Report

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A survey of the lakes of the English Lake District:

The Lakes Tour 2010

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EXECUTIVE SUMMARY

1. This report presents information resulting from a survey of the limnology of the 20 major lakes and tarns in the English Lake District based on samples taken in January, April, July and October 2010. This 'Lakes Tour' supplements similar tours in 1984, 1991, 1995, 2000 and 2005.
2. On each sampling occasion depth-profiles were collected of water temperature and oxygen concentration and Secchi depth was measured. An integrated water sample was analysed for pH and alkalinity, major cations and anions, plant nutrients, phytoplankton chlorophyll *a* and species composition and zooplankton abundance and species composition. Some of the field work and chemical analyses were carried out collaboratively between staff from CEH and the Environment Agency.
3. The lakes had a range in tendency to stratify in summer with the weakest stratification in large, relatively shallow and exposed lakes such as Bassenthwaite Lake. During summer stratification oxygen-depletion at depth was only found in the more productive lakes.
4. Water clarity, assessed by Secchi disc, varied between about 13 m in clear unproductive lakes such as Wastwater to less than 2 m in the more productive lakes during summer such as Esthwaite Water.
5. Major ion composition varied with geology and altitude. Lakes on the Silurian slates (those in the Windermere and Coniston Water catchments) tended to have anions dominated by alkalinity (bicarbonate) and cations dominated by calcium whereas the other lakes tended to have anions dominated by chloride and cations dominated by sodium.

6. Availability of phosphorus is the main factor that affects lake productivity. Concentrations were lowest in Wastwater and Ennerdale Water and highest in Elterwater and Esthwaite Water. Nitrate was the dominant form of nitrogen. Nitrate concentrations tended to be lowest in July because of biological uptake and seasonal fluctuations were most marked in the productive lakes. Silica, an essential nutrient for diatoms, showed a similar seasonal pattern to nitrate but the depletion was more marked in April because the spring bloom is typically dominated by diatoms. In unproductive lakes such as Wastwater and Ennerdale Water concentrations of silica did not vary seasonally.
7. The concentration of chlorophyll *a* was used as a measure of phytoplankton abundance. Comparisons across lakes showed low concentrations all the year in the unproductive lakes and seasonally high concentrations in the more productive lakes. Loughrigg Tarn had the highest annual average concentration of chlorophyll *a*.
8. The species composition varied seasonally in all the lakes, even unproductive ones with limited seasonal changes in nutrient concentrations, underlying the sensitivity of phytoplankton to environmental conditions. Overall, diatoms dominated in January and particularly, April, but in .July and October a range of different groups dominated depending on the lake.
9. Zooplankton abundance was very variable and greatest in the productive lakes and seasonally, abundance tended to be greatest in July and October. Seventeen genera of zooplankton were recorded in total. The unproductive lakes tended to be dominated by *Eudiaptomus gracilis* and this species dominated most of the lakes in January. *Daphnia* spp. were often important in the summer in the more productive lakes. Another cladoceran, *Bosmina* spp. was in appreciable numbers in January in some

lakes. *Ceriodaphnia* and *Mesocyclops* were an important part of the zooplankton community in some lakes.

10. The known status of fish populations, although not undertaken in the project, was summarised. Eighteen species have been recorded in these lakes, but of these six are probably introduced. Some lakes have very little fish-data and require more research.
11. Heavy metals were measured for the first time. Although many samples were below the limit of detection, copper concentrations were elevated in Coniston Water and Haweswater, lead was elevated in Haweswater and zinc was elevated in Bassenthwaite Lake, Brothers Water, Buttermere and Haweswater.
12. Micro-organic pollutants were measured for the first time and most samples were below current detection limits. Of the 128 compounds analysed, 16 gave values above the detection limit but only five exceeded the limit more than once. Of these, Diazinon, an organophosphorus insecticide, had concentrations that exceeded Environmental Quality Standards in Buttermere and was high in a number of other lakes; this merits further investigation.
13. The current state of each lake was summarised in terms of key limnological variables, trophic state and ecological status under the current definitions of the Water Framework Directive.
14. Only Buttermere and Wastwater were at High ecological status for both total phosphorus and chlorophyll *a*. Brothers Water, Coniston Water, Crummock Water, Derwent Water, Ennerdale Water and Haweswater were at Good ecological status. Bassenthwaite Lake, Blelham Tarn, Elterwater, Esthwaite Water, Grasmere, Loweswater, Rydal Water, Thirlmere, Ullswater and the North and South Basins of Windermere were at Moderate ecological status, although Ullswater was close to Good status. Loughrigg Tarn was at Poor status because of high phytoplankton

chlorophyll *a*. Lakes at Moderate or Poor ecological status will require further work to bring them to Good ecological status by 2015 under the Water Framework Directive (WFD), although Rydal Water and Loughrigg Tarn are not on the UK –list of WFD lakes.

15. Long-term change from 1984 to 2010 (1991 to 2010 for some variables) were analysed. There have been changes in the concentration of major ions in many sites. This has largely been caused by reduction in sulphate deposition from acid rain, causing widespread increases in alkalinity and pH and reductions in concentration of calcium, magnesium, sodium and potassium because of reduced cation-exchange in the soil. Reducing concentrations of sodium and chloride are probably related to reductions in stormy weather since the mid 1990s and hence reduced input of sea-salt in rain. On average, in comparison to the 2005 Lakes Tour, there has been a reduction in concentration of TP and phytoplankton chlorophyll *a* and an increase in Secchi depth. While the magnitude of change is small, it is, encouragingly in the right direction.

16. The lakes in the English Lake District are extremely valuable scientifically as they are highly diverse. This was illustrated by showing the link between catchment altitude (as a proxy for land use and soil type) and a range of water chemistry variables and the relationship between phytoplankton chlorophyll *a* and total phosphorus which shows that the productivity of these lakes is controlled by phosphorus. The magnitude of the seasonal changes in silica and nitrate is positively linked to lake productivity. Secchi depth is negatively correlated with phytoplankton, but in January Secchi depth is less for a given chlorophyll *a* concentration, probably because of attenuation by dissolved organic carbon and particulate material brought

in to the lakes by winter rains. Minimum oxygen concentration at depth is also negatively related to phytoplankton chlorophyll *a*.

17. It is suggested that more work is needed at lakes which have failed Good ecological status, and at Ennerdale Water in particular where there has been a dramtic decrease in Secchi depth that appears to be linked to increased productivity. The fish populations in many lakes need to be studied in more detail.
18. The joint-manning of the Lakes Tour by CEH and the EA worked well and could be a model for other work in the future.

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1. INTRODUCTION

The lakes that form the English Lake District have been sampled by the Freshwater Biological Association and the Natural Environment Research Council research institutes the Institute of Freshwater Ecology and its successor the Centre for Ecology and Hydrology, since the 1920s. At about this time Pearsall (1921) arranged some of these lakes in an order corresponding to trophic status, which he recognised was related to their surrounding geology and land use. The lakes range from the unproductive, e.g. Wastwater, which are situated in mountainous regions on hard volcanic rocks to the more productive e.g. Esthwaite Water, which lie on softer rocks usually situated in fertile valleys with deep alluvial soils. The English Lake District is unique, certainly in the UK, in having this wide range of lake types.

Since the 1920s a number of surveys of the English Lakes have been carried out (Pearsall, 1932; Gorham *et al.*, 1974; Jones *et al.*, 1979; Kadiri & Reynolds, 1993). Some of these data were reviewed by George (1992) and Talling (1999) summarised what is known for some of these lakes. The current form of the 'Lakes Tour' started in 1984, although not all the current determinands were measured, and has been repeated in 1991, 1995, 2000 and 2005 (Hall *et al.*, 1992, 1996; Parker *et al.*, 2001; Maberly 2006). The scheme is of a low intensity: samples are only taken four times per year, but nevertheless provides a robust and fairly comprehensive picture of how lakes have responded to environmental pressures.

The English Lake District is one of the most popular tourist regions in the UK because of its relatively unspoilt and dramatic landscapes, of which the lakes form an integral part. This popularity, along with an increasing local population, increased agricultural use of fertilisers, climate change and introduction of alien species by Man's activities has put large ecological pressures on the lakes. Recent legislation originating from the European Commission, the

Water Framework Directive (WFD; 2000/60/EC), 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. Quality or ecological status is determined not just by water chemistry but also by a range of ecological characteristics including the composition and abundance of phytoplankton. The data from the Lakes Tour have already been used to help determine various ecological quality boundaries for the implementation of the WFD. The Lakes Tour also serves to identify lakes that may be showing signs of deterioration and which deserve further more detailed study, and documents the recovery of lakes that have already been subject to management.

For the first time, the 2010 Tour included measurements of heavy metals and micro-organic pollutants and (although not part of this research) also summarised what is known about fish populations in the twenty lakes.

2. MATERIALS & METHODS

2.1 Sites

The location of the twenty lake basins (Windermere is treated as two basins: North and South) sampled in this work is shown in Figure 2.1 and their geographical and physical features are recorded in Table 2.1.

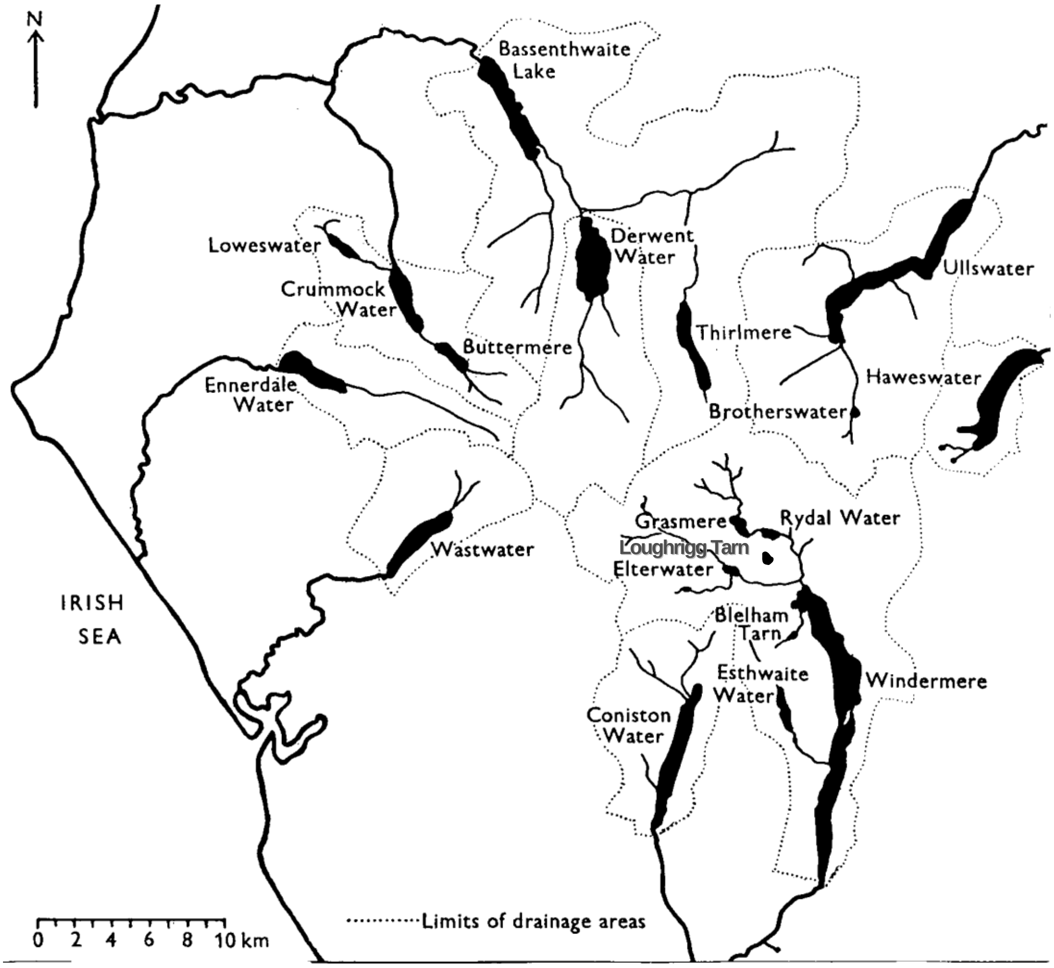


Figure 2.1. The English Lake District showing the 20 lake basins surveyed in this study (based on Knudsen, 1954).

Table 2.1. Geographical and physical characteristics of the 20 lakes basins in the Lakes Tour.

Lake	Catchment area (km^2)	Mean catchment 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	6.2	1.10	5.3	27.9	5.3	19.0	30
Blelham Tarn	4.3	105	0.67	0.29	0.1	0.7	6.8	14.5	50
Brothers Water	13.2	437	0.60	0.40	0.2	1.5	7.2	15.0	21
Buttermere	18.7	377	2.0	0.54	0.9	15.2	16.6	28.6	140
Coniston Water	62.5	227	8.7	0.73	4.9	113.3	24.1	56.1	340
Crummock Water	62.7	327	4.0	0.85	2.5	66.4	26.7	43.9	200
Derwent Water	85.4	354	4.6	1.91	5.4	29.0	5.5	22.0	55
Elterwater	1.0	108	1.0	0.4	0.03	0.1	3.3	7.0	20
Ennerdale Water	43.5	374	3.8	1.10	3.0	53.2	17.8	42.0	200
Esthwaite Water	17.0	148	2.5	0.62	1.0	6.4	6.4	15.5	100
Grasmere	30.2	328	1.6	0.60	0.6	5.0	7.7	21.5	25
Haweswater	32.3	463	6.9	0.90	3.9	76.6	23.4	57.0	500
Loughrigg Tarn	0.95	175	0.4	0.3	0.07	0.5	6.9	10.3	117
Loweswater	8.2	243	1.8	0.55	0.6	5.4	8.4	16.0	150
Rydal Water	33.8	312	1.2	0.36	0.3	1.5	4.4	18.0	9
Thirlmere	53.8	398	6.0	0.78	3.3	52.5	16.1	46.0	280
Ullswater	147	393	11.8	1.02	8.9	223.0	25.3	63.0	350
Wastwater	42.5	385	4.8	0.82	2.9	115.6	40.2	76.0	350
Windermere North Basin	175	231	7.0	1.6	8.1	201.8	25.1	64.0	180
Windermere South Basin	250	231	9.8	1.0	6.7	112.7	16.8	42.0	100

2.2 Sampling

2.2.1 *Location and dates*

Each lake was sampled from approximately the deepest point, the location of which is shown in Table 2.2. The aim of the protocol is to collect all samples within a 2-week period, weather allowing. In 2010, the sample period was nine days in January, eight days in April, eight days in July and seven days in October (Table 2.2) so this criteria was met. The date each lake was sampled is given in Table 2.2. Overall, CEH sampled lakes on 43 occasions, the Environment Agency on 28 occasions and sampling was carried out jointly on 9 occasions.

2.2.2 *Oxygen and temperature profiles in the water column*

Oxygen and temperature profiles were at the deepest point in the lake. This was also the location for all of the limnological measurements and sampling. Because of the combined sampling the CEH and EA a range of different probes were used and these are detailed in Table 2.3. They included a Wissenschaftlich-Technische Werstätten (WTW) Oxi 340i meter fitted with a combination thermistor and oxygen electrode (WTW TA197), a Hach HQd with LD0101 probe, and a Yellow Springs Instrument YSI6600 sonde.

Table 2.2. Sampling location and dates for the Lakes Tour 2010. Sampling Teams are designated as superscripts: C= CEH, C/E = joint CEH and EA, E = EA.

Lake	Sampling location (NGR)	January	April	July	October
Bassenthwaite Lake	NY214295	21-Jan^{C}	15-Apr^{C}	9-Jul^{C}	14-Oct^{C}
Blelham Tarn	NY366006	25-Jan^{C}	15-Apr^{C}	5-Jul^{C}	11-Oct^{C}
Brothers Water	NY403127	22-Jan^{E}	14-Apr^{E}	5-Jul^{E}	11-Oct^{E}
Buttermere	NY188154	21-Jan^{E}	15-Apr^{E}	7-Jul^{E}	14-Oct^{E}
Coniston Water	SD298935	19-Jan^{E}	13-Apr^{E}	6-Jul^{E}	12-Oct^{E}
Crummock Water	NY158192	21-Jan^{E}	15-Apr^{E}	7-Jul^{E}	14-Oct^{E}
Derwent Water	NY267207	21-Jan^{C}	15-Apr^{C}	9-Jul^{C}	14-Oct^{C}
Elterwater	NY329043	27-Jan$^{C/E}$	8-Apr$^{C/E}$	8-Jul^{C}	7-Oct^{C}
Ennerdale Water	NY103153	25-Jan^{E}	9-Apr^{E}	9-Jul^{E}	8-Oct^{E}
Esthwaite Water	SD358972	19-Jan^{C}	13-Apr^{C}	6-Jul^{C}	12-Oct^{C}
Grasmere	NY340064	25-Jan^{C}	12-Apr^{C}	5-Jul^{C}	11-Oct^{C}
Haweswater	NY478139	18-Jan$^{C/E}$	7-Apr$^{C/E}$	1-Jul^{C}	6-Oct^{C}
Loughrigg Tarn	NY344044	27-Jan$^{C/E}$	8-Apr$^{C/E}$	8-Jul^{C}	7-Oct^{C}
Loweswater	NY127215	22-Jan^{C}	9-Apr^{C}	7-Jul^{C}	8-Oct^{C}
Rydal Water	NY358063	27-Jan$^{C/E}$	8-Apr$^{C/E}$	8-Jul^{C}	7-Oct^{C}
Thirlmere	NY318154	18-Jan$^{C/E}$	9-Apr^{C}	7-Jul^{C}	8-Oct^{C}
Ullswater	NY400190	19-Jan^{E}	13-Apr^{E}	6-Jul^{E}	12-Oct^{E}
Wastwater	NY160058	25-Jan^{E}	9-Apr^{E}	8-Jul^{E}	7-Oct^{E}
Windermere North Basin	NY383006	19-Jan^{C}	13-Apr^{C}	6-Jul^{C}	12-Oct^{C}
Windermere South Basin	SD382914	19-Jan^{C}	13-Apr^{C}	6-Jul^{C}	12-Oct^{C}

Table 2.3. Details of the probes used for the temperature and oxygen profiles. H- Hach; Y- YSI; W- WTW. Details of probes are given above.

Lake	January	April	July	October
Bassenthwaite Lake	W	H	H	H
Blelham Tarn	W	H	H	H
Brothers Water	Y	Y	Y	Y
Buttermere	Y	Y	Y	Y
Coniston Water	Y	Y	Y	Y
Crummock Water	Y	Y	Y	Y
Derwent Water	W	H	H	H
Elterwater	W	H	H	H
Ennerdale Water	Y	Y	Y	Y
Esthwaite Water	W	H	H	H
Grasmere	W	H	H	H
Haweswater	Y	Y	W	W
Loughrigg Tarn	W	H	H	H
Loweswater	W	H	H	H
Rydal Water	W	H	H	H
Thirlmere	Y	W	H	W
Ullswater	Y	Y	Y	Y
Wastwater	Y	Y	Y	Y
Windermere North Basin	W	W	W	W
Windermere South Basin	W	W	W	W

2.2.3 Secchi disc transparency

A white painted metal disc, 30 cm in diameter, was lowered into the water until it disappeared from view. The disc was then raised slightly until it reappeared and that depth was noted.

2.2.4 Water samples

An integrated sample of surface water was taken using a weighted 5 m long plastic tube (except on the two basins of Windermere where a 7 m long tube was used). 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: -

a) two disposable 500 cm^3 plastic bottles, for nutrient analysis.

b) a 1 dm^3 plastic bottle containing 5 cm^3 of Lugols iodine for subsequent enumeration and identification of algal populations (Lund *et al.,* 1958). The iodine was added to the algal cells to preserve them and increase their rate of sedimentation during subsequent processing in the laboratory.

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

A small glass bottle with a ground glass stopper was completely filled with lake water by submerging it just below the water surface and inserting the stopper so that no air was trapped within the bottle. This sample was used to determine the pH and alkalinity of the sample.

2.2.5 Nutrient and 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).

2.2.6 Algal pigments and populations

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

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 algae were enumerated as described by Lund *et al.* (1958). Microplankton and nanoplankton were counted at x100 magnification and x400 magnification respectively. The counts were then converted to numbers per dm^3

2.2.7 Zooplankton populations

A standard 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 70% ethanol. The zooplankton were identified and enumerated under a stereozoom microscope, according to Scourfield & Harding (1966) and Gurney (1931-1933). The counts were then converted to numbers per dm^3.

2.2.8 Fish Populations

The additional information on fish populations present in this report, were obtained from a range of sources, using different methods. These are described in the information for each lake.

3. PRESENT STATUS & LONG-TERM CHANGE

3.1 Weather during 2010

The weather during 2010 in relation to the sampling periods is illustrated using data from Esthwaite Water (Fig. 3.1). The January survey took place immediately after a period of relatively cold weather. The April samples were taken during a period of dry and relatively bright weather. The samples in July were taken during a period of cloudy but warm weather with periods of rain and wind. The October samples were collected during a period of dry weather when the air temperature was relatively high for the time of year.

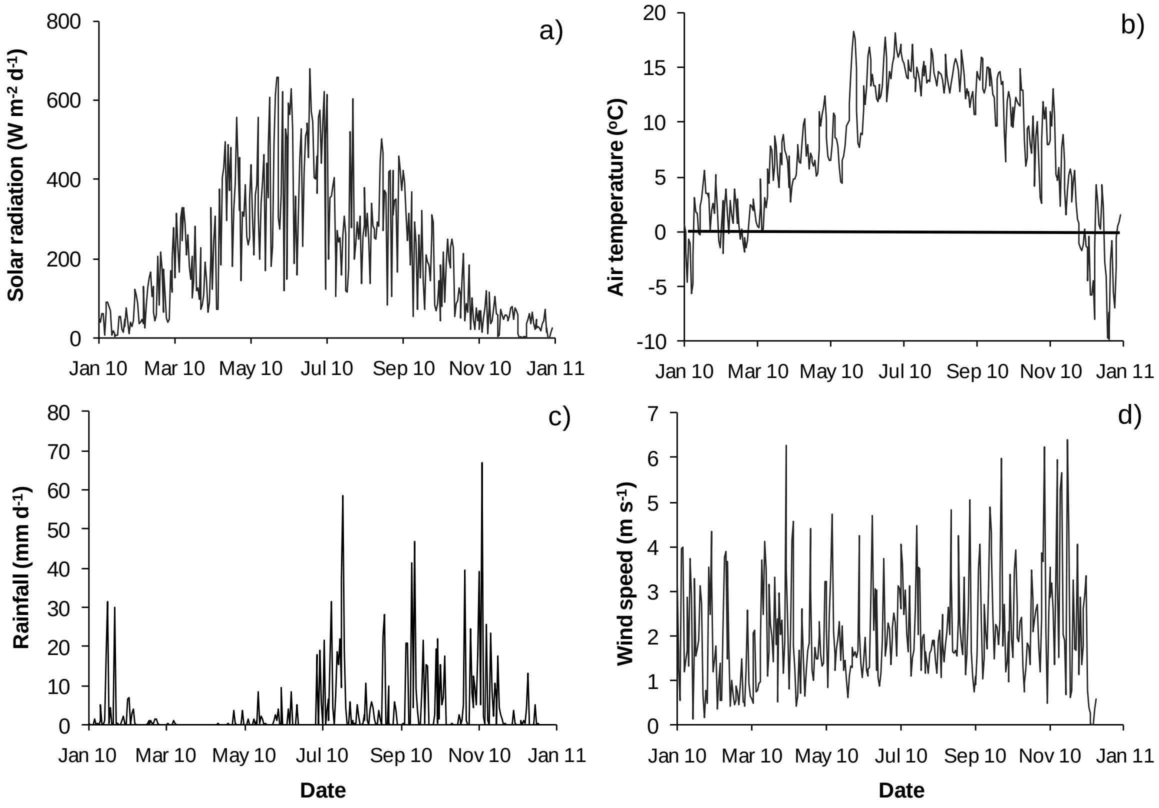


Figure 3.1. Daily mean meteorological data for Esthwaite Water during 2010 comprising: a) total daily solar radiation; b) average air temperature; c) daily rainfall and d) average wind speed (data from the last few weeks of the year were lost because of ice-damage). Values were recorded at the boathouse immediately adjacent to the lake, apart from windspeed that was measured on the buoy on the lake (wind data stopped on 10 December 2010 because of ice-damage to the buoy).

3.2 The limnology of individual lakes in 2010

3.2.1 Depth-profiles of temperature and oxygen concentration

All the lakes showed a seasonal temperature cycle typical of temperate lakes (Fig. 3.2). All the lakes were fully mixed in January, with the possible exception of Elterwater that showed an inverse stratification with a layer of cold (below 4ºC) but less dense water at the surface. In April, water temperature was slightly greater than in January, although only marginally so in lakes with a large volume, and hence large heat capacity, such as Wastwater or Ullswater, and some of the smaller lakes, such as Blelham Tarn, had a weak stratification. All the lakes had stratified to some extent in July (Fig. 3.2). However, shallow lakes with a relatively large surface area, such as Bassenthwaite Lake (Table 2.1), tended to have a much weaker stratification than a small relatively deep lake such as Brothers Water. In October, stratification persisted in some of the lakes, such as the two basins of Windermere, but had broken down in others such as Loweswater. The raw temperature data are given in Appendix 1.

In a very unproductive lake the concentration of oxygen will approach 100% equilibrium at all times and depths. This is approximately the pattern in Wastwater (Fig. 3.3) where the slight reduction in concentration at the surface in summer (the orthograde oxygen distribution which is a classical feature of oligotrophic lakes) is a result of lower oxygen solubility in the warmer surface waters. An approximately uniform concentration of oxygen in stratified lakes in summer is also seen in Ennerdale Water, Haweswater and Thirlmere which are also unproductive lakes. Slight oxygen depletion at depth during stratification results from decomposition processes in the hypolimnion and sediments consuming oxygen faster than it can be replaced from the epilimnion by mixing processes. This pattern is seen to a slight extent in lakes such as Coniston Water and Crummock

Water and to a slightly greater extent in lakes such as Derwent Water and Brothers Water (Fig. 3.3). In the most productive lakes, such as Blelham Tarn or Elterwater, oxygen becomes completely depleted at depth: ie. the lower layers of the lake become anoxic (Fig. 3.3). In Blelham Tarn, slight oxygen depletion was apparent even in the January sample taken shortly after ice-melt, indicating the propensity for oxygen-depletion under ice in a productive lake. Oxygen depletion can have severe ecological consequences as is discussed in Section 4.1 and is a symptom of extreme eutrophication. In some lakes, there is an indication of metalimnetic phytoplankton, because the oxygen profile shows a mid-lake peak, for example in Grasmere and Elterwater in July.

Table 3.1 gives the minimum concentration of oxygen recorded at depth in each lake. This usually occurred in July but in some lakes occurred in October. It should be noted that in some lakes where fortnightly data are available, such as Bassenthwaite Lake and the South Basin of Windermere, substantially greater oxygen depletion was recorded between July and October, so this coarse sampling does not necessarily capture the true extent of oxygen-depletion in a lake. The raw oxygen concentration profile data are presented in Appendix 1.

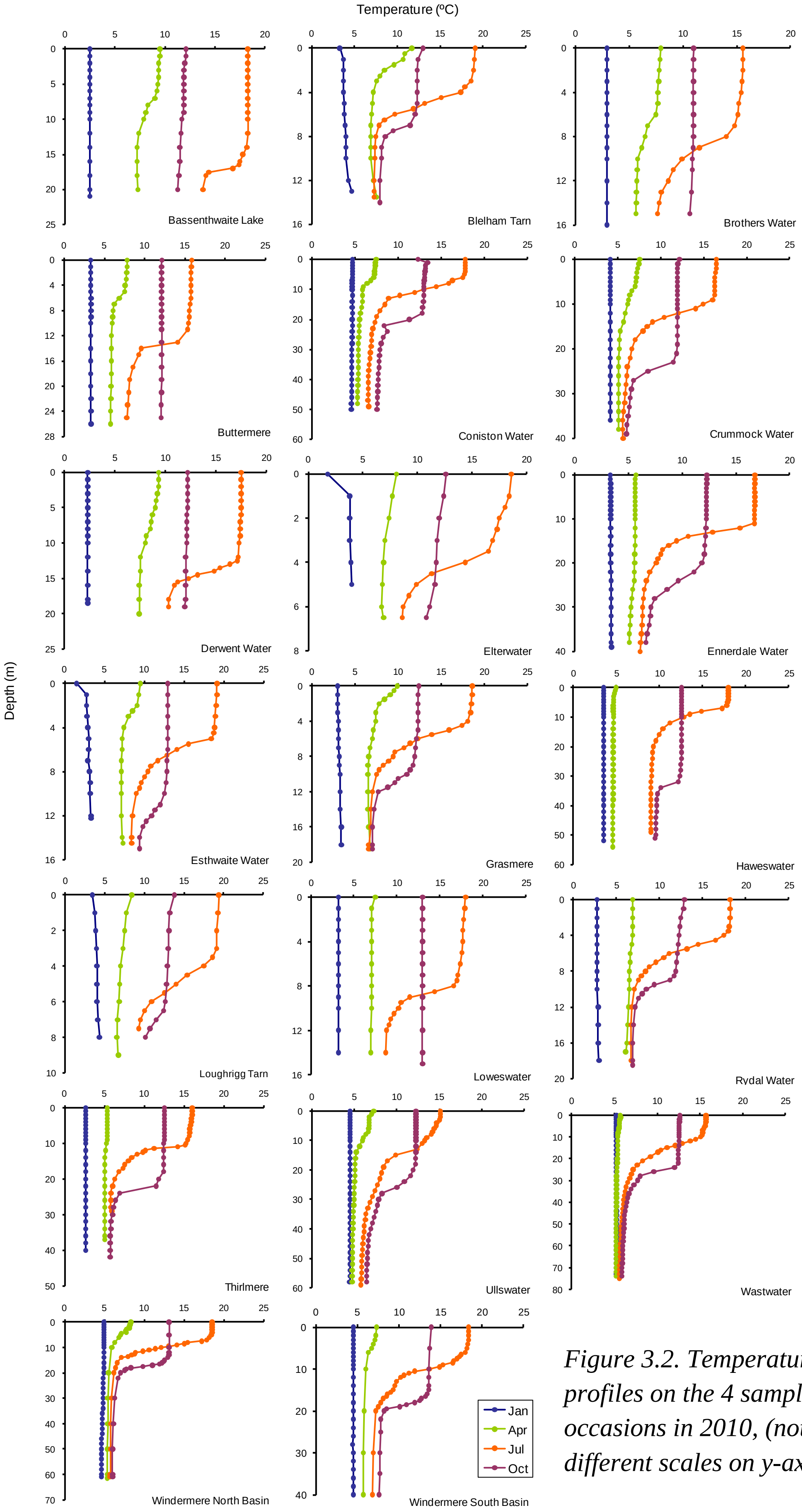


Figure 3.2. Temperature profiles on the 4 sampling occasions in 2010, (note different scales on y-axis).

Table 3.1. Annual minimum concentrations of oxygen at depth in 2010. The annual minimum at depth was found in the July or October sample.

Lake	Minimum oxygen concentration at depth ($g\ m^{-3}$)
Bassenthwaite Lake	0.19
Blelham Tarn	0.06
Brothers Water	0.11
Buttermere	7.87
Coniston Water	6.76
Crummock Water	6.15
Derwent Water	1.59
Elterwater	0.05
Ennerdale Water	8.43
Esthwaite Water	0.10
Grasmere	0.10
Haweswater	6.46
Loughrigg Tarn	0.11
Loweswater	0.13
Rydal Water	0.06
Thirlmere	5.34
Ullswater	5.17
Wastwater	9.83
Windermere North Basin	7.19
Windermere South Basin	3.07

Minimum oxygen concentrations at depth are lowest in productive lakes such as Esthwaite Water and Blelham Tarn where there is a lot of degradable organic matter and highest in unproductive lakes such as Wastwater and Ennerdale Water where there is little degradable organic matter (see also Fig. 4.5).

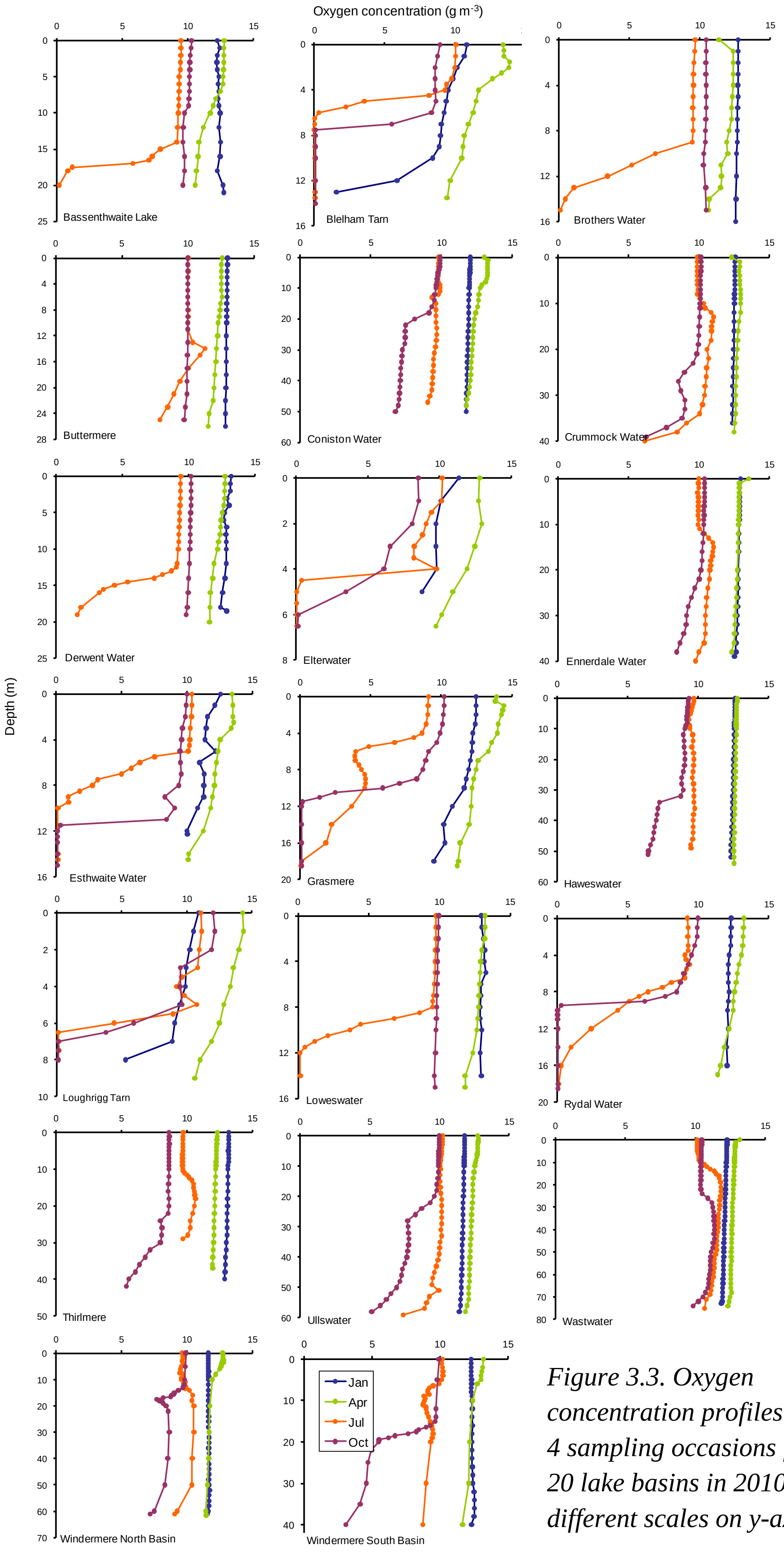


Figure 3.3. Oxygen concentration profiles on the 4 sampling occasions for the 20 lake basins in 2010, (note different scales on y-axis).

3.2.2 *Secchi disc transparency*

The depth of the Secchi disc is a rough but convenient measure of water transparency. Figure 3.4 shows that in very unproductive lakes, such as Wastwater, the Secchi depth was visible down to between 10 and 14.5 m and in contrast, in productive lakes such as Bassenthwaite Lake, the Secchi depth was between 1.2 and 3.1 m. Seasonal patterns of change followed phytoplankton abundance in the more productive lakes, while in the unproductive lakes there were still seasonal variation but presumably this results more from the amount of particulate material brought in by winter rainfall and events within the catchment. The raw Secchi disc data are presented in Appendix 2.

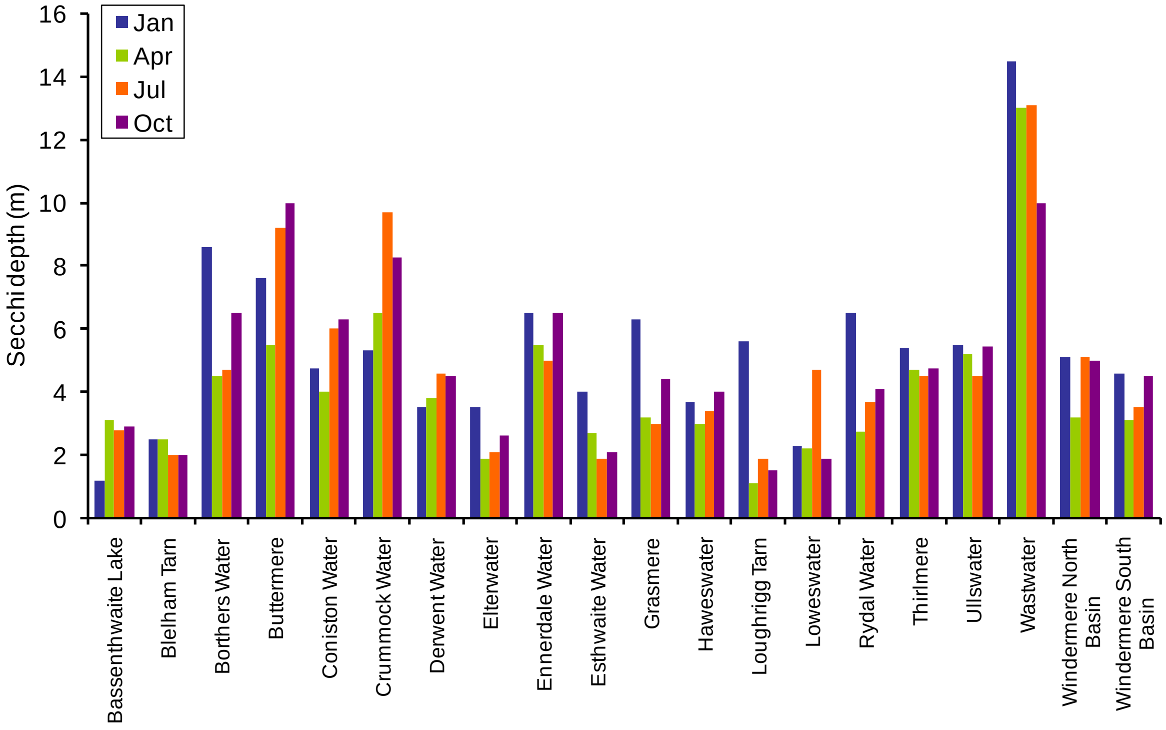


Figure 3.4. Seasonal changes in Secchi disc transparency in the 20 lake basins during 2010.

3.2.3 Major ions

The ionic composition of the major lakes and tarns of the English Lake District has been widely studied (e.g Sutcliffe *et al*. 1982, Sutcliffe 1998). Although there is seasonal variation in ionic composition of the major ions, caused partly by seasonal changes in input via precipitation and partly by differential dilution resulting from evapo-transpiration, ionic composition is relatively conservative and presented here as an annual average. The raw seasonal data are given in Appendix 3. The underlying geology (Fig. 3.5) has a large effect on the composition of the lake water. The annual average data are shown in Figure 3.6 ordered by the main underlying geological rock type and by altitude within each category following Sutcliffe (1998).

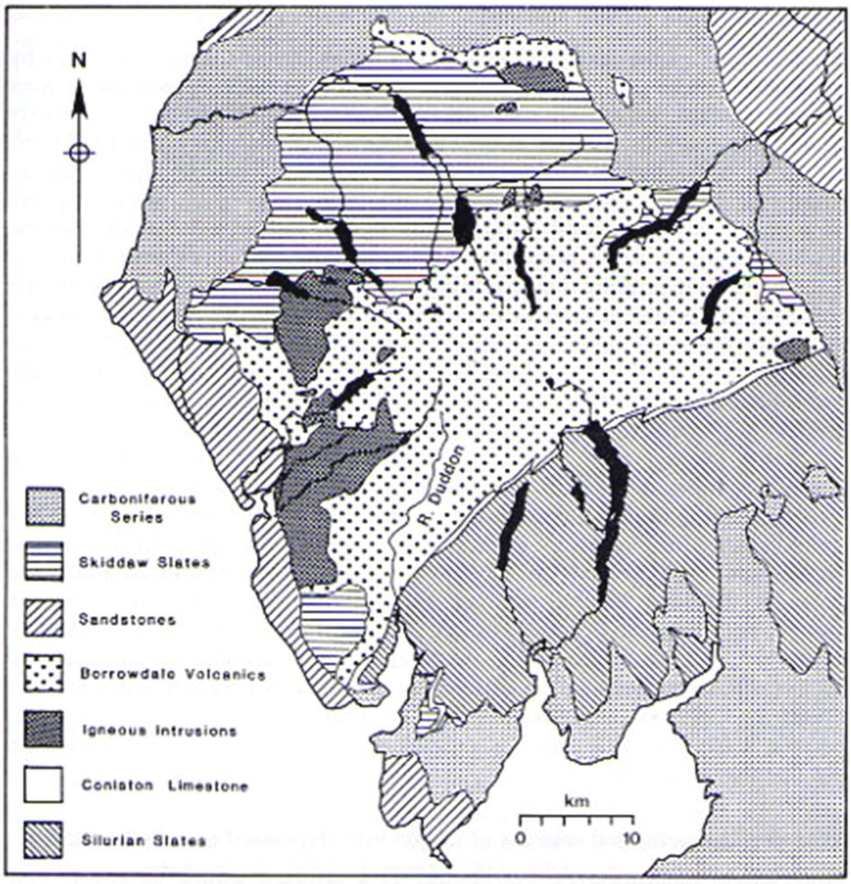


Figure 3.5. The underlying geology of the English Lake District (based on Sutcliffe, 1998).

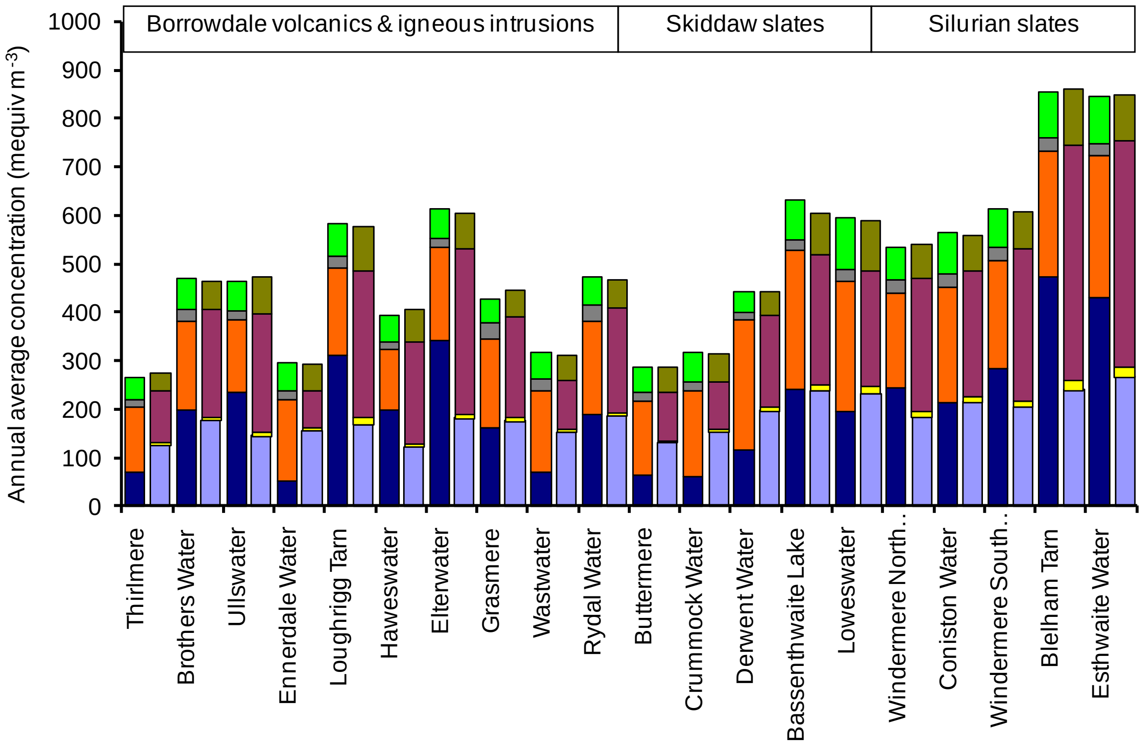


Figure 3.6. Annual average concentration of major anions (first column) and cations (second column) for the 20 lake basins in 2010. Lakes are ordered by underlying geology and then by decreasing catchment altitude following Sutcliffe (1998). Anions are: alkalinity (dark blue), chloride (orange), nitrate (grey) and sulphate (green). Cations are: sodium (light blue), potassium (yellow), calcium (purple) and magnesium (olive green).

In all lakes there is a good balance between cation and anion concentrations which shows that the analyses have been carried out accurately (Fig. 3.6). In lakes on the Silurian slates bicarbonate (alkalinity) tends to be the dominant anion, but chloride has a higher concentration in many of the lakes on the Borrowdale volcanics and Skiddaw slates. This is largely because alkalinity tends to be lower on the Borrowdale and Skiddaw series while chloride concentrations are fairly similar across the 20 lakes. A similar difference is seen in the cations with the balance between calcium and sodium: calcium tends to be the dominant cation in lakes on the Skiddaw slates but sodium tends to dominate in lakes on the two other geologies.

Data on alkalinity, as well as pH, are shown in more detail in Figure 3.7. There is a large range of alkalinities from Ennerdale Water and Wastwater with very low alkalinities to Blelham Tarn and Esthwaite Water with high alkalinities. None of these major lakes have a negative alkalinity (i.e. a net acidity). Almost all the lakes show a weak seasonality in alkalinity with lowest values in January and highest values in July or October. This probably results largely from changing hydrology and evapo-transpiration. The pH varied between 6.49 and 8.83 (Fig. 3.7b). Seasonal variation was mainly apparent in the more productive lakes where it will result from depletion of carbon dioxide as a result of rapid photosynthesis by the phytoplankton. More detailed records (ie. 15-minutely) have shown even more extreme pH variation: for example the pH exceeds 10 in Esthwaite Water in most years (Maberly 1996) although these peak pH values have not been present in more recent years (Maberly *et al*. 2011).

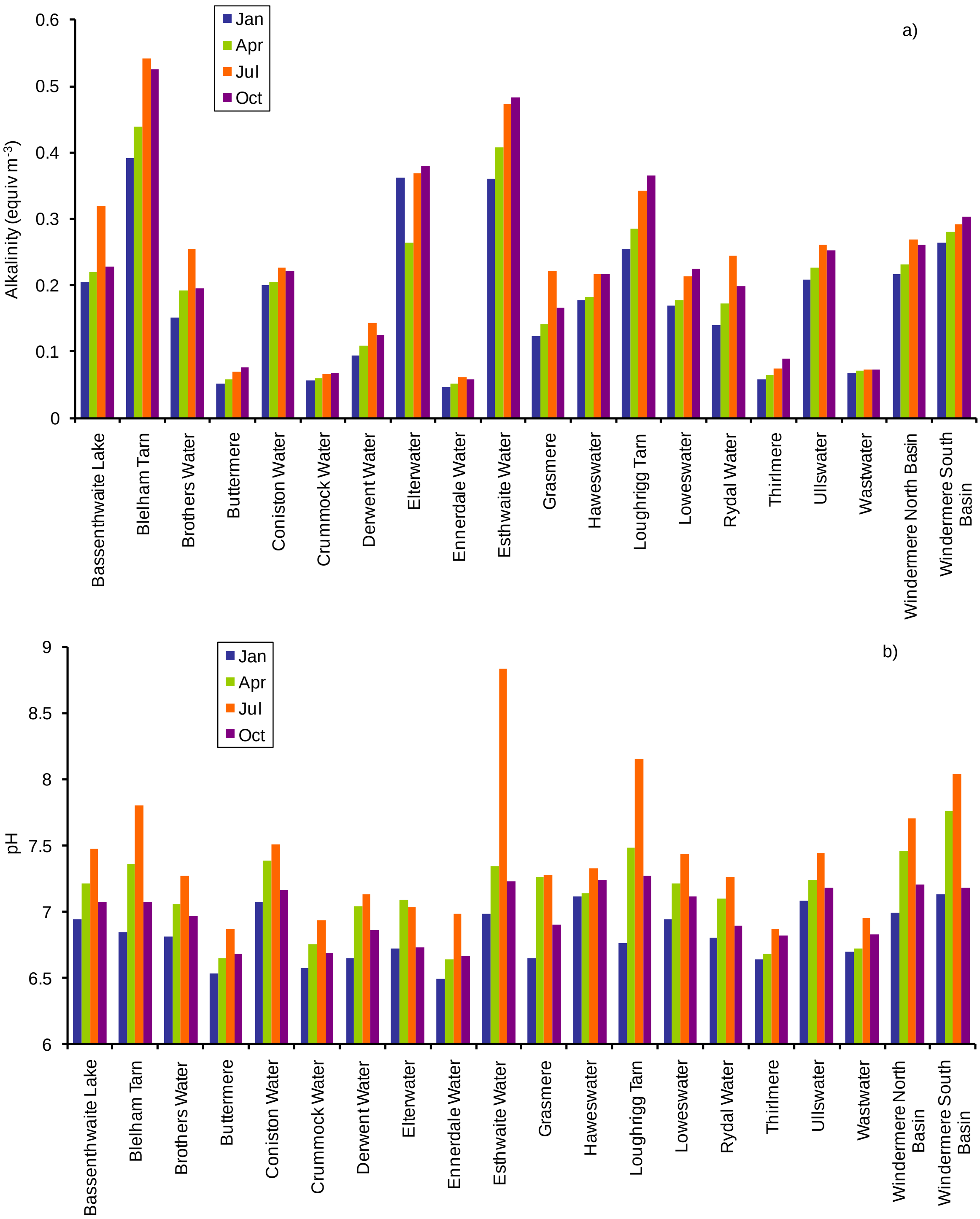


Figure 3.7. Seasonal changes in a) alkalinity and b) pH in the 20 lake basins during 2010.

3.2.4 Nutrient chemistry

Phosphorus, nitrogen and silicon are the three elements required in large amounts by some or all phytoplankton. Each of these is discussed in turn and the raw results are presented in

Appendix 4. The productivity of the major English lakes is primarily controlled by the concentration of phosphorus, the limiting nutrient. The concentration of total phosphorus (TP) represents the total concentration of the element in dissolved and particulate fractions including inorganic and organic forms. While not all this TP is available to phytoplankton, it does indicate the trophic status of a lake. Overall concentrations range from very low concentrations in Wastwater, to consistently high concentrations in Esthwaite Water and Grasmere (Fig. 3.8). The seasonal variation in concentration of total phosphorus is not very great but on average over all 20 lake basins, concentrations of TP were highest in October and lowest in April (Fig. 3.9).

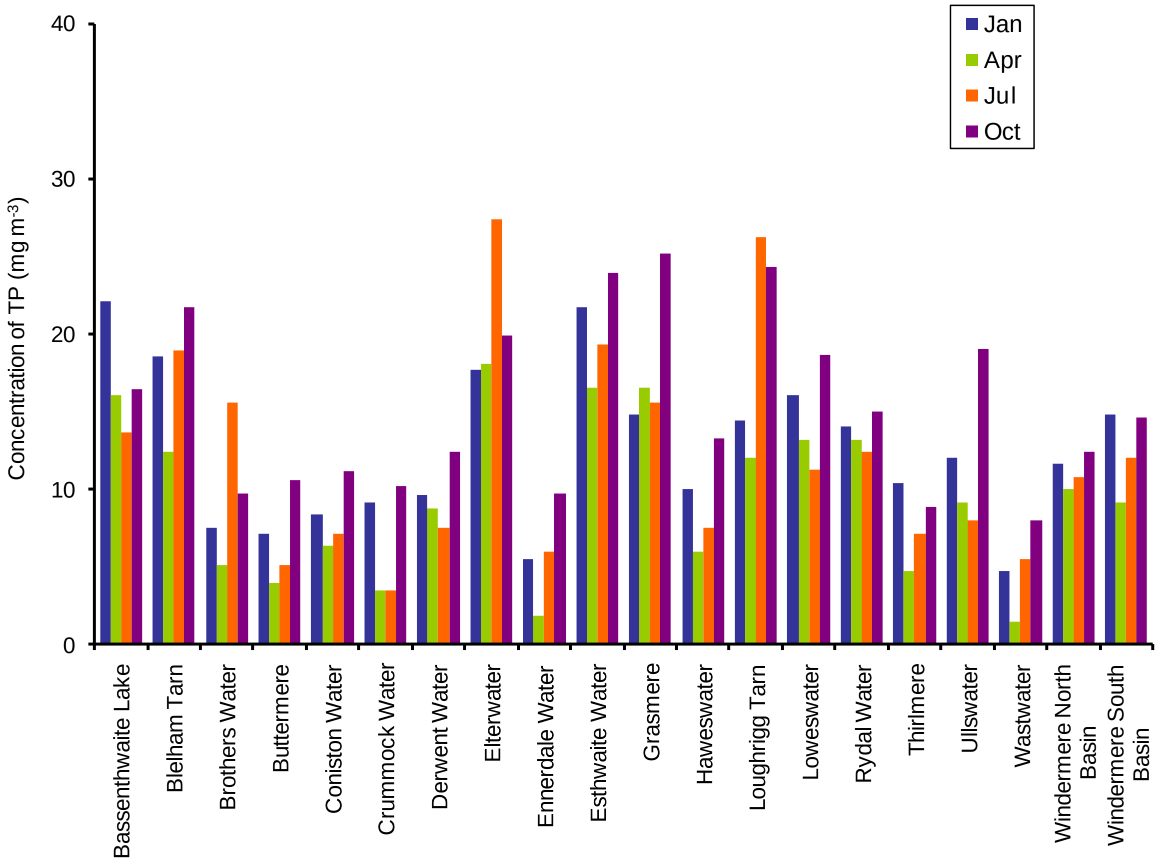


Figure 3.8. Seasonal changes in the concentration of total phosphorus in the 20 lake basins during 2010.

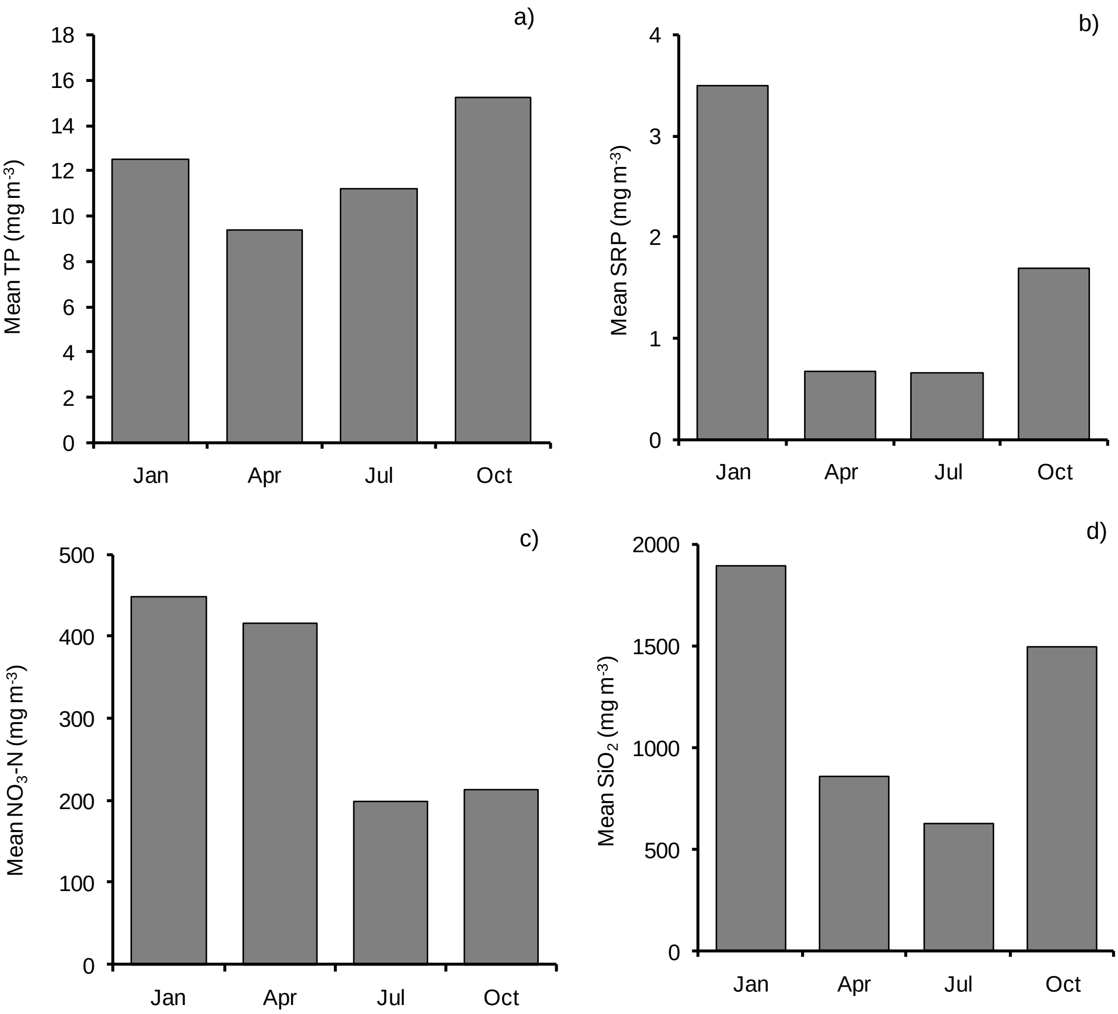


Figure 3.9. Average seasonal concentrations of: a) total phosphorus, b) soluble reactive phosphorus, c) nitrate-nitrogen and d) silica in the 20 lake basins during 2010.

Soluble reactive phosphorus (SRP), the analysed form of phosphorus which most closely reflects that available to microbes including the phytoplankton, showed large seasonal changes and differences among the 20 lake basins (Fig. 3.10). In contrast to TP, concentrations of SRP were highest in January (Fig. 3.9) when demand by phytoplankton was reduced because temperature and daily light levels were low. Concentrations were at about 1 mg m^{-3} or lower in April and July during the period of intensive phytoplankton growth and had increased in most lakes in October.

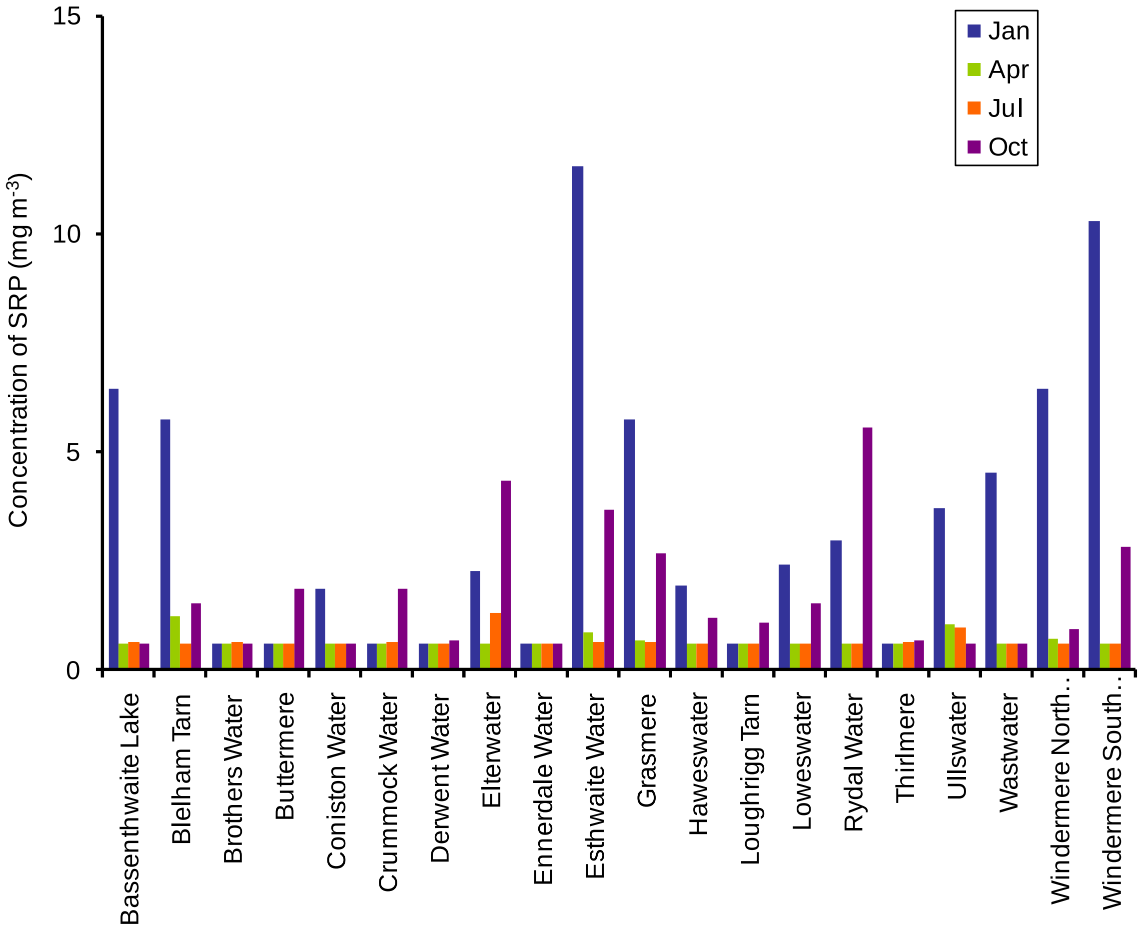


Figure 3.10. Seasonal changes in the concentration of soluble reactive phosphorus in the 20 lake basins during 2010.

Nitrate is usually the main form of nitrogen available to phytoplankton. Like SRP, concentrations were highest in January but the concentration in April was only slightly depleted in contrast to SRP in April where concentrations were already strongly depleted (Fig. 3.9). Crummock Water had the lowest maximum concentrations of nitrate of the 20 lakes and Thirlmere and Haweswater also had low concentrations while Grasmere had the highest maximum concentration (Fig. 3.11) but the difference in nitrate concentration among lakes was less than for TP or SRP.

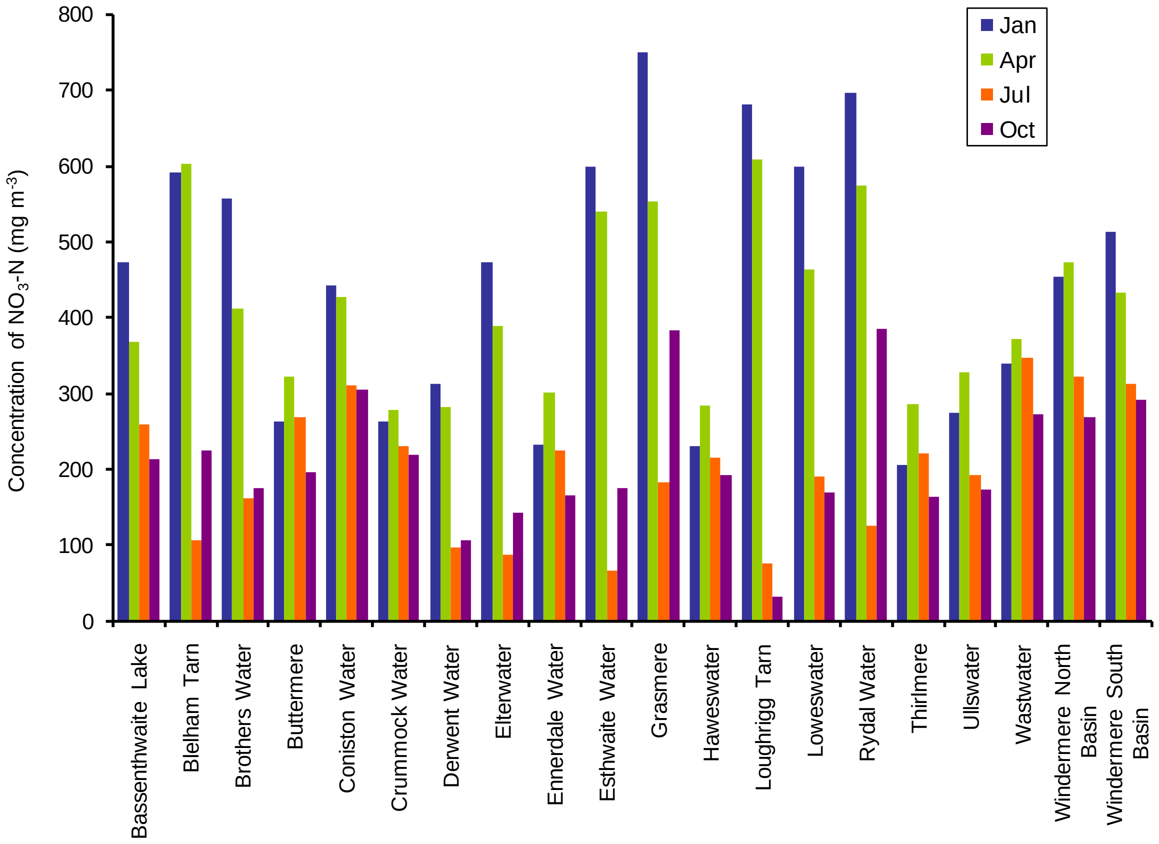


Figure 3.11. Seasonal changes in the concentration of nitrate-nitrogen in the 20 lake basins during 2010.

Ammonium was generally present in very low concentrations (Fig. 3.12). Concentrations of nitrate exceeded those of ammonium in all samples apart from in Loughrigg Tarn in October. This tarn also had a very high concentration in October. Some of the more productive lakes such as Grasmere and Loweswater showed relatively high concentrations of ammonium in October possibly as a result of entrainment of ammonium into surface waters from depth as stratification broke down.

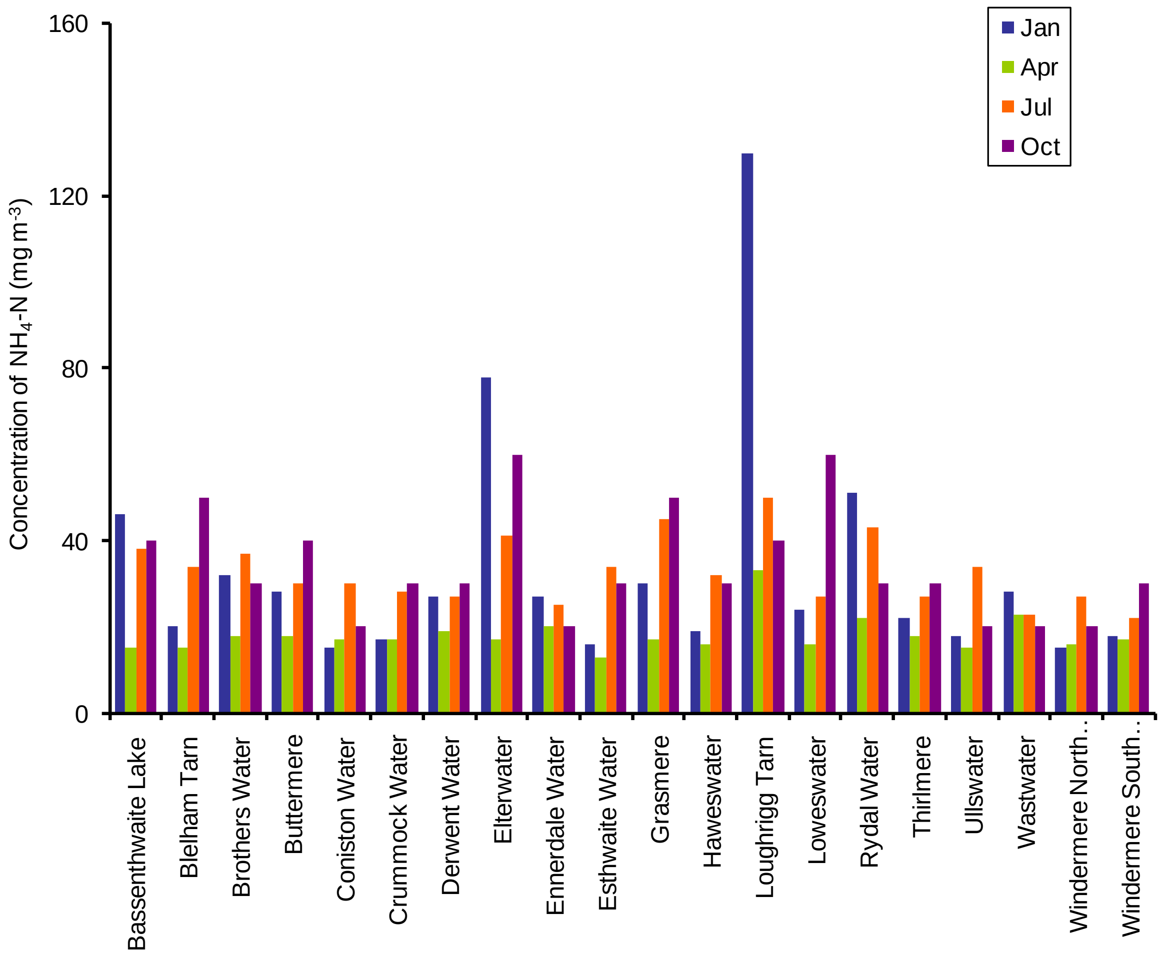


Figure 3.12. Seasonal changes in the concentration of ammonium-nitrogen in the 20 lake basins during 2010.

Silicon is used by a number of groups of phytoplankton, such as the chrysophytes, but is an essential major nutrient for the diatoms. The average seasonal pattern of change of silica is rather similar to that of nitrate (Fig. 3.9) although the depletion of concentration in April is slightly more marked for silica since spring is usually a major period of diatom growth. Ennerdale Water and Esthwaite Water had the highest maximum concentrations in silica, both in January (Fig. 3.13). The concentration in unproductive Ennerdale Water showed very little seasonal variation in concentration, as in other unproductive lakes such as Wastwater, Crummock Water and Thirlmere. In contrast, the concentration in productive Esthwaite Water varied markedly as it also did in other productive lakes such as Grasmere and the South Basin of Windermere. In twelve of the lakes the concentration of silica fell below 500 mg m^{-3} which is the approximate concentration at which diatom growth becomes limited by this nutrient (Lund 1950).

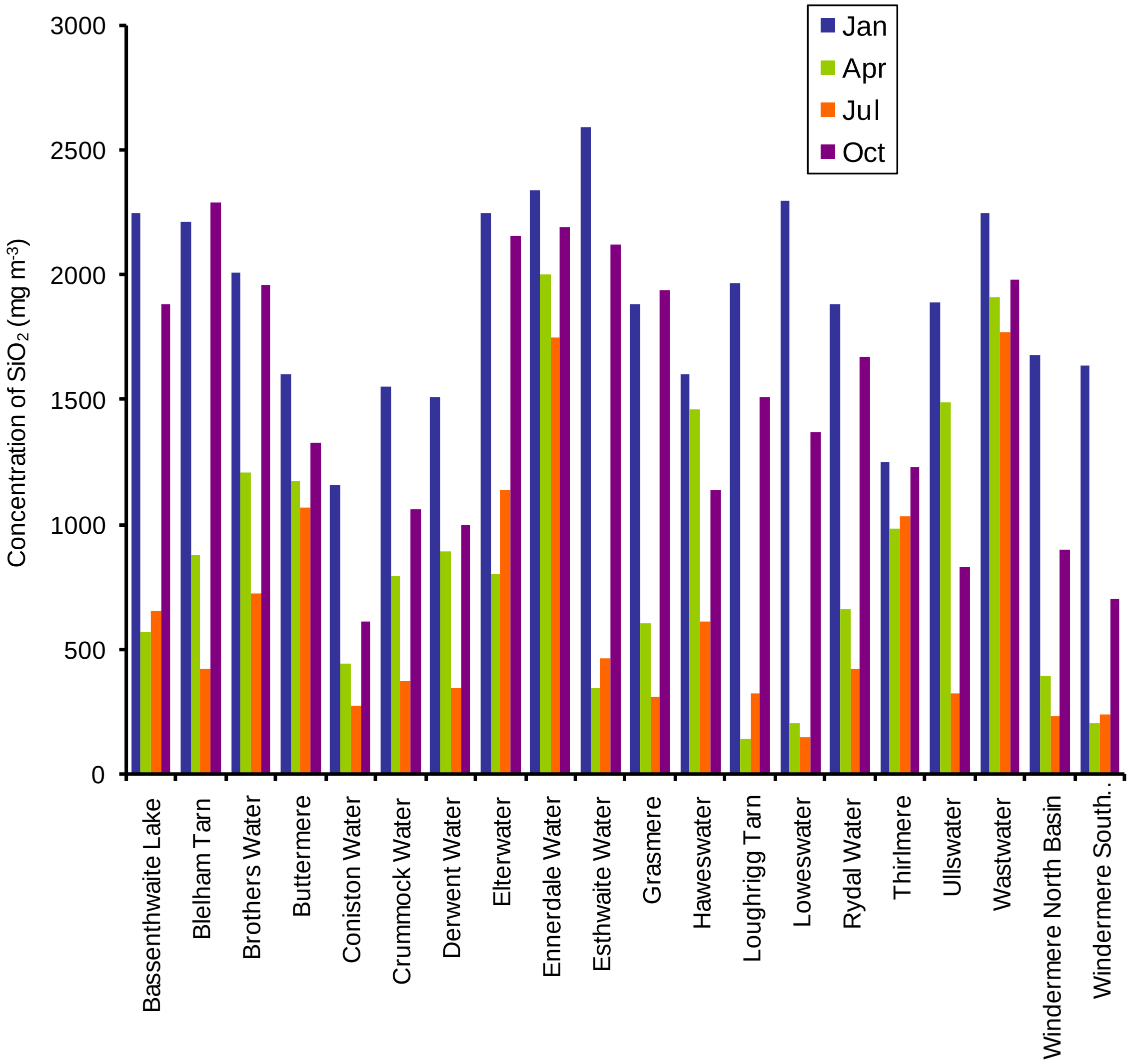


Figure 3.13. Seasonal changes in the concentration of silica in the 20 lake basins during 2010.

3.2.5 Phytoplankton chlorophyll **a** *concentration*

Phytoplankton biomass is estimated here using the concentration of the photosynthesis pigment chlorophyll *a*. Figure 3.14 shows the large variation in the concentration of chlorophyll *a* both among lakes and at different times within a lake. In 2010, the concentration of chlorophyll *a* varied between 0.33 mg m^{-3} in Wastwater in January and

55.2 mg m^{-3} for Blelham Tarn in July. The pattern of phytoplankton chlorophyll *a* is broadly the inverse of that for Secchi depth with low concentrations in lakes like Wastwater and Buttermere, and high concentrations in lakes like Blelham Tarn and Loughrigg Tarn (see Section 4.1). In January, concentrations were generally low in all lakes since there is little phytoplankton growth at this time of year because of low temperature and light availability, made worse by full mixing of cells throughout the lake depth as the lakes are not stratified. Furthermore, especially for the more rapidly flushed lakes (Table 2.1), washout of phytoplankton by hydraulic discharge is likely to be particularly rapid. Many of the lakes, such as Rydal Water and Grasmere showed an annual maximum concentration of chlorophyll *a* in April corresponding to the spring bloom (Fig. 3.14). In others, such as Blelham Tarn and Elterwater the maximum occurred in July and in Loughrigg Tarn, unusually, the maximum was in October. The raw data on phytoplankton chlorophyll *a* are presented in Appendix 2.

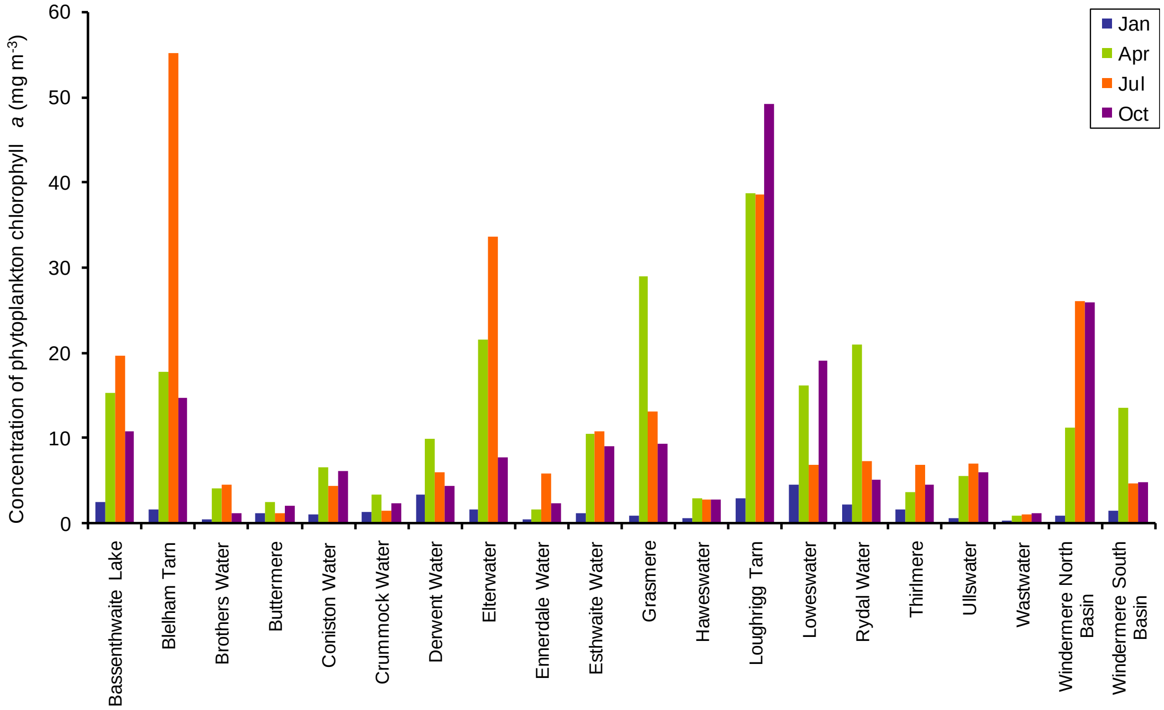


Figure 3.14. *Seasonal changes in the concentration of phytoplankton chlorophyll* a *in the 20 lake basins during 2010.*

3.2.6 Phytoplankton species composition

The phytoplankton are a sensitive and responsive component of the biology of a lake and one of the key ecological characteristics used by the Water Framework Directive to assess the ecological status of a lake. The raw data on phytoplankton species composition are recorded in Appendix 5.

Over all 80 samples, 159 taxa and 90 genera were recorded. The five most frequent genera were *Plagioselmis* (previously named *Rhodomonas*) in 99% of samples, then *Cryptomonas* (98%), *Chlorella* (95%), *Nitzschia* (84%) and *Asterionella* (73%).

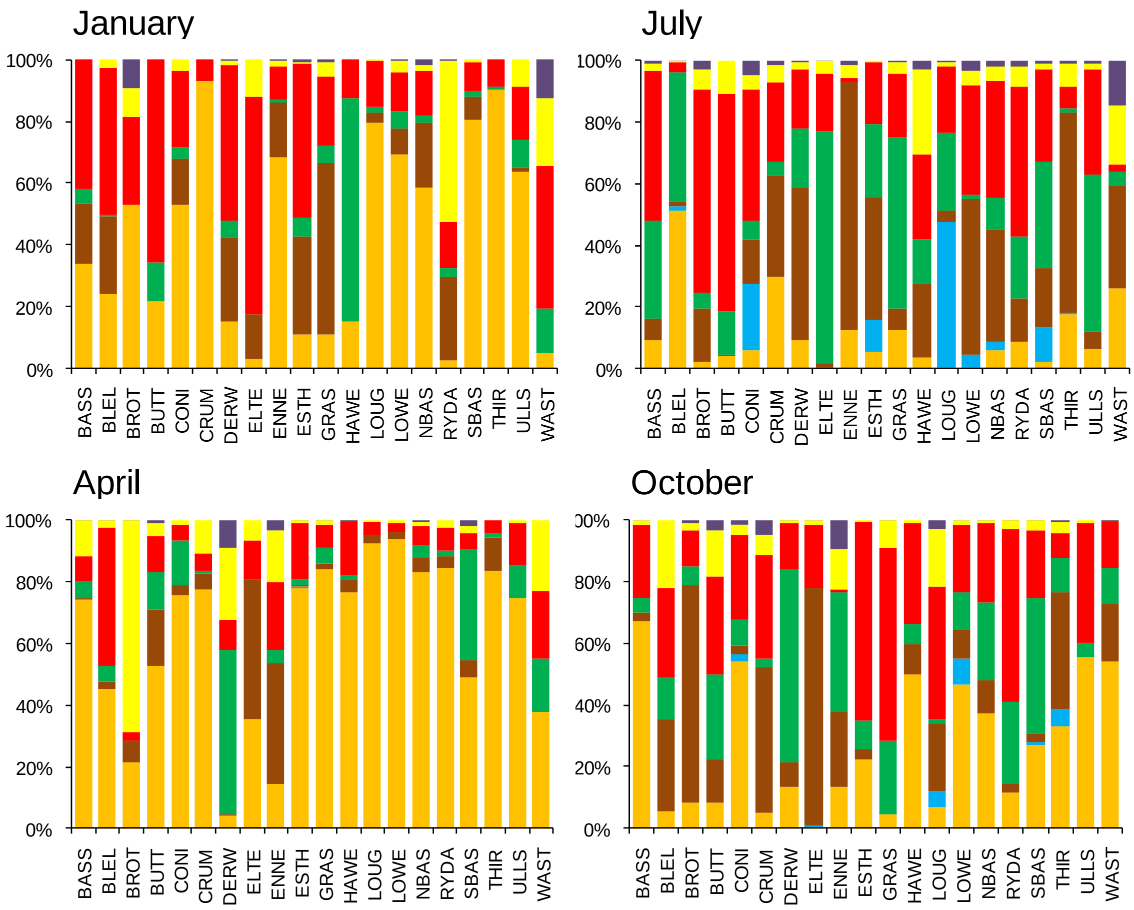


Figure 3.15. Composition of the major groups of phytoplankton in the 20 lake basins during 2010. Diatoms (gold); cyanobacteria (blue); dinoflagellates (brown); euglenophytes (dark green); chlorophytes (green); cryptophytes (red); chrysophytes (yellow) and haptophytes (purple).

There was a clear seasonality in all the lakes, even unproductive ones such as Wastwater where nutrient chemistry was relatively constant (Fig. 3.15). In January, diatoms and cryptophytes were dominant in most lakes apart from in Haweswater where green algae were dominant and Rydal Water where chrysophytes were dominant. Over all the 20 lakes in January the most important taxa were the cryptophyte *Plagioselmis* sp., the diatoms *Aulacoseira subarctica, Asterionella formosa* and *Urosolenia* sp. and the chlorophyte *Chlorella* sp. In April, diatoms tended to be even more dominant in many of the lakes as this month coincides more or less with the ‘spring bloom’ which is often dominated by diatoms. Notable exceptions to this pattern were Brothers Water that was dominated by chrysophytes, Derwent Water with a preponderance of green algae and Ennerdale Water with a mix of algal groups. Over all 20 lakes in April, the most important taxa were the diatoms *Asterionella formosa* and *Aulacoseira subarctica*, the cryptophytes *Plagioselmis* sp and the chlorophyte *Chlorella* sp. Phytoplankton populations were very diverse in July (Fig. 3.15). Cyanobacteria were dominant in Loughrigg Tarn. Diatoms were dominant in Blelham Tarn. Green algae (chlorophytes) were dominant in Elterwater. Dinoflagellates were dominant in Derwent Water and Ennerdale Water and cryptophytes were dominant in Brothers Water and Buttermere. Over all 20 lakes in July the most important taxa were the cyanobacterium *Anabaena circinalis / flos-aquae,* the colonial green alga *Coenochloris fottii*, the cryptophytes *Plagioselmis* sp., the chlorophyte *Chlorella* sp. and the haptophyte *Chrysochromulina parva*. In October, diatoms were slightly more important again but as in July there was a wide range of different groups present. Over the 20 lakes in October the most important taxa were the chlorophyte *Chlorella* sp., the cryptophyte *Plagioselmis* sp. the diatom *Aulacoseira subarctica*, the cyanobacterium *Aphanizomenon flos-aquae* and the the haptophyte *Chrysochromulina parva*.

3.2.7 Zooplankton populations

The total zooplankton abundance recorded across the lakes was highly variable, ranging between 0.03 and 13.47 individuals dm^{-3} for Bassenthwaite Lake in January and Loughrigg Tarn in July, respectively. Mean winter and spring abundances were lower than mean abundances in summer and autumn (January mean = 0.60 ind. dm^{-3}, April mean = 0.59 ind. dm^{-3}, July mean = 3.24 ind. dm^{-3}, October mean = 1.57 ind. dm^{-3}). Esthwaite Water supported comparatively high abundances in all seasons, with Loughrigg Tarn also producing abundant zooplankton populations on the first three sampling dates (Fig. 3.16).

During the summer, Blelham Tarn and Elterwater were also among the most productive lakes, with respect to zooplankton abundance. Consistently low zooplankton abundances were recorded in Buttermere, Coniston Water, Crummock Water, Ennerdale Water, Haweswater, Thirlmere, Ullswater and Wastwater.

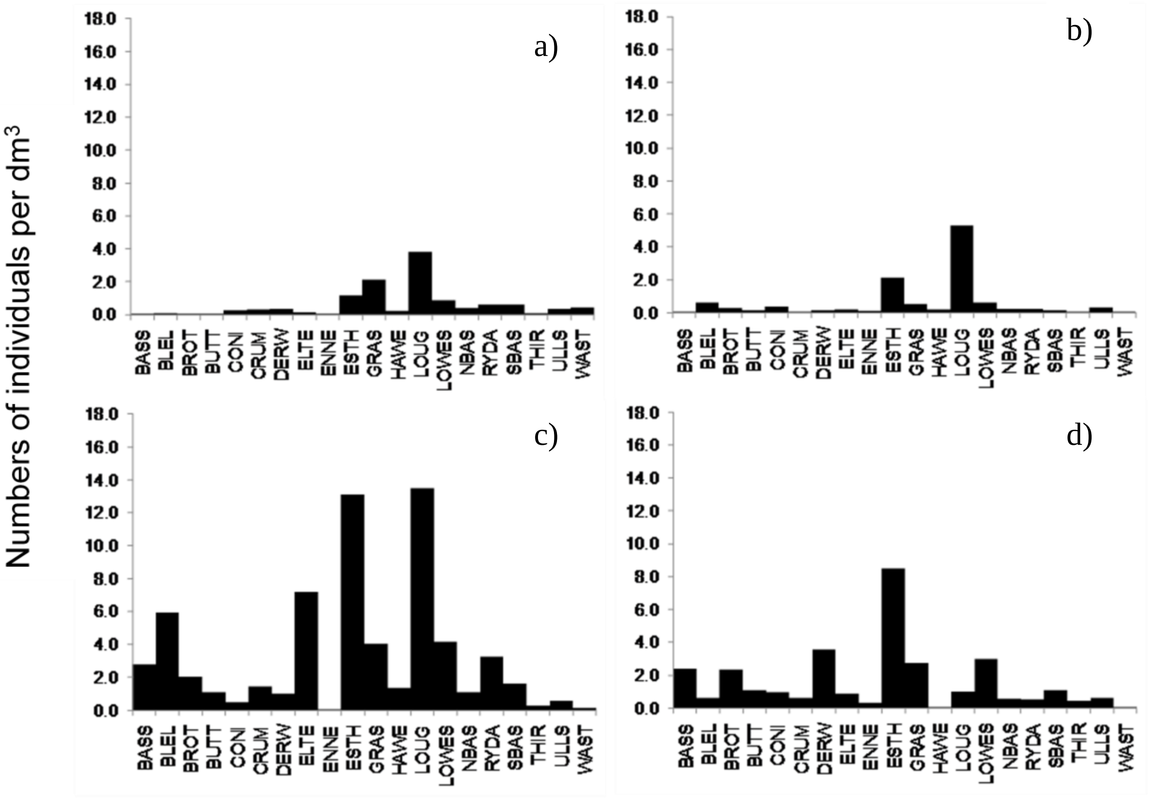


Figure 3.16. Total crustacean zooplankton abundance in the 20 lakes monitored during (a) winter, (b) spring, (c) summer and (d) autumn 2010.

In total, representatives of 17 crustacean genera were recorded, including members of the cladocera, calanoid copepods and cyclopoid copepods. Strictly, some of the genera recorded include only species that live for much of the time in close association with the sediment surface or aquatic macrophyte beds, rather than in the open water environment (*Alona*, *Chydorus*, *Diacyclops*, *Eucyclops*, *Sida*, *Simocephalus*). However, small numbers of such taxa can be captured in pelagic plankton tows by “chance” after being dislodged from their usual habitats.

The taxonomic composition of the zooplankton varied widely among lakes and seasons (Fig. 3.17)As was the case in 2005 (Maberly *et al*. 2006), the calanoid copepod *Eudiaptomus* was widespread. This copepod was abundant in all lakes and in all seasons, constituting a large proportion of the community particularly in winter and autumn (Fig. 3.17 a,d). The well-established starvation resistance and flexible feeding habits of calanoid copepods, and *Eudiaptomus* in particular, as well as the ability of copepods to evade capture by planktivorous fish may in part explain this dominance. While *Eudiaptomus* dominated the community of many lakes in winter, other taxa (*Bosmina*, *Cyclops*, *Daphnia*) made substantial numerical contributions to the community in some lakes. *Bosmina* is known to be able to feed efficiently at low food concentrations, perhaps a contributory factor explaining the high contribution of this taxon to the sparse populations during winter in Bassenthwaite Lake, Derwent Water, Ennerdale and Thirlmere.

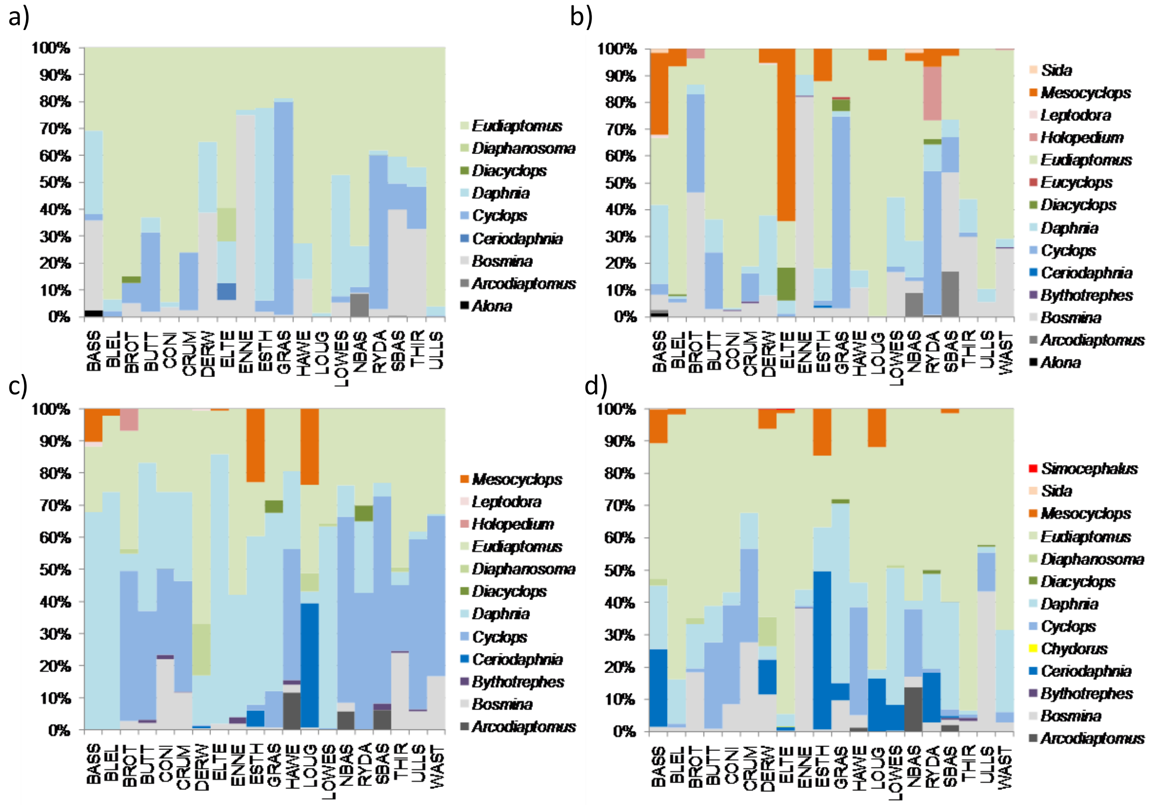


Figure 3.17. The taxonomic composition of the crustacean zooplankton in the 20 lakes monitored during (a) winter, (b) spring, (c) summer and (d) autumn 2010. Each taxon is represented as a percentage contribution to the total zooplankton abundance.

Zooplankton communities appeared to generally be more diverse during spring, summer and autumn. During the summer, *Daphnia* made a substantial contribution to the comparatively high zooplankton abundances recorded in Esthwaite Water, Elterwater and Blelham Tarn, while in Loughrigg Tarn *Ceriodaphnia* and *Mesocyclops* contributed to the high observed total abundance. *Ceriodaphnia* also made a substantial contribution to the comparatively high total abundance observed in Esthwaite Water in autumn (Figs 3.16 & 3.17). High rates of *Daphnia* population growth are most likely to have been supported by the availability of readily ingestible microalgae as a food resource. Whilst microalgae would also support populations of *Ceriodaphnia* and juvenile *Mesocyclops,* it is likely that an abundant supply of smaller zooplankton (e.g. rotifers) supported the latter, which is omnivorous during its adult stages. Population densities of the zooplankton may be found in Appendix 6.

3.2.8 Fish populations

Introduction

Primarily due to resource constraints, previous Lakes Tours have not covered fish. However, recent developments including the EU Water Framework Directive have considerably increased interest in these species, although their study remains relatively expensive and involves numerous complications arising from logistics, fisheries and other interests. Although dedicated surveys were not feasible within Lakes Tour 2010 itself, for the first time information is collated here from a range of other projects undertaken by the Centre for Ecology & Hydrology and others which have addressed a substantial number of the lakes in 2010 and other recent years. Such activities have ranged in frequency between monthly and single surveys and at different lakes they have involved various sampling techniques including hydroacoustics, gill netting, trapping, fyke netting, entrapment and fishery data. As a result, the information produced by these activities varies considerably between lakes in its extent and in its timing. With respect to the latter, although some of the recent information collated here was not gathered during 2010 the relatively great longevities of fish species mean that it probably remains indicative of the current characteristics of the lake's fish communities. Where a lake has not been subjected to any recent scientific study of its fish populations, a brief and conservative account of its fish community is given based on earlier scientific studies and/or current information available on reputable angling websites.

Bassenthwaite Lake

The fish community of Bassenthwaite Lake has been studied extensively since the early 1990s, as reviewed in part by Winfield *et al.* (in press) and references therein. A gill-net and night-time hydroacoustics monitoring programme conducted since 1995 has documented the development of introduced roach (*Rutilus rutilus*), ruffe (*Gymnocephalus cernuus*) and dace (*Leuciscus leuciscus*) and the local extinction of the rare vendace (*Coregonus albula*), for which no specimens have been recorded since 2001. Reasons for this loss are thought to include eutrophication, sedimentation and species introductions and it is fortunate that prior to its local extinction, a refuge population was successfully established in Loch Skeen (or Skene) in south-west Scotland (Winfield *et al.*, in press). Monitoring in 2010 produced a sample of 491 fish of five species comprising 1 brown trout (*Salmo trutta*), 384 perch (*Perca fluviatilis*), 7 pike (*Esox lucius*), 43 roach and 56 ruffe, with total fish population density peaking in July at 899.0 fish ha^{-1} (geometric mean with lower and upper 95% confidence limits of 634.6 and 1273.6 fish ha^{-1}) (Winfield *et al.*, 2011a).

Blelham Tarn

The fish community of Blelham Tarn has never been subjected to thorough scientific study, although Le Cren (1955) and Smyly (1978) make reference to its perch population and Frost (1989) notes that brown trout and pike are also present. Angling information suggests that the lake now holds mainly pike, perch and roach, with all three species reaching relatively large sizes and the former attaining individual weights in excess of 9 kg (WADAA, 2011). In a review of fish species introductions in the Lake District, Winfield *et al.* (2010a) concluded that the roach population of Blelham Tarn was likely to have been introduced in relatively recent times.

Brotherswater

The fish community of Brotherswater has been subjected to very little scientific study. Frost (1989) mentioned the 'possible' occurrence of the rare schelly (*Coregonus lavaretus*) and Ellison (1966) noted a single schelly found dead on the lake's shoreline in 1963. Winfield *et al.* (1993) surveyed the fish community in August 1992 and recorded brown trout, perch and schelly and considered that the population of the latter showed signs of poor recruitment. Night-time hydroacoustic surveys of Brotherswater were subsequently undertaken by the Environment Agency in August 1996 and August 2000 (Hateley, 2000). Mean single target density estimates with 95% confidence limits were 1.91 ± 0.60 fish 1000 m^{-3} and 2.45 ± 1.25 fish 1000 m^{-3} for 1996 and 2000, respectively. A second and most recent biological scientific sampling of the fish community of Brotherswater was undertaken by the Environment Agency using survey gill nets in July 2008 as part of a wider study collecting material for genetic and morphometric analysis (A. Gowans, Environment Agency, unpublished data). Although net placement was directed towards obtaining schelly and so purposefully under-sampled habitats where perch may have been expected, the exercise resulted in the capture of 16 brown trout, 2 perch and 19 schelly. On the basis of these investigations as a whole, the status of the schelly population was concluded by Winfield *et al.* (2011b) to be unfavourable but maintained.

Buttermere

The fish community of Buttermere has received relatively little scientific attention but was surveyed using gill nets and hydroacoustics in July 2010 as part of an assessment of its Arctic charr (*Salvelinus alpinus*) population by Winfield *et al.* (2011b). The gill nets produced a sample of 108 fish of five species comprising 1 Arctic charr, 11 brown trout, 4 minnow (*Phoxinus phoxinus*), 90 perch and 2 pike, with a total fish night-time population density of 1.4 fish ha^{-1} (geometric mean with lower and upper 95% confidence limits of 0.7 and 3.1 fish ha^{-1}). On the basis of this information, the status of the Arctic charr population was concluded by Winfield *et al.* (2011b) to be unfavourable but maintained.

Coniston Water

The fish community of Coniston Water has been subjected to relatively little scientific study, although such study as had been undertaken at the time was reviewed and the community assessed using gill nets and hydroacoustics in 2003 by Winfield *et al.* (2004a), after which its Arctic charr and brown trout populations were specifically assessed in 2004 by Winfield *et al.* (2005a). In 2003, the gill nets produced a sample of 403 fish of six species comprising Arctic charr, Atlantic salmon (*Salmo salar*), brown trout, minnow, perch and pike, with total fish population density peaking in October at 1244.9 fish ha^{-1} (geometric mean with lower and upper 95% confidence limits of 898.6 and 1724.6 fish ha^{-1}) (Winfield *et al.*, 2004a). Although a marked decline was observed in the catch-per-unit-effort of the local Arctic charr fishery from 1990 to 2003 (Winfield *et al.*, 2004a), this trend was temporarily reversed in 2004 (Winfield *et al.*, 2005a), before being subsequently resumed up to 2008 (Winfield *et al.*, 2010b) and then remaining at low levels in 2009 and 2010 (Centre for Ecology & Hydrology, unpublished data). In 2009, the first record of roach in Coniston Water was reported by an angler fishing off Limestone Rock, a submerged limestone outcrop towards the north end of the lake (J. Carroll, Coniston & Torver District Angling Association, *pers. comm.*).

Crummock Water

The fish community of Crummock Water has received relatively little scientific attention but was surveyed using gill nets and hydroacoustics in July 2010 as part of an assessment of its Arctic charr population by Winfield *et al.* (2011b). The gill nets produced a sample of 112 fish of three species comprising 41 Arctic charr, 10 brown trout and 61 perch, with a total fish night-time population density of 43.8 fish ha^{-1} (geometric mean with lower and upper 95% confidence limits of 20.0 and 95.8 fish ha^{-1}). On the basis of this information, the status of the Arctic population was concluded by Winfield *et al.* (2011b) to be favourable.

Derwent Water

The fish community of Derwent Water has been studied extensively since the early 1990s, as reviewed in part by Winfield *et al.* (in press) and references therein. A gill net and night-time hydroacoustics monitoring programme conducted since 1998 has documented the development of introduced roach, ruffe and dace and the local persistence of the rare vendace. Given that this is the last remaining native population of vendace in the U.K., attempts have been and continue to be made to establish refuge populations although with as yet no demonstrable success (Winfield *et al.*, in press). Monitoring in 2010 produced a sample of 120 fish of six species comprising 1 brown trout, 58 perch, 5 pike, 30 roach, 18 ruffe and 8 vendace, with total fish population density peaking in September at 364.9 fish ha^{-1} (lower and upper 95% confidence limits of 135.5 and 982.9 fish ha^{-1}) (Winfield *et al.*, 2011a). The vendace population was concluded to be in an acceptable condition, although its abundance is still relatively low in a European context and there is concern over the introduced populations of roach and ruffe.

Elterwater

The fish community of Elterwater has never been subjected to scientific study, although Smyly (1955) mentions a local stone loach (*Barbatula barbatula*) population and Frost (1989) notes the local presence of brown trout, perch and pike. Angling information refers to the same three species (Eltermere Country House Hotel, 2011).

Ennerdale Water

The fish community of Ennerdale Water has been subjected to a moderate amount of scientific study, with its population of Arctic charr having received attention including significant monitoring and conservation efforts in recent years. This Arctic charr population is very unusual in a Lake District context because, in contrast to almost all other populations which spawn within their lakes, it lays its eggs apparently exclusively in the inflowing River Liza (Frost, 1965; McCubbing *et al.*, 1998). Redd counts indicated that the numbers of spawning Arctic charr declined dramatically in the 1990s (B. Bayliss, Environment Agency, *pers. comm.*), which led to the undertaking of a single hydroacoustic survey by the Environment Agency in 1997 which was subsequently repeated in 2003 and thereafter at annual intervals to the present (Hateley, 2010). In addition, a review and assessment of the Arctic charr and brown trout stocks of the lake was undertaken by

Winfield *et al.* (2005b) and identified pH-related problems on the riverine spawning grounds, with gill netting producing a total of 40 fish of three species comprising 7 Arctic charr, 17 brown trout and 16 three-spined stickleback (*Gasterosteus aculeatus*). This assessment led to a conservation programme being undertaken by the Environment Agency from 2007 to 2010, inclusive, in which adult Arctic charr have been stripped of eggs and milt as they ascended the River Liza to spawn during the autumn (B. Bayliss, Environment Agency, *pers. comm.*). Each year, the resulting fertilised eggs have been taken to a hatchery for safe incubation prior to their return to the lake as young fish during the following year. Although hydroacoustic monitoring had shown that the Arctic charr population had demonstrably declined between 1997 and 2008 (Winfield *et al.,* 2010b), in 2010 the annual survey produced encouraging indications that this decline may have been reversed by the conservation initiative (Hateley, 2010). A recent analysis of intermittent fyke net catches made in 1992/1993, 2008 and 2010 has also suggested recent improvement in the abundance of Arctic charr ascending the River Liza to spawn (J. Hateley, Environment Agency, *pers. comm.*). On the basis of this information, the status of the Arctic population was concluded by Winfield *et al.* (2011b) to be unfavourable but recovering.

Esthwaite Water

The fish community of Esthwaite Water has received relatively little scientific attention, but it was surveyed using gill nets in September 2009 (Environment Agency / Centre for Ecology & Hydrology, unpublished data). This resulted in the sampling of a total of 192 fish of four species comprising 6 brown trout, 124 perch, 6 rainbow trout (*Oncorhynchus mykiss*) and 56 roach. A near-simultaneous hydroacoustic survey was compromised by very high levels of weak echoes thought to originate from the lake's abundant plankton community (J. Hateley, Environment Agency, *pers. comm.*). The roach population is probably not native to the lake, with Le Cren *et al.* (1972) concluding that its long-standing presence may be related to the fact that the fisheries of Esthwaite Water were historically owned by monks, who have a long history of cyprinid cultivation and stocking, although somewhat in contrast Frost (1989) suggested that live-baiting activities by anglers fishing for pike may be responsible for the local presence of this species. The origin of the non-native rainbow trout is clearly the stocking activities of the local fishery and cage fish farm which has operated since 1981, but which removed the cages in late 2009 and will make the last stockings of rainbow trout in 2012 (B. Bayliss, Environment Agency, *pers. comm.*). Unpublished electrofishing surveys of the lake's streams carried out between 2005 and 2010 by the Environment Agency have recorded brown trout, eel (*Anguilla anguilla*), minnow, perch, pike, stone loach, rainbow trout and roach (B. Bayliss, Environment Agency, unpublished data).

Grasmere

The fish community of Grasmere has never been subjected to thorough biological scientific study, although Smyly (1955) mentions a local stone loach population, Smyly (1957) refers to a local bullhead (*Cottus gobio*) population and Frost (1989) notes the local presence of brown trout, perch and pike. Vertical and horizontal night-time hydroacoustic surveys were performed in October 2007 by the Environment Agency, during which the vertical survey (comparable with all other hydroacoustic surveys covered in this review) recorded a total fish population density of 299.4 fish ha^{-1} (lower and upper 95% confidence limits of 240.3 and 358.5 fish ha^{-1}) (J. Hateley, Environment Agency, unpublished data). A second hydroacoustic survey was conducted in July 2009 within the EU project WISER (www.wiser.eu) but the resulting data have not yet been analysed (Centre for Ecology &

Hydrology, unpublished data) and objections from local fisheries interests prevented a simultaneous gill-netting survey. The lake is considered to be one of the region’s best natural coarse fisheries holding larger numbers of perch, pike and roach (WADAA, 2011). Perch of 1.4 kg are by no means unusual, pike over 13 kg have been caught in the past and 9 kg fish are caught every year, and the roach have a high average size with 0.9 kg fish not uncommon. In a review of fish species introductions in the Lake District, Winfield *et al.* (2010a) concluded that the common bream (*Abramis brama*), roach and possibly pike populations of Grasmere had been introduced.

Haweswater

Frost (1989) noted that the fish community of Haweswater contains Arctic charr, brown trout, perch and the rare schelly, but also specifically commented on the local absence of pike. However, small numbers of pike were sampled from the lake several decades ago (L. Walton, formerly United Utilities, *pers. comm.*) although they have not been recorded since. Prior to the 1990s, the only substantial publications concerned with the fish of this reservoir were those of Swynnerton & Worthington (1940), Bagenal (1970) and Maitland (1985) addressing the schelly population before and after impoundment. A limited amount of further information on the schelly from the 1970s and 1980s is available in the unpublished theses of Broughton (1972) and Mubamba (1989), but the first survey of the lake’s fish community as a whole was undertaken in 1991 by Winfield *et al.* (1994) and resulted in the capture of 64 fish of five species comprising 16 Arctic charr, 27 brown trout, 5 minnow, 12 perch and 4 schelly. Winfield *et al.* (1994) concluded that the schelly population was in poor condition and so substantial effort was subsequently directed towards understanding its local ecology (Winfield *et al.*, 1995), which identified in particular the historic negative impact of fluctuating water levels (Winfield *et al.*, 1998) and a more recent impact of predation by a local cormorant breeding colony (Winfield *et al.*, 2004b). Several conservation measures were put in place in the 1990s (Winfield *et al.*, 2002), including the ultimately successful introductions of Haweswater schelly to nearby Blea Water and Small Water (Winfield *et al.*, 2011c), and monitoring of the schelly population began through a combination of very limited gill netting, hydroacoustics and entrapment. The latter two approaches, which also generate information on the Arctic charr population, have continued to 2010 and have recently shown some signs of recovery in the schelly population, with the Arctic charr population also showing a positive trend (Winfield *et al.*, 2011c). Nevertheless, both populations remain relatively low in abundance and an annual hydroacoustic survey of Haweswater undertaken in July 2010 recorded a total fish abundance of 10.1 fish ha^{-1} with lower and upper 95% confidence limits of 4.7 and 21.6 fish ha^{-1} (Winfield *et al.*, 2011c).

Loughrigg Tarn

The fish community of Loughrigg Tarn has never been subjected to scientific study, although angling information suggests that it holds brown trout, perch, pike and roach growing to notable individual sizes (Carlsons, 2011).

Loweswater

Until recently, the fish community of Loweswater had never been subjected to appreciable scientific study, although Le Cren (1955) makes brief reference to a local perch population, and Frost (1989) notes the presence of brown trout, perch and pike. Unpublished electrofishing surveys of the lake’s streams carried out between 1993 and 2006 by the Environment Agency have recorded Atlantic salmon, brown trout, eel and minnow (A. Gowans, Environment Agency, unpublished data). The fish community of the lake itself was assessed using limited gill nets, fyke nets and hydroacoustics in June 2007 and found a total of 85 fish of three species comprising 3 brown trout, 1 minnow and 81 perch and with a total fish population density of 11.3 fish ha^{-1} (lower and upper 95% confidence limits of 2.8 and 45.2 fish ha^{-1}), although analysis and interpretation of the hydroacoustic data was complicated by very high levels of weak echoes thought to originate from the lake's abundant *Chaoborus* population (Centre for Ecology & Hydrology, unpublished data). Hydroacoustic surveys were repeated in June 2008 and August 2009, but the resulting data have not yet been analysed (Centre for Ecology & Hydrology, unpublished data). The latter survey was accompanied by a very extensive gill-net survey within the EU project WISER (www.wiser.eu) and recorded a total of 831 fish of four species comprising 2 brown trout, 1 minnow, 825 perch and 3 pike (Centre for Ecology & Hydrology, unpublished data).

Rydal Water

The fish community of Rydal Water has never been subjected to significant scientific study, although Smyly (1955) mentions a local stone loach population and Frost (1989) notes the local presence of brown trout, perch and pike. Angling information indicates that the main species are eel, perch, pike and roach (WADAA, 2011). The pike are present in substantial numbers, with individual weights commonly over 9 kg and the local record being an individual in excess of 14 kg. A review of fish species introductions in the Lake District, (Winfield *et al.*, 2010a) presented evidence to suggest that the crucian carp (*Carassius carassius*), roach and ruffe populations of Rydal Water had been introduced.

Thirlmere

The fish community of Thirlmere has never been subjected to appreciable scientific study, although Le Cren (1955) makes brief reference to a local perch population, Frost (1977) comments on its Arctic charr population and Frost (1989) notes the local presence of Arctic charr, brown trout, perch and pike. Angling information notes the same four species, observing that the brown trout are relatively numerous and average around 0.2 kg in weight with frequent larger fish and a few ferox in excess of 4 kg, but the pike are relatively scarce and rarely exceed 6 kg (WADAA, 2011).

Ullswater

Frost (1989) noted that the fish community of Ullswater contains brown trout, perch and the rare schelly, but also specifically commented on the local absence of pike and Arctic charr. While there is no evidence to suggest that pike were ever recorded from this lake, there are definite local historical records of Arctic charr which appear to have been lost during the mid-nineteenth century. Although the reason or reasons behind this demise are uncertain, it has been suggested that it was the result of lead ore washings in the Glenridding Beck where the population was known to spawn. Studies of the lake's perch population were made by Le Cren (1955), McCormack (1965) and Kelso & Bagenal (1977), with the first study of its schelly population being undertaken by Bagenal (1970) and followed with less intensity by Mubamba (1989). The first survey of the lake's fish community as a whole was undertaken in 1991 by Winfield *et al.* (1994) and resulted in the capture of 156 fish of six species comprising 11 brown trout, 1 eel, 10 minnow, 80 perch, 49 schelly and 5 three-spined stickleback. The most recent biological scientific sampling of the fish community of Ullswater was undertaken by the Environment Agency using survey gill nets in August and September 2008 as part of a wider study collecting material for genetic and morphometric analysis and resulted in the capture of 859 fish of three species comprising 9 brown trout, 821 perch and 29 schelly (A. Gowans, Environment Agency, unpublished data). Finally, a night-time hydroacoustic survey of Ullswater undertaken by the Environment Agency in October 2008 recorded a total fish abundance of 95.7 fish ha^{-1} with lower and upper 95% confidence limits of 60.1 and 116.5 fish ha^{-1} (J. Hateley, Environment Agency, unpublished data). On the basis of this information, the status of the schelly population was concluded by Winfield *et al.* (2011b) to be favourable.

Wastwater

The fish community of Wastwater has received relatively little scientific attention but was surveyed using gill nets and hydroacoustics in August 2010 as part of an assessment of its Arctic charr population by Winfield *et al.* (2011b). The gill nets produced a sample of 52 fish of four species comprising 4 Arctic charr, 26 brown trout, 4 minnow and 18 three-spined stickleback, with a total fish night-time population density of 15.9 fish ha^{-1} (geometric mean with lower and upper 95% confidence limits of 7.0 and 35.9 fish ha^{-1}). Winfield *et al.* (2011b) were able to compare these results with those of an identical survey carried out in August 2005 by Winfield *et al.* (2006) and found that over the last 5 years the Arctic charr population had reduced in its length and weight ranges, its contribution to the sampled fish community had declined by approximately 80% and its absolute abundance had declined by approximately 50%. On the basis of this information, the status of the Arctic charr population was concluded by Winfield *et al.* (2011b) to be unfavourable and declining.

Windermere North Basin

The fish community of Windermere comprises at least 16 species, but it is dominated by Arctic charr, perch, pike and, in recent years, roach (Winfield *et al.*, 2008a). This is without doubt the best studied standing water fish community in the U.K., although historically attention was strongly focussed on its Arctic charr, perch and pike populations. Much of the resulting extensive literature of the previous century was reviewed by Le Cren (2001), with many of the more recent studies being reviewed and extended by Winfield *et al.* (2008a) and Winfield *et al.* (2008b) which focussed on its Arctic charr and pike populations, respectively. In addition, Winfield *et al.* (2010a) and Winfield *et al.* (2011d) have reviewed the history of fish species introductions to the lake, among which the principal species of concern are common bream and particularly roach. The lake fish community has been monitored using hydroacoustics, gill nets and fishery statistics for a number of years in a programme which was reported for 2010 by Winfield *et al.* (2011e), which also gave recent trends from the long-standing Arctic charr, perch and pike population studies. Taking the findings of these investigations together, the overall picture for the North Basin is one of a declining Arctic charr population and an expanding roach population, although both of these trends are less marked and more recent than in the South Basin. Although robust data are lacking, Atlantic salmon and brown trout have also apparently declined in both basins. In recent decades pike abundance and condition have tended to be higher in the North Basin, but the magnitudes of these inter-basin differences have declined in recent years. Perch abundance has varied considerably, although with no noticeable inter-basin differences, and population size structure has tended to become more diverse in recent years in both basins. Common bream abundance remains very low in the North Basin. In 2010, total fish population density in the North Basin as recorded by night-time hydroacoustic surveys peaked in July at 1838.0 fish ha^{-1} (Winfield *et al.*, 2011e).

Windermere South Basin

All of the general information given above for Windermere North Basin also applies to Windermere South Basin, with fish movements between these areas known to be extensive and Winfield *et al.* (2008a), Winfield *et al.* (2008b), Winfield *et al.* (2010a), Winfield *et al.* (2011d) and Winfield *et al.* (2011e) also addressing the South Basin. Taking the findings of these investigations together, the overall picture for the South Basin is one of a markedly declining Arctic charr population and a greatly expanding roach population, with both of these trends being more marked and beginning earlier than in the North Basin. In recent decades pike abundance and condition have tended to be lower in the South Basin, but the magnitudes of these inter-basin differences have declined in recent years. Perch abundance has varied considerably, although with no noticeable inter-basin differences, and population size structure has tended to become more diverse in recent years in both basins. Common bream abundance remains low in the South Basin, but appears to be increasing. In 2010, total fish population density in the South Basin as recorded by night-time hydroacoustic surveys peaked in July at 2410.0 fish ha^{-1} (Winfield *et al.*, 2011e).

Table 3.2. Summary of the distribution of fish species in the 20 lakes in the Lakes Tour indicated as Y = present, (Y) = present in the past but now presumed extinct, and y = present in at least one tributary but not necessarily also in the lake itself. Note that sampling effort has varied significantly between lakes in terms of both its nature and its degree. Extent of knowledge on the fish populations of each lake is categorised as H= high, M = moderate, or L = low. The text in section 3.2.8 gives more detailed information.

Lake	Atlantic salmon	Brown trout	Rainbow trout	Arctic charr	Schelly	Vendace	Pike	Minnow	Crucian carp	Dace	Roach	Common bream	Stone loach	Eel	Perch	Ruffe	Bullhead	3-spined stickleback	Extent of knowledge
Bassenthwaite Lake		Y				(Y)	Y			Y	Y				Y	Y			H
Blelham Tarn		Y					Y				Y				Y				L
Brothers Water		Y			Y										Y				M
Buttermere		Y		Y			Y	Y							Y				M
Coniston Water	Y	Y		Y			Y	Y			Y				Y				M
Crummock Water		Y		Y											Y				M
Derwent Water		Y				Y	Y			Y	Y				Y	Y			H
Elterwater		Y					Y						y		Y				L
Ennerdale Water		Y		Y														Y	M
Esthwaite Water		Y	Y				Y	y			Y		y	y	Y				M
Grasmere		Y					Y				Y	Y	y		Y		y		L
Haweswater		Y		Y	Y		(Y)	Y							Y				H
Lougrigg Tarn		Y					Y				Y				Y				L
Loweswater		Y					Y	Y						y	Y				M
Rydal Water		Y					Y		Y		Y		y	Y	Y				L
Thirlmere		Y		Y			Y								Y				L
Ullswater		Y		(Y)	Y			Y						Y	Y			Y	M
Wastwater		Y		Y				Y										Y	M
Windermere North Basin	Y	Y		Y			Y				Y	Y			Y				H
Windermere South Basin	Y	Y		Y			Y				Y	Y			Y				H

3.2.9 Metals

Metals have not been measured before in the Lakes Tour. The data collected serve to determine the current concentrations of metals in the lakes and also to serve as a baseline for future studies. These data are briefly described below but not analysed in detail.

Aluminium

Concentrations for soluble aluminium ranged from less than the level of detection (10 mg m^{-3}) to 37.6 mg m^{-3} in Elterwater in October (Table 3.3). Total aluminium ranged from 11.1 mg m^{-3} (Ullswater in July) to 93 mg m^{-3} (Derwent Water in January). Elterwater, Ennerdale Water and Derwent Water had the highest concentrations of aluminium (Fig. 3.18a).

Cadmium

All samples, filtered and total, were below the limit of detection which was 0.1 mg m^{-3} (Table 3.3, Fig. 3.18b).

Chromium

Almost all filtered and total samples were below the limit of detection at 0.5 mg m^{-3}. An exception was filtered chromium at Wastwater in April at 2.7 mg m^{-3} but since the concentration in the total samples was <0.5 mg m^{-3} this is probably the result of contamination or analytical error (Table 3.3). Total chromium in Grasmere in October was reported at 0.7 mg m^{-3}, just above the limit of detection (Fig. 3.18c).

Copper

Concentrations of filtered copper ranged between less than the limit of detection (1 mg m^{-3}) to a maximum of 7.63 mg m^{-3} in Haweswater in July (Table 3.3). This appears to be a real value from an analytical viewpoint as it was confirmed in the total sample (7.7 mg m^{-3}; also the maximum for total copper), but more work is needed to understand the source of the copper in Haweswater. The highest average concentrations were present in Coniston Water, with known copper mines in the catchment, plus Haweswater, Elterwater, Bassenthwaite Lake, Blelham Tarn and Crummock Water where the annual average filtered (soluble) concentration exceeded the WFD UKTAG proposed annual maximum concentration for low alkalinity lakes like the ones here of 1 mg m^{-3}. Copper was not detectable in Buttermere, Crummock Water, Ullswater or Wastwater (Fig. 3.18d).

Nickel

Nickel was below detection limit (1 mg m^{-3}) in all samples apart from one from the filtered samples from Wastwater in April (Table 3.3). Like the value for chromium in January, this is likely to result from contamination or experimental error because it was not reflected in values in the total sample (Fig. 3.18e). All concentrations were below the Environmental Quality Standard for nickel of 20 mg m^{-3} (UKTAG, 2010).

Lead

Total lead was below the limit of detection (2 mg m^{-3}) in ten lakes: Brothers Water, Buttermere, Coniston Water, Crummock Water, Ennerdale Water, Esthwaite Water, Grasmere, Ullswater and the two basins of Windermere (Table 3.3, Fig. 3.18f). The low concentrations of lead in Ullswater are notable since lead mining occurred locally in the past. Highest concentrations of total lead were found in Haweswater, Loweswater, Derwent Water, Loughrigg Tarn and Rydal Tarn. Haweswater was the only site with detectable filtered lead (5.19 mg m^{-3} in July) apart from a probably aberrant value in Wastwater in January. This is below the Environmental Quality Standard for lead of 7.2 mg m^{-3} (UKTAG, 2010).

Zinc

Concentrations of total zinc varied from below the limit of detection of 5 mg m^{-3} to 23.3 mg m^{-3} in Loweswater in July. It was undetectable in most of the lakes in the Windermere catchment: Blelham Tarn, Esthwaite Water, Grasmere, Loughrigg and the two basins of Windermere (Table 3.3, Fig. 3.18g). Total concentrations were highest in Bassenthwaite Lake, where the annual concentration (13.25 mg m^{-3}) exceeded the proposed annual maximum concentration for low alkalinity lakes like the ones here of 8 mg m^{-3} (UKTAG, 2010). Concentrations were about half this threshold in Brothers Water, Buttermere, Haweswater and Ullswater.

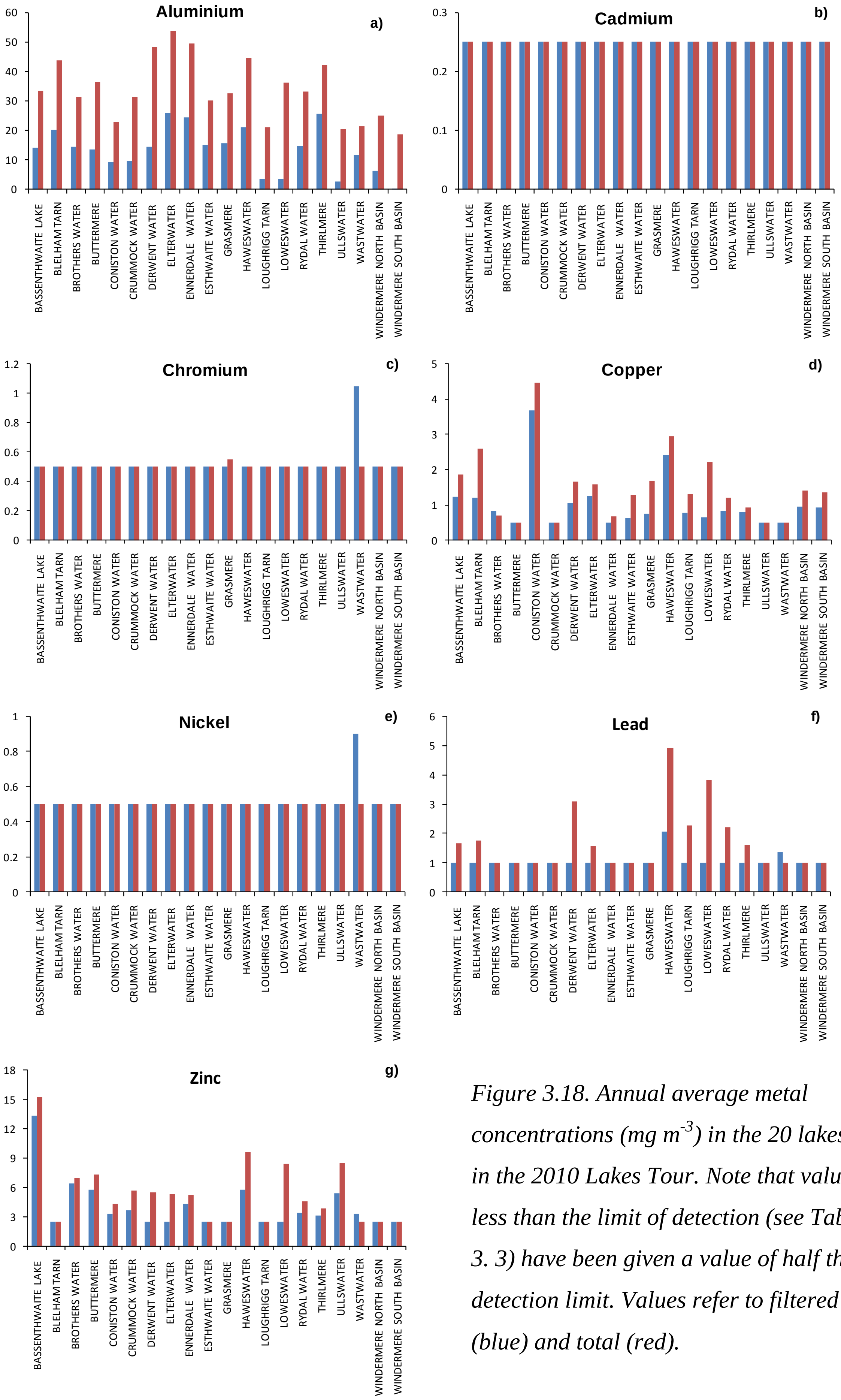


Figure 3.18. Annual average metal concentrations (mg m^{-3}) in the 20 lakes in the 2010 Lakes Tour. Note that values less than the limit of detection (see Table 3. 3) have been given a value of half the detection limit. Values refer to filtered (blue) and total (red).

Table 3.3. Heavy metals concentration (mg m^{-3}) in the Lakes Tour samples in 2010. The 4-figure number below each determinand is the E A 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
Lake	Date	6037	6057	0106	0108	3409	3164	6450	6452	3410	6462	0052	0050	3408	6455
Bassenthwaite Lake	21/01/2010	22.3	26	< .1	< .1	< .5	< .5	1.08	1.1	< 1	< 1	< 2	< 2	18	19
Bassenthwaite Lake	15/04/2010	18	55	< .1	< .1	< .5	< .5	1.2	3.4	< 1	< 1	< 2	2.5	16.9	19.9
Bassenthwaite Lake	09/07/2010	< 10	15	< .1	< .1	< .5	< .5	1.25	1.1	< 1	< 1	< 2	< 2	< 5	< 5
Bassenthwaite Lake	14/10/2010	16.6	38	< .1	< .1	< .5	< .5	1.41	1.8	< 1	< 1	< 2	2.2	15.6	19.5
Blelham Tarn	25/01/2010	18	55	< .1	< .1	< .5	< .5	< 1	1	< 1	< 1	< 2	< 2	< 5	< 5
Blelham Tarn	12/04/2010	23	43.6	< .1	< .1	< .5	< .5	1.1	5.48	< 1	< 1	< 2	< 2	< 5	< 5
Blelham Tarn	05/07/2010	16	34.2	< .1	< .1	< .5	< .5	1.61	2.13	< 1	< 1	< 2	4.04	< 5	< 5
Blelham Tarn	11/10/2010	23.3	42	< .1	< .1	< .5	< .5	1.63	1.8	< 1	< 1	< 2	< 2	< 5	< 5
Brothers Water	22/01/2010	10	30	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	10.6	9.8
Brothers Water	14/04/2010	18	42	< .1	< .1	< .5	< .5	< 1	1.3	< 1	< 1	< 2	< 2	< 5	9.1
Brothers Water	05/07/2010	-	28	-	< .1	-	< .5	-	< 1	-	< 1	-	< 2	-	6.4
Brothers Water	11/10/2010	15.3	26	< .1	< .1	< .5	< .5	1.48	< 1	< 1	< 1	< 2	< 2	5.9	< 5
Buttermere	21/01/2010	15.8	47	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	7.84	10.7
Buttermere	15/04/2010	14	49	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	6.5	8.2
Buttermere	07/07/2010	12	22.1	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Buttermere	14/10/2010	12.9	28	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	6	7.6
Coniston Water	19/01/2010	13	29	< .1	< .1	< .5	< .5	3.8	4.3	< 1	< 1	< 2	< 2	5.5	6.7
Coniston Water	13/04/2010	12	25.7	< .1	< .1	< .5	< .5	3.4	3.87	< 1	< 1	< 2	< 2	< 5	< 5
Coniston Water	06/07/2010	< 10	12.5	< .1	< .1	< .5	< .5	3.87	5.65	< 1	< 1	< 2	< 2	< 5	< 5
Coniston Water	12/10/2010	11.8	24	< .1	< .1	< .5	< .5	3.61	4	< 1	< 1	< 2	< 2	< 5	5.4
Crummock Water	21/01/2010	15	55.2	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	7.21	12.6
Crummock Water	15/04/2010	11	32	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	5.1
Crummock Water	07/07/2010	< 10	12.1	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Crummock Water	14/10/2010	11.8	26	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Derwent Water	21/01/2010	21.5	93	< .1	< .1	< .5	0.5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	5.9
Derwent Water	15/04/2010	18	37	< .1	< .1	< .5	< .5	1.5	2.8	< 1	< 1	< 2	2.8	< 5	< 5
Derwent Water	09/07/2010	< 10	23.8	< .1	< .1	< .5	< .5	< 1	1.28	< 1	< 1	< 2	3.52	< 5	8.09
Derwent Water	14/10/2010	17.8	39	< .1	< .1	< .5	< .5	1.77	2.1	< 1	< 1	< 2	5	< 5	5.3
Elterwater	27/01/2010	17	33	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	8.2
Elterwater	08/04/2010	31	67.1	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	5.39
Elterwater	08/07/2010	18.2	44.5	< .1	< .1	< .5	< .5	1.07	1.71	< 1	< 1	< 2	3.31	< 5	5.11
Elterwater	07/10/2010	37.6	70	< .1	< .1	< .5	< .5	2.94	3.6	< 1	< 1	< 2	< 2	< 5	< 5
Ennerdale Water	25/01/2010	28	61	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	6.9
Ennerdale Water	09/04/2010	24	44	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Ennerdale Water	09/07/2010	18.5	40	< .1	< .1	< .5	< .5	< 1	1.2	< 1	< 1	< 2	< 2	< 5	5.9
Ennerdale Water	08/10/2010	27.5	53	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	9.76	5.6
Esthwaite Water	19/01/2010	23	38	< .1	< .1	< .5	< .5	< 1	1.6	< 1	< 1	< 2	< 2	< 5	< 5
Esthwaite Water	13/04/2010	11	29.8	< .1	< .1	< .5	< .5	< 1	1.06	< 1	< 1	< 2	< 2	< 5	< 5
Esthwaite Water	06/07/2010	12.7	25	< .1	< .1	< .5	< .5	1.01	1.4	< 1	< 1	< 2	< 2	< 5	< 5
Esthwaite Water	12/10/2010	13.1	28	< .1	< .1	< .5	< .5	< 1	1.1	< 1	< 1	< 2	< 2	< 5	< 5
Grasmere	25/01/2010	18	32	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Grasmere	12/04/2010	20	38.2	< .1	< .1	< .5	< .5	< 1	3.29	< 1	< 1	< 2	< 2	< 5	< 5
Grasmere	05/07/2010	< 10	18.3	< .1	< .1	< .5	< .5	1.55	1.64	< 1	< 1	< 2	< 2	< 5	< 5
Grasmere	11/10/2010	25.1	42	< .1	< .1	< .5	0.7	< 1	1.3	< 1	< 1	< 2	< 2	< 5	< 5
Haweswater	18/01/2010	23.5	46	< .1	< .1	< .5	< .5	< 1	1.7	< 1	< 1	< 2	< 2	< 5	14.7
Haweswater	07/04/2010	23	51.9	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	5.68
Haweswater	01/07/2010	16	43	< .1	< .1	< .5	< .5	7.63	7.1	< 1	< 1	5.19	16.7	15.3	15.3
Haweswater	06/10/2010	21.7	38	< .1	< .1	< .5	< .5	1.01	2.5	< 1	< 1	< 2	< 2	< 5	< 5
Loughrigg Tarn	27/01/2010	< 10	16	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Loughrigg Tarn	08/04/2010	< 10	24.9	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Loughrigg Tarn	08/07/2010	13.6	27.2	< .1	< .1	< .5	< .5	< 1	1.31	< 1	< 1	< 2	5.05	< 5	< 5
Loughrigg Tarn	07/10/2010	< 10	16	< .1	< .1	< .5	< .5	1.58	2.9	< 1	< 1	< 2	2	< 5	< 5
Loweswater	22/01/2010	14	74	< .1	< .1	< .5	< .5	< 1	1.7	< 1	< 1	< 2	< 2	< 5	< 5
Loweswater	09/04/2010	< 10	34.1	< .1	< .1	< .5	< .5	< 1	1.28	< 1	< 1	< 2	< 2	< 5	< 5
Loweswater	07/07/2010	< 10	19.3	< .1	< .1	< .5	< .5	< 1	4.26	< 1	< 1	< 2	9.82	< 5	23.3
Loweswater	08/10/2010	< 10	17	< .1	< .1	< .5	< .5	1.12	1.6	< 1	< 1	< 2	3.4	< 5	5.2
Rydal Water	27/01/2010	17	37	< .1	< .1	< .5	< .5	< 1	1.2	< 1	< 1	< 2	< 2	6	10.6
Rydal Water	08/04/2010	17	36.2	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Rydal Water	08/07/2010	< 10	16.4	< .1	< .1	< .5	< .5	1.01	1.06	< 1	< 1	< 2	2.29	< 5	< 5
Rydal Water	07/10/2010	25.2	43	< .1	< .1	< .5	< .5	1.35	2.1	< 1	< 1	< 2	4.5	< 5	< 5
Thirlmere	18/01/2010	37.2	55	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	5.04	7.7
Thirlmere	09/04/2010	31	39.9	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Thirlmere	07/07/2010	11	38	< .1	< .1	< .5	< .5	1.15	1.46	< 1	< 1	< 2	2.18	< 5	< 5
Thirlmere	08/10/2010	22.9	36	< .1	< .1	< .5	< .5	1.04	1.3	< 1	< 1	< 2	2.2	< 5	< 5
Ullswater	19/01/2010	11	29	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	6.2	8.7
Ullswater	13/04/2010	< 10	24.9	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	6.6	10.2
Ullswater	06/07/2010	< 10	11.1	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	6.6
Ullswater	12/10/2010	< 10	17	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	6.38	8.4
Wastwater	25/01/2010	10	22	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	2.4	< 2	< 5	< 5
Wastwater	09/04/2010	10	19.2	< .1	< .1	2.7	< .5	< 1	< 1	2.1	< 1	< 2	< 2	< 5	< 5
Wastwater	08/07/2010	10.7	16.8	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	5.67	< 5
Wastwater	07/10/2010	16.6	28	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Windermere N Basin	19/01/2010	11	23	< .1	< .1	< .5	< .5	< 1	< 1	< 1	< 1	< 2	< 2	< 5	< 5
Windermere N Basin	13/04/2010	< 10	23	< .1	< .1	< .5	< .5	< 1	1.43	< 1	< 1	< 2	< 2	< 5	< 5
Windermere N Basin	06/07/2010	< 10	27.3	< .1	< .1	< .5	< .5	< 1	1.3	< 1	< 1	< 2	< 2	< 5	< 5
Windermere N Basin	12/10/2010	13.6	27	< .1	< .1	< .5	0.5	2.29	2.4	< 1	< 1	< 2	< 2	< 5	< 5
Windermere S Basin	19/01/2010	< 10	22	< .1	< .1	< .5	< .5	< 1	1.4	< 1	< 1	< 2	< 2	< 5	< 5
Windermere S Basin	13/04/2010	< 10	17.2	< .1	< .1	< .5	< .5	< 1	1.38	< 1	< 1	< 2	< 2	< 5	< 5
Windermere S Basin	06/07/2010	< 10	18	< .1	< .1	< .5	< .5	1.22	1.21	< 1	< 1	< 2	< 2	< 5	< 5
Windermere S Basin	12/10/2010	< 10	17	< .1	< .1	< .5	< .5	1.48	1.4	< 1	< 1	< 2	< 2	< 5	< 5

3.2.10 Micro-organic pollutants

As for the metals, the 2010 Lakes Tour was the first time that a consistent set of micro-organic compounds were analysed. The 128 compounds analysed and their limits of detection are listed in Table 3.4. Of the 10,240 analyses carried out, 104 gave values above the detection limit. Sixteen of the 128 compounds gave values above detection limit but of these only five exceeded the detection limit more than once (Table 3.5).

Table 3.4 Micro-organic chemicals analysed, their EA methods code and the minimum and maximum limit of detection for the analyses (mg m^{-3}).

EA code	Chemical	Min	Max
0483	Aldrin	0.001	0.001
0487	HCH Alpha	0.003	0.004
0491	HCH Beta	0.003	0.004
0495	HCH Delta	0.001	0.001
0499	HCH Gamma	0.003	0.004
0503	Chlorfenvphs	0.01	0.01
0507	Dichlorvos	0.004	0.006
0511	Dieldrin	0.001	0.001
0527	Heptachlor	0.001	0.001
0535	Malathion	0.002	0.003
0539	DDT (OP')	0.003	0.004
0543	Parathion	0.004	0.006
0547	Phorate	0.02	0.03
0551	DDE (PP')	0.001	0.001
0555	DDT (PP)	0.001	0.001
0559	TDE (PP)	0.001	0.001
0562	Endrin	0.003	0.004
0569	EndosulphanA	0.001	0.001
0570	EndosulphanB	0.002	0.002
0573	TDE (OP)	0.001	0.001
0576	Hexachlorbnz	0.001	0.001
0577	Chlrdn-cs/Z/	0.001	0.001
0578	Chlordane-tr	0.001	0.001
0579	Methoxychlor	0.001	0.001
0581	DDE (OP')	0.001	0.001
0723	Diazinon	0.002	0.003
1118	Fenthion	0.008	0.01
1119	ParathionMyl	0.003	0.004
3001	Simazine	0.003	0.004
3002	Atrazine	0.003	0.004
3009	Terbutryne	0.004	0.006
3113	Chloroprophm	0.005	0.006
3119	Propachlor	0.001	0.001
3545	2,4-Ethenoic	0.005	0.048
3546	245-Ethenoic	0.005	0.048
3547	4-CAA	0.005	0.048
3548	MCPA	0.005	0.048
3549	Mecoprop	0.005	0.048
3550	Dicamba	0.04	0.048
3551	Dichlorprop	0.005	0.048
3552	Fenoprop	0.005	0.048
3555	Triclopyr	0.005	0.048
3790	MCPB	0.005	0.048
3791	2,4-DB	0.005	0.048
3792	Benazolin	0.005	0.048
4064	Fluoroxypyr	0.005	0.048
4065	Bentazone	0.005	0.048
5563	Prometryn	0.005	0.007
5861	PCB 149	0.001	0.01
5862	Vinclozolin	0.002	0.002
5863	PClBenzene	0.001	0.001
6447	Dimethoate	0.006	0.009
6448	Propyzamide	0.005	0.007
6449	Bromoxynil	0.005	0.048
6487	Triazophos	0.004	0.006
6615	Chlorothalnl	0.001	0.001
6620	Clopyralid	0.01	0.048
6628	Cyanazine	0.006	0.009
6635	Desmetryne	0.005	0.007
6640	Fenchlorphos	0.005	0.007
6648	HEXACHLORO 1	0.003	0.004
6649	Iprodione	0.008	0.01
6666	PCB Con 31	0.001	0.001
6671	PhenoxytcAcd	0.005	0.048
6673	PHENOXYPROPY	0.005	0.048
6776	Fenpropimrph	0.007	0.01
6976	Napropamide	0.005	0.007
7071	Prochloraz	0.007	0.01
7135	TRIALLATE	0.006	0.007
7154	ETHOFUMESATE	0.005	0.007
7159	FONOFOS	0.001	0.001
7181	ClPyrphosMe	0.001	0.001
7726	2,3,6-TBA	0.04	0.048
8287	PCB 126	0.001	0.001
8342	PCB 128	0.001	0.001
8804	ATRZ-ETHYL	0.02	0.03
8864	c-Hept Epox	0.003	0.004
8865	t-Hept Epox	0.003	0.004
8942	HCH Epsilon	0.003	0.004
8995	2,3,5,6-TClT	0.001	0.001
8997	ATRZ-ISOPR	0.02	0.03
8998	PirimiphsEth	0.005	0.007
8999	Irgarol 1051	0.005	0.007
9000	Iodofenphos	0.001	0.001
9002	Metazachlor	0.005	0.007
9050	1,2,3-TCB	0.01	0.01
9051	1,2,4-TCB	0.01	0.01
9052	1,3,5-TCB	0.01	0.01
9068	Ioxynil	0.005	0.048
9196	PCB Con 077	0.001	0.001
9197	PCB Con 105	0.001	0.001
9198	PCB Con 169	0.001	0.001
9199	PCB Con 170	0.001	0.001
9258	PCB Con 156	0.001	0.001
9338	Bendiocarb	0.005	0.007
9350	2,3,5,6-Tetr	0.001	0.001
9466	PCB Con 008	0.001	0.001
9467	PCB Con 035	0.001	0.001
9468	PCB Con 020	0.001	0.001
9474	Coumaphos	0.005	0.007
9477	Dichlobenil	0.001	0.001
9479	Mevinphos	0.008	0.01
9494	Isodrin	0.001	0.001
9519	Carbophenthn	0.002	0.003
9586	Propetamphos	0.005	0.007
9606	Bupirimate	0.005	0.007
9634	Propazine	0.002	0.003
9715	Azinphos Myl	0.003	0.004
9716	Fenitrothion	0.001	0.001
9768	PCB Con 028	0.001	0.001
9769	PCB Con 052	0.001	0.001
9770	PCB Con 101	0.001	0.001
9771	PCB Con 118	0.001	0.001
9772	PCB Con 138	0.001	0.001
9773	PCB Con 153	0.001	0.001
9774	PCB Con 180	0.001	0.001
9851	PirimiphsMyl	0.003	0.004
9860	Metalaxyl	0.008	0.01
9863	AzinphsEthyl	0.006	0.009
9883	Pichloram	0.01	0.048
9892	Pendimethaln	0.01	0.01
9911	Trietazine	0.002	0.003
9959	Pirimicarb	0.004	0.006
9978	Chlorpyrifos	0.002	0.003
9979	Ethion	0.005	0.007
9989	Trifluralin	0.02	0.02
9990	Tecnazene	0.001	0.001

Table 3.5 Micro-organic compounds, the number of samples that exceeded the limit of detection, the maximum concentration detected and the allowable annual average concentration (concentrations in mg m^{-3}) '–' indicates no information.

Name	Number exceeding detection	Maximum concentration detected	Annual allowable average[*]
6671 Phenoxy acetic acid (PAA)	50	0.295	-
0723 Diazinon	27	0.033	0.01
3548 MCPA (4-Chloro-2-methylphenoxyacetic acid)	8	0.232	12 – 80[**]
6620 Clopyralid	4	0.781	-
3549 Mecoprop	3	0.017	18
3547 4-CAA (4-Chlorophenoxyacetic acid)	2	0.113	-
3545 2,4-D (2,4-Dichlorophenoxyacetic acid)	1	0.025	0.3
3555 Triclopyr	1	0.011	-
3790 MCPB (4-Chloro-2-methylphenoxybutyric acid)	1	0.006	-
3791 2,4-DB (4-(2,4-dichlorophenoxy)butyric acid)	1	0.006	-
4065 Bentazone	1	0.025	500
6448 Propyzamide	1	0.005	100
6449 Bromoxynil	1	0.005	100
7726 2,3,6-TBA (2,3,6-Trichlorobenzoic acid)	1	0.238	-
9000 Iodofenphos	1	0.003	-
9883 Pichloram	1	0.012	-

[*] Values kindly provided by the Environment Agency and are the proposed standards by the UKTAG WFD Annex VIII substances http://www.wfduk.org/stakeholder_reviews/stakeholder_review_1-2007/LibraryPublicDocs/final_specific_pollutants.

** lower value if pH<7, higher value of pH>7.

Phenoxy acetic acid

This compound was detected in 50 samples with a maximum concentration of 0.295 mg m^{-3} in Haweswater in July.

Diazinon

Diazinon (O,O-Diethyl O-[4-methyl-6-(propan-2-yl)pyrimidin-2-yl] phosphorothioate) is a contact organophosphorus acaricide, miticide or insecticide. It was detected on 27 occasions, with the maximum recorded concentration of 0.033 mg m^{-3} at Buttermere in January (Table 3.6). Diazinon was found on all four sampling occasions in Buttermere, Crummock Water, Ullswater and the North Basin of Windermere. The annual maximum allowable average concentration of 0.01 mg m^{-3} (Table 3.5) was exceeded in Buttermere (0.016 mg m^{-3}) but not quite in Crummock Water (0.008 mg m^{-3}), Ullswater (0.004 mg m^{-3}) or the North Basin of Windermere (0.002 mg m^{-3}). Assuming that the high concentrations in Buttermere in particular enter the lake via specific streams there is a likelihood that concentrations in those streams will be much higher and possibly causing ecological damage.

Table 3.6. Samples where the concentration of Diazinon (mg m^{-3}) exceeded the limit of detection.

Lake	DATE	Diazinon
BUTTERMERE	21/01/2010	0.033
BUTTERMERE	15/04/2010	0.015
CRUMMOCK WATER	21/01/2010	0.012
CRUMMOCK WATER	15/04/2010	0.010
BUTTERMERE	14/10/2010	0.010
LOUGHRIGG TARN	07/10/2010	0.009
ULLSWATER	12/10/2010	0.007
RYDAL WATER	07/10/2010	0.007
BUTTERMERE	07/07/2010	0.007
CRUMMOCK WATER	07/07/2010	0.006
GRASMERE	11/10/2010	0.006
ULLSWATER	19/01/2010	0.006
CRUMMOCK WATER	14/10/2010	0.005
GRASMERE	12/04/2010	0.004
ULLSWATER	13/04/2010	0.004
ESTHWAITE WATER	12/10/2010	0.003
ULLSWATER	06/07/2010	0.003
BASSENTHWAITE LAKE	14/10/2010	0.003
THIRLMERE	08/10/2010	0.003
WINDERMERE NORTH	19/01/2010	0.003
LOUGHRIGG TARN	08/07/2010	0.003
RYDAL WATER	08/04/2010	0.002
WINDERMERE NORTH	19/01/2010	0.002
WINDERMERE NORTH	13/04/2010	0.002
WINDERMERE NORTH	12/10/2010	0.002
LOUGHRIGG TARN	27/01/2010	0.002
ELTERWATER	07/10/2010	0.002

MCPA

4-Chloro-2-methylphenoxyacetic acid (MCPA) is a powerful, selective, widely-used phenoxy herbicide. The detection limit was exceeded on eight occasions, but the maximum concentration recorded (0.232 mg m^{-3} in Blelham Tarn in October) is at least 50-times below the suggested maximum annual average concentrations (Table 3.5).

Clopyralid

3,6-dichloro-2-pyridinecarboxylic acid (Clopyralid) is a selective herbicide used for control of broadleaf weeds, especially thistles and clovers. It was detected on four occasions (Table 3.5) with a maximum concentration of 0.781 mg m^{-3} at Thirlmere in October. This is the highest concentration of any of the micro-organic compounds measured here, but there does not appear to be any information on acceptable concentrations in standing waters.

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 (Table 3.5) with a maximum concentration of 0.017 mg m^{-3} in Thirlmere in October. This concentration is about one-thousand times below the recommended maximum annual average.

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 and the maximum concentration was 0.113 mg m^{-3} in the South Basin of Windermere in January.

The other ten compounds detected only once were all below the maximum allowable average concentration where these values exist (Table 3.5).

3.3 Current status of the English Lakes and evidence for change

This section assesses the current status of each of the 20 lakes basins surveyed in 2010 on a lake-by-lake basis. In addition to a general assessment, each lake is categorised according to its trophic state and likely ecological status in the terms of the EC Water Framework Directive. The OECD (1982) boundaries for trophic state based on concentration of total phosphorus and chlorophyll *a* and Secchi depth are shown in Table 3.7.

Table 3.7. 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-oligtrophic	≤ 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 ≤ 1.5
Eutrophic	35 < 100	8 < 25	25 < 75	3 > 1.5	1.5 ≤ 0.7
Hypertrophic	≥ 100	≥ 25	≥ 75	≤ 1.5	≤ 0.7

A legislative framework for the classification of lakes is provided by the European Union Water Framework Directive (WFD; 2000/60/EC). This requires lakes and other surface waters to be maintained or returned to Good Ecological Status by 2015 wherever feasible. Boundaries for ecological status of different Biological Quality Elements or Supporting-elements are set depending on the type of lake. Two features are relevant here 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 3.8 gives the WFD categories for each of the 20 lakes.

Table 3.8. 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 at reference state (Ref) and the High:Good (H:G), Good:Moderate (G:M), Moderate:Poor (M:P) and Poor:Bad (P:B) boundaries.

Lake	Type	Ref	H:G	G:M	M:P	P:B
Bassenthwaite Lake	MAS	7.23	9.61	14.45	28.9	57.8
Blelham Tarn	MAS	8	11	16	32	64
Brothers Water	LAS	5	7	10	20	40
Buttermere	LAD	3.87	5.24	8.163	16.33	32.7
Coniston Water	LAD	5.1	6.95	11.02	22.05	44.1
Crummock Water	LAD	3.52	5	8	16	32
Derwent Water	LAS	6.16	8.21	12.38	24.76	49.5
Elterwater	LAVS	7.88	10.5	15.65	31.29	62.6
Ennerdale Water	LAD	3.72	5.05	8	16	32
Esthwaite Water	MAS	8.26	11	16.42	32.83	65.7
Grasmere	LAS	6.18	8.25	12.5	25.01	50
Haweswater	MAD	4.48	6.11	9.666	19.33	38.7
Loughrigg Tarn*	MAS	8	11	16	32	64
Loweswater	LAS	6.04	8.06	12.22	24.45	48.9
Rydal Water*	LAS	5	7	10	20	40
Thirlmere	LAD	3.98	5.38	8.368	16.74	33.5
Ullswater	MAD	4.91	6.7	10.63	21.27	42.5
Wastwater	LAD	3.4	5	8	16	32
Windermere North Basin	MAD	5.85	7.94	12.45	24.9	49.8
Windermere South Basin	MAD	5.85	7.94	12.45	24.9	49.8

* Not a WFD lake

Table 3.9. 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.*

Lake	Ref	H:G	G:M	M:P	P:B
Bassenthwaite Lake	2.7	5.5	8.3	16.6	50.3
Blelham Tarn	3.1	6.1	9.3	18.6	56.2
Brothers Water	1.8	3.6	6.3	12.6	38.1
Buttermere	1.6	3.2	4.9	9.8	29.8
Coniston Water	2.0	4.0	6.0	12.0	36.4
Crummock Water	1.5	3.0	4.6	9.2	27.8
Derwent Water	2.3	4.6	7.9	15.8	47.9
Elterwater	3.0	4.8	9.1	18.2	55.3
Ennerdale Water	1.6	3.2	4.8	9.5	28.9
Esthwaite Water	3.2	6.3	9.6	19.2	58.3
Grasmere	2.3	4.6	7.9	15.9	48.1
Haweswater	1.8	3.6	5.5	10.9	33.1
Loughrigg Tarn*	3.1	6.1	9.3	18.6	56.2
Loweswater	2.2	4.5	7.7	15.5	46.9
Rydal Water*	1.8	3.6	6.3	12.6	38.1
Thirlmere	1.7	3.3	5.0	10.0	30.4
Ullswater	1.9	3.9	5.8	11.7	35.4
Wastwater	1.5	3.0	4.5	9.0	27.3
Windermere North Basin	2.2	4.4	6.6	13.3	40.3
Windermere South Basin	2.2	4.4	6.6	13.3	40.3

* Not a WFD lake.

The appropriate measured concentrations to compare the values in Tables 3.8 and 3.9 against are the annual mean concentration for total phosphorus and the ‘observed chlorophyll concentration’ for chlorophyll. The latter is calculated from the annual geometric mean (the mean of the Log10 chlorophyll concentrations converted back to unlogged concentrations), corrected for the effect of the geometric calculation using the following formula:

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 in the English Lake District 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 samples are available for analysis here, albeit spaced seasonally, so this may introduce some inaccuracy. Furthermore, while the boundary values are the currently accepted values, they have not yet been officially agreed and so may change subsequently.

In this section, records from the 2010 Lakes Tour are assessed for the current status of the lakes and also compared to those in 1991, 1995 and 2000, 2005 and, where possible, 1984, to assess the extent of any change in these lakes. For all the correlations, especially for chlorophyll *a* and Secchi depth where values were not recorded in 1984, there are a limited number of degrees of freedom and so some changes may be real even though they are not statistically significant. The major changes are reported on a lake-by-lake basis. Although results for SRP and NH_4-N are presented, they are not analaysed in detail as many of the concentrations were below the detection limit. The overall statistical analyses of change for the twenty lakes are presented below in Table 3.10 and then discussed for each lake in the context of their current state.

Table 3.10 Correlation coefficient of mean annual change in nutrient chemistry for the 20 lake basins between 1984 and 2010. Significant correlations are shown in bold and shaded green when P<0.05, yellow when P<0.01 and orange when P<0.001. Data below detection limit, so not analysed, indicated by '-'.

Lake	TP	SRP	NO_3-N	NH_4-N	SiO_2	Chla	SD	H^+	Alk	SO_4	Cl	Ca	Mg	Na	K
Bassenthwaite Lake	-0.14	0.06	-0.67	**0.95**	0.04	0.64	-0.43	**-0.85**	**0.86**	**-0.90**	-0.72	-0.30	**-0.84**	-0.70	**-0.77**
Blelham Tarn	-0.17	0.31	**-0.93**	**-0.81**	-0.19	0.76	0.50	0.44	**0.89**	**-0.91**	-0.50	-0.22	-0.40	-0.52	**-0.86**
Brotherswater	0.08	-0.37	0.01	0.33	0.30	0.68	0.27	-0.68	**0.89**	**-0.94**	**-0.78**	-0.45	**-0.84**	-0.73	**-0.91**
Buttermere	0.26	-0.10	0.62	**0.78**	**-0.91**	0.21	**-0.92**	**-0.84**	**0.86**	**-0.96**	**-0.79**	0.15	**-0.88**	**-0.86**	-0.68
Coniston Water	0.43	0.36	-0.30	**0.80**	0.50	0.51	-0.70	**-0.84**	**0.89**	**-0.99**	-0.68	-0.41	**-0.84**	-0.69	-0.51
Crummock Water	0.34	0.05	0.58	**0.80**	-0.07	-0.07	-0.55	**-0.86**	**0.80**	**-0.97**	**-0.79**	-0.18	**-0.94**	**-0.79**	-0.70
Derwentwater	0.30	-0.07	**-0.78**	**0.82**	**-0.92**	**0.86**	-0.33	**-0.86**	**0.98**	**-0.99**	-0.72	0.01	**-0.90**	**-0.76**	-0.68
Elterwater	-0.19	-0.11	-0.03	-0.61	-0.31	0.43	-0.64	-0.69	0.71	**-0.92**	-0.55	-0.16	0.35	-0.64	-0.59
Ennerdale Water	0.38	-0.08	**-0.88**	**0.87**	-0.66	**0.84**	**-0.94**	-0.71	**0.95**	**-0.95**	**-0.79**	-0.02	**-0.93**	**-0.81**	-0.72
Esthwaite Water	-0.06	0.06	**-0.96**	-0.51	0.55	-0.76	**0.87**	-0.70	**0.79**	**-0.97**	-0.68	-0.31	-0.67	-0.53	-0.64
Grasmere	-0.67	-0.25	**0.85**	-0.24	-0.25	**0.92**	0.07	-0.74	**0.97**	**-0.95**	**-0.77**	-0.24	**-0.82**	**-0.79**	**-0.89**
Haweswater	0.12	-0.06	**-0.84**	-	-0.33	-0.36	-0.42	**-0.77**	**0.90**	**-0.94**	**-0.94**	0.03	**-0.93**	**-0.92**	**-0.87**
Loughrigg Tarn	-0.48	**-0.85**	0.41	-0.36	-0.11	0.47	-0.51	-0.71	**0.79**	**-0.97**	-0.73	-0.25	-0.40	-0.74	-0.41
Loweswater	**0.80**	0.23	**-0.92**	0.68	0.62	**0.89**	-0.63	-0.73	**0.83**	**-0.95**	-0.71	-0.49	-0.72	-0.74	-0.33
Rydal Water	0.16	0.05	0.28	0.51	-0.58	0.57	-0.16	**-0.89**	**0.99**	**-0.98**	**-0.78**	-0.07	**-0.82**	**-0.79**	-0.75
Thirlmere	0.38	-0.27	-0.61	0.75	**-0.82**	**0.86**	-0.79	**-0.86**	**0.92**	**-0.97**	**-0.87**	-0.00	**-0.94**	**-0.88**	**-0.83**
Ullswater	0.12	0.05	-0.52	0.72	**0.83**	-0.77	-0.54	**-0.77**	**0.77**	**-0.97**	**-0.87**	-0.34	**-0.90**	**-0.90**	**-0.93**
Wastwater	0.23	0.44	-0.04	**0.79**	0.15	0.47	-0.42	**-0.79**	0.72	**-0.90**	**-0.86**	-0.37	**-0.85**	**-0.87**	**-0.81**
Windermere North Basin	-0.74	-0.16	-0.26	0.54	-0.18	0.73	-0.38	-0.57	**0.96**	**-0.97**	**-0.76**	-0.21	-0.69	**-0.82**	-0.33
Windermere South Basin	**-0.81**	-0.43	0.09	-	0.07	-0.47	-0.77	-0.57	**0.96**	**-0.97**	**-0.80**	-0.07	**-0.80**	**-0.84**	-0.52

NB. A declining concentration of H^+ is equivalent to an increase in pH.

3.3.1 Bassenthwaite Lake

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

Bassenthwaite Lake is a large shallow lake in the north-west of the English Lake District (Fig. 2.1). It has a very short average retention time for a lake of this size because it has a large catchment area (Table 2.1). Derwent Water and Thirlmere lie within the catchment of Bassenthwaite Lake. Key limnological features in 2010 are shown in Table 3.11. A comprehensive review of the ecology of Bassenthwaite Lake has recently been published (Thackeray *et al*., 2006).

Table 3.11. Summary of limnological conditions and trophic and Water Framework Directive classifications in Bassenthwaite Lake in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	244		
Mean pH (geometric mean)	7.1		
Mean total phosphorus (mg m^{-3})	17.0	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.1		
Mean nitrate-nitrogen (mg m^{-3})	329		
Mean silica (mg m^{-3})	1338		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	12.0	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	19.7	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	13.0		Moderate
Mean Secchi depth (m)	2.5	Eutrophic	
Minimum Secchi depth (m)	1.2	Eutrophic	
Minimum oxygen concentration (mg m^{-3})	0.2		

Bassenthwaite Lake appears to be on the meso-eutrophic boundary: The mean concentration of TP, maximum concentration of chlorophyll *a* and minimum Secchi depth are within the mesotrophic range, while the mean concentration of phytoplankton chlorophyll *a* and mean Secchi depth suggest the lake is eutrophic (Table 3.11). In terms of the current WFD classification boundaries, Bassenthwaite Lake is categorised as being in a Moderate ecological state for TP and for phytoplankton chlorophyll *a* .

There are no statistically significant changes in the main nutrients in Bassenthwaite Lake (Table 3.10) but there is an indication of declining concentrations of TP (Fig. 3.19). This is possibly reflected in declining concentrations of chlorophyll *a* but the change is not significant with these data. During this period there have been small detectable changes in the lake resolved by more detailed fortnightly sampling (Thackeray *et al*., 2004, 2006). Of the major ions, pH and alkalinity have increased, while sulphate, magnesium and potassium have decreased (Table 3.10).

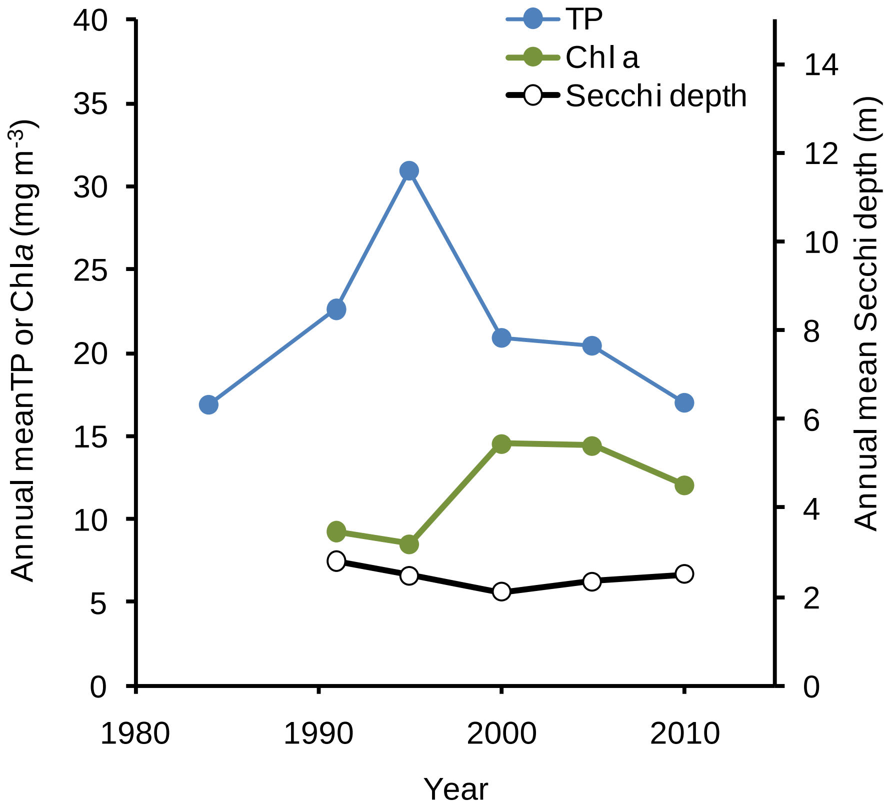


Figure 3.19. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Bassenthwaite Lake.*

Bassenthwaite Lake is studied fortnightly as part of the CEH long-term monitoring programme that started in 1990 on this lake and CEH has an Automatic Water Quality Monitoring Station (AWQMS) on the lake.

3.3.2 Blelham Tarn

Blelham Tarn is a small lake that drains into the North Basin of Windermere (Table 2.1, Fig. 2.1). In 2010 it had the highest annual mean alkalinity and concentration of potassium, calcium and magnesium of any of the 20 lakes studied here. It also had the second highest concentration of phytoplankton chlorophyll *a* and shallowest Secchi depth (Table 3.31).

Blelham Tarn (Photo: S.C. Maberly)

Table 3.12. Summary of limnological conditions and trophic and Water Framework Directive classifications in Blelham Tarn in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	475		
Mean pH (geometric mean)	7.1		
Mean total phosphorus (mg m^{-3})	17.9	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.3		
Mean nitrate-nitrogen (mg m^{-3})	382		
Mean silica (mg m^{-3})	1450		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	22.3	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	55.2	Eutrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	16.9		Moderate
Mean Secchi depth (m)	2.3	Eutrophic	
Minimum Secchi depth (m)	2.0	Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Blelham Tarn appears to be on the meso-eutrophic boundary (Table 3.12) but it suffers severe oxygen depletion at depth during summer. The ecological state in terms of WFD classification is Moderate.

There has been a statistically significant decrease in the concentration of nitrate in Blelham Tarn (Table 3.10). The concentration of TP in 2010 was markedy lower than in previous years (Fig. 3.20) but the overall change is not significant. This is unlikely to represent a recovery in the tarn because there has been a tendency for phytoplankton chlorophyll *a* to increase (Fig. 3.20). Of the major ions, alkalinity has increased and sulphate and potassium have decreased (Table 3.10). Overall, the lake therefore appears to be fairly stable.

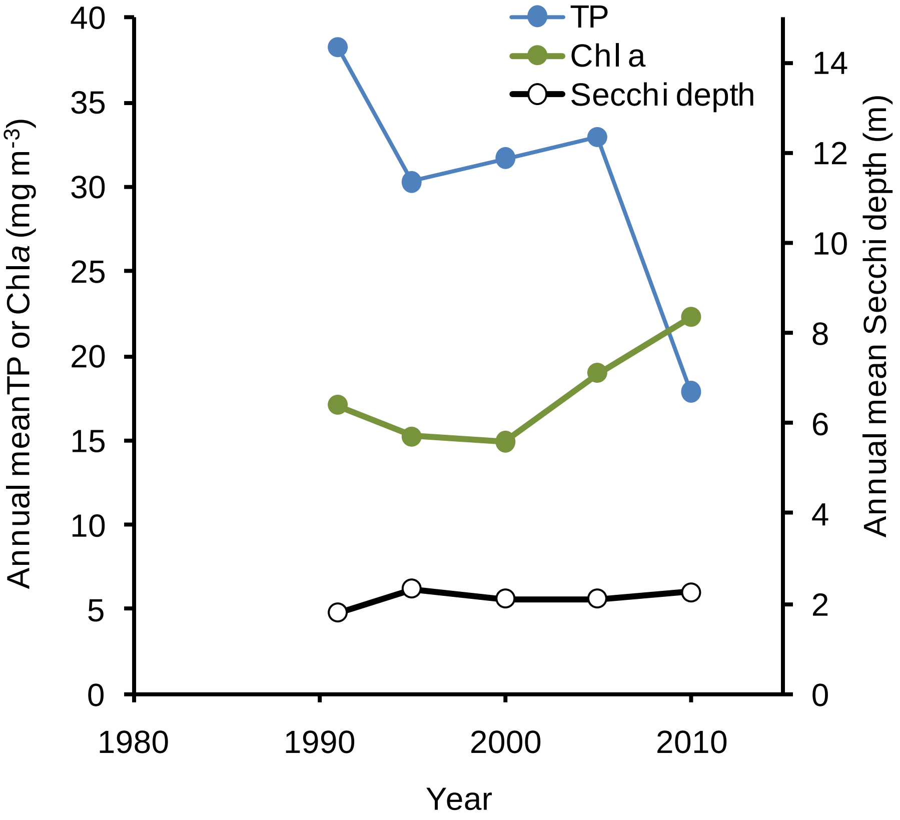


Figure 3.20. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Blelham Tarn.*

Blelham Tarn is studied fortnightly as part of the CEH long-term monitoring programme that was started by the Freshwater Biological Association in 1945 and continued by CEH since 1989. There is a CEH AWQMS on the lake.

3.3.3 Brothers Water

Brothers Water is a small lake with a fairly high-altitude catchment that drains into the southern end of Ullswater (Table 2.1). Of the 20 lakes in the Lakes Tour it had the fourth highest annual mean concentration of silica and the fourth deepest Secchi depth (Table 3.31).

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

Table 3.13. Summary of limnological conditions and trophic and Water Framework Directive classifications in Brothers Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	199		
Mean pH (geometric mean)	7.0		
Mean total phosphorus (mg m^{-3})	9.5	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	327		
Mean silica (mg m^{-3})	1475		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	2.6	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	4.5	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.6		High
Mean Secchi depth (m)	6.1	Oligotrophic	
Minimum Secchi depth (m)	4.5	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Brothers Water is close to the mesotrophic-oligotrophic boundary. Surprisingly for such a lake, there is quite a substantial oxygen depletion at depth (Table 3.10) but mainly in the bottom water which may reflect the fact that the water at depth is isolated in a fairly small volume because of the lake bathymetry (see section 4.1). Nevertheless when mapping onto the WFD classification it is classified as being at Good or High status (Table 3.13) although it is only just in the High status for chlorophyll *a*.

There have been no changes in the nutrient chemistry of Brothers Water (Table 3.10). There was a significant increase in alkalinity in Brothers Water. It was associated with declines in concentrations of sulphate, chloride, magnesium and potassium. There were no significant changes in chlorophyll *a* or Secchi depth.

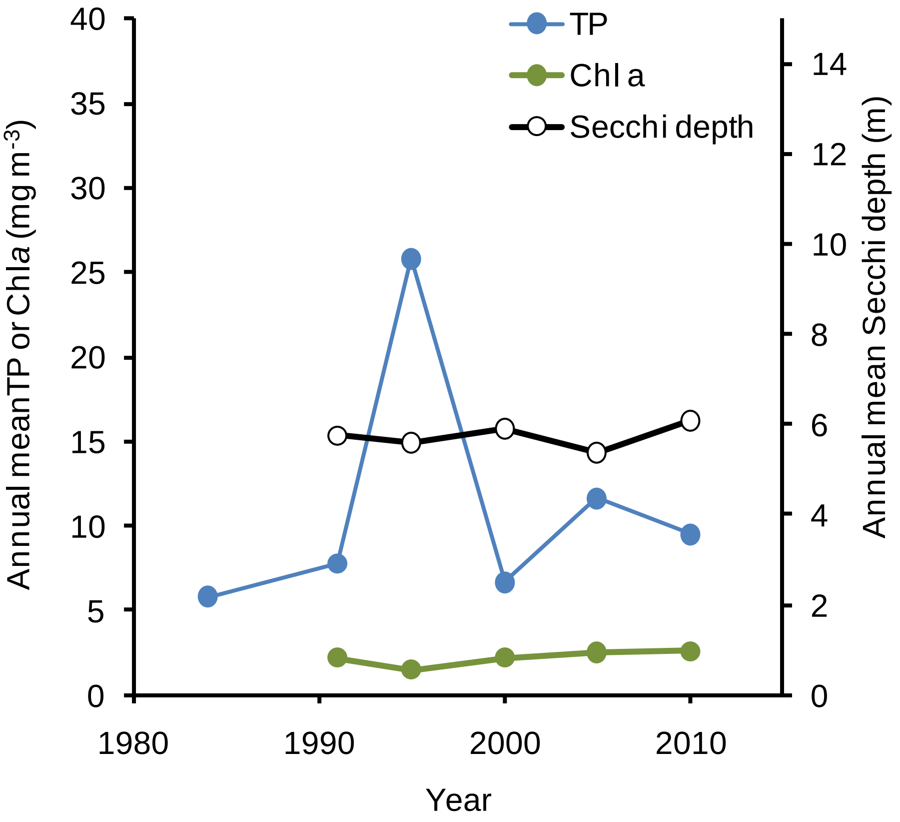


Figure 3.21. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Brothers Water.*

3.3.4 Buttermere

Buttermere (Photo R. Groben).

Buttermere is a moderately sized lake in the north-west of the English Lake District that drains into Crummock Water (Fig. 2.2). The Secchi depth is surprisingly variable (Fig. 3.4) with relatively low transparency in April despite phytoplankton chlorophyll *a* also being low. This suggests input of particulate or dissolved coloured material during heavy rainfall or disturbance of sediment during high winds, but nevertheless has the second deepest Secchi depth on average. It had the third lowest concentration of TP of any of the lakes in the Lakes Tour (after Wastwater and Ennerdale Water) and low concentrations of alkalinity and major ions (Table 3.31).

Table 3.14. Summary of limnological conditions and trophic and Water Framework Directive classifications in Buttermere in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	64		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	6.7	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.9		
Mean nitrate-nitrogen (mg m^{-3})	263		
Mean silica (mg m^{-3})	1293		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	1.7	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	2.4	Ultra-oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.3		High
Mean Secchi depth (m)	8.1	Oligotrophic	
Minimum Secchi depth (m)	5.5	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	7.9		

All the measures suggest that Buttermere is oligotrophic (Table 3.14). This is also reflected in the limited oxygen depletion at depth. In terms of the WFD, Buttermere is classified as being at Good or High ecological status.

There no significant changes in nutrient concentrations in Buttermere apart from a decline in silica (Table 3.10) which could possibly result from slight nutrient enrichment, especially as it is associated with a marked, statistically significant reduction in Secchi depth (Table 3.10, Fig. 3.22) and so this lake should be monitored closely even though phytoplankton chlorophyll *a* has not changed. There has been a statistically significant increase in pH and alkalinity (Table 3.10). Concentrations of sulphate, chloride, magnesium and sodium have all declined. The altered major ions are probably caused by reduced sulphur deposition causing a reversal of acidification in some poorly buffered lakes and streams in Cumbria (Tipping *et al*., 1998).

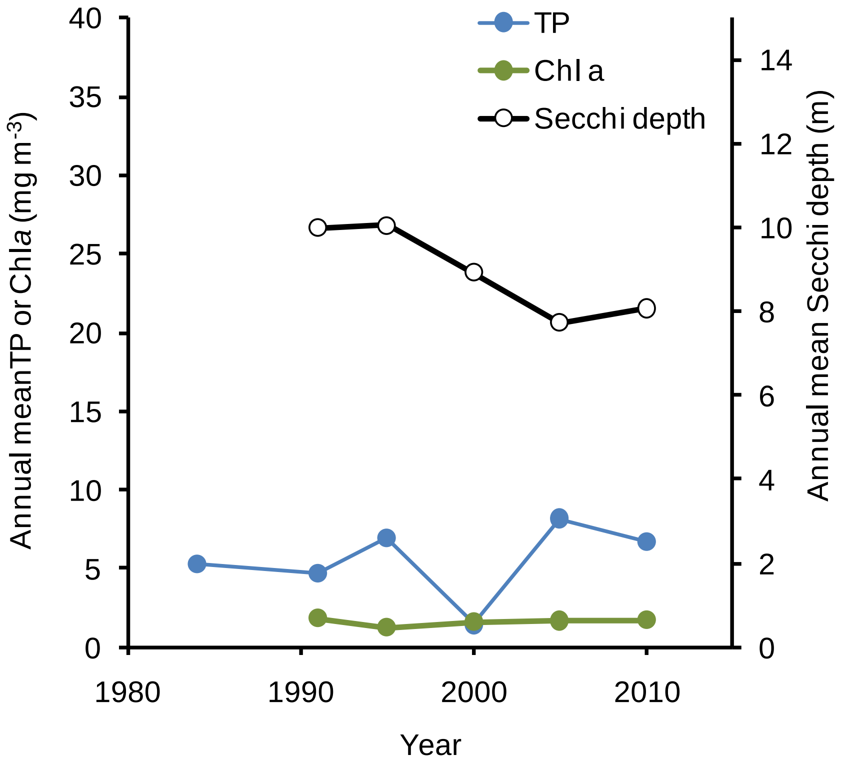


Figure 3.22. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Buttermere.*

3.3.5 Coniston Water

Coniston Water is the fifth largest lake in the study in terms of area and the fourth largest in terms of volume (Table 2.1).

Coniston Water (Photo I.J. Winfield).

Table 3.15. Summary of limnological conditions and trophic and Water Framework Directive classifications in Coniston Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	214		
Mean pH (geometric mean)	7.2		
Mean total phosphorus (mg m^{-3})	8.2	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.9		
Mean nitrate-nitrogen (mg m^{-3})	371		
Mean silica (mg m^{-3})	620		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	4.5	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	6.5	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	5.0		Good
Mean Secchi depth (m)	5.3	Mesotrophic	
Minimum Secchi depth (m)	4.0	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	6.8		

Various measures suggest that Coniston Water is mesotrophic or oligo-mesotrophic and this is reflected in the slight oxygen depletion at depth (Table 3.15). In terms of the WFD the ecological status is Good in terms of TP and chlorophyll *a*. A review of the ecology of Coniston Water was carried out by Maberly *et al*. (2003). The Coniston-Crake Partnership was set up to promote good water quality in Coniston Water (http://www.scrt.co.uk/coniston-and-crake-partnership/coniston-and-crake-partnership).

The nutrient chemistry of Coniston Water is relatively stable. There have been no real trends in nutrient chemistry or phytoplankton chlorophyll *a* or Secchi depth (Table 3.10, Fig. 3.23). As in many lakes, pH and alkalinity have increased while sulphate, and magnesium have decreased.

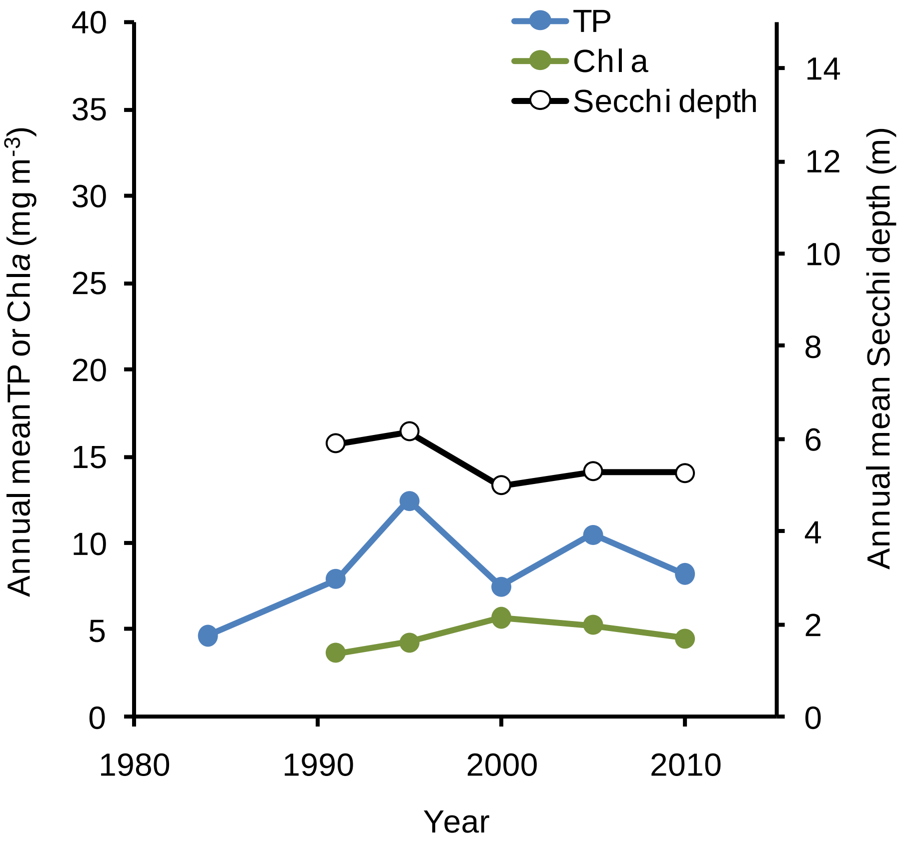


Figure 3.23. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Coniston Water.*

3.3.6 Crummock Water

Crummock Water receives water from Buttermere to the south and Loweswater to the north-west (Fig. 2.2). It had the second lowest alkalinity and pH (Table 3.31) of the 20 lakes.

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

Table 3.16. Summary of limnological conditions and trophic and Water Framework Directive classifications in Crummock Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	63		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	6.6	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.9		
Mean nitrate-nitrogen (mg m^{-3})	248		
Mean silica (mg m^{-3})	942		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	2.1	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	3.4	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.8		High
Mean Secchi depth (m)	7.4	Oligotrophic	
Minimum Secchi depth (m)	5.3	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	6.2		

Its trophic status is essentially oligotrophic and it had the third lowest concentration of TP and chlorophyll *a* and the third deepest Secchi depth. The lack of a substantial depletion of oxygen at depth is consistent with its oligotrophic status. Its ecological status in terms of the WFD is Good for TP and High for phytoplankton chlorophyll *a*.

There have been no statistically significant changes in nutrient chemistry or indications of change in trophic state (Table 3.10). The pattern of gradually increasing alkalinity and pH seen elsewhere is also present in Crummock Water (Table 3.10) but basically the lake appears to be in a stable state.

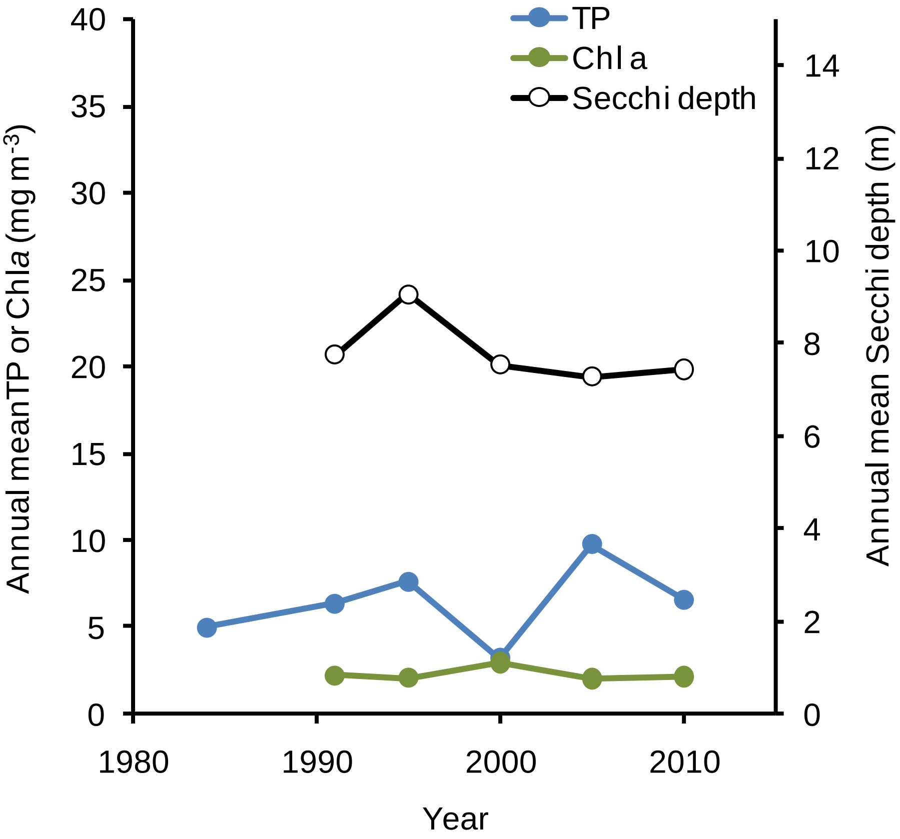
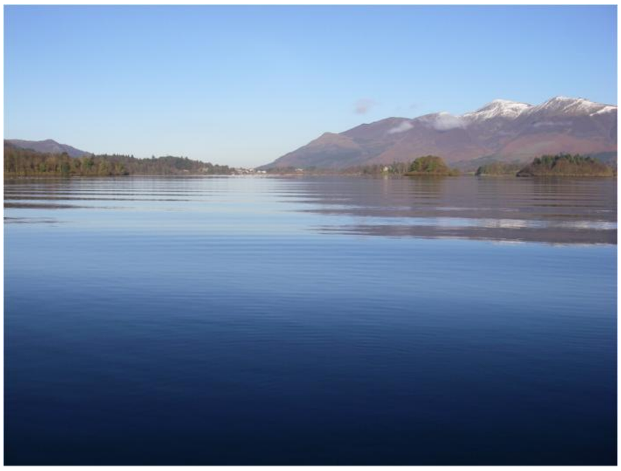


Figure 3.24. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Crummock Water.*

3.3.7 Derwent Water



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

Derwent Water lies in the north of the English Lake District within the catchment of Bassenthwaite Lake (Fig. 2.2). It is relatively shallow but has some deep water down to 22 m (Table 2.1). Of the 20 lakes in the Lakes Tour, Derwent Water had the lowest annual average concentration of nitrate and sulphate and low concentrations of magnesium, but the third highest concentration of chloride (Table 3.31).

Table 3.17. Summary of limnological conditions and trophic and Water Framework Directive classifications in Derwent Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	118		
Mean pH (geometric mean)	6.9		
Mean total phosphorus (mg m^{-3})	9.6	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	200		
Mean silica (mg m^{-3})	935		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	5.9	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	9.9	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	7.6		Good
Mean Secchi depth (m)	4.1	Mesotrophic	
Minimum Secchi depth (m)	3.5	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	1.6		

The trophic status of Derwent Water is clearly mesotrophic (Table 3.17) but oxygen depletion is quite substantial, although this is restricted to the deep water (Fig. 3.3). The status in terms of the WFD was ‘Good’ for the annual mean concentration of TP and phytoplankton chlorophyll *a* but the concentration was not far from the G:M threshold.

Derwent Water is basically stable but there are continuing hints of slight nutrient enrichment. Concentrations of TP have increased, although not significantly (Table 3.10), but concentrations of nitrate and silica have declined indicating increased demand. This is supported by slightly increased concentrations of chlorophyll *a* (Fig. 3. 25). The pattern of changing major ions is similar to that seen in many of the other lakes (Table 3.10).

Derwent Water is studied fortnightly as part of the CEH long-term monitoring programme that began on this lake in 1990. A nutrient budget and modelling study has been carried out (Maberly, Elliott & Thackeray 2006).

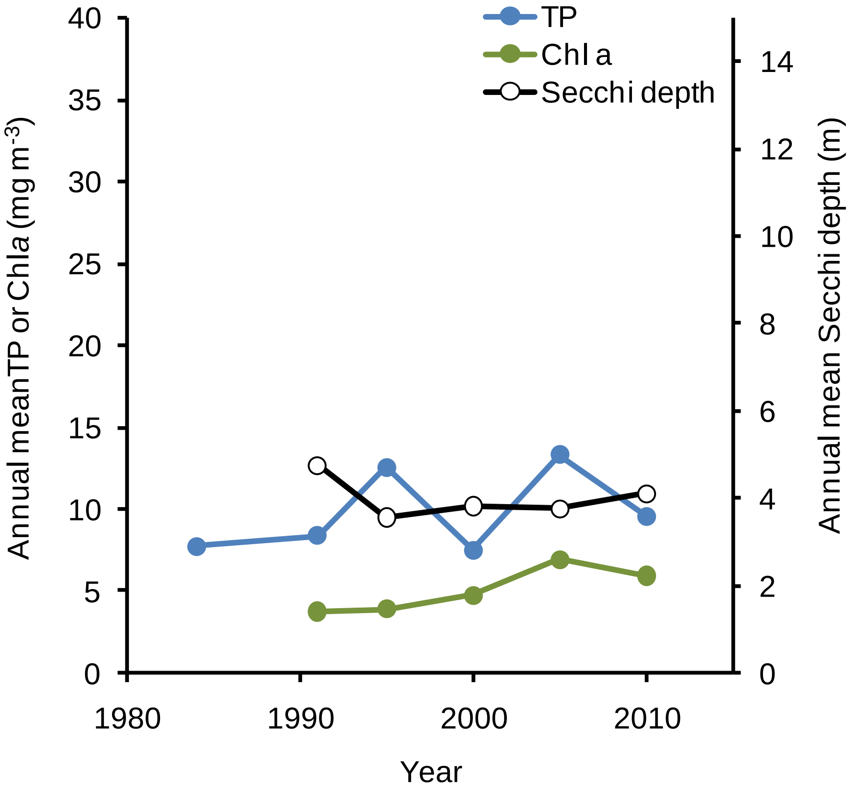


Figure 3.25. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Derwent Water.

3.3.8 Elterwater

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

The inner basin of Elterwater is the smallest of the 20 lakes studied here in terms of area and volume and also has the second shortest average retention time. Elterwater had the highest mean concentration of TP and the third highest concentration of chlorophyll *a* and the third shallowest Secchi depth (Table 3.31).

Table 3.18. Summary of limnological conditions and trophic and Water Framework Directive classifications in Elterwater in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	344		
Mean pH (geometric mean)	6.9		
Mean total phosphorus (mg m^{-3})	20.8	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.1		
Mean nitrate-nitrogen (mg m^{-3})	273		
Mean silica (mg m^{-3})	1588		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	16	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	34	Eutrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	13.6		Moderate
Mean Secchi depth (m)	2.5	Eutrophic	
Minimum Secchi depth (m)	1.9	Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Elterwater can be allocated to a range of trophic categories depending on the feature used (Table 3.18). Thus it is classified as mesotrophic based on TP and its minimum Secchi depth but eutrophic based on mean chlorophyll *a* and mean Secchi depth. A trophic classification of eutrophic is probably the fairest category and consistent with the complete oxygen depletion at depth. In terms of the WFD, Elterwater is categorised as Moderate for TP and phytoplankton chlorophyll *a*.

There have been no statistically significant long-term changes in the nutrient concentrations in Elterwater (Table 3.10). However, it is clear from the long-term changes in annual mean concentration of TP that there has been a marked reduction in concentration since a peak in 1995 of 139 mg m^{-3}: the concentration in 2010 is now lower than the first record in 1984 and continues the downward trend noted in 2005 (Fig. 3.26). This is also reflected in lower concentrations of phytoplankton chlorophyll *a* and a very slightly increased Secchi depth. At least some of this improvement will have resulted from re-routing the sewage outfall from Elterwater to the River Brathay below the lake.

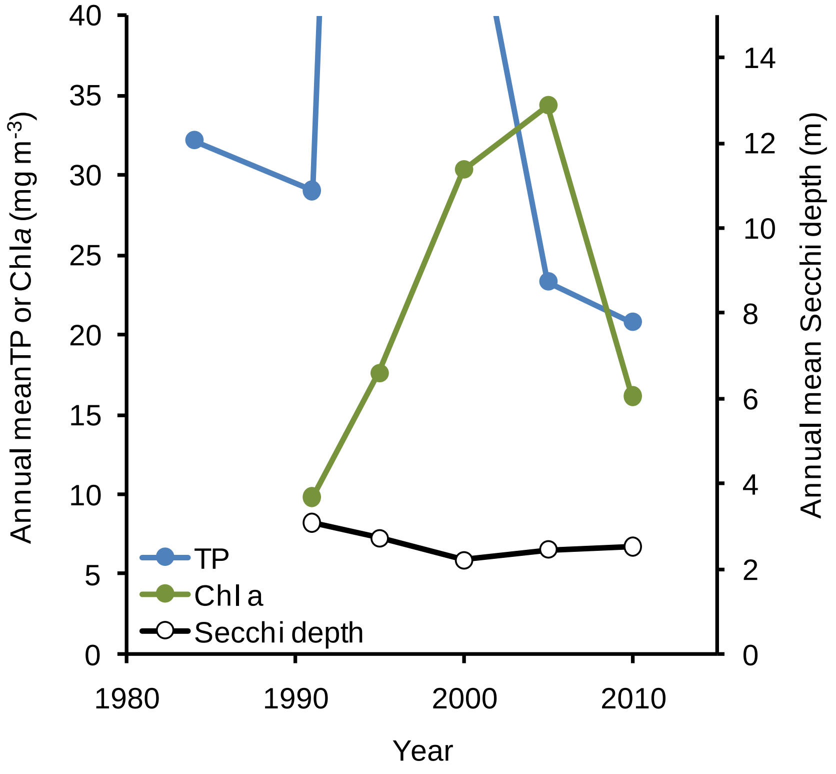


Figure 3.26. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Elterwater. A high mean concentration in 1995 of 139 mg m^{-3} is not plotted for clarity.

3.3.9 Ennerdale Water

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

Ennerdale Water is a moderate-sized lake in the west of the English Lake District (Fig. 2.2). It had the lowest alkalinity and concentration of calcium and potassium and the highest concentration of silica of any of the studied lakes (Figs 3.7, 3.13). It also had the second lowest concentration of TP after Wastwater, but the concentration of chlorophyll *a* was sixth lowest and the Secchi depth was fifth deepest (Table 3.31) and compared to 2005, both of these indicate a marked deterioration in water quality (see section 4.2.9).

Table 3.19. Summary of limnological conditions and trophic and Water Framework Directive classifications in Ennerdale Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	54		
Mean pH (geometric mean)	6.6		
Mean total phosphorus (mg m^{-3})	5.8	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	232		
Mean silica (mg m^{-3})	2070		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	2.6	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	5.8	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.4		High
Mean Secchi depth (m)	5.9	Mesotrophic	
Minimum Secchi depth (m)	5.0	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	8.4		

Ennerdale Water is an unproductive lake, classified as oligotrophic but recent increases in chlorophyll *a* and decreases in Secchi depth have pushed it into mesotrophic for these variables (Table 3.19). There is very little evidence for oxygen depletion at depth. In terms of the WFD it is categorised as Good for TP and High for phytoplankton chlorophyll *a*. The recent increase in phytoplankton chlorophyll *a* and reduction in Secchi depth are causes of considerable concern.

In Ennerdale Water the concentration of TP has increased slightly and there has been a significant decrease in the concentration of nitrate (Table 3.10). There is an indication of increased productivity in the lake: annual concentrations of chlorophyll *a* have increased significantly (Table 3.10; Fig. 3.27). The most dramatic change in Ennerdale Water is a marked decline in Secchi depth in spring, summer and autumn (Table 3.10; Fig. 3.27). Alkalinity has increased while many of the other major ions have decreased.

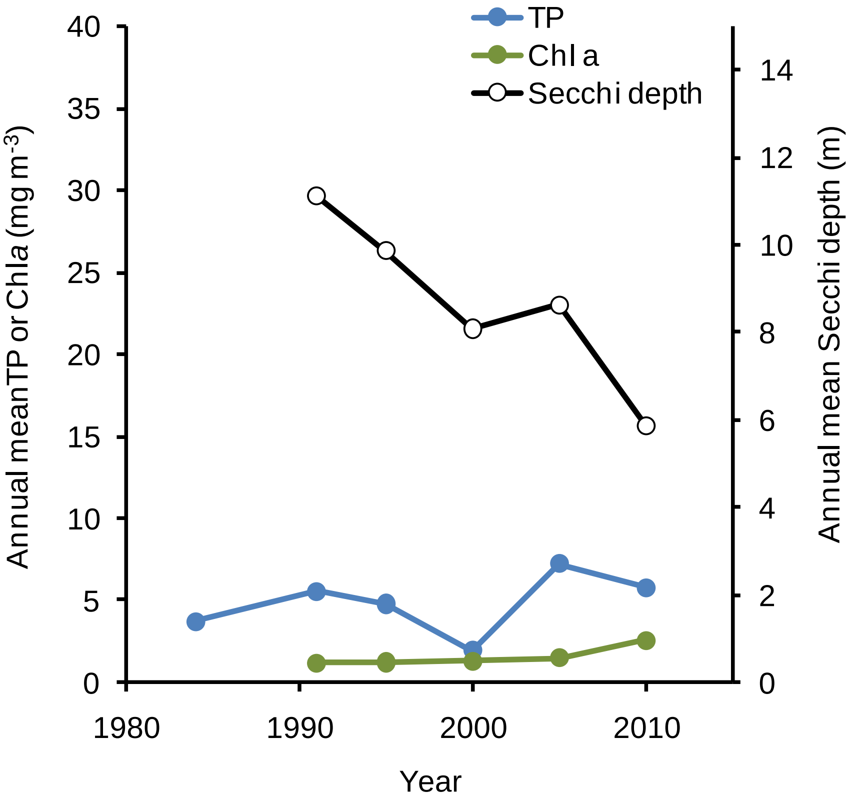


Figure 3.27. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Ennerdale Water.*

One explanation for this dramatic decline in water clarity is an increase in particulate material as result of management within the catchment or an increase in coloured dissolved organic matter as a result of land management or reduction in acidification (Monteith *et al*., 2007). However, it is also possible that the slight increase in phytoplankton chlorophyll *a* is the, or one of the, causes of the reduction in Secchi depth. To test this possibility, the relationship between annual mean Secchi depth and annual mean phytoplankton chlorophyll *a* were plotted for the twenty lakes over the six available years. The results show a very clear relationship that follows a power curve (Fig. 3.28). The annual relationship between Secchi depth and phytoplankton chlorophyll *a* follows a very similar relationship. This suggests that some or all of the reduction in Secchi depth results from the slight increase in productivity detected in Ennerdale Water. Clearly the cause of this dramatic change in water quality requires further study.

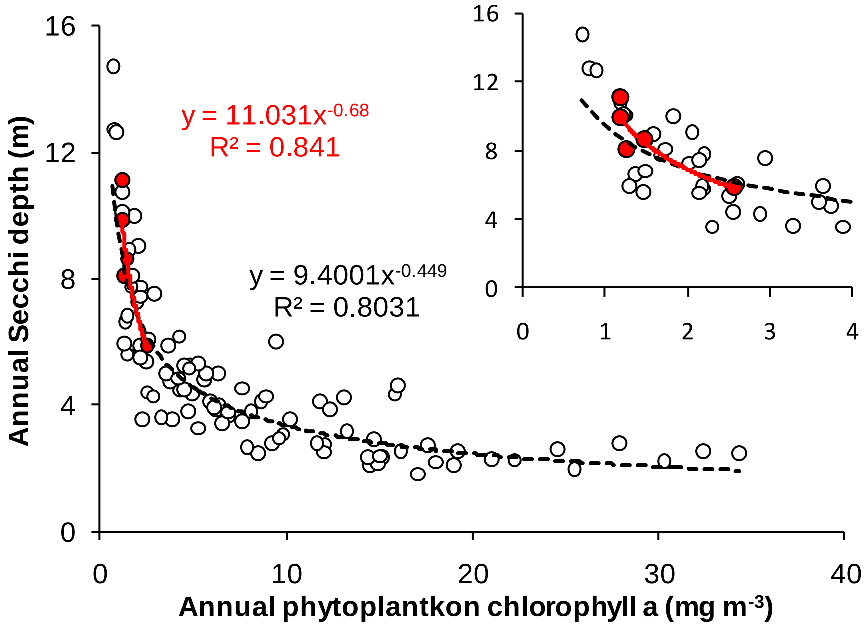


Figure 3.28 Relationship between annual mean Secchi depth and annual mean phytoplankton chlorophyll a *for the twenty lakes over the six available years from 1984 to 2010 (open symbols). The red symbols show the data for Ennerdale Water. The fitted power curve is given for both data sets and the inset show the same data at low concentrations of phytoplankton chlorophyll* a.

3.3.10 Esthwaite Water

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

Esthwaite Water is a small to moderate sized lake that drains into the South Basin of Windermere via the Cunsey Beck. It was classified as the most productive lake in the English Lake District when Pearsall made his original trophic classification (Pearsall, 1921). In 2010 Esthwaite had the highest annual average concentration of SRP, chloride and sodium and the second highest concentration of TP, pH, alkalinity, sulphate, potassium and calcium (Table 3.31).

Table 3.20. Summary of limnological conditions and trophic and Water Framework Directive classifications in Esthwaite Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	431		
Mean pH (geometric mean)	7.3		
Mean total phosphorus (mg m^{-3})	20.4	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	4.2		
Mean nitrate-nitrogen (mg m^{-3})	346		
Mean silica (mg m^{-3})	1378		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	7.9	Meso/Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	10.8	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	8.2		Moderate
Mean Secchi depth (m)	2.7	Eutrophic	
Minimum Secchi depth (m)	1.9	Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Different ways of assessing trophic status give categories of mesotrophic or eutrophic, (Table 3.20) and Esthwaite is probably on the eutrophic-mesotrophic boundary following the dramatic improvement in water quality in 2009 and 2010 (Maberly *et al*. 2011), although the pronounced oxygen depletion at depth (Table 3.20) still indicates a eutrophic lake. WFD criteria suggest that the lake is at Moderate ecological status. There is an attempt currently to remediate the lake with closure of the fish-farm and upgrades to the waste water handling and treatment (Maberly *et al*. 2011).

There has been little statistical change in the nutrient chemistry in Esthwaite Water apart from a marked decline in concentration of nitrate (Table 3.10) but unlike, for example, Derwent Water this does not seem to be associated with an increase in nutrient availability. In fact, there is evidence for a reduction in phytoplankton chlorophyll *a* and a significant increase in Secchi depth (Table 3.10; Fig. 3.28), although the CEH fortnightly monitoring shows this to have occurred over the last two to three years (Maberly *et al*. 2011). There has been a significant increase in alkalinity but no change in the concentration of other major ions apart from the ubiquitous reduction in sulphate concentrations (Table 3.10).

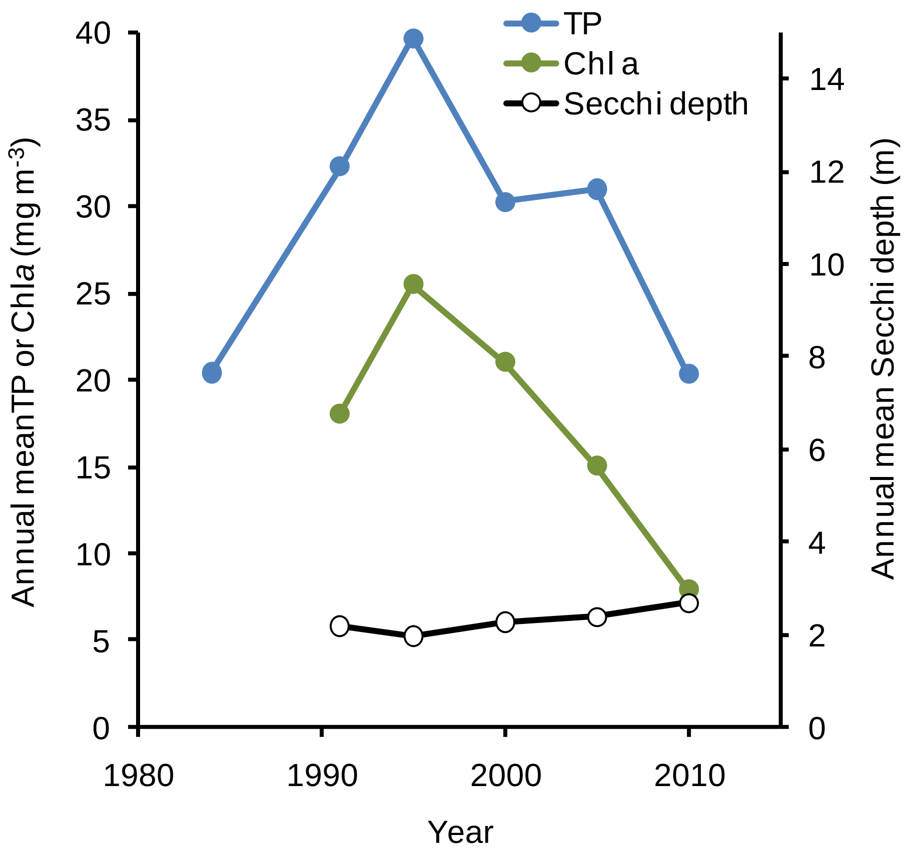


Figure 3.29. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Esthwaite Water.*

Esthwaite Water is studied fortnightly as part of the CEH long-term monitoring programme that was started by the Freshwater Biological Association in 1945 and continued by CEH since 1989. There is a CEH AWQMS on the lake.

3.3.11 Grasmere

Grasmere is a fairly small lake at the northern end of the Windermere catchment with a short retention time (Fig. 3.2).

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

Table 3.21. Summary of limnological conditions and trophic and Water Framework Directive classifications in Grasmere in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	163		
Mean pH (geometric mean)	6.9		
Mean total phosphorus (mg m^{-3})	18.0	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.4		
Mean nitrate-nitrogen (mg m^{-3})	467		
Mean silica (mg m^{-3})	1182		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	13.1	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	29.0	Eutrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	10.3		Moderate
Mean Secchi depth (m)	4.2	Mesotrophic	
Minimum Secchi depth (m)	3.0	Oligo/Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Its trophic status is somewhere on the mesotrophic to eutrophic boundary but it experiences quite pronounced oxygen depletion at depth (Table 3.21). In terms of the WFD, its ecological status is Moderate for TP and phytoplankton chlorophyll *a*.

There has been a statistically significant increase in concentration of nitrate in Grasmere (Table 3.10) associated with a reduction, although not significant, in concentration of TP (Fig. 3.30). Surprisingly, this is associated with a relatively stable concentration of phytoplankton chlorophyll *a* over the last three Lakes Tours, although these concentrations are greater than those from the 1990s (Fig. 3.30). The major ions show the same pattern of increasing alkalinity, decreasing sulphate concentration and decreasing concentrations or many other major ions (Table 3.10).

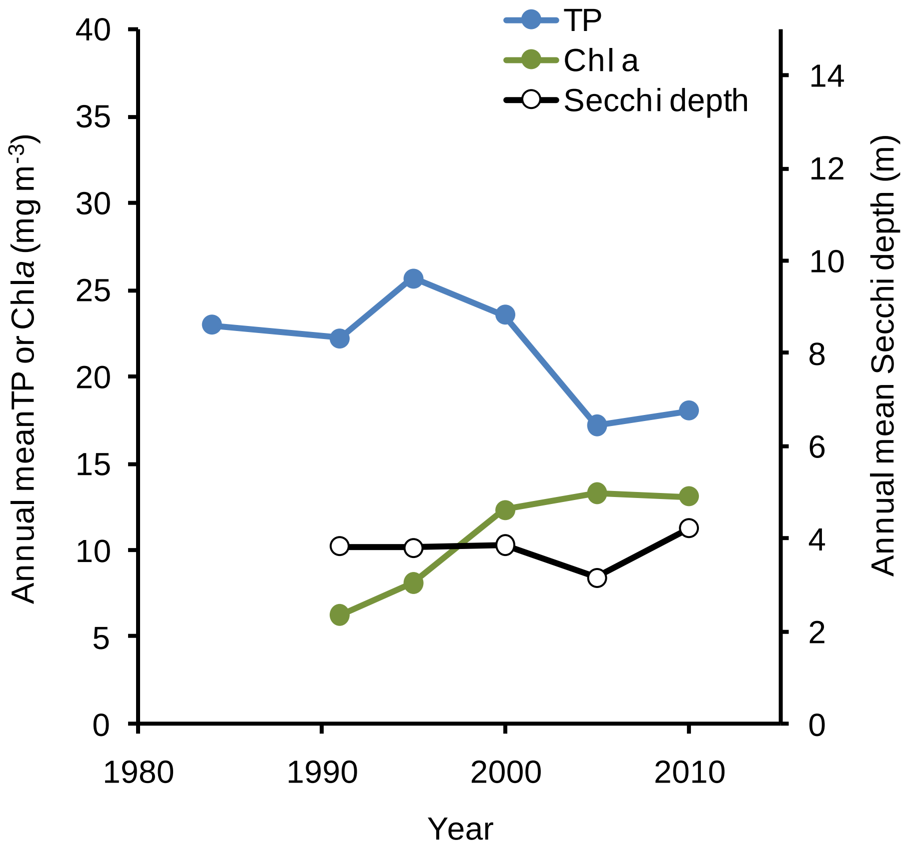


Figure 3.30. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Grasmere.*

Grasmere is studied fortnightly as part of the CEH long-term monitoring programme that was started by the Freshwater Biological Association in 1969 and continued by CEH since 1989. A recent review of Grasmere can be found in Reynolds *et al.* (2001).

3.3.12 Haweswater

Haweswater is the fifth largest lake in terms of volume and fourth deepest (Table 2.1). It is a reservoir and was greatly increased in size in about 1930 by the construction of a dam at the north-east end of the lake. As an annual mean it had the lowest concentration of chloride and sodium of any of the 20 lakes in 2010 (Table 3.31).

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

Table 3.22. Summary of limnological conditions and trophic and Water Framework Directive classifications in Haweswater in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	198		
Mean pH (geometric mean)	7.2		
Mean total phosphorus (mg m^{-3})	9.2	Oligotrophic	High
Mean soluble reactive phosphorus (mg m^{-3})	1.1		
Mean nitrate-nitrogen (mg m^{-3})	231		
Mean silica (mg m^{-3})	1202		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	2.3	Oligotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	3.0	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	2.7		Good
Mean Secchi depth (m)	3.5	Mesotrophic	
Minimum Secchi depth (m)	3.0	Oligo/Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	6.5		

The trophic status of Haweswater is mesotrophic, tending towards oligotrophic which is consistent with the minimal oxygen depletion at depth (Table 3.22). In terms of the WFD, it has High ecological status for TP and Good ecological status for phytoplankton chlorophyll *a* although the concentration is only just above the Good:Moderate boundary.

Nutrient concentrations in Haweswater have not changed apart from a reduction in nitrate concentration (Table 3.10). There is a clear indication that the alkalinity and pH of Haweswater has increased since 1984. Concentrations of sulphate, chloride, magnesium sodium and potassium have all declined statistically significantly (Table 3.10). There have been no statistically significant changes in phytoplankton chlorophyll *a* or Secchi depth (Table 3.10) although it is possible that chlorophyll *a* has decreased slightly in recent years. (Fig. 3.31).

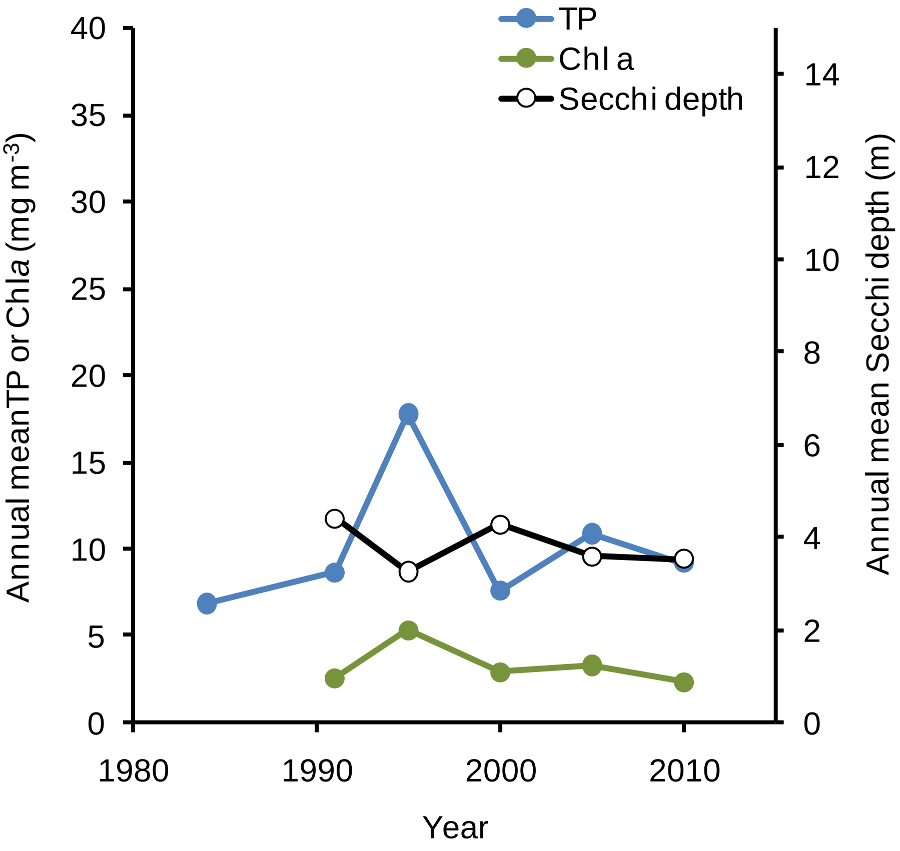


Figure 3.31. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Haweswater.*

3.3.13 Loughrigg Tarn

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

Loughrigg Tarn is in the Windermere catchment. It is the second smallest lake studied here in terms of both area and volume. It has a relatively long retention time for a lake of its size (Table 2.1). It had the highest annual concentration of phytoplankton chlorophyll *a* and the third highest concentration of TP of any of the 20 lakes in 2010 (Table 3.31).

Table 3.23. Summary of limnological conditions and trophic and Water Framework Directive classifications in Loughrigg Tarn in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	312		
Mean pH (geometric mean)	7.2		
Mean total phosphorus (mg m^{-3})	19.2	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	0.7		
Mean nitrate-nitrogen (mg m^{-3})	350		
Mean silica (mg m^{-3})	985		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	32.4	Hypertrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	49.3	Eutrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	29.7		Poor
Mean Secchi depth (m)	2.5	Eutrophic	
Minimum Secchi depth (m)	1.1	Eutrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Loughrigg Tarn has a range of trophic state assessments depending on which feature is used. The mean TP concentration suggest that the tarn is mesotrophic whereas other measures suggest the tarn is eutrophic and the mean phytoplankton chlorophyll *a* concentration indicates hypertrophy (Table 3.23). On balance, Loughrigg Tarn is probably eutrophic and this is consistent with the substantial oxygen depletion at depth (Table 3.23). The classification in terms of the WFD suggests that Loughrigg Tarn has Moderate ecological status in terms of TP but only Poor ecological status for phytoplankton chlorophyll *a*. This may result from the relatively long retention time that reduces hydraulic loss of phytoplankton populations.

The nutrient chemistry in Loughrigg Tarn has been relatively stable (Table 3.10) but there has been a generally decreasing concentration of TP (Fig. 3.32). This has occurred at a time of generally increasing annual concentration of phytoplankton chlorophyll *a* (Fig. 3.32). Analysis of the data shows this to have been largely caused by dramatic increases in autumn phytoplankton as was noted in the previous report (Maberly *et al*., 2006). In 1991, autumn phytoplankton chlorophyll *a* was only 11 mg m^{-3} and this increased in the succeeding surveys and in 2005 and 2010 was 49 mg m^{-3}. The causes of this increase are not immediately apparent. The major ions are little changed apart from an increase in alkalinity and decrease is sulphate (Table 3.10).

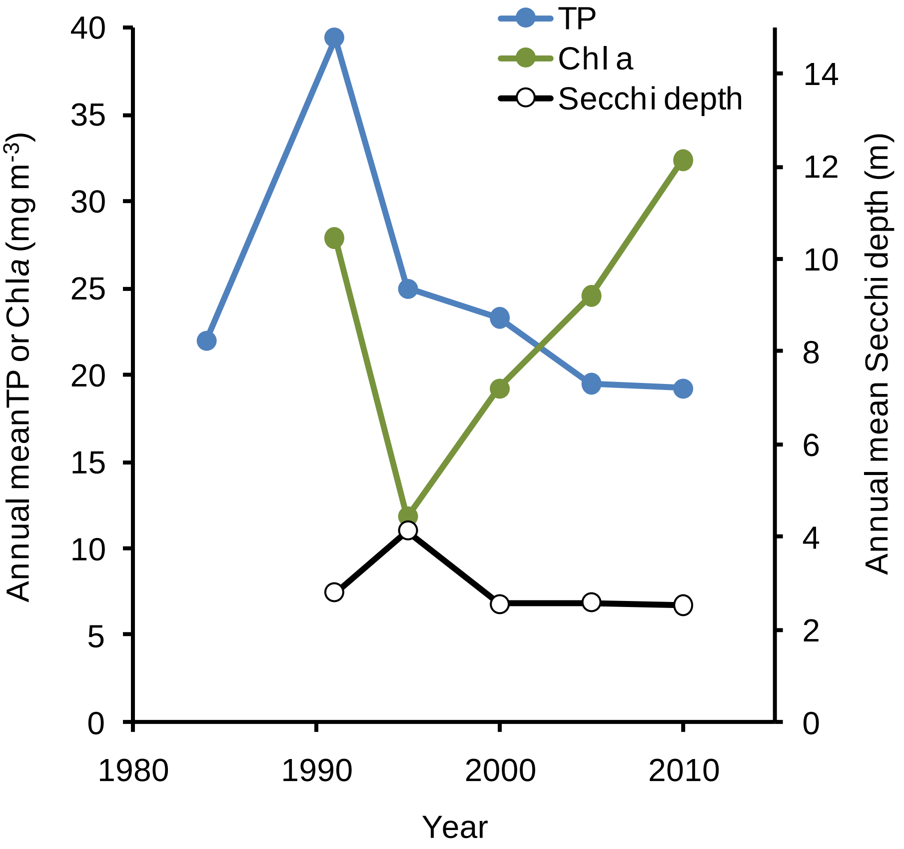


Figure 3.32. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Loughrigg Tarn.

3.3.14 Loweswater

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

Loweswater is a moderate to small lake in the north-west of the English Lake District that drains into Crummock Water Fig. 2.1). It has a relatively long retention time for a lake of its size (Table 2.1). As an annual mean for the 20 lakes in 2010, Loweswater had the highest concentration of sulphate and second highest concentration of magnesium (Table 3.31).

Table 3.24. Summary of limnological conditions and trophic and Water Framework Directive classifications in Loweswater in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	197		
Mean pH (geometric mean)	7.1		
Mean total phosphorus (mg m^{-3})	14.8	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.3		
Mean nitrate-nitrogen (mg m^{-3})	356		
Mean silica (mg m^{-3})	1005		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	11.7	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	19.2	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	13.6		Moderate
Mean Secchi depth (m)	2.8	Eutrophic	
Minimum Secchi depth (m)	1.9	Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Loweswater is close to the mesotrophic-eutrophic boundary, probably tending to be eutrophic given the complete oxygen depletion at depth (Table 3.24). In terms of the WFD, Loweswater is classified as Moderate for TP and for phytoplankton chlorophyll *a*.

Loweswater shows clear evidence for nutrient enrichment. There has been a significant increase in concentration of TP and a decline in concentration of nitrate probably as a result of increased demand (Table 3.10). The phytoplankton chlorophyll *a* has increased significantly and Secchi depth has tended to decrease (Table 3.10; Fig. 3.33). There has been an increase in alkalinity and a reduction in sulphate but no significant changes in the other major ions (Table 3.10).

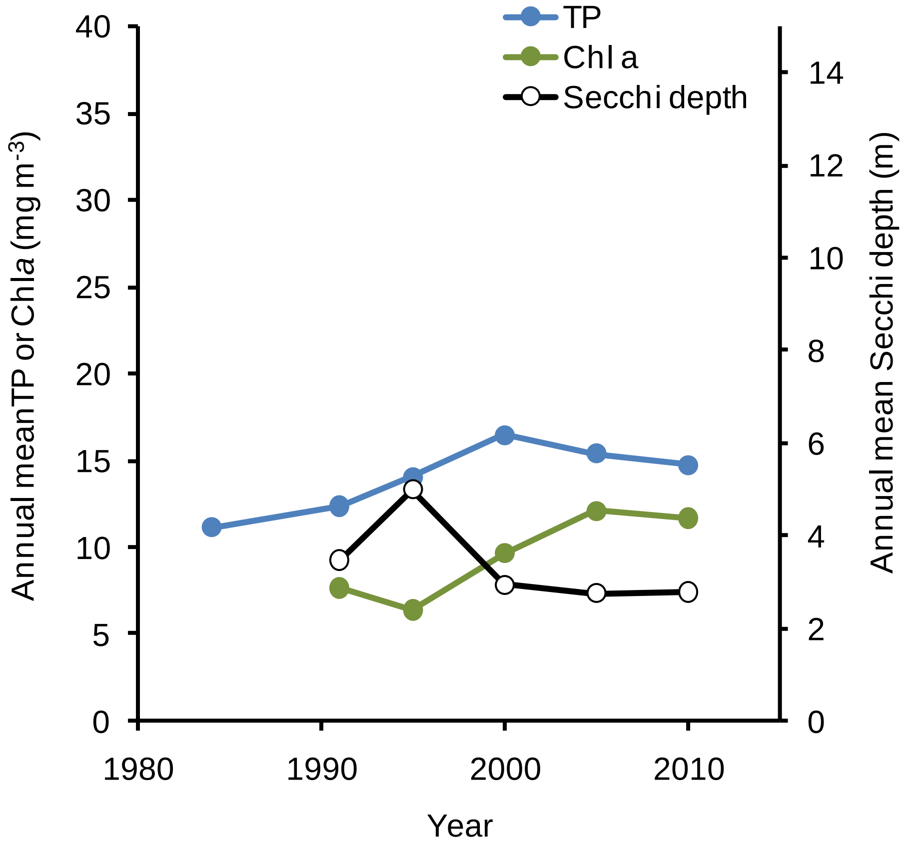


Figure 3.33. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Loweswater.*

Loweswater has been the subject of a community-led catchment management project by CEH and Lancaster University (http://www.lancaster.ac.uk/fass/projects/loweswater/noticeboard.htm). The results of a 12-month study of Loweswater are given in Maberly *et al*. (2006).

3.3.15 Rydal Water

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

Rydal Water is a small lake that receives water from the slightly larger Grasmere less than 1 km upstream (Fig. 2.1). Rydal Water eventually flows into the River Rothay and thence into the North Basin of Windermere. As an annual mean Rydal Water had the second highest concentration of nitrate (Table 3.31).

Table 3.25. Summary of limnological conditions and trophic and Water Framework Directive classifications in Rydal Water in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	189		
Mean pH (geometric mean)	7.0		
Mean total phosphorus (mg m^{-3})	13.7	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	2.4		
Mean nitrate-nitrogen (mg m^{-3})	446		
Mean silica (mg m^{-3})	1158		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	8.9	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	21.1	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	8.9		Moderate
Mean Secchi depth (m)	4.3	Mesotrophic	
Minimum Secchi depth (m)	2.8	Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	0.1		

Rydal Water appears to be on the mesotrophic-eutrophic boundary, probably tending towards mesotrophic. In terms of the WFD, the mean concentration of TP and phytoplankton chlorophyll *a* are both categorised as Moderate.

Rydal Water shows signs of mild nutrient enrichment. Overall, however, nutrient concentrations are relatively stable (Table 3.10; Fig. 3.34). Compared to 2005, conditions in 2010 were encouraging with a decline in TP and chlorophyll *a* and an increase in Secchi depth (Fig. 3.34). 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.

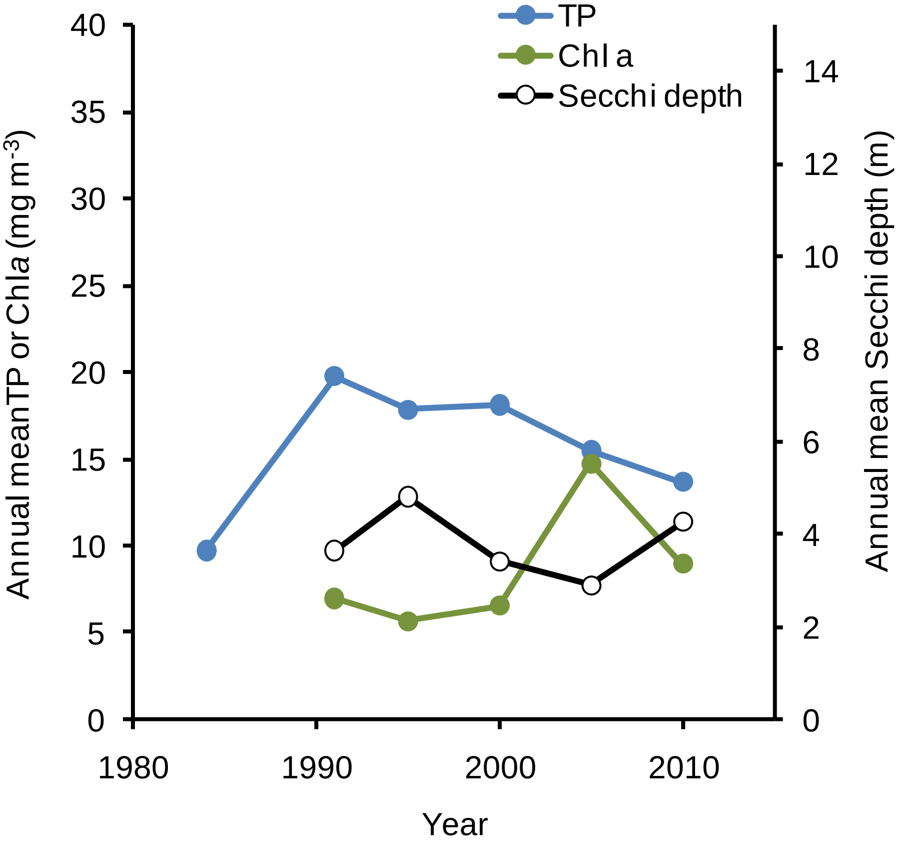


Figure 3.34. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Rydal Water.*

3.3.16 Thirlmere

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

Thirlmere is a moderate sized lake in the centre of the English Lake District and is part of the Bassenthwaite catchment (Fig. 2.1). It is dammed at its northern end to form a reservoir and as a result experiences quite marked changes in water level. As an annual mean in 2010, Thirlmere had the lowest concentration of magnesium the second lowest concentration of nitrate, chloride, sulphate and sodium (Table 3.31).

Table 3.26. Summary of limnological conditions and trophic and Water Framework Directive classifications in Thirlmere in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	72		
Mean pH (geometric mean)	6.7		
Mean total phosphorus (mg m^{-3})	7.8	Oligotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	0.6		
Mean nitrate-nitrogen (mg m^{-3})	219		
Mean silica (mg m^{-3})	1123		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	4.2	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	6.9	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	5.1		Moderate
Mean Secchi depth (m)	4.8	Mesotrophic	
Minimum Secchi depth (m)	4.5	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	5.3		

Thirlmere is oligotrophic with some indication of mesotrophy as mean Secchi depth and phytoplankton chlorophyll *a* lie in this higher category (Table 3.26). The relatively shallow Secchi depth may result from dissolved organic carbon as some streams, from the coniferous plantations on the western side, have quite high concentrations of dissolved organic carbon (S.C. Maberly, unpub.). Tipping *et al*. (1988) found that Thirlmere had a relatively high absorbance at 340 nm compared to other Cumbrian lakes. The chlorophyll *a* in 2010 was double that in 2005 which gives some cause for concern (see section 4.2.16). There is virtually no oxygen depletion at depth which is consistent with its generally oligotrophic nature. The ecological status in terms of the Water Framework Directive suggests that Thirlmere is in a Good ecological state for TP but Moderate state for phytoplankton chlorophyll *a*, although the value was close to the G:M boundary (Table 3.26).

There have been no significant changes in nutrient concentrations in Thirlmere between 1984 and 2010 apart from a reduction in silica concentration (Table 3.10). This is probably linked to nutrient enrichment as the phytoplankton chlorophyll *a* has increased and Secchi depth has tended to decline (Table 3.10; Fig. 3.35). Alkalinity and pH has increased and sulphate, chloride, magnesium, sodium and potassium have decreased, but this is a fairly common pattern in several lakes (Table 3.10).

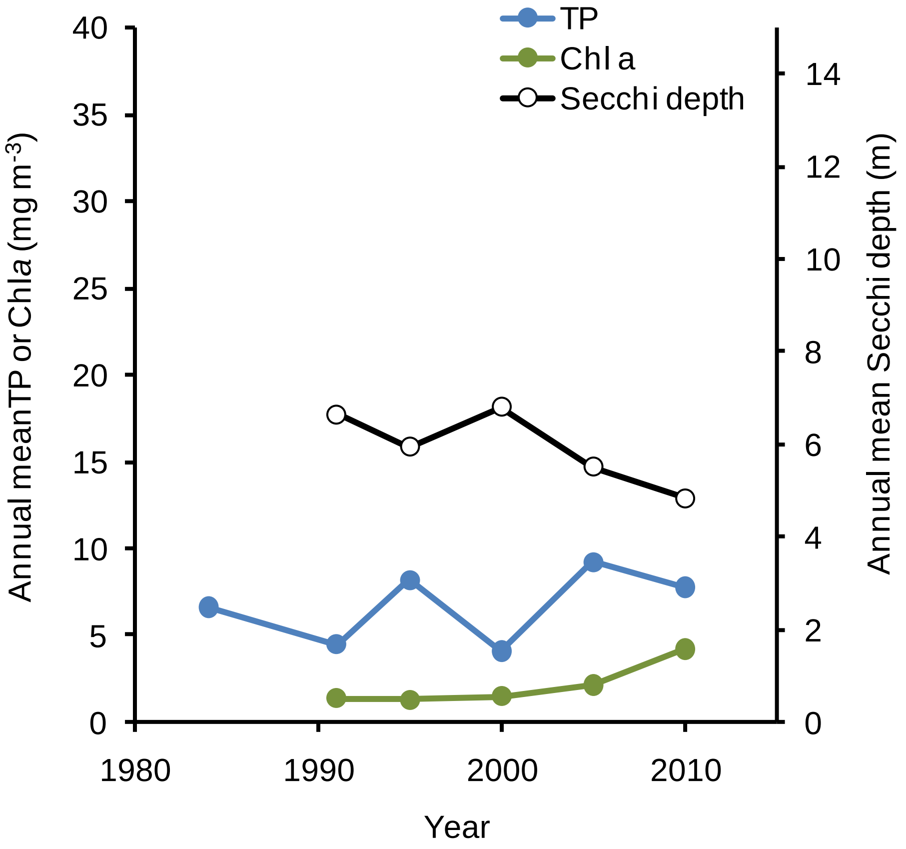


Figure 3.35. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in Thirlmere.

3.3.17 Ullswater


Ullswater (Photo I.J. Winfield).

Ullswater is the second largest lake in the English Lake District after Windermere in terms of area and volume and the largest if Windermere is separated into two basins. It is situated in the north-east of the English Lake District and drains eventually into the River Eden (Fig. 2.1).

Table 3.27. Summary of limnological conditions and trophic and Water Framework Directive classifications in Ullswater in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	238		
Mean pH (geometric mean)	7.3		
Mean total phosphorus (mg m^{-3})	12.0	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	1.6		
Mean nitrate-nitrogen (mg m^{-3})	242		
Mean silica (mg m^{-3})	1133		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	4.8	Mesotrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	7.1	Oligotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	4.8		Good
Mean Secchi depth (m)	5.2	Mesotrophic	
Minimum Secchi depth (m)	4.5	Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	5.2		

Ullswater is on the mesotrophic-oligotrophic boundary (Table 3.27). In terms of the WFD, the lake has a Good ecological status for phytoplankton chlorophyll *a*, but only moderate for TP. This latter status resulted largely from high concentrations of TP recorded in

January. A nutrient budget and modelling study has been carried out (Maberly, Elliott & Thackeray 2006).

There is no evidence for changing nutrient status in Ullswater apart from an increase in silica that could represent a slight decline in productivity (Table 3.10). This is supported by a tendency for declining phytoplankton chlorophyll *a* (Table 3.10; Fig. 3.36). Major ions show the same patterns noted for many of the other lakes lakes of increasing pH and alkalinity and decreasing sulphate, chloride, magnesium sodium and potassium (Table 3.10).

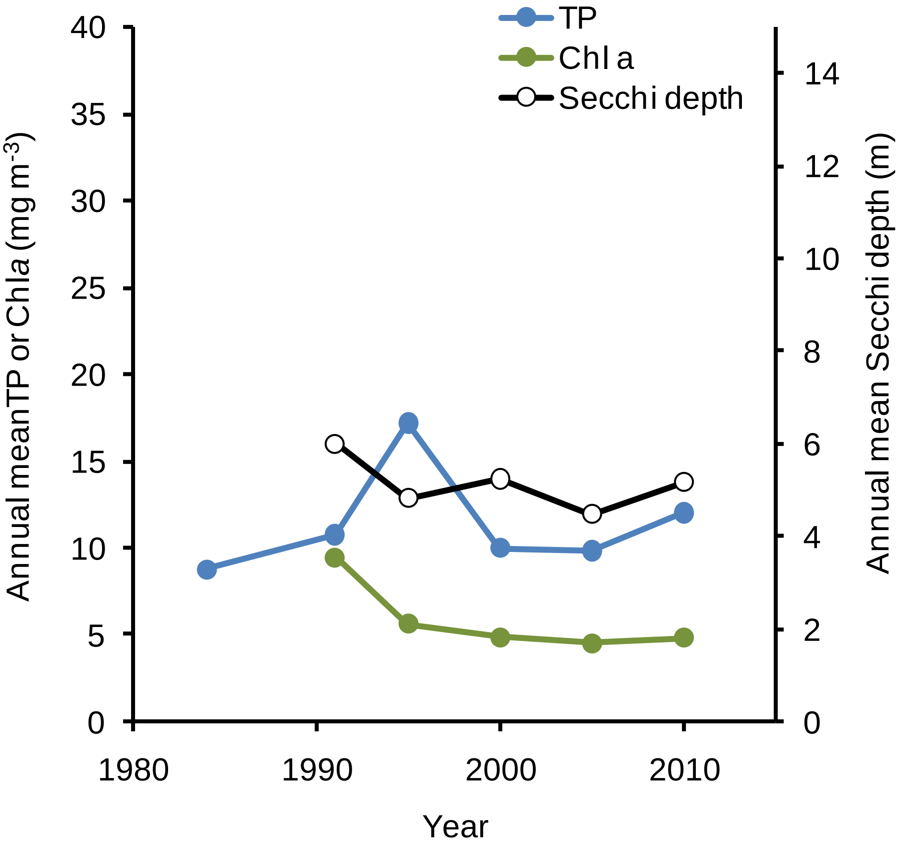


Figure 3.36. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Ullswater.*

3.3.18 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 difference results from the great average depth of the lake with the greatest mean depth (40 m) and maximum depth (76 m; Table 2.1) of any lake in the English Lake District.


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

Table 3.28. Summary of limnological conditions and trophic and Water Framework Directive classifications in Wastwater in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	71		
Mean pH (geometric mean)	6.8		
Mean total phosphorus (mg m^{-3})	4.9	Oligotrophic	High
Mean soluble reactive phosphorus (mg m^{-3})	1.6		
Mean nitrate-nitrogen (mg m^{-3})	334		
Mean silica (mg m^{-3})	1978		
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})	1.1		Ref
Mean Secchi depth (m)	12.7	Ultra-oligotrophic	
Minimum Secchi depth (m)	10.0	Ultra-oligotrophic	
Minimum oxygen concentration (mg m^{-3})	9.8		

Wastwater is also the prime example of an oligotrophic lake in the region and was the most unproductive lake in the lake series devised by Pearsall (1921). As an annual mean in

2010, Wastwater had the lowest concentration of TP, chlorophyll *a* and the greatest Secchi depth and oxygen concentration at depth. (Table 3.31). It is ultra-oligotrophic or oligotrophic in terms of its trophic state and both TP and phytoplankton chlorophyll *a* indicate it is in a High or Reference ecological state in terms of the WFD (Table 3.28).

Wastwater appears to be relatively stable. There have been no changes in concentration of nutrients and a slight increase in pH. Alkalinity has increased, but not significantly (Table 3.10; Fig. 3.37). There has been a decline in concentrations of sulphate, chloride, magnesium, sodium and potassium but this is quite a common pattern across all the lakes. The only very slightly worrying response is evidence for a small increase in spring chlorophyll *a* (not shown) and a slight decline in Secchi depth although neither is statistically significant (Table 3.10). Nevertheless, this warrants further investigation given that Wastwater is the premier oligotrophic lake in the region.

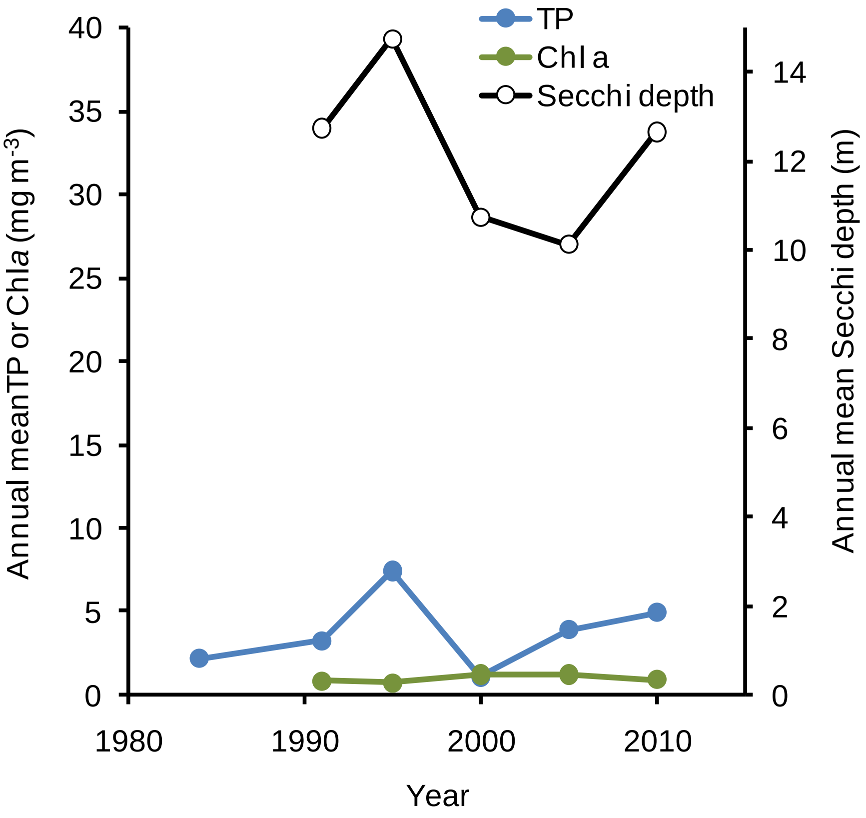


Figure 3.37. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in Wastwater.*

3.3.19 Windermere North Basin

Windermere is the largest lake in the English Lake District and the largest natural lake in England. Limnologically it is divided into a larger North Basin and a slightly smaller South Basin, separated by shallow water and islands. The North Basin has the second-largest maximum and mean depth, area and volume of any of the lakes studied.

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

Table 3.29. Summary of limnological conditions and trophic and Water Framework Directive classifications in the North Basin of Windermere in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	244		
Mean pH (geometric mean)	7.3		
Mean total phosphorus (mg m^{-3})	11.2	Mesotrophic	Good
Mean soluble reactive phosphorus (mg m^{-3})	2.2		
Mean nitrate-nitrogen (mg m^{-3})	380		
Mean silica (mg m^{-3})	800		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	16.0	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	26.1	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	12.3		Moderate
Mean Secchi depth (m)	4.6	Mesotrophic	
Minimum Secchi depth (m)	3.2	Oligo/Mesotrophic	
Minimum oxygen concentration (mg m^{-3})	7.2		

The North Basin is mesotrophic with a slight hint of it being meso-eutrophic (Table 3.29). There is relatively modest oxygen depletion, consistent with its mesotrophic status. It produced an unusually high concentration of chlorophyll *a* in 2010. In terms of the WFD however, the annual mean concentration of TP is Good and categorised by phytoplankton chlorophyll *a* it is only Moderate.

Windermere North Basin shows no indication for changes in nutrient concentrations based on Lakes Tour data although there is a slight reduction in TP (Table 3.10; Fig. 3.38). Fortnightly data have shown, however, some more subtle changes (see e.g. Maberly *et al.*, 2005, 2008). Although there are no long-term changes in phytoplankton chlorophyll *a* or Secchi depth (Table 3.10) there has been a noticeable increase in chlorophyll *a* and in 2010 the Lakes Tour concentrations of chlorophyll *a* were greater in the North Basin than the South Basin. Of the major ions the only significant change is an increase in alkalinity and a reduction in concentration of sulphate, chloride and sodium (Table 3.10).

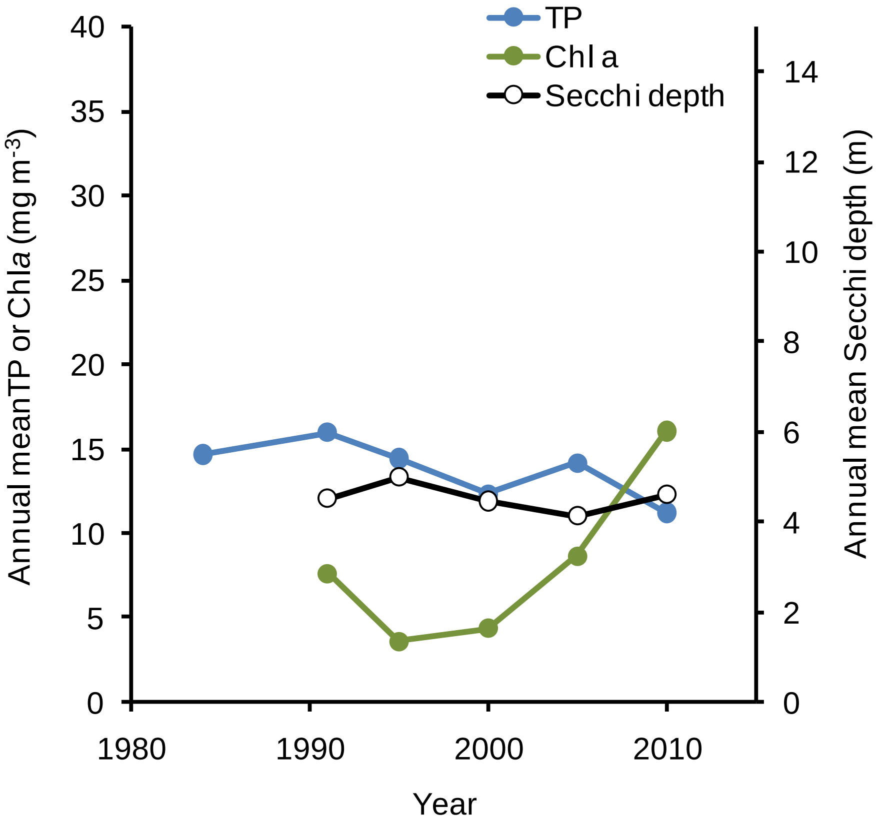


Figure 3.38. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a and Secchi depth in the North Basin of Windermere.

The North Basin of Windermere is studied fortnightly as part of the CEH long-term monitoring programme that was started by the Freshwater Biological Association in 1945 and continued by CEH since 1989. A recent nutrient budget and assessment of long-term change are given in Maberly (2008, 2009) and Maberly *et al*. (2008) respectively. It is the subject of a CEH project studying the impacts on water quality of species invasion and climate change (http://www.windermere-science.org.uk/home) that will investigate, among other things, the causes of the increased productivity in the lake.

3.3.20 Windermere South Basin

The South Basin of Windermere is about half the volume and 80% of the area of the North Basin. In addition to receiving water from the North Basin, Esthwaite Water flows into the South Basin via Cunsey Beck.

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

Table 3.30. Summary of limnological conditions and trophic and Water Framework Directive classifications in the South Basin of Windermere in 2010.

Characteristic	Value	Trophic	WFD
Mean alkalinity (mequiv m^{-3})	285		
Mean pH (geometric mean)	7.4		
Mean total phosphorus (mg m^{-3})	12.6	Mesotrophic	Moderate
Mean soluble reactive phosphorus (mg m^{-3})	3.6		
Mean nitrate-nitrogen (mg m^{-3})	388		
Mean silica (mg m^{-3})	695		
Mean phytoplankton chlorophyll *a* (mg m^{-3})	6.1	Eutrophic	
Maximum phytoplankton chlorophyll *a* (mg m^{-3})	13.6	Mesotrophic	
Arithmetic Observed chlorophyll *a* (mg m^{-3})	6.3		Good
Mean Secchi depth (m)	3.9	Mesotrophic	
Minimum Secchi depth (m)	3.1	Meso/Oligotrophic	
Minimum oxygen concentration (mg m^{-3})	3.1		

The South Basin of Windermere is generally more productive than the North Basin and is categorised as somewhere between mesotrophic and eutrophic. Its status in terms of the WFD, South Basin of Windermere is Moderate for TP but Good for phytoplankton chlorophyll *a* (Table 3.30).

There has been a significant reduction in TP in the South Basin of Windermere but no changes in the concentration of other nutrients (Table 3.10; Fig. 3.39). However, the more detailed fortnightly data do reveal subtle long-term changes (Maberly *et al.*, 2005, 2008). Like the North Basin, alkalinity has increased significantly and other major ions have tended to decline (Table 3.10). There have been no statistically significant changes in phytoplankton chlorophyll *a* or Secchi depth (Table 3.10; Fig. 3.39).

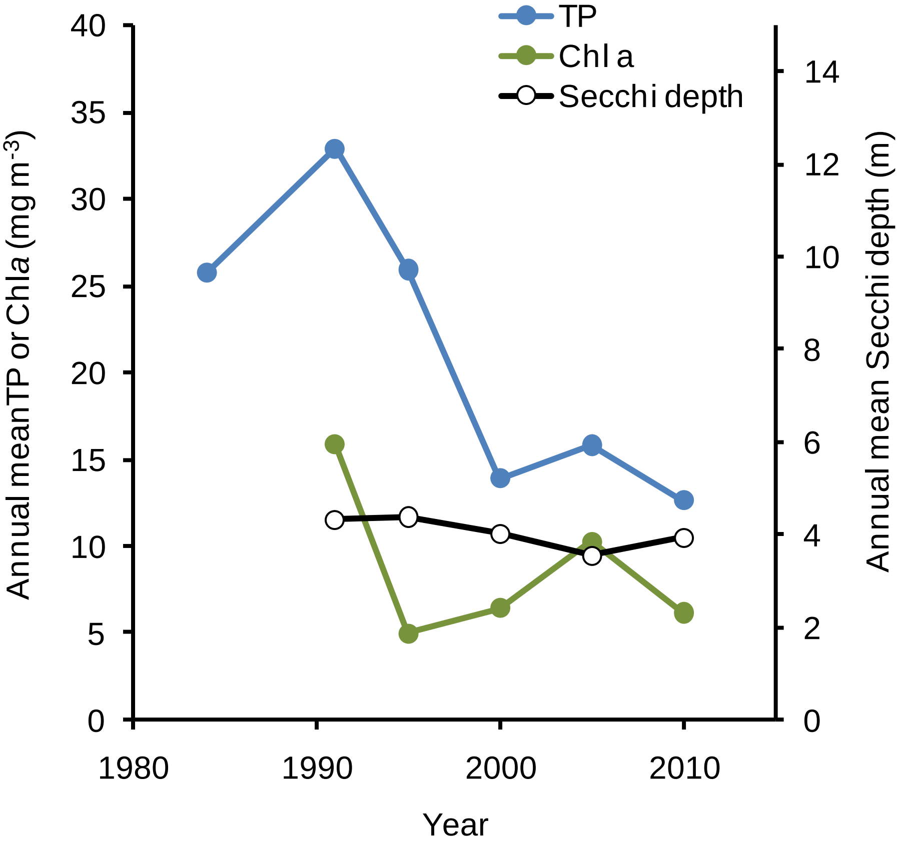


Figure 3.39. Long term changes in annual concentration of total phosphorus, phytoplankton chlorophyll a *and Secchi depth in the South Basin of Windermere.*

The South Basin of Windermere is studied fortnightly as part of the CEH long-term monitoring programme that was started by the Freshwater Biological Association in 1945 and continued by CEH since 1989. There is a CEH AWQMS on the lake. A recent nutrient budget and assessment of long-term change are given in Maberly (2008, 2009) and Maberly *et al*. (2009) respectively. It is the subject of a CEH project studying the impacts on water quality of species invasion and climate change (http://www.windermere-science.org.uk/home).

3.3.21 Summary of the lakes in 2010.

The annual mean (for oxygen minimum at depth) values for each lake in 2010 are summarised in Table 3.31. Raw values are given in the appendices.

Table 3.31. Annual mean (oxygen minimum at depth) for the 20 lakes of the Lakes Tour in 2010. 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	17.0	2.0	329	1.34	12.0	2.5	0.19	7.1	244	285	80.6	239	6.2	269	86.5
Blelham Tarn	17.9	2.2	382	1.45	22.3	2.3	0.06	7.1	475	259	96.3	241	12.2	486	117.3
Brothers Water	9.5	0.4	327	1.48	2.6	6.1	0.11	7.0	199	184	66.3	177	5.1	224	58.1
Buttermere	6.7	0.7	263	1.29	1.7	8.1	7.87	6.7	64	153	53.1	131	1.6	102	50.0
Coniston Water	8.2	0.7	372	0.62	4.5	5.3	6.76	7.2	214	240	85.3	216	5.5	260	74.8
Crummock Water	6.6	0.7	248	0.94	2.1	7.4	6.15	6.7	63	176	61.3	154	1.6	97	59.2
Derwent Water	9.6	0.3	200	0.94	5.9	4.1	1.59	6.9	118	269	43.1	198	3.0	191	48.1
Elterwater	20.8	2.1	273	1.59	16.2	2.5	0.05	6.9	344	191	60.9	182	8.8	344	71.7
Ennerdale Water	5.8	0.2	232	2.07	2.6	5.9	8.43	6.7	54	168	58.1	157	1.4	77	55.0
Esthwaite Water	20.4	4.2	346	1.38	7.9	2.7	0.1	7.3	431	294	98.1	267	11.0	468	96.7
Grasmere	18.0	2.4	467	1.18	13.1	4.2	0.1	6.9	163	183	48.8	176	4.2	207	55.6
Haweswater	9.2	1.0	231	1.20	2.3	3.5	6.46	7.2	198	126	53.4	123	5.1	211	69.4
Loughrigg Tarn	19.2	0.4	350	0.99	32.4	2.5	0.11	7.2	312	181	66.3	169	8.0	303	93.5
Loweswater	14.8	1.1	356	1.01	11.7	2.8	0.13	7.1	197	269	104.4	233	5.0	237	106.5
Rydal Water	13.7	2.3	446	1.16	8.9	4.3	0.06	7.0	189	194	60.8	186	4.9	215	58.5
Thirlmere	7.8	0.3	219	1.12	4.2	4.8	5.34	6.7	72	135	44.8	126	1.8	108	36.7
Ullswater	12.0	1.5	242	1.13	4.8	5.2	5.17	7.2	238	149	62.2	146	6.1	245	76.0
Wastwater	4.9	1.4	334	1.98	0.9	12.7	9.83	6.8	71	168	55.5	153	1.8	101	54.0
Windermere North Basin	11.2	2.1	380	0.80	16.0	4.6	7.19	7.3	244	198	67.5	183	6.3	275	70.8
Windermere South Basin	12.6	3.5	388	0.70	6.1	3.9	3.07	7.4	285	224	78.0	204	7.3	314	76.7

4. PATTERNS OF RESPONSE ACROSS ALL THE LAKES

4.1 Patterns to elucidate environmental drivers of lake response

The English Lake District is unusual as there is a large range of lake types in terms of depth, size, hydrology, basic water chemistry and trophic state within a small geographic area. This results essentially from the varied geology in the catchments (Fig. 3.5) but also from the varied land-use in the catchments and the altitude and morphology of individual lakes. Furthermore it is extremely fortunate that these 20 lakes have been studied in a reasonably consistent way since 1984, and some for much longer, so that comparisons can be made across years as well as types. This gives an excellent opportunity to analyse and illustrate the inter-relationships among various limnological variables to help understand how lakes function and respond to environmental perturbation.

An example of the importance of the catchment in determining the ecology of the lake is shown in Figure 4.1 where concentrations of potassium, alkalinity, total phosphorus and nitrate all decline with altitude. All the correlations are significant at $P<0.001$. Altitude is not likely to be the direct cause of the relationship but is probably correlated with: i) erodability of rock, ii) accumulation of ions because the water has travelled through more geology and soil and iii) changes in land-use and soil types. Water chemistry has been shown to be closely linked to land-use in small upland tarns (Maberly *et al*., 2003) and it likely that this is a key factor in these larger lakes as well.

Although nitrogen may be an equally important limiting nutrient in certain types of lakes, including upland tarns in the Lake District (Maberly *et al.* 2002; James *et al.*, 2003) in the large lowland lakes of the English Lake District studied here, phosphorus is the key nutrient limiting phytoplankton production. This is apparent from Figure 4.2 where concentrations of phytoplankton chlorophyll *a* are closely linked to the concentration of total phosphorus.

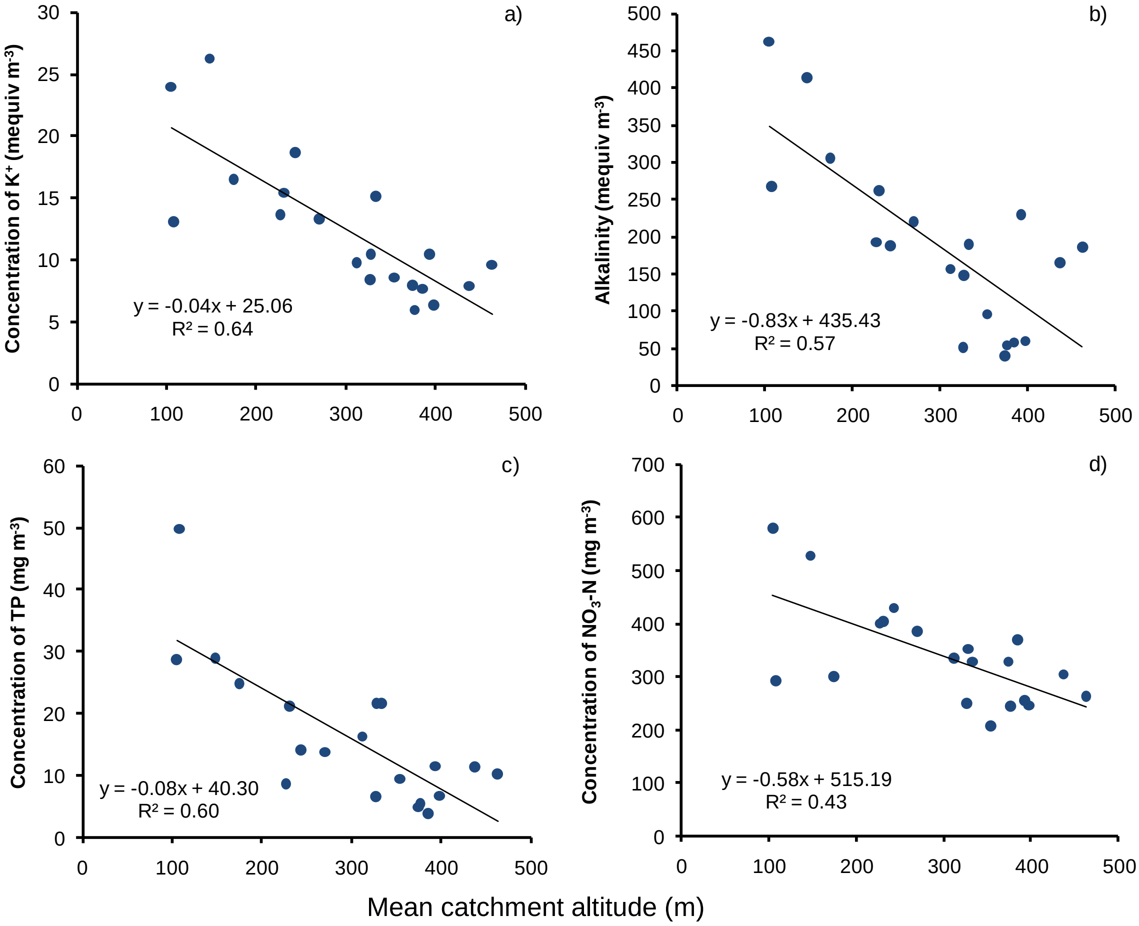


Figure 4.1. Relationships between annual mean concentrations of two major ions (a) potassium; (b) alkalinity) and two nutrients (c) total phosphorus and (d) nitrate-nitrogen) and mean catchment altitude. Data are average from Lakes Tours in 1984, 1991, 1995, 2000, 2005 and 2010.

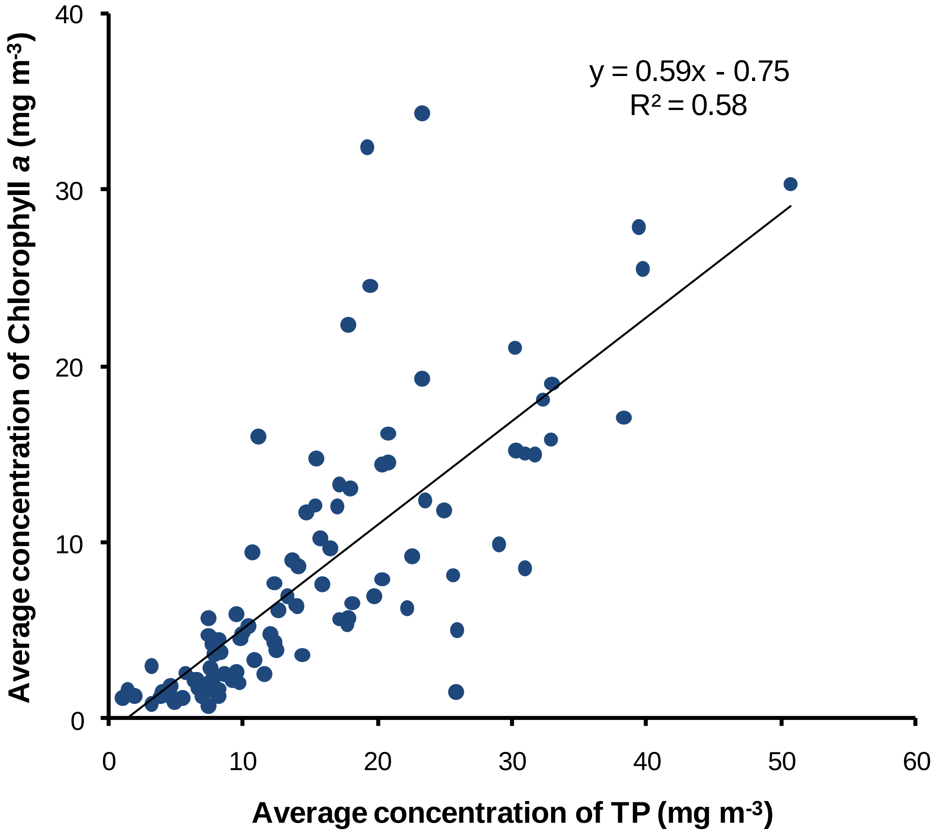


Figure 4.2. Relationship between average concentration of phytoplankton chlorophyll a *and total phosphorus plotted. Data from 1991, 1995, 2000, 2005 and 2010 Lakes Tours.*

The greater the productivity of lake, the greater effect the biology has on the seasonal dynamics of a lake. Figure 4.3 shows how in productive lakes, with high concentrations of TP such as Esthwaite Water and Blelham Tarn, seasonal changes in concentrations of nitrate and silica are great, but in unproductive lakes such as Wastwater and Ennerdale Water there is very little seasonal change in these two other nutrients. Analysing seasonal changes in concentrations of nitrate and silica is, therefore, a useful additional method to describe the productivity of a lake. They have the advantage of being more conservative than soluble reactive phosphorus and being closer to an available nutrient than TP which often shows relatively little seasonal change.

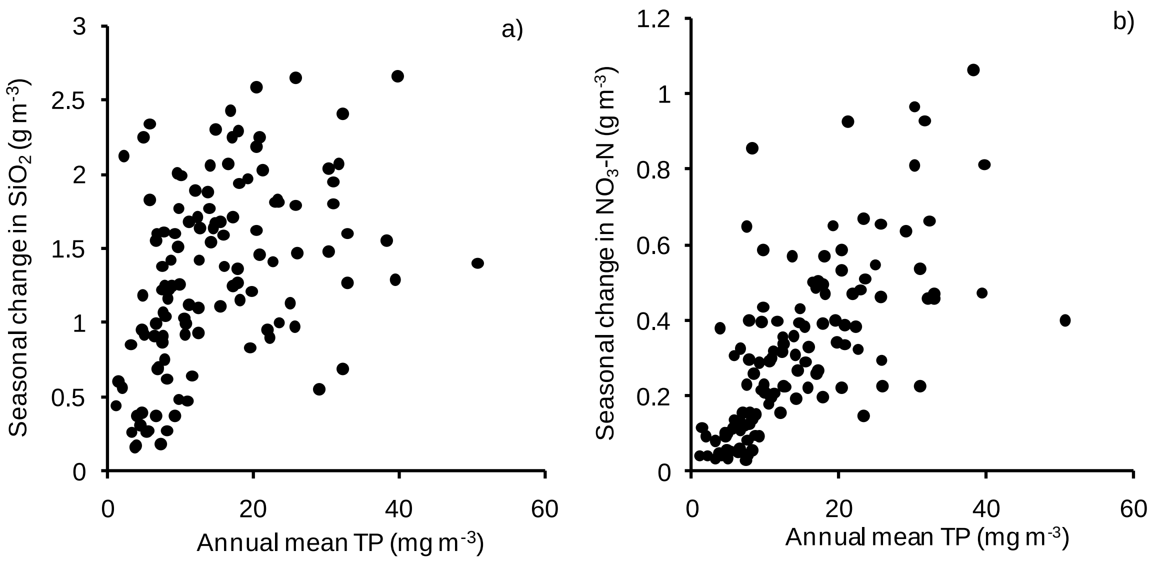


Figure 4.3. Seasonal change (annual maximum minus annual minimum) in concentration of: a) silica and b) nitrate as a function of annual mean TP for the 20 lakes in 1984, 1991, 1995, 2000, 2005 and 2010.

The greater productivity of these types of lakes is expressed in the amount of phytoplankton chlorophyll *a* (Fig. 4.2). This in turn has a number of consequences for the limnology of a lake. An obvious consequence is that a large population of phytoplankton reduces water clarity. Figure 4.4 show this relationship for data between 1991 and 2010 categorised per month. The responses in April, July and October are very similar and clearly dominated by the phytoplankton with the proportion of the variance accounted for (R^2) ranging from 0.60 to 0.80. There was a slightly different response in January: Secchi depth tended to be lower for the same concentration of phytoplankton chlorophyll *a* and the proportion of the variance accounted for (R^2) was lower at 0.31. This is probably the result of non-phytoplankton material such as suspended solids, being relatively more important in January than in the three other months, because phytoplankton populations are generally at their lowest and winter rains will bring in suspended solids from the catchment.

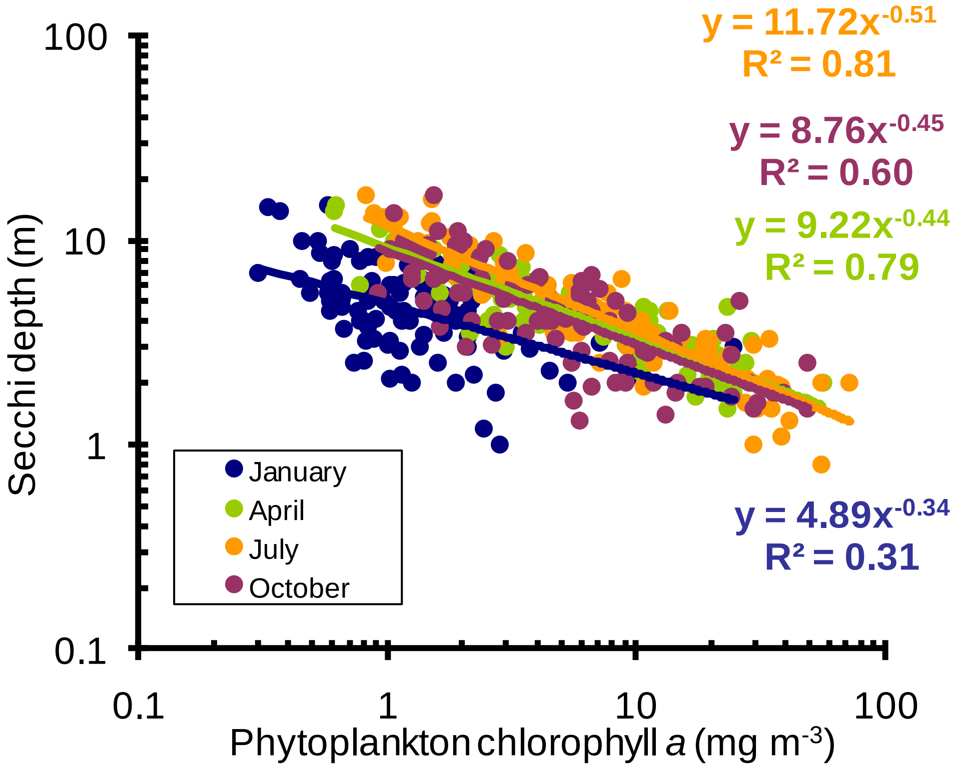


Figure 4.4. Relationship between Secchi depth and concentration of phytoplankton chlorophyll a *in the 20 lake basins and four sampling occasions in the 1991, 1995, 2000, 2005 and 2010 Lakes Tours. The best-fit line is shown with equation and proportion of the variance accounted for (R^2).*

Another consequence of increased phytoplankton productivity is the depletion of oxygen at depth in the summer. This has a number of potentially undesirable consequences. First, oxygen depletion changes the redox potential at the sediment surface converting iron from ferric (Fe^{3+}) which is able to bind phosphorus to ferrous (Fe^{2+}) which does not, and as a result phosphorus bound in the sediment may be released into the water column, causing a positive feedback increasing nutrient enrichment.

Secondly, low oxygen concentrations at depth will limit the ability of fish to exploit these depths and this, in turn, may have negative consequences, especially for fish, such as the Arctic charr, which avoid the low concentrations of oxygen in the hypolimnion (Jones *et* *al*. 2008). It is important to note that the peak oxygen depletion in the lakes of the English Lake District typically occurs between the end of August and the start of October, depending on when exactly stratification breaks down. Therefore the oxygen minimum measured in the Lakes Tour, which generally occurred in July, but occasionally in October, will be an underestimate of the true extent of oxygen depletion. Furthermore, a number of factors other than productivity will influence the extent of oxygen depletion such as the ratio of volume of water in the epilimnion to the volume of water in the hypolimnion. Nevertheless, the data show a clear negative relationship between oxygen concentration at depth and phytoplankton chlorophyll *a*. Lakes with very little phytoplankton have oxygen minima which approach those at air-equilibrium and lakes where the annual mean concentration of phytoplankton *a* exceeds about 10 mg m^{-3} have complete oxygen depletion at depth (Fig. 4.5). The five points highlighted enclosed in an ellipse are from Brothers Water where oxygen depletion is much more substantial than predicted from the concentration of phytoplankton chlorophyll a. This may result in part from the bathymetry of the lake with steep sloping shores down to about 12 m and then a large sediment area down to 16.7 m (Haworth *et al*. 2003) or labile organic matter from the catchment is oxidised within the lake, or both.

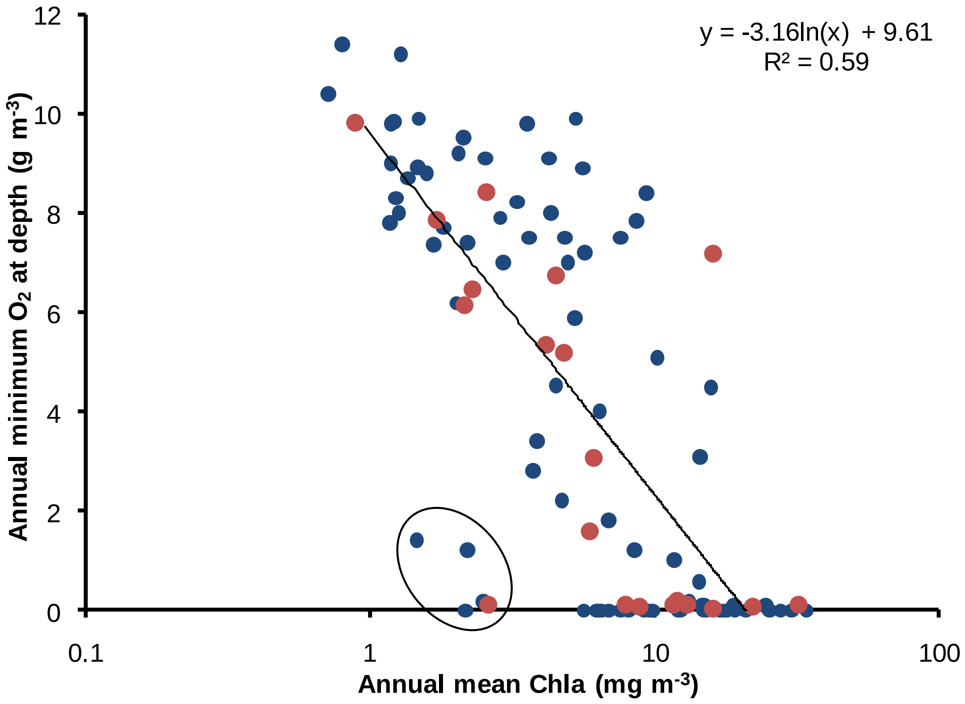


Figure 4.5. Data for from 1991 to 2010 showing the relationship between annual minimum concentration of oxygen at depth and the annual mean phytoplankton chlorophyll a *(on a log scale). The data for 2010 are highlighted in brown. The five points falling outside the main cluster and highlighted with an ellipse are for Brothers Water- see text.*

Finally, there is a strong link between alkalinity (acid neutralising capacity) and the concentration of sulphate. There is a baseline concentration of sulphate derived from weathering the rocks in the catchment and from input in rainfall derived from sea-salts. However, in recent years a large amount of sulphate was deposited in ‘acid rain’ derived from burning fossil fuels, acidifying the catchment and the freshwaters. This deposition is now declining and this can be seen in the lower concentrations of sulphate in recent years (Fig. 4.6a). At the same time, the average alkalinity has increased as the acidifying effect of sulphate has declined (Fig. 4.6a) and there has been an approximate equimolar relationship between decreasing sulphate concentrations and increasing alkalinity (Fig. 4.6b)

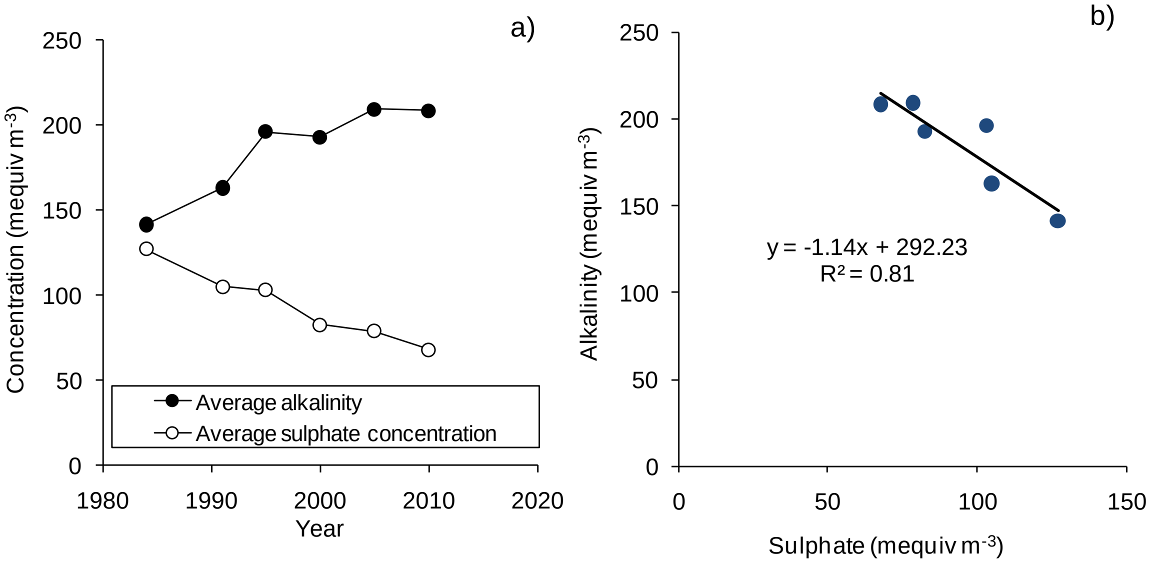


Figure 4.6. Relationship between annual average alkalinity and concentration of sulphate for the 20 lakes in the Lakes Tour as (a) a time-course, and (b) a scatter-plot.

The overall annual average changes for the 20 lakes in the Lakes Tour are shown in Figure 4.7. These have not been analysed statistically, but there is a small indication that the concentration of chlorophyll *a*, and TP were slightly lower and the Secchi depth slightly greater in 2010 compared to 2005. However this possible slight improvement is set against a larger deterioration in previous years and conditions in 2010 are worse than the average at the start of the data-set.

The increasing alkalinity and decreasing sulphate concentration are large obvious patterns in the concentration of major ions. The increase in pH corresponds to the increase in alkalinity. The reduction in concentration of the cations: calcium, magnesium, sodium and potassium, also results from the reduced input of acid on the catchment soils. Protons (hydrogen ions) bind to the soil, releasing other cations, such as calcium, that can then enter the water. As acid rain decreases, the concentration of these cations tends to decline. A second factor that introduces variability into the data is the deposition of sea-salt, largely from winter storms. Storminess was high in the early 1990s and part of the decline in sodium, and the decline in chloride, probably derive that.

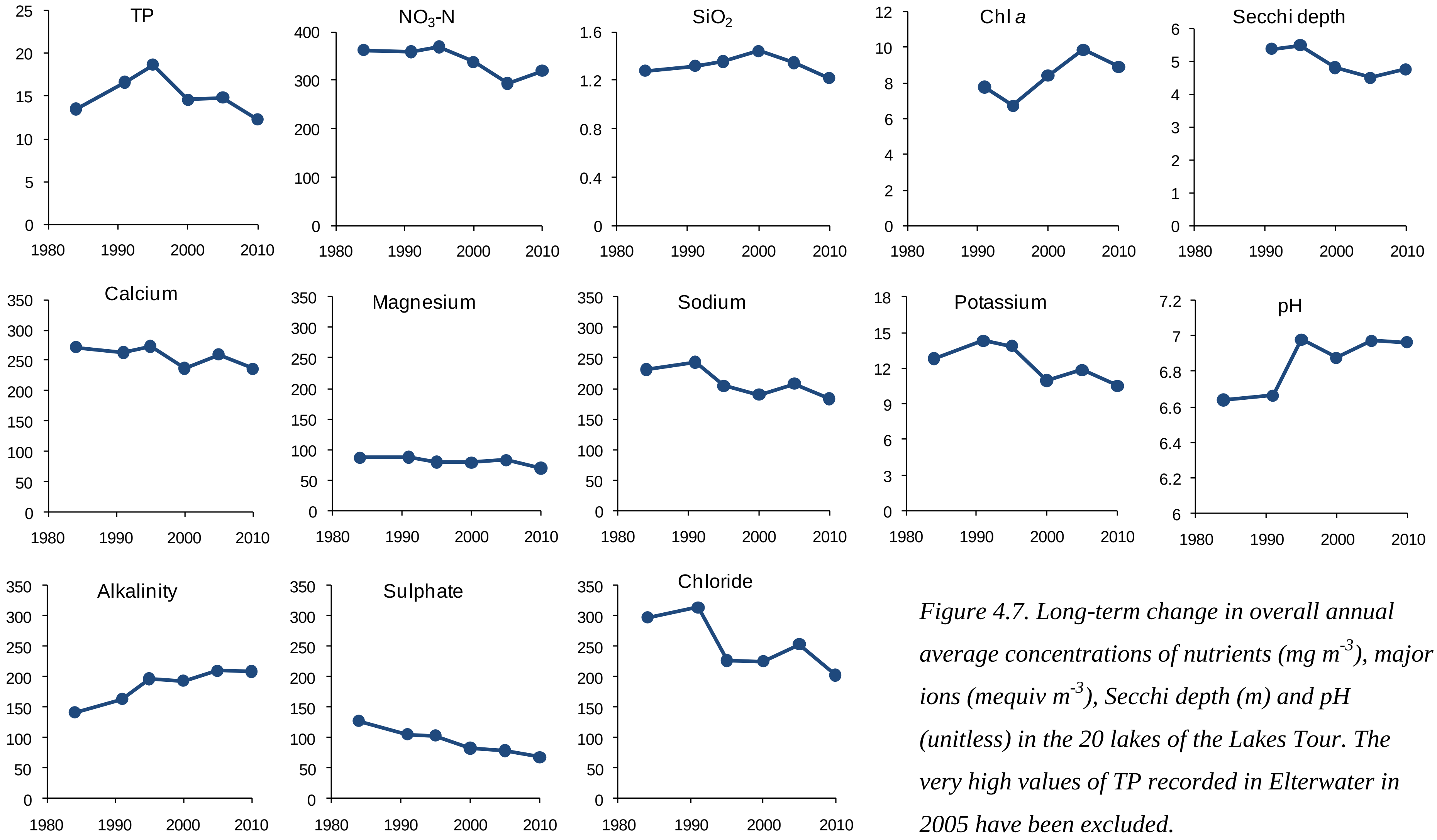


Figure 4.7. Long-term change in overall annual average concentrations of nutrients (mg m^{-3}), major ions (mequiv m^{-3}), Secchi depth (m) and pH (unitless) in the 20 lakes of the Lakes Tour. The very high values of TP recorded in Elterwater in 2005 have been excluded.

4.2 Summary of ecological status of the lakes under the WFD

Figure 4.8 summarises the ecological status of the 20 lakes based on TP and phytoplankton chlorophyll *a* based on the results presented in Tables 3.11 to 3.30. It is important to note again that the ecological boundaries are still being fine-tuned and the ones used here were correct at the date of writing but may change slightly in the future. These data are compared to the assessments made in 2005, but the boundaries used between the different ecological statuses are not identical in 2005 and 2010. The TP concentrations are slightly more stringent than in 2005 and the chlorophyll *a* concentrations are similar overall but slightly different lake-to-lake.

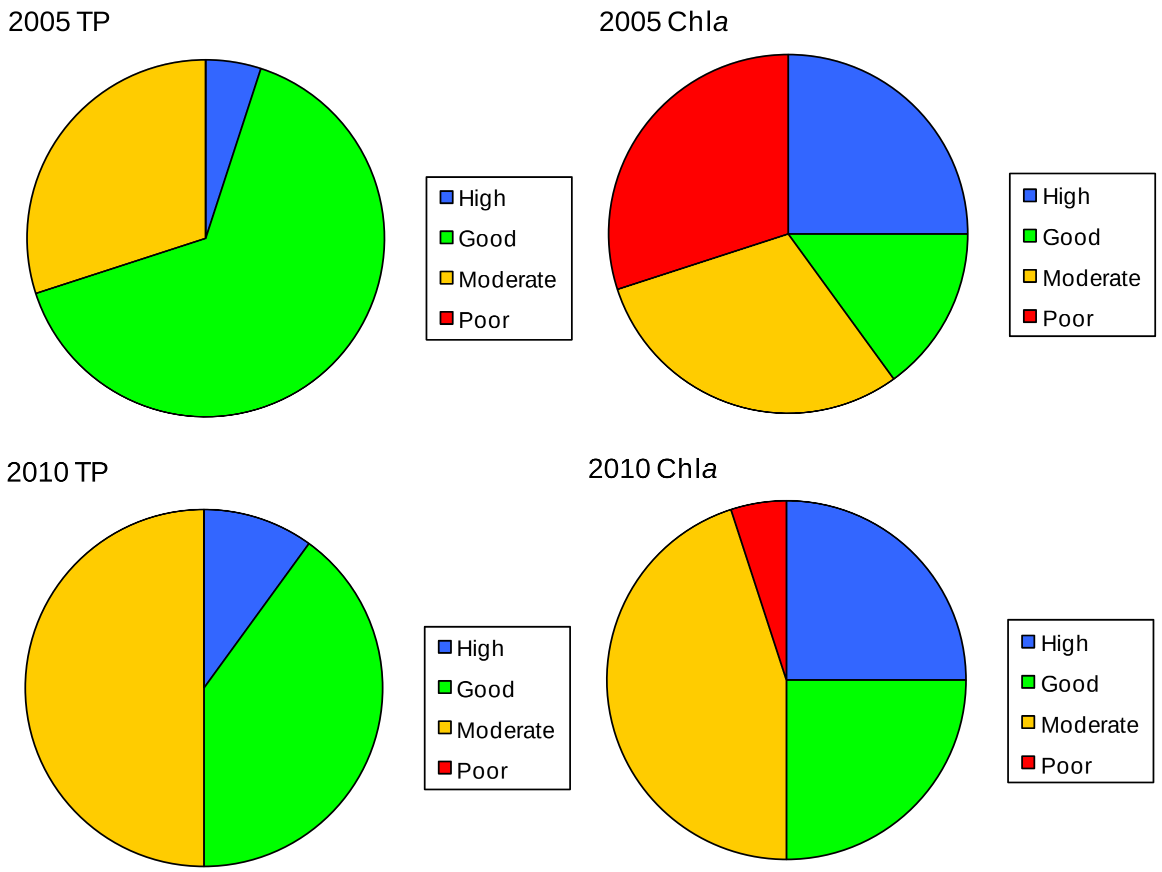


Figure 4.8 *Summary of overall ecological status for the 20 lakes according to TP or phytoplankton chlorophyll* a *in 2005 and 2010.*

The critical ecological boundary for the Water Framework is the Good:Moderate boundary, because at lakes that are only Moderate or worse, measures will need to be put in place to improve ecological status. In 2010, half the lakes were at Moderate ecological status or worse for TP and chlorophyll *a*. However, on the principle of ‘one-out-all-out’, eleven lakes were below Good ecological status. Of these, Loughrigg Tarn (although not a WFD site) was categorised as Poor ecological status on the basis of the high chlorophyll *a* concentration.

Compared to 2005, there has been an increase in 2010 of the number of lakes failing Good ecological status from 6 to 10, but this may result from changes to the TP boundaries. In contrast, for phytoplankton chlorophyll *a*, there has been a slight improvement. In 2005 12 lakes failed Good ecological status: six lakes were Moderate and six were Poor. In 2010 this had improved to ten lakes failing Good ecological status, of which only one was classified as Poor.

Many of the major lakes in the English Lake District are currently still not at Good ecological status and therefore stringent management plans need to be drawn up to produce measures that will achieve Good ecological status by 2015 as required by the Water Framework Directive.

4.3 Suggestions for further work

Based on the work reported here, the lakes that fail Good ecological status will need some remedial work and therefore probably a better understanding of their limnology and the reasons for poor water quality which will probably require a better understanding of the sources of nutrients to the lake. The current scheme for assessing ecological status based on phytoplankton chlorophyll *a* suggests that Bassenthwaite Lake, Blelham Tarn, Elterwater, Esthwaite Water, Grasmere, Loughrigg Tarn, Loweswater, Rydal Water, Thirlmere, Ullswater and the North Basin of Windermere are not at Good ecological status. Of these 11 lakes, Thirlmere and Ullswater are close to Good ecological status.

- Ullswater was pushed into moderate status by one high concentration of TP and is probably largely in Good status: this probably just requires continued baseline monitoring.
- Thirlmere was only Moderate for phytoplankton chlorophyll *a* and there is clear evidence that the water quality is deteriorating with increasing chlorophyll *a* and decreasing Secchi depth: the cause of this needs to be understood and ameliorated.
- Loughrigg Tarn has the worst water quality of the 20 lakes and was only categorised as Poor ecological status for phytoplankton chlorophyll *a* and there is clear evidence of rising phytoplankton populations, especially in autumn. The causes of this need to be investigated.
- Ennerdale Water is still in High or Good ecological status but shows clear, worrying evidence of declining Secchi depth that appears to be linked to increasing phytoplankton chlorophyll *a*. Since Ennerdale Water is an important oligotrophic

lake in the region, it needs especially to be protected and the cause of the enrichment understood and reduced.

- Wastwater is the premier oligotrophic lake in England. It is clearly still at reference condition with High ecological status. However, there are some signs that water quality is deteriorating, albeit slightly. Spring chlorophyll *a* concentrations are getting higher and Secchi depth is getting shallower (Table 3.10) and annual mean phytoplankton chlorophyll *a* and annual mean Secchi depth are also deteriorating (Figs 4.8 and 4.9). There has not been a comprehensive limnological survey of Wastwater, and this combined with signs of change in the lake need to be investigated.
- Buttermere, although currently at High ecological status is showing signs of weak eutrophication and the cause of this needs to be determined.
- Rydal Water has, so far as we are aware, never had a comprehensive limnological survey and so this would be a useful addition to our knowledge of the lakes.
- The section on fish (3.2.8, Table 3.2) highlighted the absence of adequate fish data on a number of lakes, in particular, the fish communities in Blelham Tarn (although well-studied for other features), Elterwater, Grasmere, Loughrigg Tarn and Thirlmere have been understudied and even the well-studied Esthwaite Water has limited information. Studies on these would be a valuable contribution.

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