth

In the previous section, a general decline in Secchi depth over time was highlighted. Although this wasn't a significant relationship across all twenty lakes, significant declines were noted in some of the less productive lakes that didn't appear to correspond with changing phytoplankton abundance. Secchi depth is however also significantly related to lake productivity and analysis in the previous Lakes Tour report (Maberly et al. 2016) revealed a clear relationship of declining Secchi depth with increasing phytoplankton abundance, measured as chlorophyll *a*. This relationship is shown in Figure 40, with differing shades of green and yellow associated with the different Lakes Tour surveys. The statistical relationship across the whole dataset is remarkably consistent over time, indicating that on average, chlorophyll *a* is likely to be an important contributor to the patterns in Secchi depth. However, it is also interesting to note that there are some changes occurring at the extremes of this graph over time. The dark green points indicate values for the 1991 survey, whilst the yellow points are for the 2021/22 survey. Examining these ends of the data series suggests that there has been a contraction in the deepest Secchi depths and lowest chlorophyll *a* values and a reduction in the highest chlorophyll *a* concentrations and lowest Secchi depths over the last 30 years. A partial explanation of this pattern is likely to be that some of the most productive lakes have shown reductions in their phytoplankton abundance over time and the Secchi depth has therefore deepened. What is currently less clear is whether a non-algal driver of Secchi depth, such as DOC concentration, is having an impact on the relationship seen below. DOC hasn’t been monitored as part of the Lakes Tour surveys, however there is strong evidence for increasing DOC concentrations across large areas in response to the reductions in acid deposition, discussed above and some indications that climate warming may increase DOC concentration exported from soils (Evans et al. 2006; Monteith et al. 2007). To investigate the role of DOC increases in driving changes in Secchi depth at unproductive sites, additional sources of data would be required.

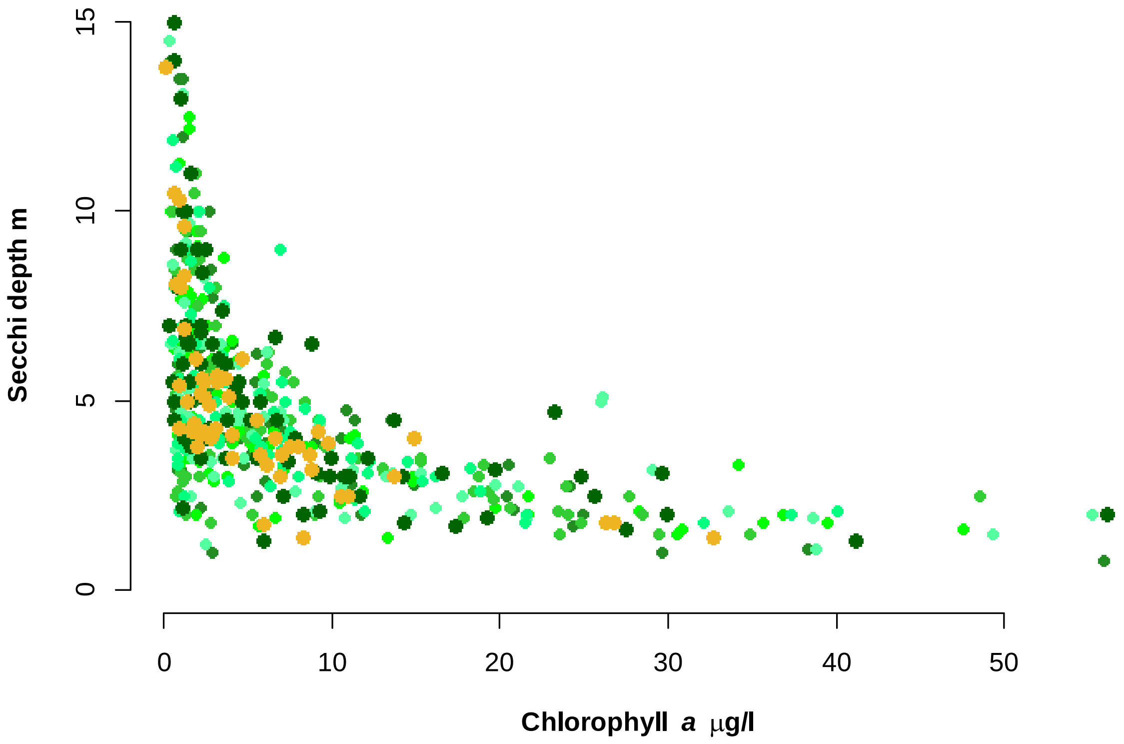


Figure 40 Relationship between Secchi depth and concentration of phytoplankton chlorophyll a in the 20 lake basins and four sampling occasions in Lakes Tours between 1991 and 2021/22.

Changes in the minimum oxygen concentration

Oxygen is essential to animal life in freshwater environments. The concentration of oxygen is also a sensitive indicator of change occurring in lake ecosystems. Very high concentrations of dissolved oxygen may be indicative of the formation of phytoplankton blooms, where the intense photosynthesis of large numbers of phytoplankton cells pushes oxygen concentrations beyond air saturation levels. Low concentrations of dissolved oxygen in the deep water of lakes are generally indicative of more productive systems where the biomass produced at the surface sinks and is decomposed by the microbial community, which consumes oxygen in the process. Where lakes thermally stratify during the summer the oxygen lost in deep water through microbial decomposition cannot be replaced by exchange at the air water interface and the concentration of oxygen in the water declines. It is important to note that recovery from oxygen depletion is likely to be a long-term and non-linear process once the causes of depletion are addressed. This is because the biogeochemical changes induced by oxygen depletion, which include internal nutrient loading from the bed sediments, creates a positive feedback of enhancing phytoplankton productivity, further entrenching the deoxygenated state. This effect highlights the importance of checking the drivers of phytoplankton productivity long before oxygen depletion can become established as a stable ecosystem state in the lake.

The relationship between a lake's productivity or a measure of the phytoplankton biomass, chlorophyll *a*, and the minimum oxygen concentration that is attained in a year is shown in Figure 41. The graph indicates that across the Lakes Tour dataset, once annual average chlorophyll *a* concentrations are above ~8 µg/l the lake is likely to experience significant oxygen depletion. The exception to this is the cluster of points below log ~1 (~2.7 µg/l) chlorophyll *a* concentration. The lake associated with these points is Brothers Water and previous Lakes Tour reports have highlighted that the minimum oxygen concentration in this lake is below that expected from the relationship with chlorophyll *a*. As highlighted in section 2, the unusual bathymetry of this lake has been investigated as a potential cause for the observed oxygen minimum. The report concluded that this was unlikely to be the main factor in this case.

Figure 41 provides an indication of how the relationship between annual average chlorophyll *a* concentration and annual oxygen minimum has changed over the time period of the Lakes Tour surveys. The different coloured points on the graph correspond to the different Lakes Tours, starting in 1991. Each set of points has an associated linear regression line of the same colour. Examining the position of these lines there is some suggestion that for much of the early Lakes Tour period, there was little change in the relationship between annual minimum oxygen concentration and chlorophyll *a* concentration. However, the two most recent surveys have regression lines that are progressively further to the left on the plot. The implication of this is that the relationship between the two variables is changing overtime. Minimum oxygen concentrations are reducing overtime, despite chlorophyll *a* concentrations being lower overall. The causes of this change are unclear, as a number of factors may be involved. For example increased inputs of other degradable organic matter, such as DOC, may be enhancing oxygen reductions. In addition, climate warming may be having a dual effect on oxygen concentrations, directly by reducing the concentration, since oxygen is less soluble in warmer water and indirectly by affecting thermal stratification duration and intensity. Further work would be required to investigate the relative roles of these factors across the Lakes Tour dataset, however a recent global study, which used data from hundreds of lakes, including Blelham Tarn, revealed that deep water oxygen concentrations were strongly associated with changes in water clarity and water density stratification (Jane et al. 2021).

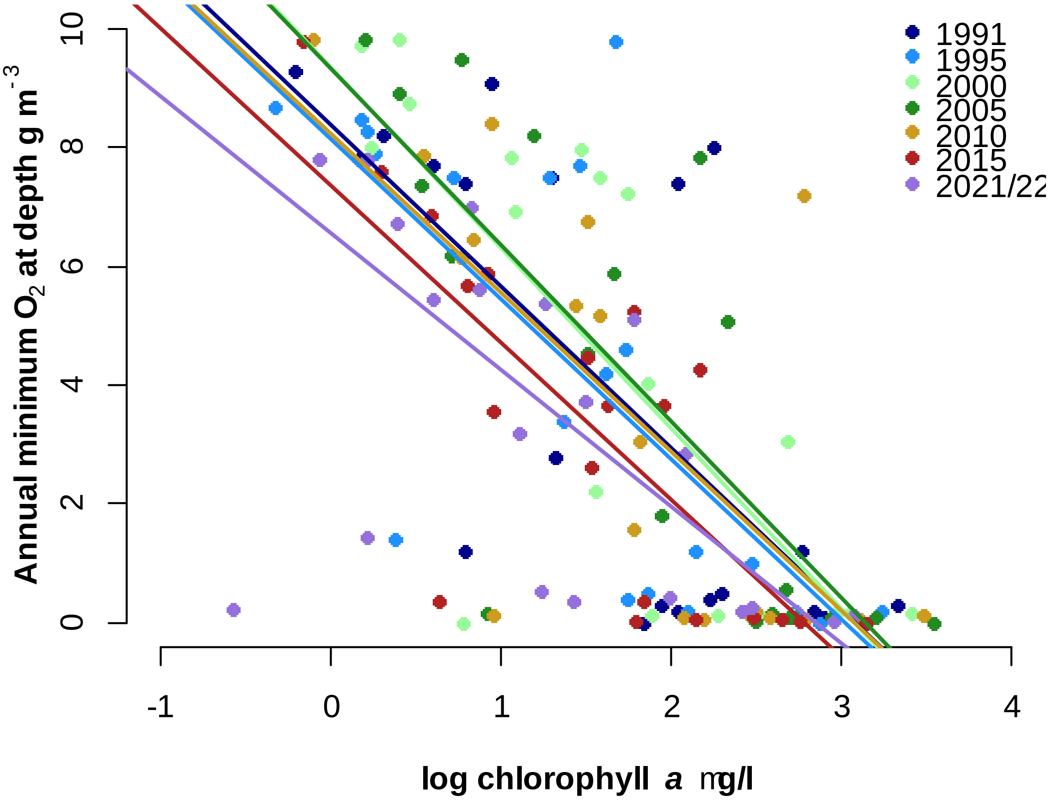


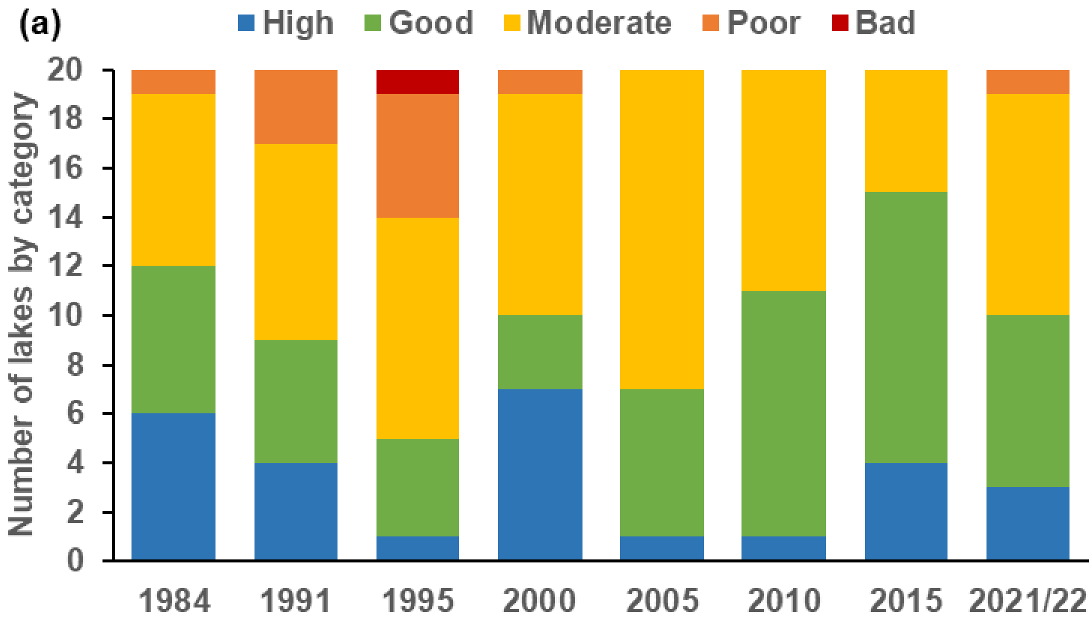
Figure 41 Relationship between annual average chlorophyll a concentration and annual minimum oxygen concentration for the twenty lakes over time. The different regression lines represent the linear regression of points for each of the Lakes Tour surveys from 1991 to 2021/22. Chlorophyll a values are on a log scale.

4.3 Change in ecological status under the WFD

The ecological status of the twenty lakes based on TP and phytoplankton chlorophyll *a* is summarised in Figure 42. These values are based on the annual average concentration of these variables, calculated as detailed in section 3 and the status class boundaries set out in Tables 9 and 10. As discussed above, these categorisations are not equivalent to the methods used by the Environment Agency to assess status, which are based on monthly data collected over a three-year time frame. Therefore, these categories may differ from the official designations. However, since the same status class boundaries and calculation methods have been applied across the full Lakes Tour dataset, they are an internally consistent classification that can be used to determine change over time.

The most important boundary in the WFD is between Good:Moderate status. If lakes fall below Good status, measures to improve ecological status are required to be implemented by the Directive. In 2021/22, 10 lakes, or half of the survey lakes were below the Good category for TP concentrations, nine with a moderate classification (Blelham Tarn, Elterwater, Grasmere, Haweswater, Loughrigg Tarn, Rydal Water, Thirlmere and Windermere, north and south basins) and 1 with a poor classification (Esthwaite Water). For the observed chlorophyll *a* concentration measure, this count was only five lakes, with four being moderate (Blelham Tarn, Loughrigg Tarn, Loweswater, Windermere, north basin) and one being poor (Esthwaite Water). Of these sites, Loughrigg Tarn and Rydal Water are not designated WFD waterbodies. Based on the principle of one-out-all-out, the ten lakes listed for TP would be classified as below Good ecological status.

Examining the number of lakes in each of the status classes in previous surveys suggests that 2021/22 represents a decline in water quality compared to 2010 and 2015 for TP, but an improvement on the 2005 values. In addition, one lake has been classified as being in poor status for TP, representing a concerning decline on the last three surveys. In contrast, 2021/22 categorisations reflect a steady improvement in status for the observed chlorophyll *a* measure, with over three quarters of lakes now at Good status or above compared to less than half in 2010 and 2005.



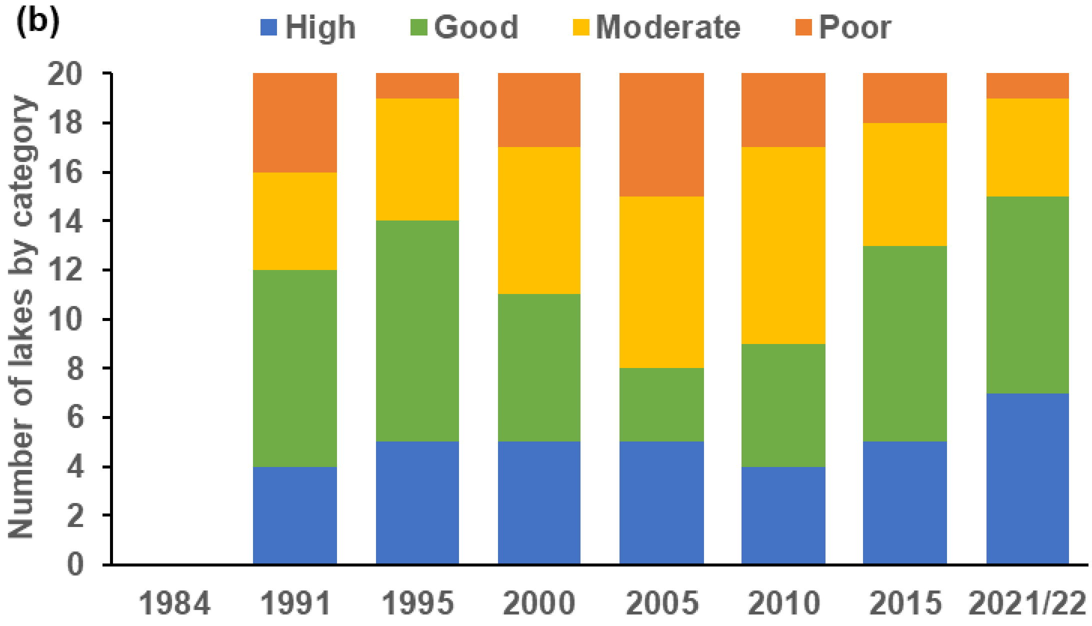


Figure 42 Summary of overall ecological status for the 20 lakes according to (a) TP or (b) phytoplankton chlorophyll a between 1984 and 2021/22.

4.4 Suggestions for further work

There are several areas of further work that have been identified in the production of this report. Some issues relate to broad patterns seen in the data across lakes, whilst others are more lake specific. A short overview of each of these areas is provided in this section.

Secchi depth changes

At several the more unproductive lakes, such as Wastwater and Ennerdale Water there has been a significant decline in the Secchi depth transparency over the time period of the Lakes Tour surveys (since 1984). The causes of this decline are currently unknown. It is unclear whether these changes relate to phytoplankton productivity, because of the sensitivity of the relationship between Secchi depth and chlorophyll *a* concentration at low concentrations, reported in previous Lakes Tour reports or if other external drivers such as increasing DOC concentration may be the cause for the reduced water transparency.

TP: chlorophyll *a* relationship

The analysis carried out in section 4.2 indicates that the relationship between TP and chlorophyll *a* concentration has changed over time. The slope of the relationship in 2021/22 is 1.13, which suggests that a unit of phosphorus will now produce more than one unit of chlorophyll *a*. This is an increase on this value from the start of the dataset. The underlying driver of this potential change is currently not understood, but it is likely to have management implications for phosphorus reduction targets necessary to achieve the same reductions in phytoplankton biomass.

Causes of bottom water oxygen decline

Analysis carried out in section 4.2 suggests that the relationship between the minimum oxygen concentration experienced by the twenty lakes and the chlorophyll *a* concentration of those lakes has changed over time. The driver of these changes is again, not currently understood in the specific case of the Lakes Tour lakes. Indeed multiple factors may be involved in driving the observed reduction in minimum oxygen concentration. Since this indicator is a highly sensitive measure of lake ecosystem health and critical oxygen thresholds exist for the persistence of sensitive species such as the rare fish. The driver of these changes needs to be investigated urgently.

Increasing nutrient concentrations

There is some evidence that TP concentrations have increased in several of the lakes since the last survey in 2015. There is also some indication that nitrate concentrations have increased in five lakes, albeit the change isn't currently statistically significant. In particular, ten lakes have TP concentrations that are classified as being at less than Good status. The cause of the failure to meet the WFD criteria warrants further investigation at Blelham Tarn, Elterwater, Grasmere, Haweswater, Loughrigg Tarn, Rydal Water, Thirlmere and Windermere, north and south basins and Esthwaite Water. Detailed fortnightly data are currently collected at four of these sites (Blelham Tarn, Esthwaite Water and Windermere, north and south basins) as part of the UKCEH Cumbrian Lakes monitoring platform (https://uk-scape.ceh.ac.uk/our-science/projects/cumbrian-lakes-monitoring-platform) and further investigations at Elterwater are being carried out by South Cumbria Rivers Trust. These data could be used to understand changes occurring in these lakes.

Declining water quality at Esthwaite Water

Of particular concern is the worsening water quality at Esthwaite Water. The lake was classified as being at poor ecological status for both TP and chlorophyll *a* concentrations and significant phytoplankton blooms were present during the summer at the site. Data collected as part of the UKCEH monitoring at this site suggests that the problem has been persistent over the last few years. Understanding the causes of the water quality decline at Esthwaite Water is an urgent priority given its status as a RAMSAR site and SSSI.

Fish populations

Owing to resource limitations, no surveys of the fish populations in the Lakes Tour lakes have been carried out in 2021/22. This is an important gap in our understanding of the condition of these lakes since fish, particularly rare fish species and salmonids, are sensitive indicators of changing ecological conditions. They are a crucial component of healthy and effectively functioning lake ecosystems and are critical for top-down control of lower trophic levels. As such, compositional changes fish communities can either support enhanced, or exacerbate poor, water quality. Fish also have important cultural and amenity value to visitors to the English Lake District and are used as indicators for the Lake District National Park Climate Change Adaptation

Report, and rare fish species are listed in the UNESCO World Heritage Site status nomination document.

5 Conclusions and recommendations

The Lakes Tour survey 2021/22 represents an overview of the condition of twenty of the major lakes and tarns in the English Lake District. The survey is the eighth edition to the roughly five-yearly surveys that have been carried out since 1984. These surveys collectively contain a wealth of information on the changing conditions of the lakes over this time period.

Analysis of the data collected over four seasons from April 2021 to February 2022 has been presented and summarised in sections three and four. The following bullet points summarise the key findings from this work.

- During the year the lakes thermally stratified, due to surface water heating. Stratification commenced in the spring when average temperatures were similar to surface temperatures (7.1°C vs 8.2 °C). Surface temperatures averaged 19.4°C in July and the average temperature difference between surface and bottom waters was 12.4°C. A similar difference between water column average temperature and surface temperature was seen in autumn as the lakes began to mix and in the winter the lakes were isothermal from the surface to the bottom of the lake, when average temperatures were 5.8°C.

- Oxygen dynamics also followed a seasonal pattern, in part explained by the thermal stratification. Some more productive lakes experienced pronounced oxygen depletion at depth, whilst unproductive lakes experienced very limited to no reduction in oxygen concentrations at depth. Minimum oxygen concentrations occurred in the summer or autumn depending on the length of stratification that the lake experiences. The relationship between minimum oxygen concentration and average chlorophyll *a* concentration appears to have changed over time and indicates that minimum oxygen concentrations are now lower for each unit of chlorophyll *a* that a lake produces. The cause of this change is currently unknown.

- Secchi depth transparency varies across the lakes, exceeding 10 m in the unproductive lakes such as Buttermere, Crummock Water and Wastwater, but being <2m in more productive lakes such as Blelham Tarn, Elterwater and Esthwaite Water. At some unproductive lakes there has been a significant decline in Secchi depth over time, the cause of which is unknown.

- The concentration of major ions in the lakes has been significantly declining over time. This regional pattern of decline is thought to be largely driven by reductions in the wet deposition of sulphur and hydrochloric acid and to a lesser extent nitrous oxide, although local catchment scale impacts for nitrate may also play a role. The general pattern of major ion concentration varies across the lakes as a function of the underlying geology and this influence, along with catchment rainfall affects the extent to which the lakes are likely to have been impacted by acid deposition in the past. Higher ionic concentrations occur on the generally softer geologies underlying the southern lakes, whilst lower buffering capacity and higher propensity to acidify are more typical of lakes that are underlain by the more acidic Borrowdale volcanics and igneous intrusions of the western and central lakes.

- Nutrient concentrations in the lakes varied during the year. TP had less of a seasonal pattern than the other nutrients but tended to peak in the winter. The highest TP concentrations were measured in Bassenthwaite Lake, Elterwater and Esthwaite Water, while Ennerdale Water and Wastwater had the lowest concentrations. SRP, nitrate (TON) and silica all followed a broadly similar seasonal pattern with minima associated with the period of highest phytoplankton growth in the summer and peaks in the winter, when demand for these nutrients is lowest. Loughrigg Tarn had the highest concentration of nitrate, while Elterwater had the lowest. Ammonium concentrations tended to be mostly below the limit of detection in the lakes, but occasions when measurable ammonium occurred could be indicative of internal nutrient supply due to anoxia of deep waters in Blelham, Esthwaite Water, Grasmere, Loughrigg Tarn, Loweswater and Rydal Water. Silica concentrations were highest in the winter time at Blelham Tarn and Bassenthwaite Lake.

- Long term patterns in the concentrations of nutrients and chlorophyll *a* were largely not significant, although the direction of the trend was negative. Compared to the most recent survey however, TP concentrations appear to have increased in some lakes. There is however a statistically significant trend of a decline in nitrate concentrations over time.

- Large seasonal variations in phytoplankton chlorophyll a were seen, with peaks generally associated with spring and summer. Large phytoplankton blooms occurred in summer samples at Blelham Tarn, Elterwater, Esthwaite Water and Loughrigg Tarn.

- The phytoplankton community across the lakes was composed of 188 taxa in total, including 65 chlorophytes, 34 diatoms and 25 cyanobacteria species. The most common genera recorded were the cryptophytes *Cryptomonas* and *Rhodomonas* the diatom *Asterionella* and the haptophyte *Chrysochromulina*. In the more productive lakes, a higher proportion of the phytoplankton diversity was made up of cyanobacteria species.
- The zooplankton community across the lakes was composed of 10 genera of rotifers and Cladocera and two groups of copepods. Copepods, particularly calanoid species, were numerically dominant across the 20 lake basins in spring, autumn and winter. However, at an individual lake level, dominant species also varied depending on season and included *Ceriodaphnia*, *Daphnia*, *Bosmina* and *Asplanchna* in different lakes.
- Heavy metal concentrations were measured in the lakes in the summer of 2021. In general, the patterns and concentrations were similar to the values reported for the 2015 Lakes Tour report. Ennerdale Water and Loweswater were the lakes where the heavy metal concentrations most frequently exceeded the limit of detection. Overall metal concentrations in all lakes were relatively low.
- Four micro-organic compounds were detected at levels above the detection limit at some sites in the summer of 2021. These were Diazinon, 2,4-Dichlorophenoxyacetic acid, MCPA and PAA. Of these, PAA was detected most frequently, occurring at measurable concentrations in 11 lakes.
- Changes in the ecological status classes of the lakes have occurred since the previous surveys. These suggest that, in general, there has been an overall decline in status based on the measure of TP, whilst there are some indications of improvements in water quality according to the observed chlorophyll *a* indicator.
- Suggestions for further work to investigate the drivers of observed changes in the Secchi depth, TP:chlorophyll *a* ratio, and minimum oxygen concentration, indications of increasing nutrient concentrations at some sites, deteriorating water quality at Esthwaite Water, and knowledge gaps around the fish populations in the lakes are made.

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