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The state of Esthwaite Water in 2010

A report to Natural England

prepared by:

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CONFIDENTIALITY STATEMENT

Executive Summary

1. Esthwaite Water is one of the most nutrient-enriched lakes in the English Lake District, but the enrichment has mainly occurred in the last 50 years and in particular since the establishment of the wastewater treatment works (WwTW) at Hawkshead in 1973 and a fish farm on the lake in 1981. The fish cages were removed from the lake in November 2009 and recent upgrades have been made to the WwTW. This report describes the conditions and water quality at Esthwaite Water in 2010, places them into the context of recent conditions and assesses evidence for any change.
2. The seasonal temperature and stratification cycle was typical with surface water reaching nearly 20 °C and the bottom temperature only 10 °C. Stratification lasted for about 180 days from the beginning of April to mid-October.
3. The average alkalinity was 0.43 equiv m^{-3} placing Esthwaite Water in the medium alkalinity category of the Water Framework Directive.
4. Nutrients showed typical seasonal patterns. Total phosphorus was relatively conservative with peaks during time of high phytoplankton biomass and an average concentration of 21.4 mg m^{-3}. Soluble reactive phosphorus had peak concentrations of about 12 mg m^{-3} at the start of the year but fell rapidly in March to the limit of detection, 0.6 mg m^{-3}, and the concentration remained low for most of the summer and only increased on the breakdown of stratification in autumn. Silica concentrations also fell rapidly in spring as is was removed by the growing spring diatoms. Nitrate was the dominant form of nitrogen and fell more slowly than phosphorus and silica and reached minima of 30 mg m^{-3} that could indicate a short-period of nitrogen limitation in an otherwise phosphorus-limited lake.
5. The phytoplankton produced a spring bloom of about 16 mg m^{-3} comprising mainly diatom and an extensive summer bloom of cyanobacteria that reached 35 mg m^{-3}

that did not decline until the beginning of November. The annual average concentration was 15.6 mg m^{-3}.

6. The phytoplankton had a major effect on the light climate with Secchi depth minim of 1.5 m in August. The annual average light attenuation coefficient of about 0.87 m-1 would allow macrophyte colonisation down to between 2 and 4.3 m depending on species.
7. Nine species of crustacean zooplankton were recorded with an early summer peak population in May dominated by *Daphnia hyalina/galeata*. Later in the year, smaller bodied *Bosmina longirostris* and *Ceriodaphnia quadrangula* produced a population peak in mid September.
8. Statistical comparisons of the monthly-average and annual-average values of various water quality parameters in 2010 and the previous ten years showed encouraging changes. Statistically significant reduction in concentration in 2010 compared to the previous ten years were found for: (i) total phosphorus in ten months and as an annual average; (ii) soluble reactive phosphorus in 4 months and as an annual average; (iii) nitrate in eight months and as an annual average. This led to statistically significant reductions in the concentration of chlorophyll a in eight months and as annnual average and increases in Secchi depth in five months and as an annual average. The minimum concentrations of oxygen at depth were essentially unchanged and the density of zooplankton was lower in some months.
9. The current ecological status of Esthwaite Water under the Water Framework Directive is ‘Moderate’ for both total phosphorus and chlorophyll *a*. In previous years, the ecological status was close to the Moderate: Poor boundary for both measures. This underlines the necessity of the programme of measures that are currently underway on the lake.

10. While these results are extremely encouraging, weather patterns can lead to periods of improvement and worsening in water quality so continued monitoring is essential. Furthermore, some of these improvements started to be evident in 2009 (concentrations of total phosphorus, soluble reactive phosphorus and nitrate) and so in order to be able, confidently, to link these to management changes, it is very to obtain more information on waste-water handling at the Hawkshead WwTW and the stocking densities and feeding regime of the fish farm on the lake.

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1. Introduction

Esthwaite Water (54° 22' N, 2° 56' W) is situated in a side valley that drains into the South Basin of Windermere in the English Lake District, Cumbria UK. It was formed at the end of the last glaciation, around 12,000 years ago. Esthwaite Water is a relatively small lake compared to many in the English Lake District: it has an area of 1 km^2 and a volume of 6.4 Mm^3. Its catchment is 17 km^2 and is lower lying than most of the other major English Lake District catchments. The average discharge recorded between 1976 and 2009 of 26.9 Mm^3 y^{-1} (equivalent to 0.85 m^3 s^{-1}) gives an average retention time of 87 days.

Esthwaite Water is one of the most nutrient-enriched lakes in the English Lake District. Palaeolimnological records show that there was little evidence for a change in nutrient status between about 800 and 1850 AD, but a gradual and accelerating increase from then until 1970 and a more dramatic increase after that time. The rapid recent increase in eutrophication coincided with two man-made changes to the lake. The first was the establishment, in 1973, of a Wastewater Treatment Works (WwTW) that serves the village of Hawkshead and discharges just upstream of where the main inflow, Black Beck, enters the lake in the north. The second was the introduction, in 1981, of a fish farm at the southern end of the lake. Upgrade of the WwTW to reduce phosphorus inputs by including tertiary phosphorus-removal in 1986 appeared to have relatively little effect on the lake, possibly because at that stage P-inputs from the fish farm were dominating the P-load. Further details about the physical, chemical and biological features of Esthwaite Water are described in Maberly et al. (2011).

Recently, two changes have been implemented to reduce further nutrient-loading to the lake: the removal of the fish cages on the lake in 2009 and upgrading of the waste water handling and treatment at the Hawkshead WwTW which began in 2010.

The purpose of this report is to describe the limnology of Esthwaite Water in 2010, the first year after the implementation of these remedial measures, to assess whether or not the first signs of a change can be discerned. Lakes usually respond relatively slowly to changes in the supply of nutrients because of internal supplies, for example, internal loads from the sediments, that take several years to dissipate. Nevertheless, it is important to assess whether a positive change can be detected especially in the face of other large scale changes, such as climate change, that can also negatively affect a lake like Esthwaite Water (Elliott 2011).

This report will describe the conditions at Esthwaite Water in 2010, place them in the context of recent conditions and assess evidence for any change.

2. Methods

The data reported here derive from two types of measurement. The first is based on traditional sampling at the deepest point in the northern bay of the lake, undertaken every two weeks. The second is automatically collected high resolution data.

Fortnight limnological data

This is a continuation of a long term monitoring series that began in 1945. Note that ice on Esthwaite Water prevented samples from being collected at the end of December 2010.

- *Oxygen and temperature profiles* were measured with a Wissenschaftlich-Technische Werstätten (WTW) Oxi 340i meter fitted with a combination thermistor and oxygen electrode (WTW TA197) and from 16th March a Hach WQD Portable Meter (LD010130).
- *Secchi disc transparency* was measured with a white painted metal disc, 30 cm in diameter, that was lowered into the water until it disappeared from view. The disc was then raised slightly until it reappeared and that depth was noted.

All the other fortnightly data presented here are based on an integrated water sample taken from the top 5 m and measurements are as described in Mackereth et al. (1978) unless otherwise stated.

- *Soluble nutrients* were measured following filtering through Whatman GF/C filter paper. Nitrate was measured on a Metrohm ion chromatograph and ammonia, dissolved reactive silicate and soluble reactive phosphate were measured colorimetrically.
- *Total phosphorus* was measured on unfiltered samples and measured colorimetrically, as for soluble reactive phosphorus after digestion.
- *Alkalinity and pH* were measured on a water sample that had been previously sealed in a glass-stoppered bottle to prevent atmospheric exchange. Alkalinity was measured by Gran titration. pH was measured with a combination electrode (Radiometer GK2401C).

- *Phytoplankton chlorophyll a* 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.
- *Phytoplankton composition and abundance* measurements were based on a 300 ml sub-sample of water, preserved with Lugol's iodine in the field, and concentrated in the laboratory 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.
- *Zooplankton* were collected with a standard zooplankton net (mesh size 120 µm, mouth diameter 0.15 m) lowered to 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 70% ethanol. In the laboratory the samples were concentrated by filtration and stored in labelled vials in 4% formalin. The zooplankton were identified and enumerated under a stereozoom microscope, according to Scourfield & Harding (1966) and Gurney (1931-1933). Additional data on zooplankton numbers were also collected based on counts of individuals trapped on the filter papers used to measure phytoplankton chlorophyll *a*.

High resolution data

High resolution (minute frequency) automatically collected data were obtained from meteotological stations on the lake and an adjacent boathouse and an Automatic Water Quality Monitoring Station on the lake.

3. Meteorological conditions at Esthwaite Water in 2010

Recognising that the weather, in addition to climate, can have a major effect on the ecology of a lake and is responsible for a large amount of the interannual variation present in long term records of change, the weather condition at Esthwaite Water are presented for 2010. They are derived from direct measurements on the CEH Automatic Water Quality Monitoring Station and the meterological station at the CEH boathouse at Fold Gate on the western shore.

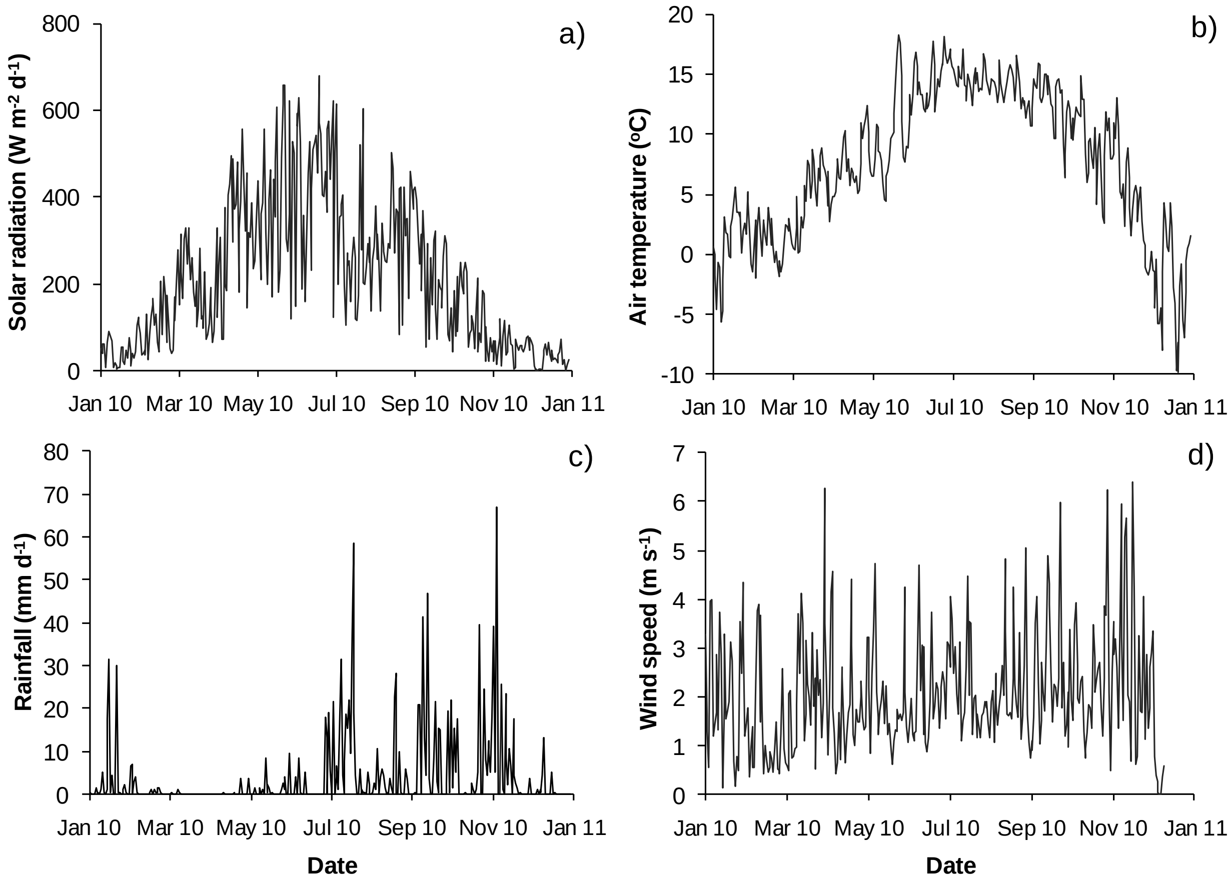

Figure 1. Daily mean meteorological data for Esthwaite Water during 2010 comprising: a) total daily solar radiation; b) average air temperature; c) daily rainfall and d) average wind speed (data from the last few weeks of the year were lost because of ice-damage). Values were recorded at the boathouse 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).

4. Physical conditions in Esthwaite Water in 2010

One reason for the importance of meteorological conditions on lake ecology is via its effect on stratification. The seasonal cycle typical of Esthwaite Water and similar lakes was present in 2010. The lake was more or less isothermal at the start of the year (Fig. 2) with a weak inverse stratification (water colder at the top than the bottom of the lake) at the start of the year. Stratification-proper commenced at the beginning of April and developed during the summer (Fig. 2, 3). Surface water temperature reached a maximum in early July at 19.1 ºC but fell temporarily during a period of wet and cloudy weather later that month.

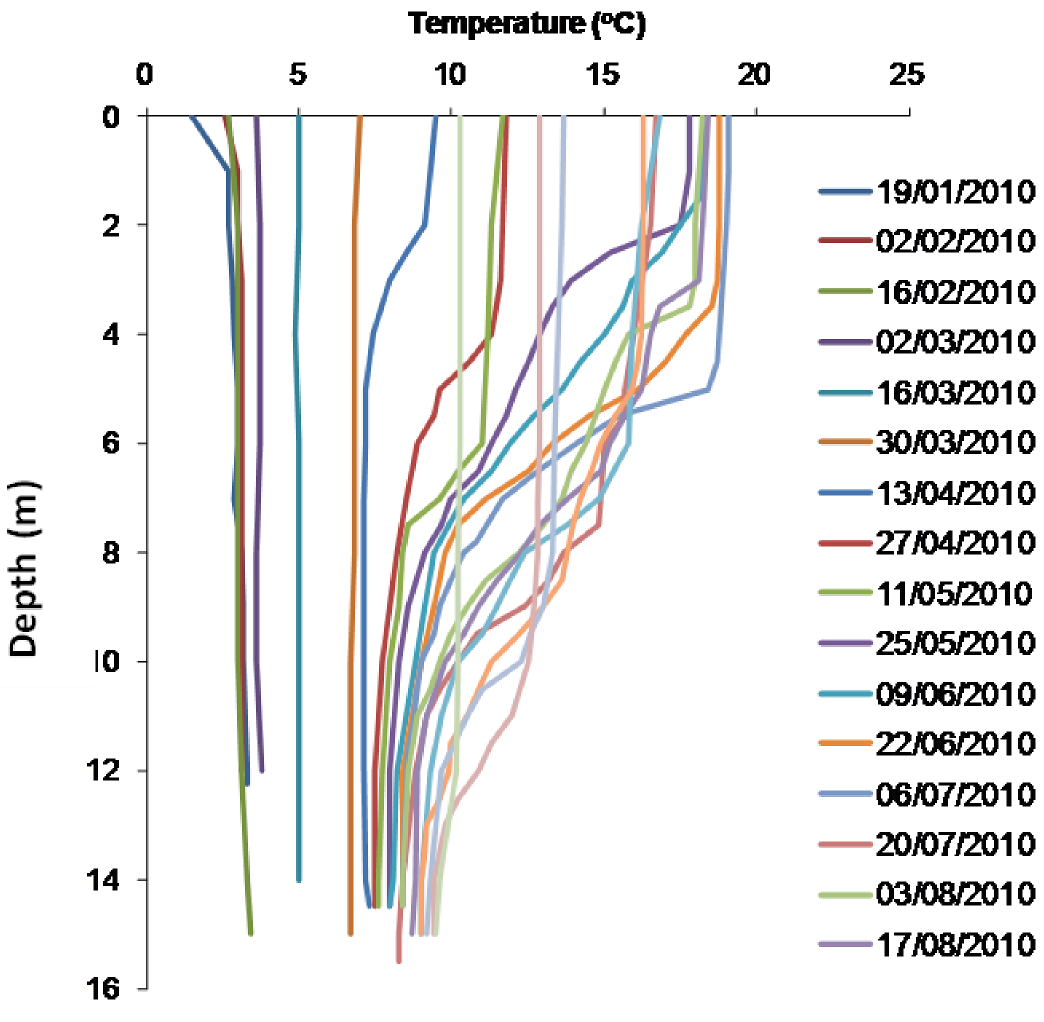

Figure 2. Temperature profiles in Esthwaite Water during 2010.

Stratification broke-down between the 12th and 26th October, again during a period of wet weather (Fig. 1, 3). The temperature at the bottom of Esthwaite Water was about 6.7 ºC when stratification began in the spring and rose slowly and steadily during the summer to reach 9.9 ºC as stratification broke down in October. Stratification, judged as the period when the temperature difference was at least 1ºC over the water column, lasted for about 180 days (Fig. 4).

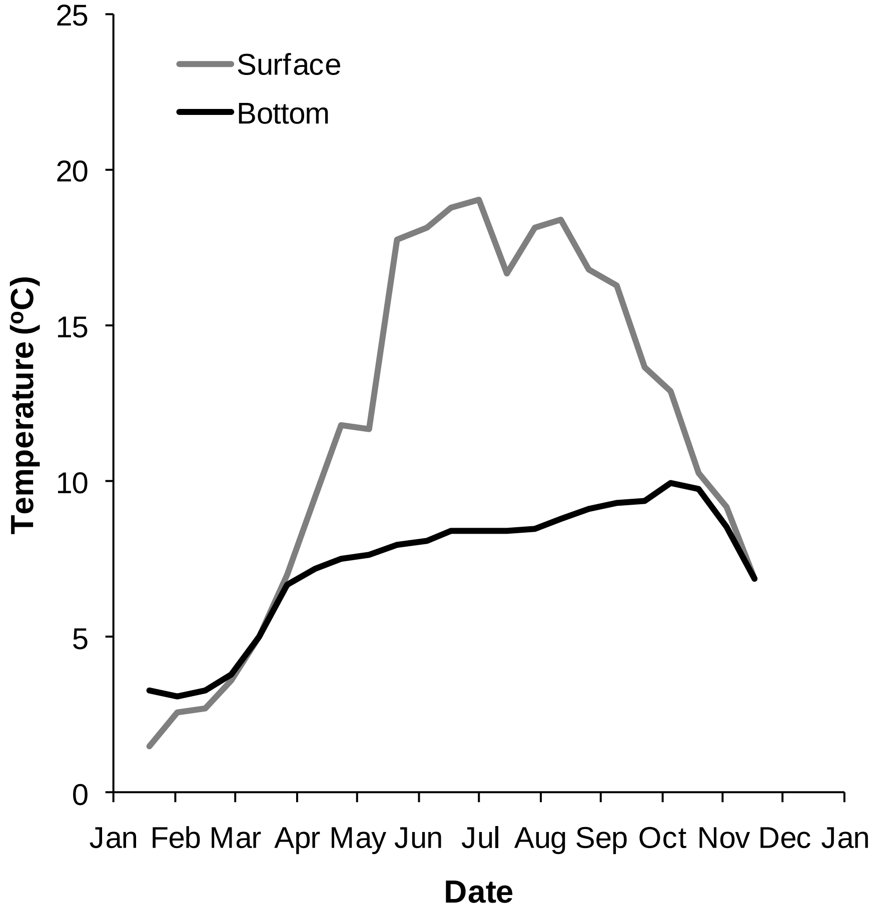

Figure 3. Temperature at the surface and bottom of the water column in Esthwaite Water in 2010.

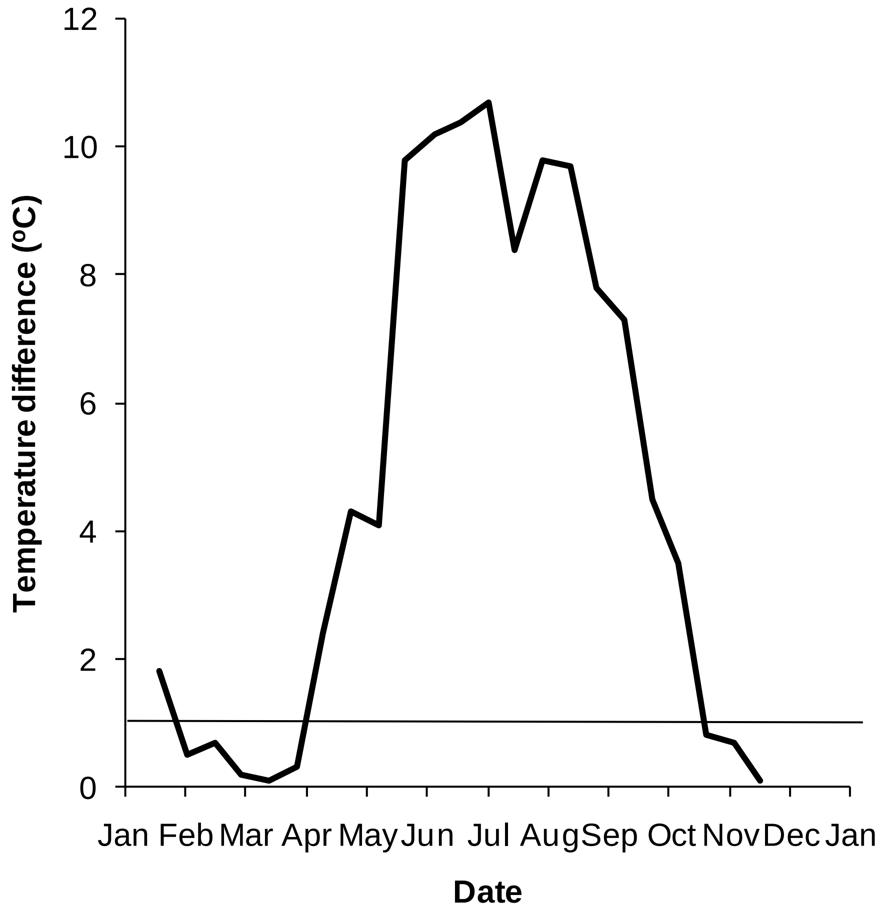

Figure 4. Strength of stratification in Esthwaite Water during 2010, estimated from the temperature difference over the water column. The horizontal line shows the 1 ºC temperature difference.

5. Water quality in Esthwaite Water in 2010

The data for Esthwaite Water in 2010 will be presented here and then in the next section these will be assessed against the conditions in the previous ten years.

Table 1. Average conditions in Esthwaite Water in 2010.

Variable	Unit	Value
Alkalinity	equiv m^{-3}	0.43
pH*	-	7.29
Total Phosphorus	mg m^{-3}	21.4
Soluble Reactive Phosphorus	mg m^{-3}	3.0
Nitrate-N	mg m^{-3}	303.4
Ammonium-N	mg m^{-3}	27.5
Silica	mg m^{-3}	1221.3
Chlorophyll *a*	mg m^{-3}	15.6
Secchi depth	m	2.7
Attenuation coefficient**	m^{-1}	0.87

**Average pH was calculated from the geometric mean.*
***The attenuation coefficient refers to photosynthetically active radiation, 400 – 700 nm.*

The average alkalinity in 2010 was 0.43 equiv m^{-3} (Table 1), placing Esthwaite Water in the medium alkalinity category for the EU Water Framework Directive (WFD; 2000/60/EC). The seasonal trend is for alkalinity to increase during the season (Fig. 5a), probably as a result of declining dilution of base material by decreasing water discharge and probably also by generation of alkalinity in the catchment and the lake by nitrate-uptake. The (geometric) average pH in 2010 based on the fortnightly samples was 7.29 (Table 1), below the pH that would be obtained if the concentration of CO_2 in the lake was in air-equilibrium with the atmosphere (about pH 7.8). Consequently, the lake is a net source of CO_2 to the atmosphere. During periods of strong stratification and large populations of phytoplankton, the pH reached pH 8.8 (Fig. 5b): about a 10-fold under saturation with CO_2. This summer maximum pH is substantially lower than values in some previous years where pH over 10 has been commonly observed (Talling 1976; Maberly 1996).

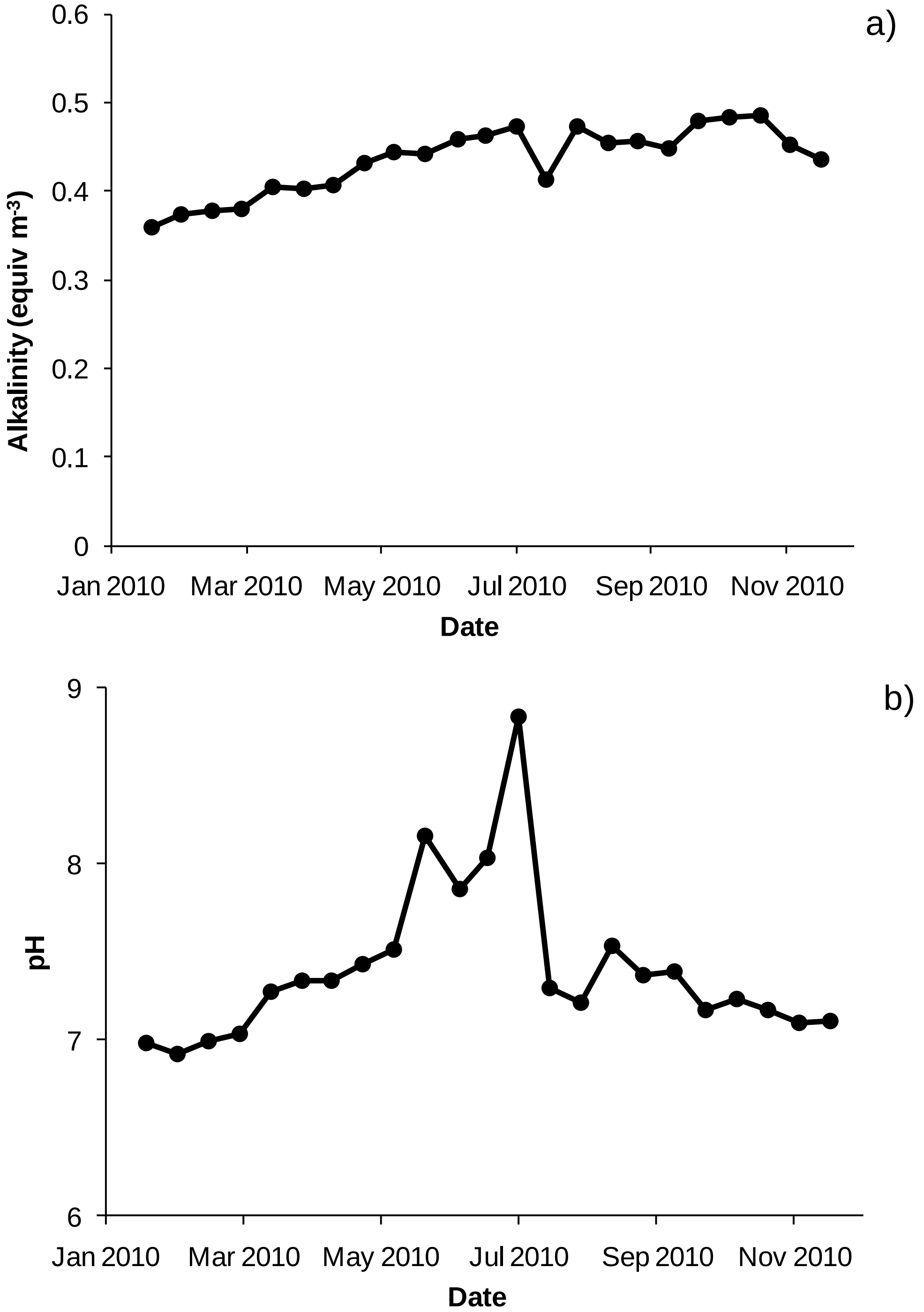

Figure 5. Changes in alkalinity (a) and pH (b) in the surface of Esthwaite Water during 2010.

The main nutrient limiting production for most of the year in Esthwaite Water is phosphorus and the annual mean concentration was 21.4 mg m^{-3} (Table 1). Concentrations of total phosphorus are relatively conservative (Fig. 6a), although there were two notable peaks, one at the end of March, coinciding with the spring phytoplankton peak, and a second at the end of October that coincided with the breakdown of stratification and so may represent total phosphorus from depth being entrained into the surface water, and also occurred at the time of the annual phytoplankton chlorophyll *a* maximum. The biologically available SRP had an annual maximum concentration of 11.6 mg m^{-3} and a mean of 3.0 mg m^{-3} (Table 1). Concentrations fell rapidly in spring during the spring phytoplankton bloom and remained low until they began to increase at the end of September (Fig. 6b). Nitrate had an annual mean concentration of 303 mg m^{-3} (Table 1). Concentrations were high in spring and gradually declined to a minimum of 30 mg m^{-3} in late summer (Fig. 6c). A value of 80 mg NO_3-N m^{-3} is taken to indicate nitrogen-limitation in the lake phytoplankton model PROTECH (Elliott 2011) and concentrations fell below this rough threshold on three sampling dates in 2010, so phytoplankton could have been transitorily nitrogen limited in late summer since concentrations of an alternative nitrogen source, ammonium, were also low (Fig. 6c).

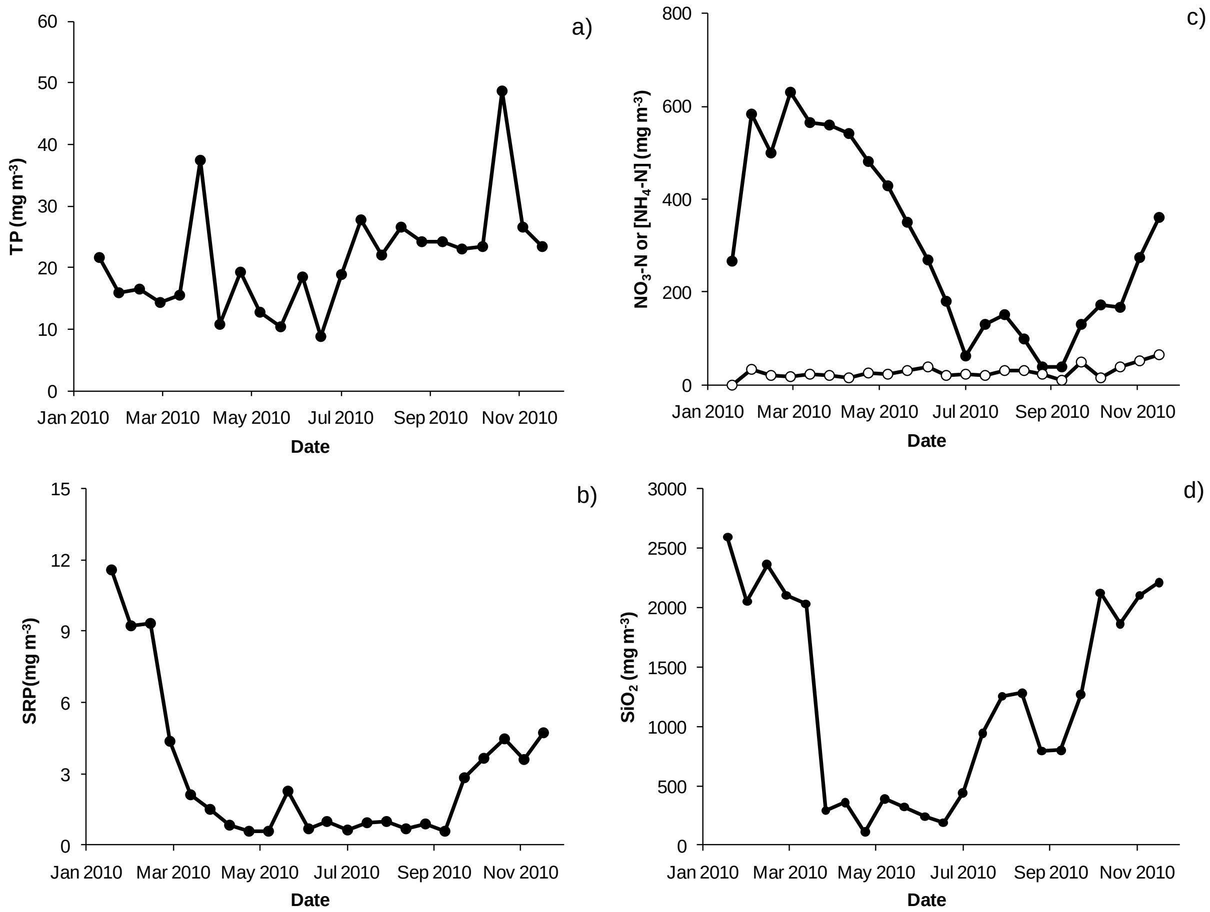

Figure 6. Changes in total phosphorus (a), soluble reactive phosphorus (b), nitrate-nitrogen (●) and ammonium-nitrogen (○) (c) and silica (d) in the surface of Esthwaite Water in 2010.

The final nutrient considered here, silica, is required in large amounts by diatoms and in smaller amounts by other phytoplankton such as chrysophytes. Concentrations fell precipitately in early spring (Fig. 6d), and remained below the threshold of 500 mg m^{-3} considered to be limiting in PROTECH until early July.

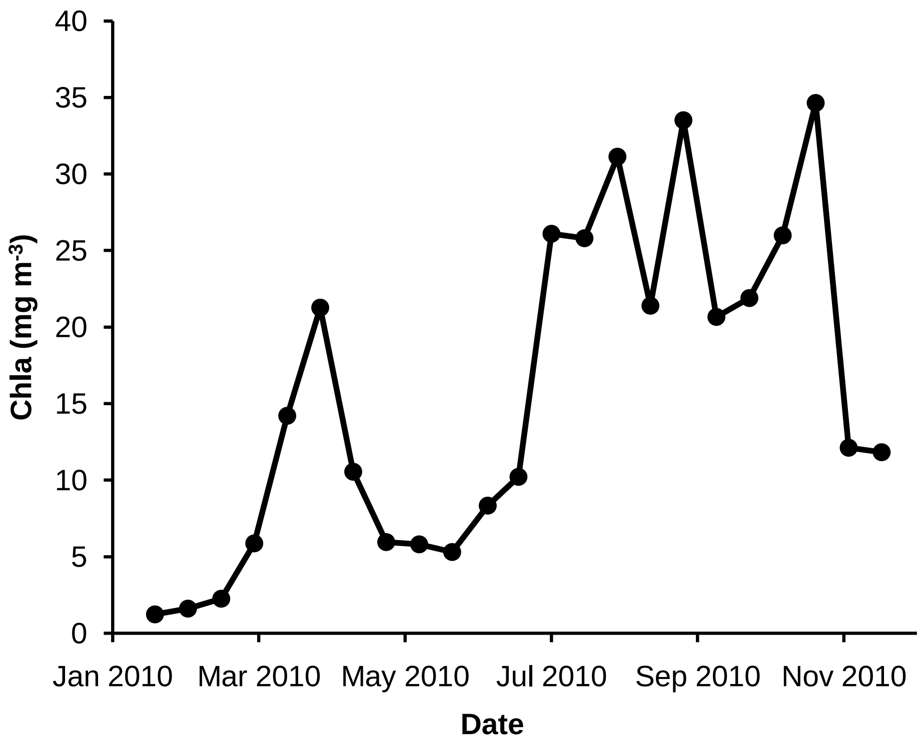

Figure 7. Changes in concentration of phytoplankton chlorophyll a in the surface of Esthwaite Water in 2010.

The phytoplankton, measured as the concentration of chlorophyll *a*, had an annual mean concentration of 15.6 mg m^{-3} (Table 1) and showed a typical seasonal pattern with a spring bloom that reached a maximum of 21 mg m^{-3} on 30 March 2010 and then declined in the 'clear water phase' in April and May (Fig. 7). A prolonged summer bloom lasted from early July to the end of October and had concentrations that ranged between 21 and the annual maximum of 35 mg m^{-3}.

The spring phytoplankton peak was dominated by diatoms, of which the centric diatom *Aulacoseira subarctica* (peak biovolume on 16 March) and the pennate diatom *Asterionella formosa* (peak population on 30 March and an autumn peak on 31 August) were dominant. The colonial green algae *Pseudosphaerocystis* sp. produced a sharp peak on 11 March and in contrast the cryptophyte *Plagioselmis* sp. (*Rhodomonas* sp.) was present throughout the year but reached a maximum on 25 May. The two cyanobacteria produced summer and autumn blooms. *Anabaena solitaria* produced a sharp peak with a maximum on 6 July while *Aphanizomenon flos-aquae* also produced a peak on that date but produced another in the autumn with a late season peak on 26 October just before stratification broke down. This is late in the year for an algal bloom but the preceding three weeks had been very dry (Fig. 1) so flushing losses will have been low.

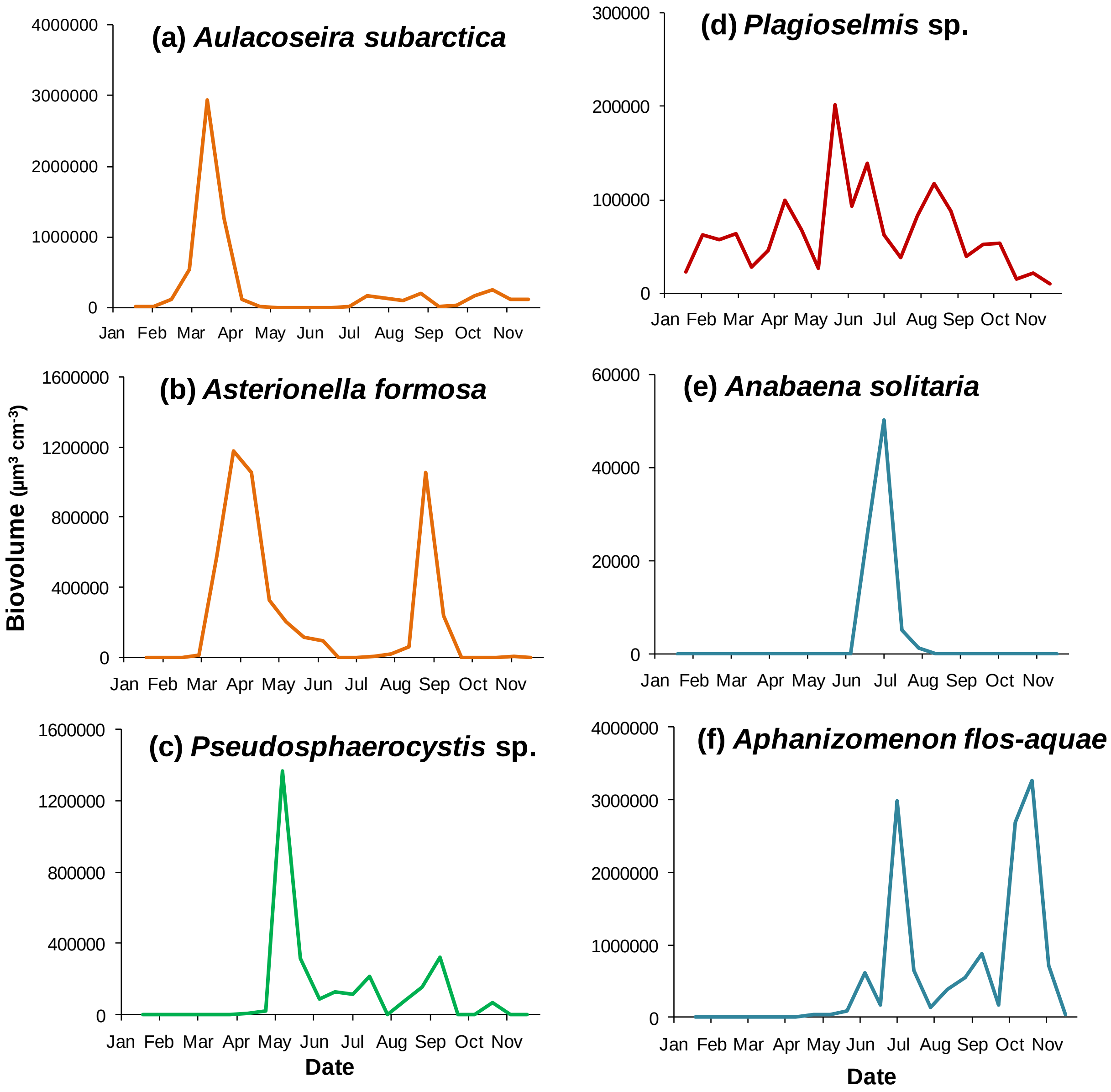

Figure 8. Seasonal patterns of biovolume change of six dominant phytoplankton in Esthwaite Water is 2010: (a) Aulacoseira italica (diatom); (b) Asterionella formosa (diatom); (c) Pseudosphaerocystis sp. (green algae); (d) Plagioselmis sp. (Cryptophyte); (e) Anabaena solitaria (cyanobacterium); (f) Aphanizomenon flos-aquae (cyanobacterium).

The average Secchi depth and light attenuation coefficient were 2.7 m and 0.87 m^{-1} respectively (Table 1). Although measuring slightly different things, the Secchi depth and attenuation coefficient followed each other closely (Fig. 9). The average attenuation coefficient of 0.87 m^{-1} and the growing season (May to September) value of 0.89 m^{-1} equate roughly to a 1% depth for subsurface light of about 5 m. Macrophyte depth limits occur at between about 2.2 and 16.3% of surface light depending on the type of plant (Middleboe & Markager 1997). Using these values and the growing season attenuation coefficient, macrophyte depth limits may occur at between 4.3 and 2 m.

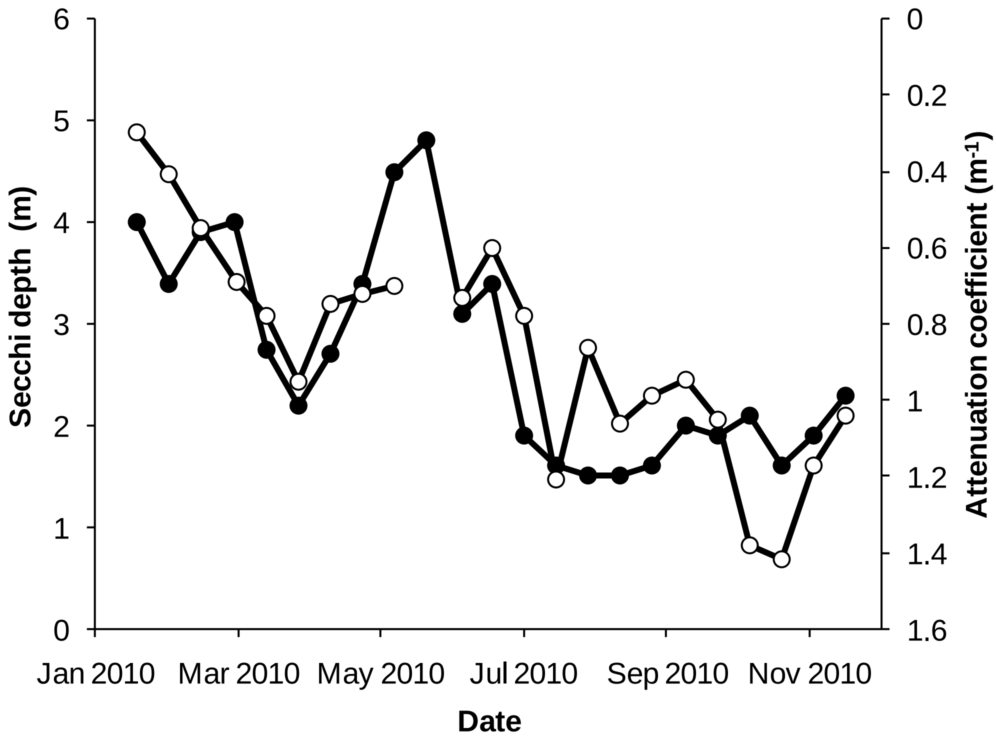

Figure 9. Seasonal changes in light transparency in Esthwaite Water during 2010 measured as Secchi depth (●) and attenuation coefficient (○) with scale reversed to show the relationship to Secchi depth.

The changing phytoplankton populations were the dominant factor controlling water transparency and Secchi depths were shallow when phytoplankton populations were high and deeper during periods such as the 'clear water phase' in April to May (Fig. 10). The trendlines fitted to the data suggest that in Esthwaite Water in the absence of phytoplankton chlorophyll a, the background Secchi depth is 4.14 m and the background attenuation coefficient is 0.36 m^{-1}.

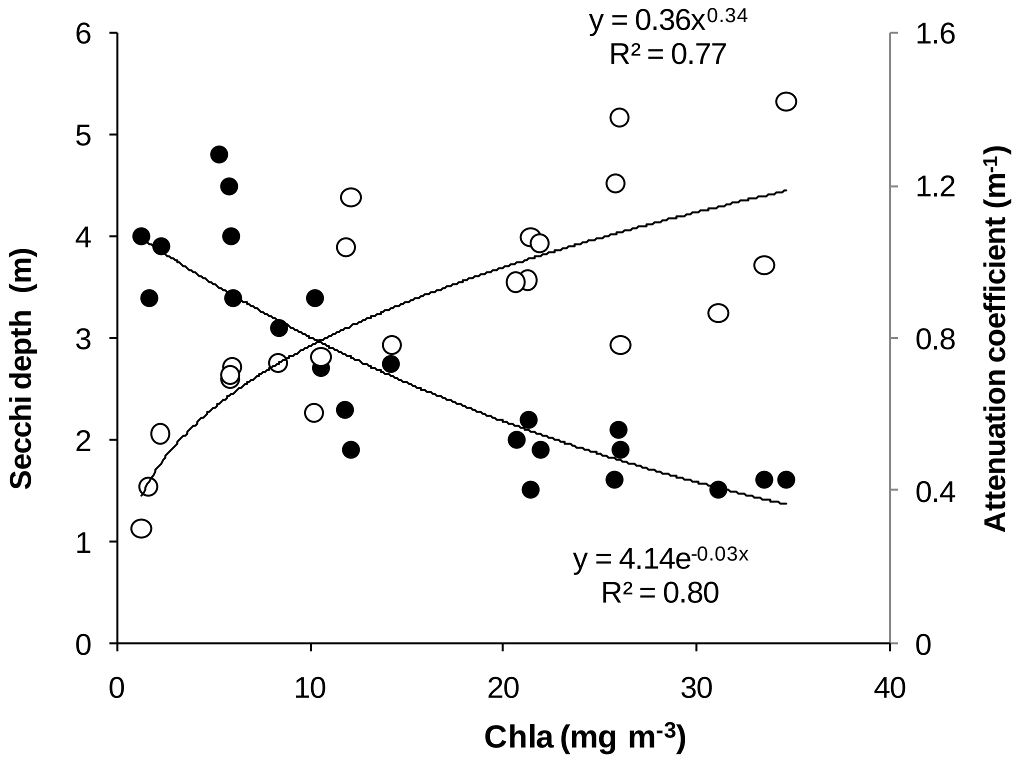

Figure 10. Relationship between Secchi depth (●) or and attenuation coefficient (○). Lines show the best fit relationships, with equations given.

Zooplankton provide the link between phytoplankton and higher trophic levels and can, via top-down control, have a large influence on phytoplankton abundance. In Esthwaite Water in 2010, the zooplankton produced two large peaks in abundance, one in April and May and another shorter lived one in the middle of September (Fig. 11).

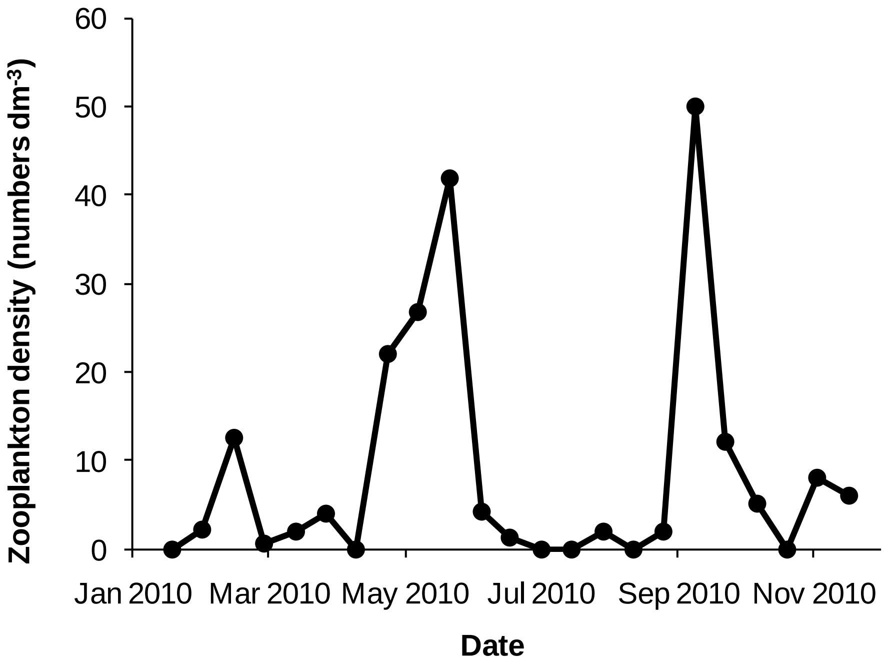

Figure 11. Changes in zooplankton density in the surface of Esthwaite Water in 2010, based on water from 0 to 5 m and counted on filters used to analyse for chlorophyll a.

Nine species of crustacean zooplankton, from eight different genera, were recorded in Esthwaite Water in 2010. These included representatives of the cladocera (*Daphnia hyalina/galeata, Bosmina longirostris, Ceriodaphnia quadrangula, Chydorus sphaericus, Leptodora kindtii*), cyclopoid copepods (*Cyclops strenuus, C. vicinus, Mesocyclops leuckarti*) and calanoid copepods (*Eudiaptomus gracilis*). The predatory planktonic stages of the phantom midge *Chaoborus* were also collected in some samples. The herbivorous cladocerans *D. hyalina/galeata* and *C. quadrangula* had the highest annual mean abundances, in excess of 2 individuals dm^{-3}, with all other species having annual mean abundances of <1 individual dm^{-3}.

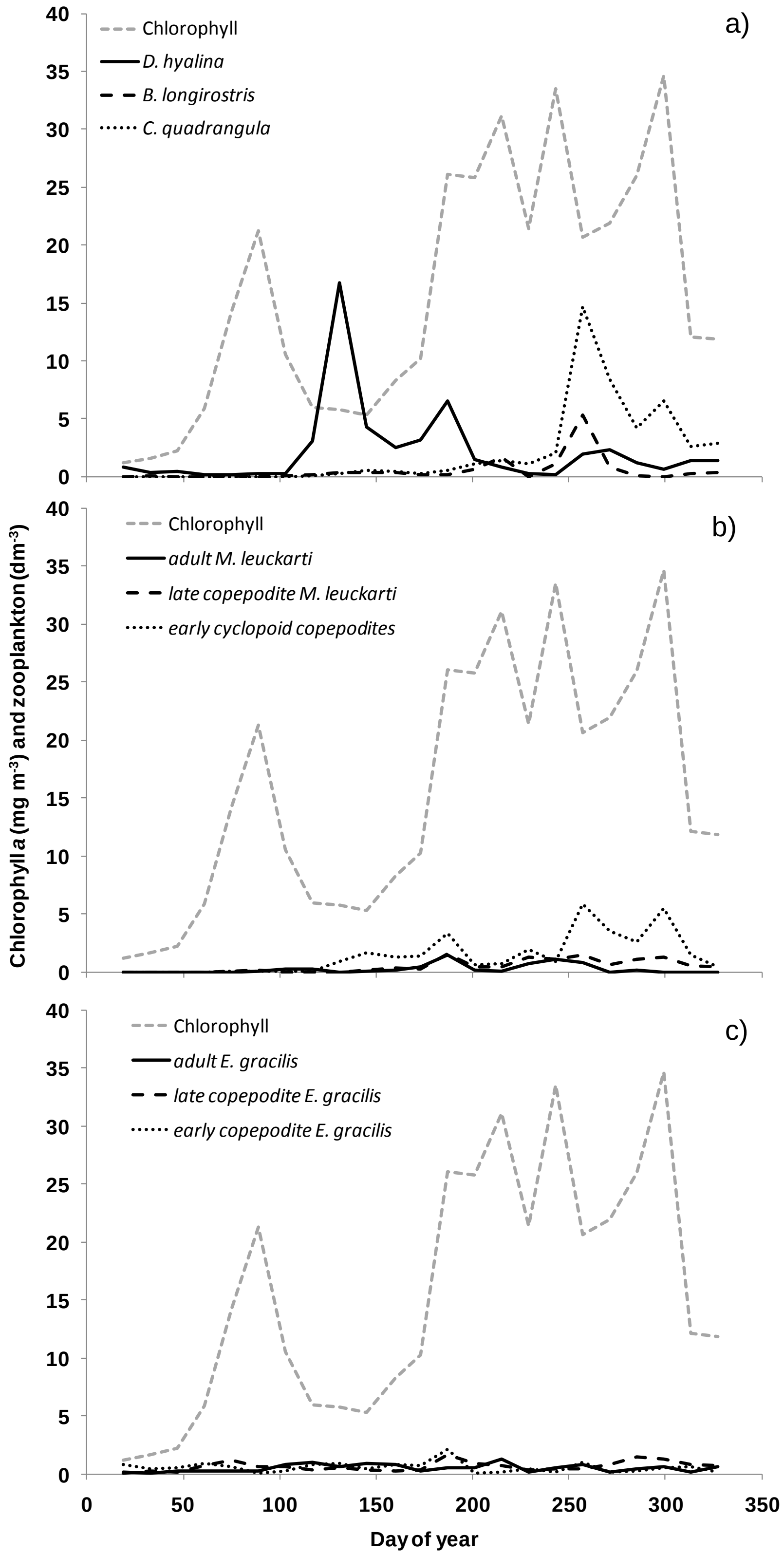

Figure 12. Temporal variation in the abundance of the dominant species of a) cladocerans, b) cyclopoid copepods and c) calanoid copepods in Esthwaite Water, 2010. Chlorophyll concentrations also plotted. Densities are the average of the whole water column.

The spring crustacean zooplankton community was dominated by *D. hyalina/galeata*, which reached a peak population density of 16.8 individuals dm^{-3} on the 11th May (Julian day 131), following the spring phytoplankton bloom (Fig. 12a). The *D. hyalina/galeata* population maximum occurred more than one month after the peak in the phytoplankton bloom. Phytoplankton biomass was already in decline before high population densities of this grazer had developed; suggesting that grazing was not the sole cause of the end of the spring phytoplankton bloom. Additional, though smaller, peaks in *D. hyalina/galeata* abundance occurred in mid to late summer. However, during the late summer, smaller bodied cladocerans (*B. longirostris* and particularly *C. quadrangula*) dominated the crustacean zooplankton community (Fig. 12a). *C. quadrangula* and *B. longirostris* reached peak population densities of 14.7 and 5.3 individuals dm^{-3} on the 14th September (Julian day 257), respectively. Chlorophyll concentrations declined temporarily during this peak in grazer abundance. Comparison of Fig. 11 and Fig. 12 suggests that the spring *D. hyalina/galeata* peak and the late summer *C. quadrangula*/*B. longirostris* peaks account for the two seasonal peaks in total zooplankton density.

Adults and juveniles (or copepodites) of the most abundant cyclopoid copepod, *M. leuckarti*, were found primarily throughout the mid to late summer (Fig. 12b), while the calanoid *E. gracilis* was found throughout the year at low population densities (Fig. 12c). At this time, late juveniles and adults of the former were likely feeding upon small crustaceans and rotifers while the latter would likely be feeding upon phytoplankton and protozoa. The predatory larvae of *Chaoborus* were recorded in the lake between the 22nd June and the 12th October, peaking at slightly above 0.1 dm^{-3} on the 14th September. It is likely that the larvae were feeding on the small bodied cladocerans also abundant on this date.

The dominant features of the zooplankton community succession during 2010 were broadly in keeping with previous observations on Esthwaite Water (Smyly 1968; Heaney et al. 1986;

George et al. 1990) and with the conceptual model proposed by Sommer et al. (1986), with a transition from fast growing large bodied cladocera (e.g. *D. hyalina/galeata*) in the spring to smaller bodied species (e.g. *C. quadrangula*, *B. longirostris*) in summer. The shift towards smaller body sizes in summer may be driven by enhanced size-selective predation by young-of-the-year fish in the prevailing warm conditions. These predators locate prey visually and will tend to feed more intensively on larger, more visible, species. In addition, the feeding processes of small bodied zooplankton are less susceptible to mechanical interference by filamentous algae which may dominate the phytoplankton community at this time (e.g. *Aphanizomenon*, Fig. 8).

Esthwaite Water and the Water Framework Directive

The Water Framework Directive (WFD: 2000/60/EC) sets out objectives for the water environment. These include the default objectives:

- prevent deterioration of the status of all surface water and groundwater bodies;
- protect, enhance and restore all bodies of surface water and groundwater with the aim of achieving good status for surface water and groundwater by 2015

For lakes, the concentration of phytoplankton chlorophyll *a* along with supporting information based on what is frequently the main driver, total phosphorus are two key criteria to judge the ecological status of a lake.

Different types of lakes typically have different water qualities and capacities to convert phosphorus into phytoplankton. Under the terms of the WFD, Esthwaite Water is classified as a medium alkalinity, shallow lake. The site-specific boundaries for Esthwaite Water, based on geometric annual means, are shown in Table 2. Compared to the geometric annual means of 19.8 and 11.2 mg m^{-3} for total phosphorus and chlorophyll *a*, respectively, Esthwaite Water is classified as ‘Moderate’ on both measures.

Table 2. Annual geometric mean values for the concentration of total phosphorus and chlorophyll a in Esthwaite Water in 2010 and the site-specific Water Framework Directive Boundaries.

	Esthwaite Water 2010	High: Good	Good: Moderate	Moderate: Poor	Poor: Bad
Total P (mg m^{-3})	19.8	11.0	16.4	32.8	65.7
Chlorophyll *a* (mg m^{-3})	11.2	4.5	6.9	13.7	41.5

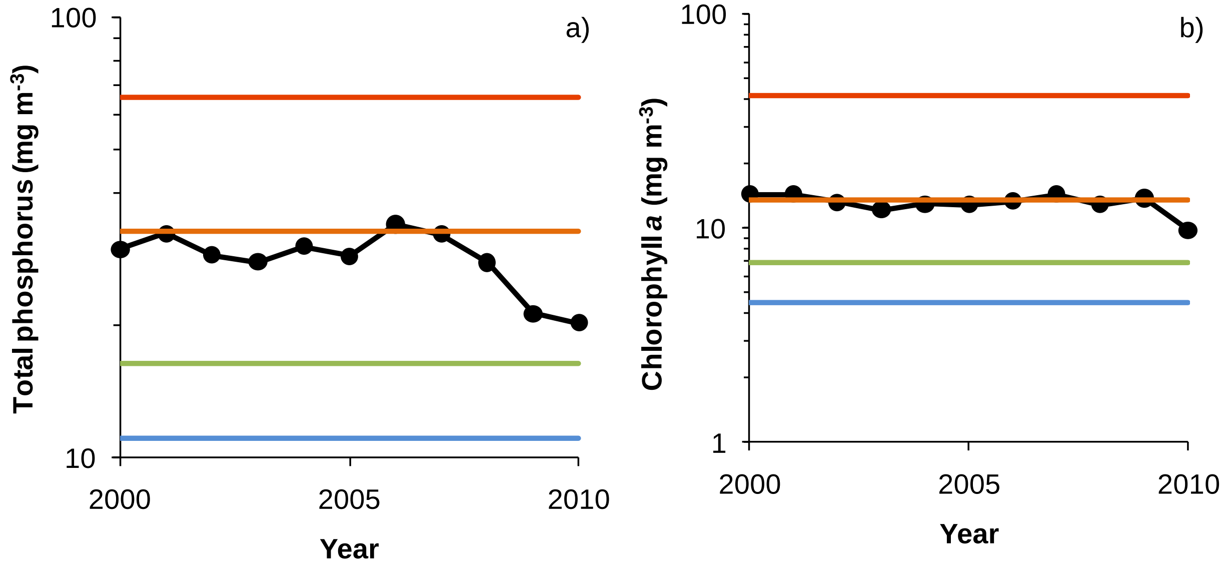

Figure 13. Comparison of geometric annual average total phosphorus (a) and chlorophyll a (b) in Esthwaite Water with site-specific boundaries for the Water Framework Directive High: Good (blue), Good: Moderate (green), Moderate: Poor (orange) and Poor: Bad (red). Note the logarithmic scale on both panels.

As a consequence, Esthwaite Water failed the 'good ecological status' criterion of the Water Framework Directive in 2010. However, in previous years the ecological status was close to the Moderate: Poor boundary (Fig. 13). These results underline the necessity of the Programme of Measures currently being undertaken on the lake.

6. Esthwaite Water in 2010 compared with the previous decade

This section places the main seasonal and annual conditions in Esthwaite Water in the context of the previous decade, to assess the extent of any changes following on from the management in the lake and its catchment. For each month and variable, 95% confidence intervals were calculated for the period 2000 to 2009 based on monthly or annual data. By comparing the monthly mean or annual data for 2010 against these values, it is possible to test statistically whether or not a monthly or annual value is significantly above or below the ten year pattern. The figures below also show the monthly data for the individual ten previous years to give a visual impression of the extent of variation in comparison with the 2010 data.

Total phosphorus

This variable showed the strongest evidence of change, with a clear reduction at the start of the year in 2010 that was maintained throughout the year, apart from in October during a peak phytoplankton bloom where the concentration of total phosphorus just significantly exceeded the long term average (Fig. 13a). The annual mean in 2010 was significantly below the average in the previous decade, but the same was also true for 2009 (Fig. 13b).

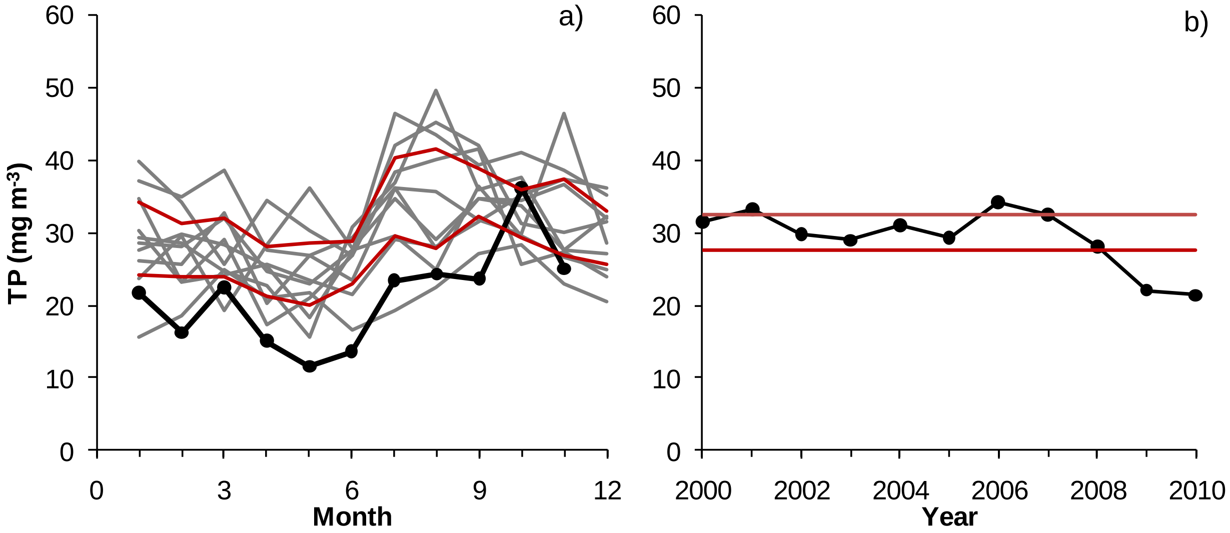

Figure 13. Seasonal and annual comparison of concentration of total phosphorus in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years

2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Soluble Reactive Phosphorus

There were fewer statistically significant changes in SRP compared with TP in 2010. Concentrations were slightly, but significantly, lower in March, April, August and November and significantly higher in September (Fig. 14a). The annual mean concentration of SRP showed a clear downward trend that started in 2005. 2010 was not significantly below the 95% confidence interval for the preceding ten years, but these low concentrations were also found in 2008 and 2009 (Fig. 14b).

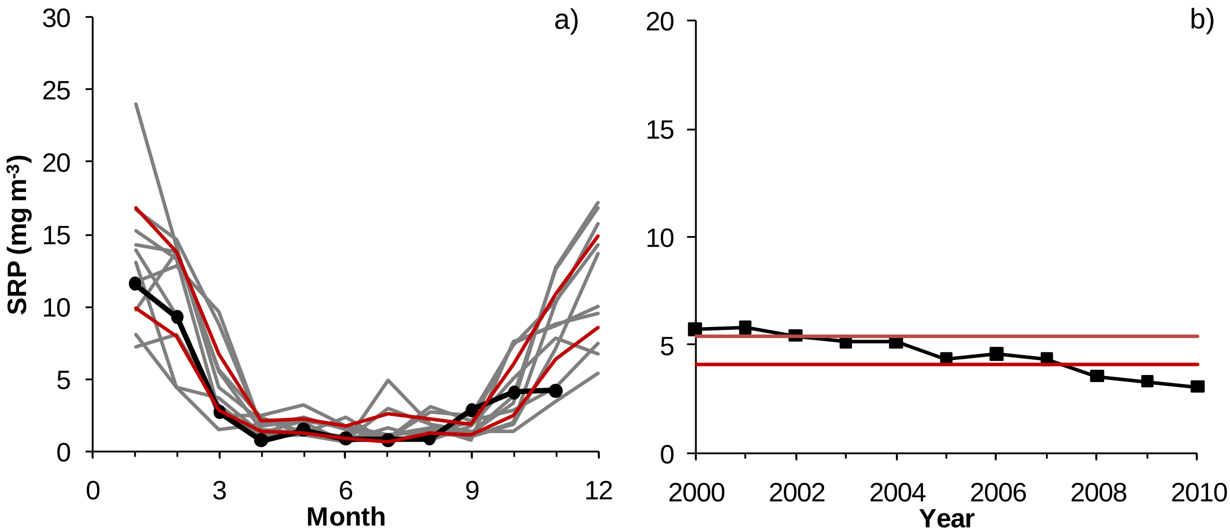

Figure 14. Seasonal and annual comparison of concentration of soluble reactive phosphorus in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years 2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Nitrate

In 2010, concentrations of nitrate were significantly below the average in the preceding ten years between January and March and again between May and July and in October and November (Fig. 15a). This may have arisen because of unusually low concentrations at the start of the start of the year. The annual mean in 2010 was significantly below that in the preceding ten years, but the same was probably also true in 2009 (Fig. 15b).

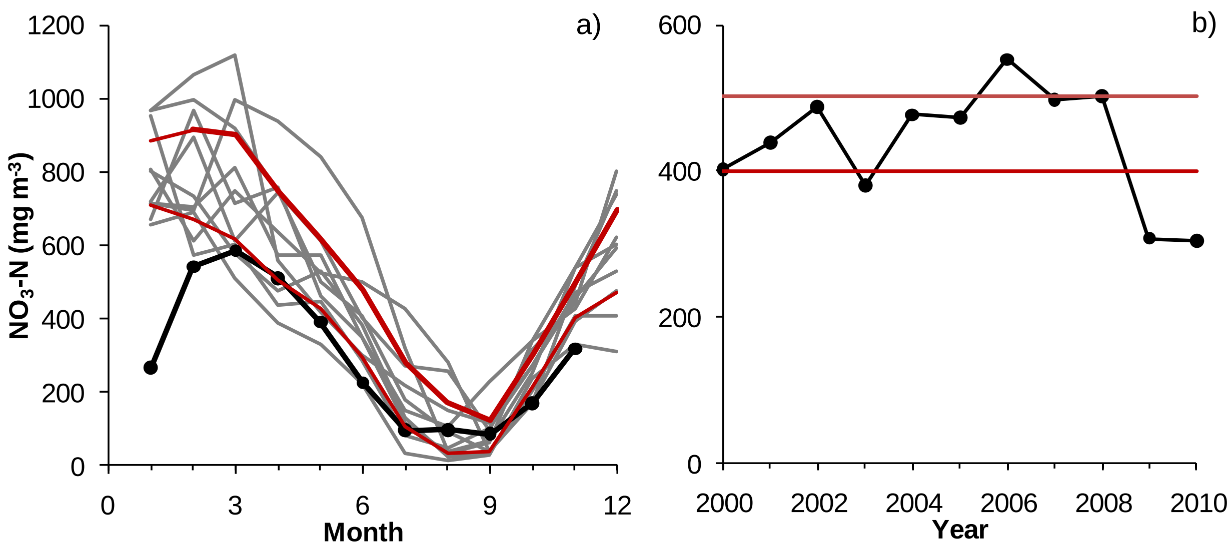

Figure 15. Seasonal and annual comparison of concentration of nitrate in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years 2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Chlorophyll a

Chlorophyll *a* also showed evidence for lower concentrations in 2010. The March spring bloom was the lowest in the last ten years and significantly lower than the previous decade and the same was true between the whole of the year apart from in July and October when the value was not significantly different from the mean and in October when chlorophyll *a* was significantly above the long term average in the previous decade (Fig. 16a). The annual concentration was lower than any recorded in the previous ten years and significantly lower than the average (Fig. 16b).

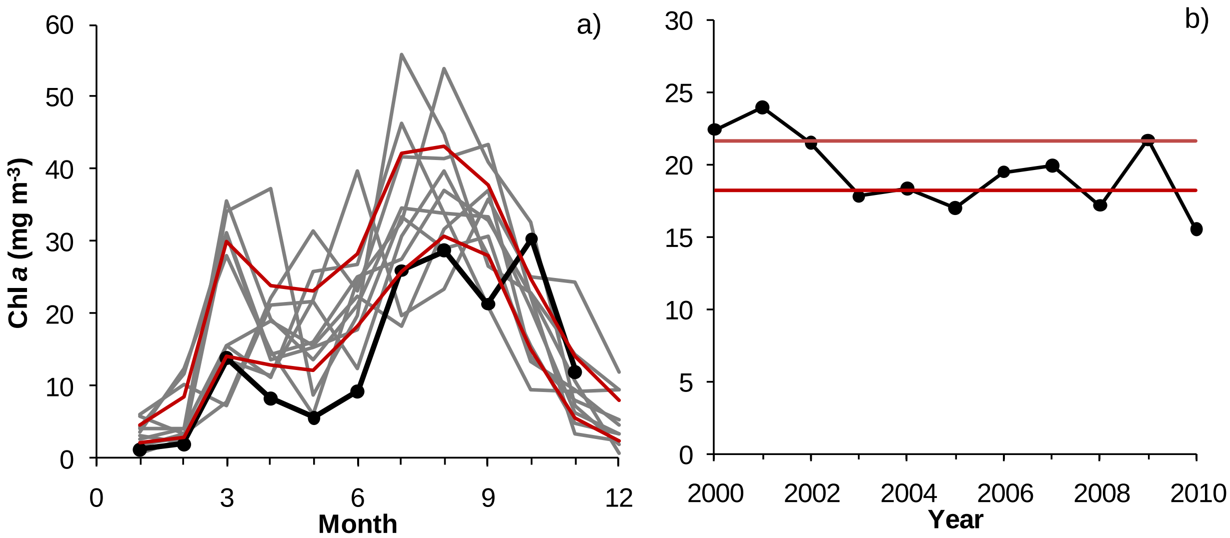

Figure 16. Seasonal and annual comparison of concentration of chlorophyll a in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years 2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Secchi depth

Secchi depth was greater (i.e. an improvement) than the average in the previous ten years in January, February, May, June (although only just in March and April) and also in September, and was significantly worse (i.e. shallower depth) in November (Fig. 17a). The annual mean depth was significantly greater than the average for the ten preceding years (Fig. 17b).

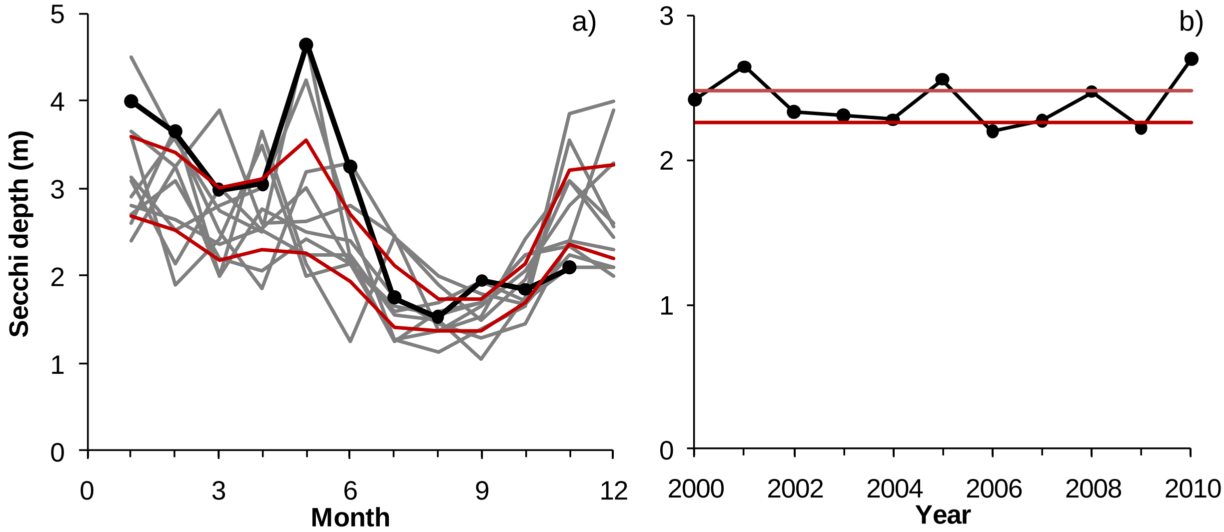

Figure 17. Seasonal and annual comparison of Secchi depth in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years 2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Minimum oxygen concentration

During stratification, the minimum concentration of oxygen occurs at the bottom of the water column and this is the significant criterion here. The stratified period is roughly from April to October and during this period the only significant difference was a slightly lower oxygen concentration in September in 2010 compared to previous years (Fig. 18a). The mean annual minimum concentration in 2010 was just significantly lower than the average in the preceding years (Fig. 18b).

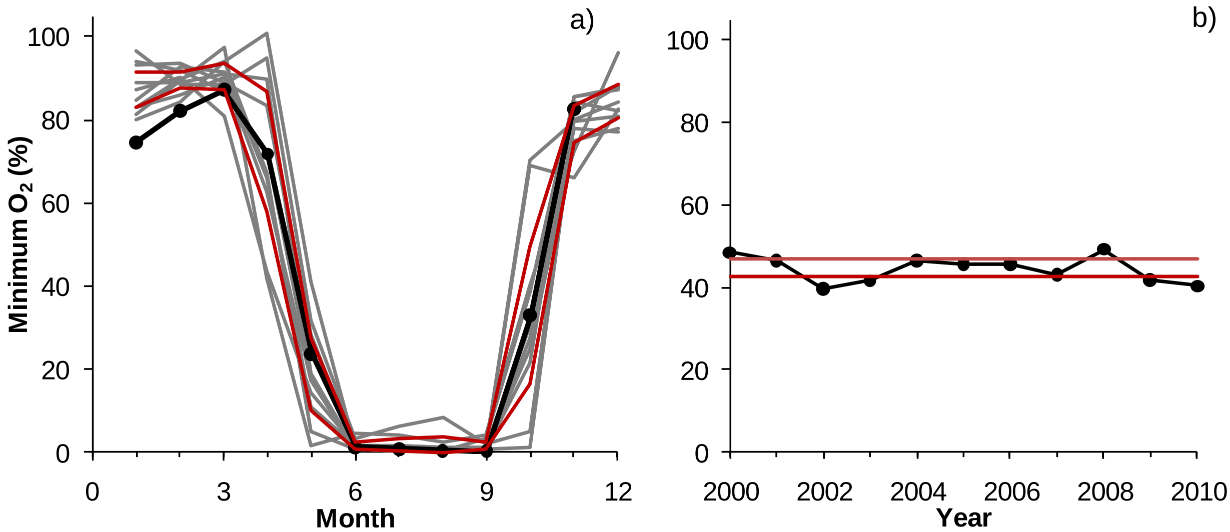

Figure 18. Seasonal and annual comparison of the minimum oxygen concentration in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years 2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Zooplankton abundance

There are quite large fluctuations in abundance of zooplankton, based on chlorophyll *a* filter paper counts, from month-to-month and year-to-year. Lower zooplankton abundance was judged a worse condition because zooplankton help to remove phytoplankton from the water. In 2010, zooplankton abundance was significantly below the monthly average in the preceding ten years in January, March, April, June, July and August, and significantly above the average in February and September (Fig. 19a). The annual mean, however, was not quite significantly different from the previous ten years.

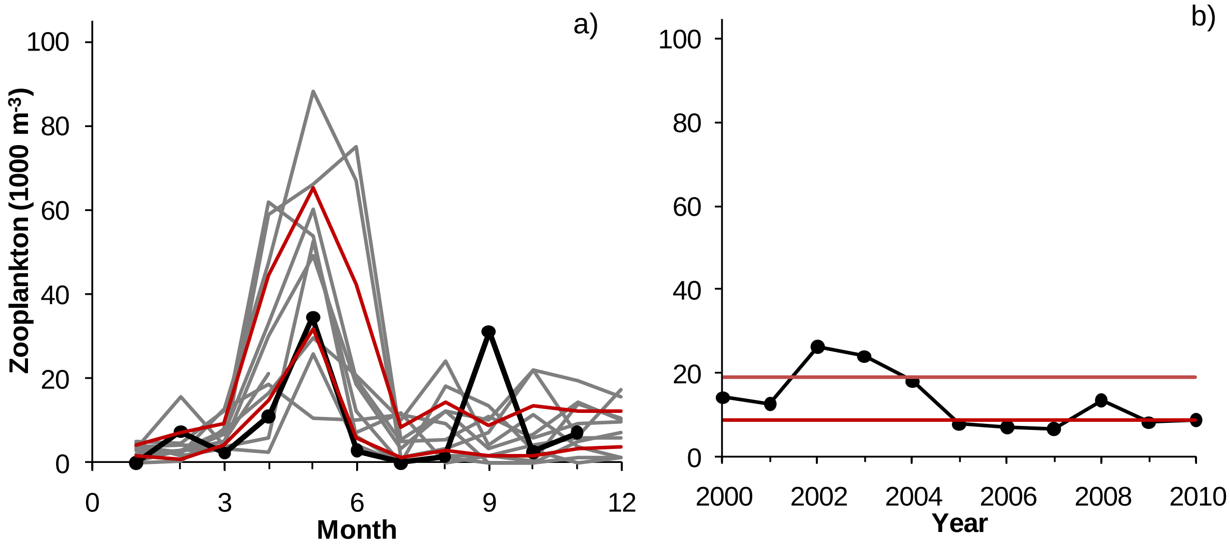

Figure 19. Seasonal and annual comparison of the zooplanklankton abundance based on counts on filter papers used to analyse for chlorophyll a in Esthwaite Water in 2010 compared with the previous ten years. (a) seasonal comparison, individual years 2000 to 2009 shown in grey, 2010 shown in black with dots for monthly mean and the red lines show the upper and lower 95% confidence intervals for 2000 to 2009 based on monthly means; (b) long term annual trend; the red lines showing the upper and lower 95% confidence intervals based on annual means.

Summary of change

The data above have been summarised in Table 3. There is evidence for improved water quality in several water quality variables in many months of the years, apart from September and October when a number of variables showed worse water quality. However, although a number of the variables showed annual trends towards improving quality, the only statistically significantly different water quality variable was total phosphorus.

On the face of it, these results are very encouraging. However, the long term record (Maberly et al. 2011) has demonstrated other periods where the water quality in Esthwaite Water has improved for a few years before deteriorating again. Also, the first signs of improvement in terms of reduced concentrations of TP and nitrate were visible in 2009, before the actual implementation of the main changes to the fish farm and the handling of the waste water before it reaches the Hawkshead WwTW. This could result, for example, from reduced fish stocking in early 2009 prior to the cessation later that year, or other changes to the waste handling by United Utilities: This would be worth investigating further. Nevertheless, the consistent range of improvement to water quality in Esthwaite Water is very encouraging.

Table 3. Summary of monthly and annual values in 2010 compared to 2000 with 2009. Green shading indicates a significant improvement, red shading a significant worsening, white shading no statistical change and grey shading indicates data missing (December because of ice) or not appropriate (min O_2 in unstratified period). N.B., high zooplankton density is scored as an improvement.

Variable	J	F	M	A	M	J	J	A	S	O	N	D	Year
Total Phosphorus	green	green	green	green	green	green	green	green	green	red	green	grey	green
SRP			green	green				green	red		green	grey	green
Nitrate	green	green	green		green	green	green			green	green	grey	green
Chlorophyll *a*	green	green	green	green	green	green		green	green	red		grey	green
Secchi depth	green	green			green	green			green		red	grey	green
Min O_2	grey	grey	grey						red		grey	grey	red
Zooplankton	red	green	red	red		red	red	red	green			grey	

7. Summary & Conclusions

Esthwaite Water is one of the most productive lakes in the English Lake District. Part of this productivity derives from its relatively low lying and fertile catchment, but palaeolimnological data clearly demonstrate a history of progressive and accelerating nutrient enrichment that was stimulated in recent years by the commissioning of a WwTW at Hawkshead in 1973 and the operation of a fish farm directly on the lake that commenced in 1981. Esthwaite Water is also one of the best-studied lakes in the world with numerous detailed studies that extend back over 65 years (Maberly et al. 2011). Recently, the fish farming with rearing of fish in cages ceased (November 2009) and the handling of waste water at, and leading to, the WwTW has been upgraded.

This study has demonstrated clear improvements in many key water quality measures. In particular, concentrations of the primary nutrient causing enrichment, phosphorus as total phosphorus and soluble reactive phosphorus has declined. This has caused reduced phytoplankton crops and slightly improved water transparency. Oxygen depletion at depth has not improved however. While these results are extremely encouraging, there are two areas of concern. The first is that the long term records show periods of improvement and worsening in water quality as a result of outside factors probably linked to weather patterns: so further work is needed to check if the observed changes are maintained or transitory. Secondly, some of the improvements were observed during 2009, before some of the main management changes had been implemented. This needs to be understood better and an important area of research will be to draw together, for the fish farm: information on fish stocking, feeding rates; and management and for the WwTW: information on discharged concentration of phosphorus and nitrogen resulting from managing the works and associated network of sewers that feed into it.

Currently, Esthwaite Water has Moderate ecological status based on total phosphorus and chlorophyll *a* but in previous years the ecological status was close to the moderate: Poor boundary. Nevertheless, if the response is real, it is surprisingly rapid and encouraging for the future improvement in the ecological status of the lake. These results underline the necessity of the Programme of Measures currently being undertaken on the lake.

8. Acknowledgements

Geoff Philips of the Environment Agency is thanked for providing the current Water Framework Directive boundaries for Esthwaite Water.

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