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ASSESSING THE LONG TERM CHANGES IN THE WATER QUALITY OF THE SENSITIVE WATERS OF THE CUMBRIAN LAKES, 2007

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Executive summary

1. The results of biological, chemical and physical analyses undertaken on samples collected monthly during 2007 from the North and South Basin of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake are presented and interpreted in this report. This work continues long-term measurements, of many years duration, although the reduction in sampling frequency from fortnightly to monthly has meant that some comparisons with historic data are difficult.
2. In many of the lakes, surface water temperature was higher than usual in April and May during a period of unseasonably hot weather, and cooler than usual during summer as a result of particularly cool and wet weather. As a result of the different volumes and depths of the lakes, temperature at depth was substantially different among lakes. Temperature at depth in the North Basin of Windermere was about 7ºC all summer while in Bassenthwaite Lake it reached 16.1ºC due to much weaker and intermittent stratification.
3. Oxygen depletion at depth was most marked in the productive and strongly stratified Grasmere with several months of anoxic water at the sediment surface. The weakly stratified Bassenthwaite Lake showed little oxygen depletion as did the relatively unproductive North Basin of Windermere.
4. Alkalinity varied seasonally with the concentration building up during the summer. Based on annual means, and using the categories of the EU Water Framework Directive, Derwent Water, Grasmere and Bassenthwaite Lake would be classified as having low alkalinity (less than 10 g $CaCO_3$ m^{-3}, although Bassenthwaite Lake is very close to the upper boundary) while the two basins of Windermere would be classified as having moderate alkalinity (between 10 and 50 g $CaCO_3$ m^{-3}). There was variation in pH across the lakes because of varying alkalinity. Superimposed on this were episodes of high pH, particularly in the South Basin of Windermere, resulting from high rates of phytoplankton carbon uptake during photosynthesis.
5. Phosphorus is the main nutrient controlling biological productivity in these lakes. Concentrations of total phosphorus are relatively conservative but tended to be lowest in summer and varied over almost a 2-fold range across the five lake basins. Soluble reactive phosphorus, the main form available to phytoplankton, was at or below detection in all lake basins in the summer but varied in the winter according to lake productivity,

being highest in productive lakes such as the South Basin of Windermere and lowest in less productive lakes such as Derwent Water.

6. There was a tendency for declining water clarity, quantified by Secchi depth, in all three basins in the Windermere catchment but little change in the two other lakes. The decrease could be linked to greater input of material from the land but there are no data to test this possibility. Secchi depth was very variable seasonally but generally lowest in Bassenthwaite, probably because of the large amount of suspended solids in this lake.
7. All five lakes produced two main maxima of phytoplankton, quantified as the concentration of chlorophyll *a*, one in the spring and the other in mid- to late-summer. Concentrations were generally lowest in Derwent Water and highest in one of the four other basins depending on the time of year. The spring peak was typically dominated by diatoms such as *Asterionella formosa* or *Aulacoseira subarctica* accompanied by a range of different species such as *Chlorella* sp., *Rhodomonas* sp. and *Chrysochromulina parva*. The summer peak was very diverse within a lake and variable among the lakes.
8. There was good evidence for coherence in year-to-year variation among lakes which indicates the importance of the weather in influencing lake function and characteristics, particularly surface temperature. However, temperature at depth, oxygen depletion at depth, secchi depth, chlorophyll *a*, concentration of total and soluble reactive phosphorus were correlated for at least one pair of lakes.
9. Long term trends were apparent in many of the data. The North Basin of Windermere is showing a worrying decline in water quality, particularly the increasing mean total phosphorus, declining Secchi depth and declining mean and minimum oxygen concentration at depth. The South Basin of Windermere has evidence for declining Secchi depth, but maximum soluble reactive phosphorus is also declining so there are mixed signals as regards water quality. Grasmere is relatively stable, although the maximum Secchi depth has declined. Derwent Water is also stable but there is a trend of increasing maximum concentration of chlorophyll *a* which is concerning and is presumably linked to the tendency for the phosphorus concentration to increase. Bassenthwaite Lake is the only lake showing signs of improvement: the maximum and mean concentration of total phosphorus has declined as has the maximum concentration of soluble reactive phosphorus, but to date the effect of on other aspects of the ecology of the lake have been marginal. Hopefully, if the current trends on Bassenthwaite continue the lake may be poised for tangible future improvements in water quality.

10. The likely status of the five lakes in terms of the Water Framework Directive were assessed. The North Basin of Windermere is in moderate ecological status for total phosphorus and chlorophyll *a*. The South Basin is close to the moderate: poor boundary for total phosphorus and chlorophyll *a*. Grasmere is in the middle of moderate ecological status for both total phosphorus and chlorophyll *a*. Derwent Water is the only lake reported on here at good ecological status, and it is at good status for both total phosphorus and chlorophyll *a*. In Bassenthwaite Lake, the total phosphorus has improved into good ecological status for the first time for many years and is at moderate ecological status for chlorophyll *a*. Accordingly, four out of these five lakes are likely to require a programme of measures to increase their ecological status.
11. The long-term monitoring, started in 1945 in some lake basins, is an essential resource to diagnose change and its likely cause. Consistency of monitoring is essential in order that these valuable datasets are not compromised. In addition to its continuation we suggest three specific pieces of research:

   - (i) **a comprehensive literature review on Windermere** to support the new Windermere Restoration Programme;
   - (ii) **an assessment of the nutrient sources to Grasmere, the causes of the failure of the lake to improve and practical suggestions on ways to manage the lake to bring it to good ecological status**; and
   - (iii) **a baseline study to identify the current distribution of *C. helmsii* in Derwent Water so that any future changes in abundance or spread of this species can be assessed.**

CONTENTS

1. INTRODUCTION

This work reported here has previously been reported under project C01752 'The Urban Waste Water Treatment Directive: observations on the water quality of Windermere, Grasmere, Derwent Water and Bassenthwaite Lake'. See Maberly *et al*. (2003, 2004, 2005, 2006a, 2007) for recent reports. The new project focuses equally on the UWWTD and the newer Water Framework Directive 2000/60/EC. Like the earlier project, the new project 'Assessing the long term changes in the water quality of the sensitive waters of the Cumbrian lakes' focuses on Windermere, North and South Basins, Grasmere, Derwent Water and Bassenthwaite Lake (Fig. 1). It differs from the earlier contract in requiring only monthly measurements. This has some important implications for how the data are reported since annual minima, mean and maxima will not be the same for a monthly sampling period as for a fortnightly sampling period (for example, minima and maxima may be missed) and so not necessarily comparable with the earlier work recorded at a high frequency. As a consequence the format of the report is necessarily different and less detailed than before. Note that the sampling frequency continues to be fortnightly. Some correlations in this report are based on the complete dataset even though these data are not presented (see later text in relevant sections).

Linked reports on the status of populations of arctic charr in Windermere and vendace in Bassenthwaite Lake and Derwent Water are given in a parallel new project Winfield *et al*., (2008a ,b).

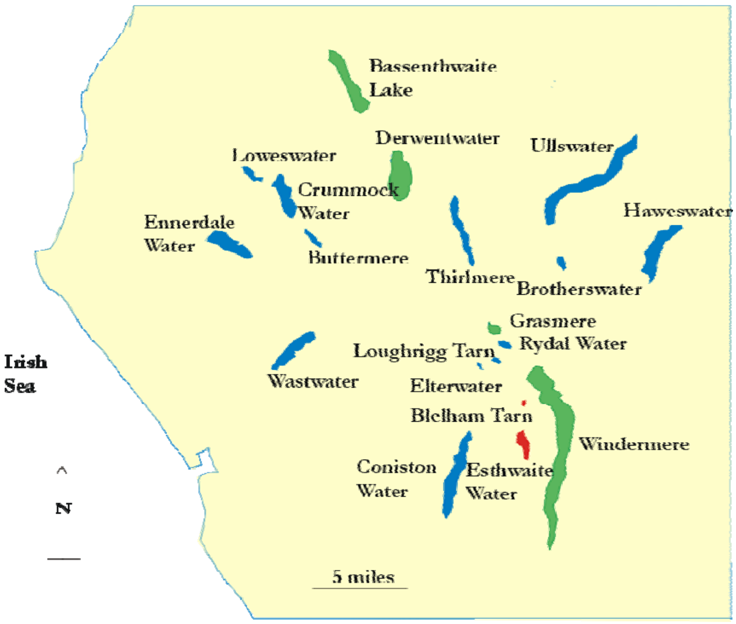

Figure 1. Location of major lakes of the English Lake District (after Pickering, 2001). Lakes included in this report are coloured green, lakes also monitored by CEH but not included in this work are coloured red.

2. GENERAL FEATURES OF THE STUDY LAKES

The five lake basins experience the same day-to-day and year-to-year fluctuations in weather. However, the influence of this varies because of physical differences among the lake basins (Table 1). Thus Grasmere (Fig. 2d) and Bassenthwaite Lake (Fig. 2e), on average, have short retention times which reduces the build up of phytoplankton under normal discharge, and can produce rapid loss of phytoplankton during high discharge resulting from high rainfall. In contrast, the North Basin of Windermere (Fig. 2a) has a relatively long average retention time which makes its biology less susceptible to changes in rainfall. The shallow lakes Bassenthwaite Lake and Derwent Water (Fig. 2c) are less strongly stratified as the energy from wind-induced surface mixing can readily break down transient thermal structures.

Table 1. General physical features of the study lake basins, largely from Talling (1999) and Reynolds & Irish (2000). Lakes are ordered by increasing area.

Lake Basin	Altitude (m)	Area (km^2)	Max. depth (m)	Average depth (m)	Volume (10^6 m^3)	Area of drainage basin (km^2)	Average retention time (d)
Grasmere	62	0.64	21.5	7.7	50	27.9	28
Bassenthwaite Lake	69	5.28	20	5.3	27.9	347.4	19
Derwent Water	75	5.35	22	5.5	29.0	82.7	67
Windermere North Basin	39	8.05	64	25.1	201.8	174.7	168
Windermere South Basin	39	6.72	42	16.8	112.7	55.8	94
Windermere total lake	39	14.77	64	21.3	314.5	230.5	263

The study lakes fall roughly in the middle of the Pearsall series from Wastwater to Esthwaite Water. Derwent Water has the lowest alkalinity, conductivity and concentration of all the plant nutrients of the study lakes, and is mesotrophic in status, while Bassenthwaite Lake and South Basin of Windermere (Fig. 2b) tend to have the highest chemical concentrations and are eutrophic. A comprehensive assessment of the status of these and other major lakes in the English Lake District in 2005 was made by Maberly *et al*. (2006b).

Figure 2. Photographs of the study lakes: a) North Basin of Windermere, b) South Basin of Windermere, c) Derwent Water, d) Grasmere and e) Bassenthwaite Lake.

3. BRIEF METHODS

The methods used are briefly noted here, more detail is available in Parker *et al*. (2001) and the reference given below.

At each basin, samples were collected or measured at the deepest point. Oxygen and temperature depth-profiles were measured with a WTW 340i oxygen meter and thermistor. Secchi disc transparency was measured with a white painted disc, 30 cm in diameter, which was lowered into the water and the depth at which it disappeared from view was noted, as was the depth at which it reappeared when the disc was then raised. The recorded depth was the average of these two depths.

An integrated water sample was taken on each occasion using a weighted plastic tube. The depth of integration was 7 m on the North and South Basin of Windermere, and 5 m at the three other sites. Replicate water samples from the tube were used to fill a previously rinsed 5 dm^3 plastic bottle. After mixing, the water was sub-sampled into:

a) a small glass bottle with a ground glass stopper. The bottle was completely filled and stoppered with no trapped air-bubbles. This was used to determine pH and alkalinity.
b) A disposable, previously rinsed, 500 cm^3 plastic bottle for chemical analysis.
c) An acid-cleaned, previously rinsed, 500 cm^3 glass bottle, for phosphate analysis.
d) A 1 dm^3 plastic bottle containing 5 cm^3 of Lugol's iodine for subsequent enumeration and identification of the phytoplankton (on Grasmere, bottle volume and volume of Lugol's iodine was half these volumes).

Alkalinity and pH. Alkalinity was measured by Gran titration and pH was measured with a calibrated combined pH-electrode (Mackereth *et al*., 1978).

Phytoplankton chlorophyll a was determined using a boiling methanol extraction of cells filtered onto a Whatman GF/C glass-fibre from a known volume of water. The pigments were quantified spectrophotometrically.

Phytoplankton species were counted after sedimenting a known volume of the iodine preserved sample. Counts were made in a Lund counting chamber with a microscope at a magnification of x100 and x400 for microplankton and nanoplankton respectively.

Total phosphorus (TP) and soluble reactive phosphorus (SRP) were measured using the molybdate-blue method, the former following digestion, (Mackereth *et al*., 1978).

Although each of the five lake basins was sampled fortnightly the data have been degraded for this report by selecting the first sampling date in each month to produce the required sampling frequency.

4. WATER TEMPERATURE

The surface water temperature followed a typical annual cycle (Fig. 3a). The temperature in winter was very slightly higher than normal and substantially higher than normal in early spring during a period of hot weather. In contrast, the surface temperature in summer was substantially cooler than normal but autumn temperatures were very close to the long-term mean. The surface water temperature in winter was nearly 2ºC lower in the smaller shallow lakes Derwent Water, Bassenthwaite Lake and Grasmere compared to the two basins of Windermere where water volume (Table 1), and hence heat capacity, will have been greater. The greater heat capacity in the two basins of Windermere also caused the water temperature in autumn to decline more slowly than in the three small lakes.

The different characteristics of the lake produced very different seasonal patterns of water temperature at depth (Fig. 3b). In the deep North Basin of Windermere, water at about 60 m (Table 1) varied little in temperature and was about 7ºC throughout summer stratification. In marked contrast, the much shallower and weakly and intermittently stratifying Bassenthwaite Lake had much higher water temperature at depth increasing up to 16.1ºC in August. The bottom water temperature in Derwent Water was also much higher than in the deeper lakes and increased up to 14.4ºC in September, just before stratification broke down.

The greatest temperature difference between the surface and bottom water is an indication of the strength of stratification. The annual maximal temperature differences occurred in June in all lake basins and were 4.3ºC in Bassenthwaite Lake, 5.4ºC in Derwent Water, 11.3ºC in South Basin of Windermere, 13.3ºC in North Basin of Windermere and 14.9ºC in Grasmere. Thus stratification was strongest in Grasmere and weakest in Bassenthwaite Lake.

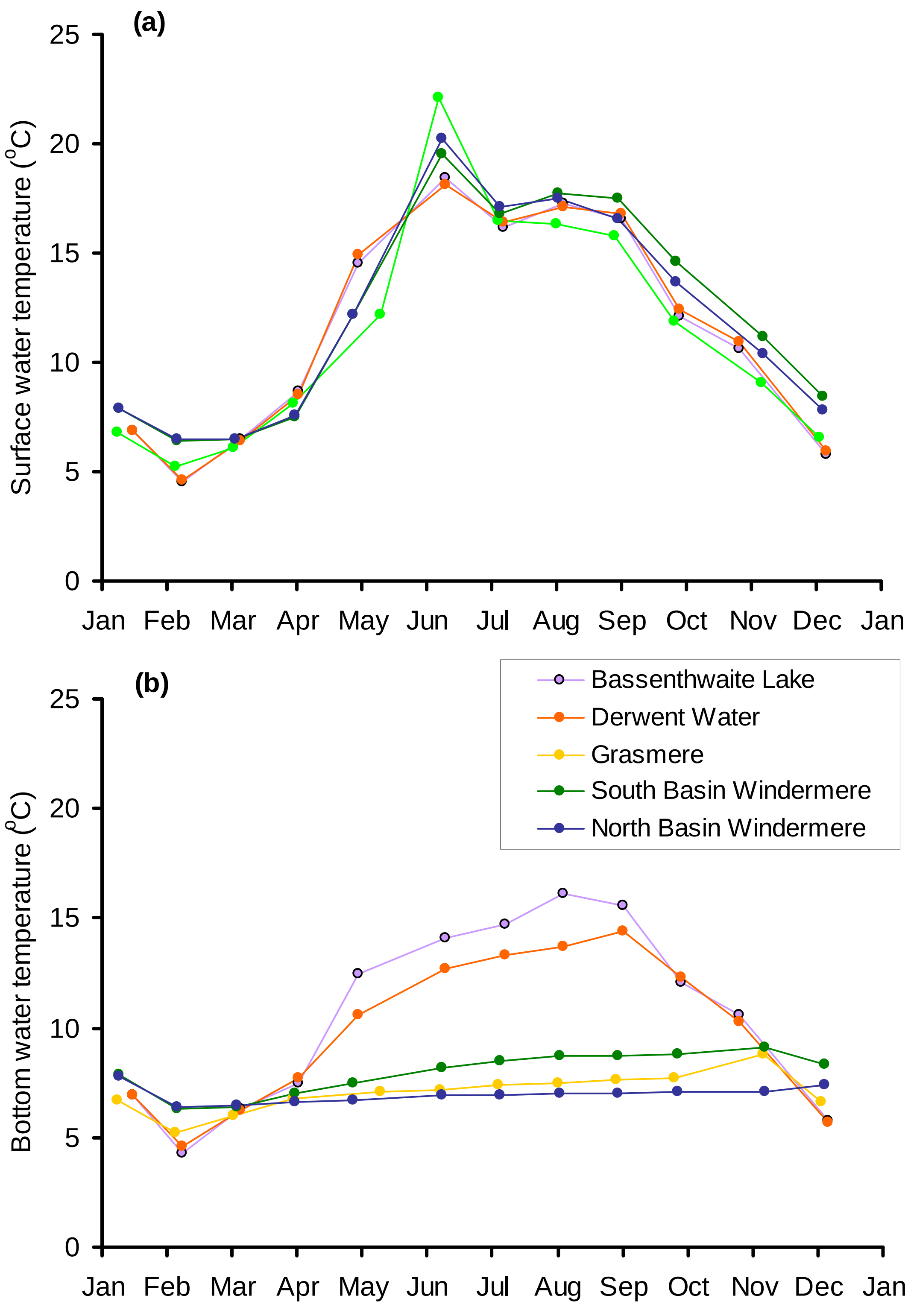

Figure 3. Monthly water temperature in the five lakes in 2007: (a) surface temperature; (b) temperature at depth.

5. OXYGEN CONCENTRATION AT DEPTH

Oxygen concentrations at the surface varied through a relatively narrow range. The concentration varies because of changes in solubility caused by varying temperature, rates of production and rates of consumption but concentration change is buffered by gas-exchange across the air-water interface.

In contrast, there were large seasonal changes in oxygen concentration at depth during stratification. Oxygen depletion was most marked in Grasmere where stratification was strong and phytoplankton biomass was high (Fig. 4). Oxygen was essentially absent from the bottom waters in July, August and September and early October. Derwent Water also had low oxygen concentrations at depth, particularly towards the end of the stratified period. In Bassenthwaite Lake, where stratification was weak and intermittent, the oxygen concentration at depth was variable (even more variable when fortnightly data are used). In the two large basins of Windermere, there was a fairly progressive decline in oxygen concentration to minima at the end of the stratification period in November.

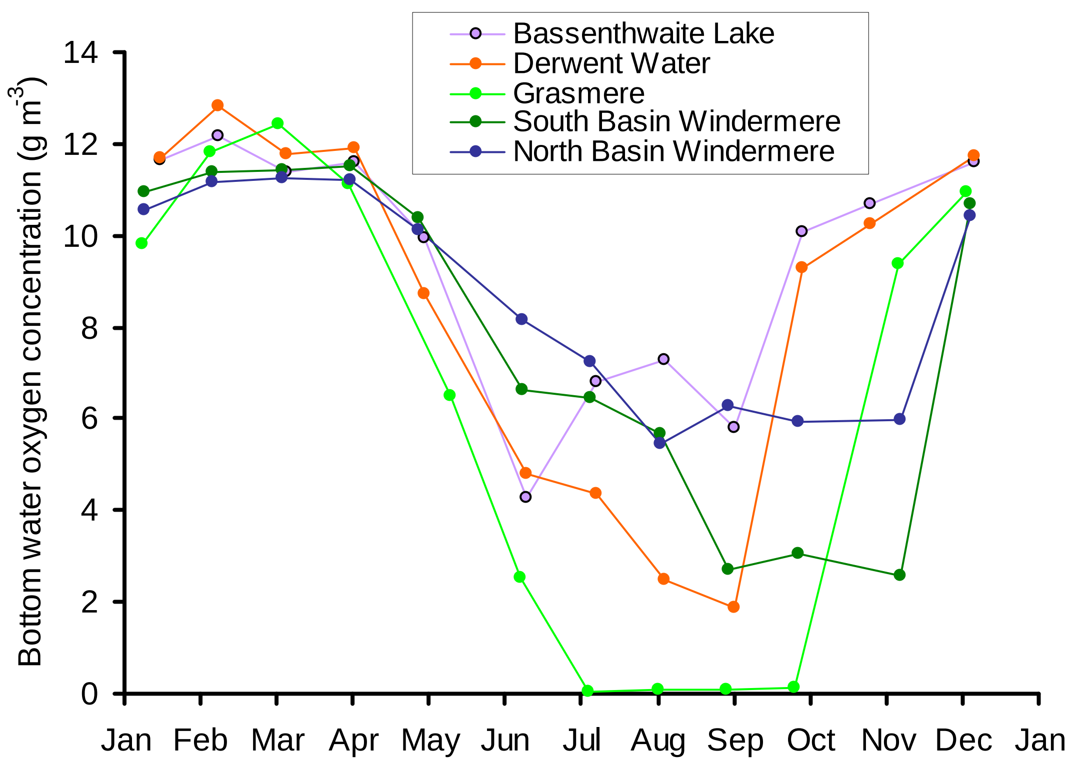

Figure 4. Monthly oxygen concentration at depth in the five lakes in 2007.

6. ALKALINITY AND PH

Alkalinity, or acid-neutralising capacity, represents the water hardness and is a relatively conservative feature of a lake controlled largely by the geology of the catchment. Alkalinity is lowest in Derwent Water and highest in the South Basin of Windermere (Fig. 5a). In the Water Framework Directive lakes are categorised, in part, in terms of alkalinity. Based on annual means, Derwent Water, Grasmere and Bassenthwaite Lake would be classified as having low alkalinity (less than 10 g $CaCO_3$ m^{-3}; although Bassenthwaite Lake is very close to this boundary) while the two basins of Windermere would be classified as having moderate alkalinity (between 10 and 50 g $CaCO_3$ m^{-3}). There is a consistent seasonal pattern in alkalinity, although of low amplitude. Alkalinity is generally lowest in winter, when rainfall is highest and inflowing waters most dilute, and highest in late summer.

The pH of a lake is controlled by a number of factors. When a lake is at equilibrium with a constant partial pressure of CO_2 in the atmosphere, pH will increase with alkalinity. In addition, changes in CO_2 concentration within the lake will cause pH to vary. When the concentration of CO_2 is high, for example because of inflow of CO_2-rich water from the catchment or rapid respiration within the lake, pH will be low. Conversely, when the concentration of CO_2 is low because of rapid uptake by phytoplankton and macrophytes during photosynthesis, the pH will be high (see Maberly 1996). The effect of these factors can be seen in the monthly pH data from the five lakes (Fig. 5b). In the winter, when biological activity is low, the differences in pH among the five lakes largely results from the different alkalinity in the lakes. Peaks in pH, such as in the South Basin of Windermere on 1st May 2007 result from a high photosynthetic demand for CO_2 and this high pH coincided with the annual maximum concentration of phytoplankton chlorophyll *a* (see Section 9).

The summer maxima were generally lower than recorded in previous years, probably because the cool, wet summer will have reduced productivity and hence demand for CO_2.

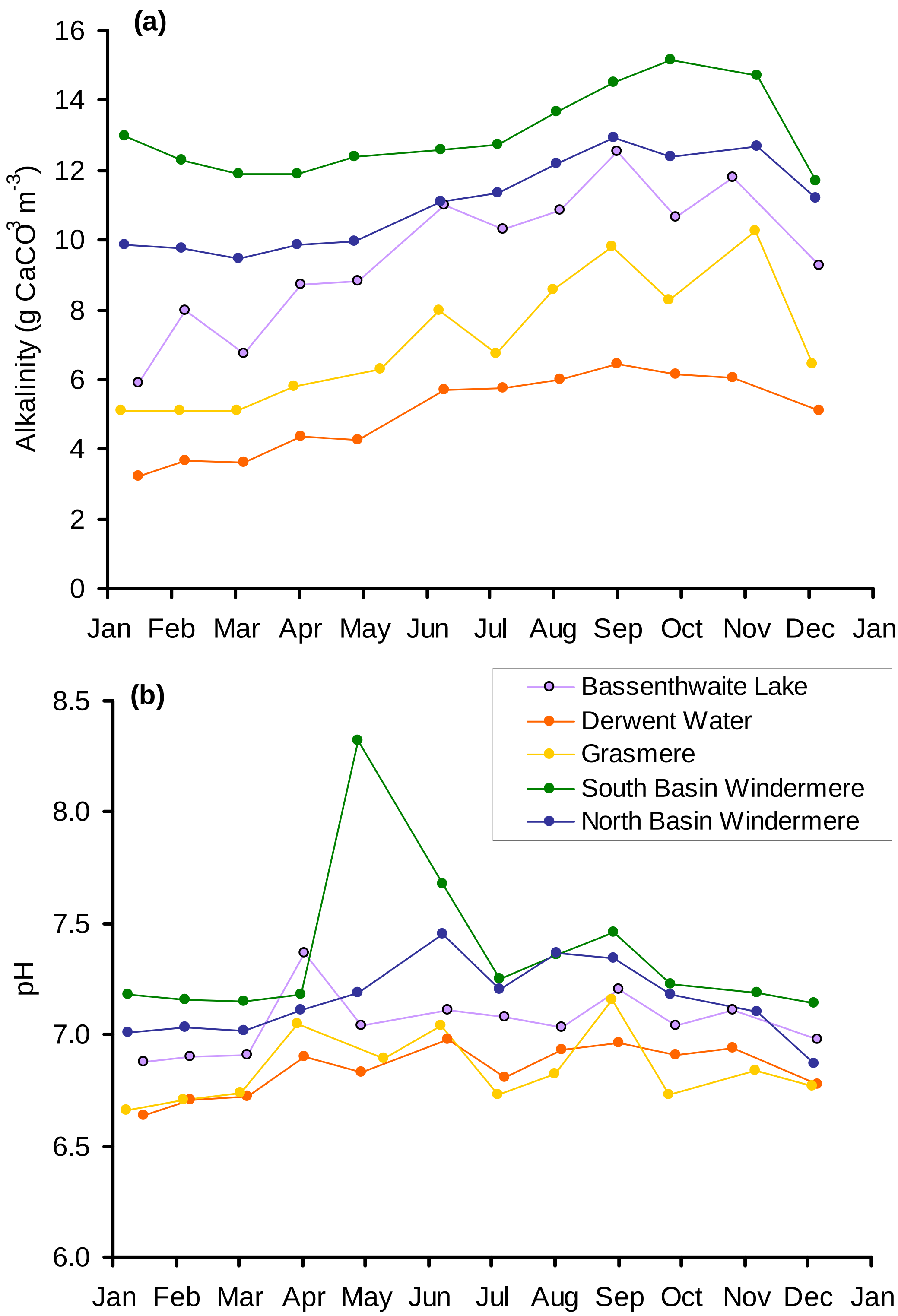

Figure 5. Seasonal changes in: (a) alkalinity and (b) pH in the five lakes in 2007.

7. TOTAL & SOLUBLE REACTIVE PHOSPHORUS

The productivity of the lowland Cumbrian lakes is controlled primarily by the availability of phosphorus. Thus across the 20 lakes studied in the CEH Lakes Tour there was a good correlation between the concentration of total phosphorus and the concentration of phytoplankton chlorophyll *a* (Maberly *et al*. 2006b).

The concentration of total phosphorus (TP) is relatively conservative but tends to be lowest in summer and highest in winter (Fig. 6a), presumably as a result of loss of phosphorus to the hypolimnion and, potentially the sediment, as phytoplankton sink and die. There is nearly a 2-fold range of TP concentration across the five lakes: concentrations of TP are lowest in Derwent Water, intermediate in the North Basin of Windermere and Bassenthwaite Lake and highest in the South Basin of Windermere and Grasmere.

Soluble reactive phosphorus (SRP), which roughly equates to phosphate, is the form that is most available to phytoplankton and consequently shows a large seasonal amplitude. SRP was at, or close to, the limit of detection (0.6 mg m^{-3}) in all five lakes during summer time when phytoplankton was growing most actively and biomass was highest (Fig. 6b). During winter, concentrations were low in Derwent Water, slightly higher in Bassenthwaite Lake, higher still in the North Basin of Windermere and Grasmere and highest in the South Basin of Windermere.

The seasonal change in proportion of TP that comprises SRP is shown in Figure 7. During winter SRP comprises a large proportion of TP especially in the more productive lakes. Thus, in the South Basin of Windermere the proportion reached nearly 0.6 in March while in comparison in the least productive of the five lakes, Derwent Water, the maximum proportion was only 0.12. In all five lakes, SRP was less than 10% of TP between May and September 2007.

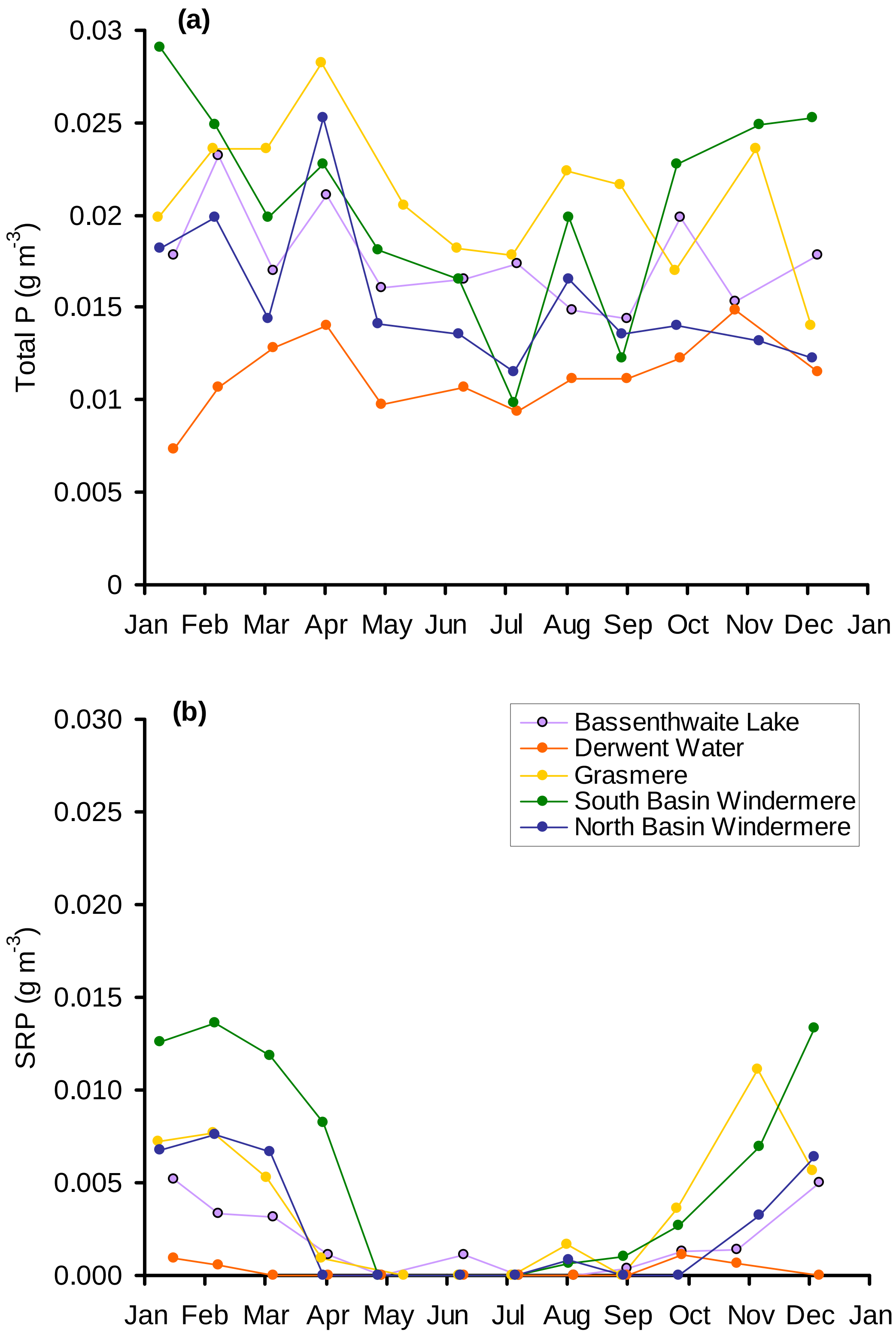

Figure 6. Seasonal changes in concentration of (a) total phosphorus and (b) soluble reactive phosphorus (SRP) in 2007.

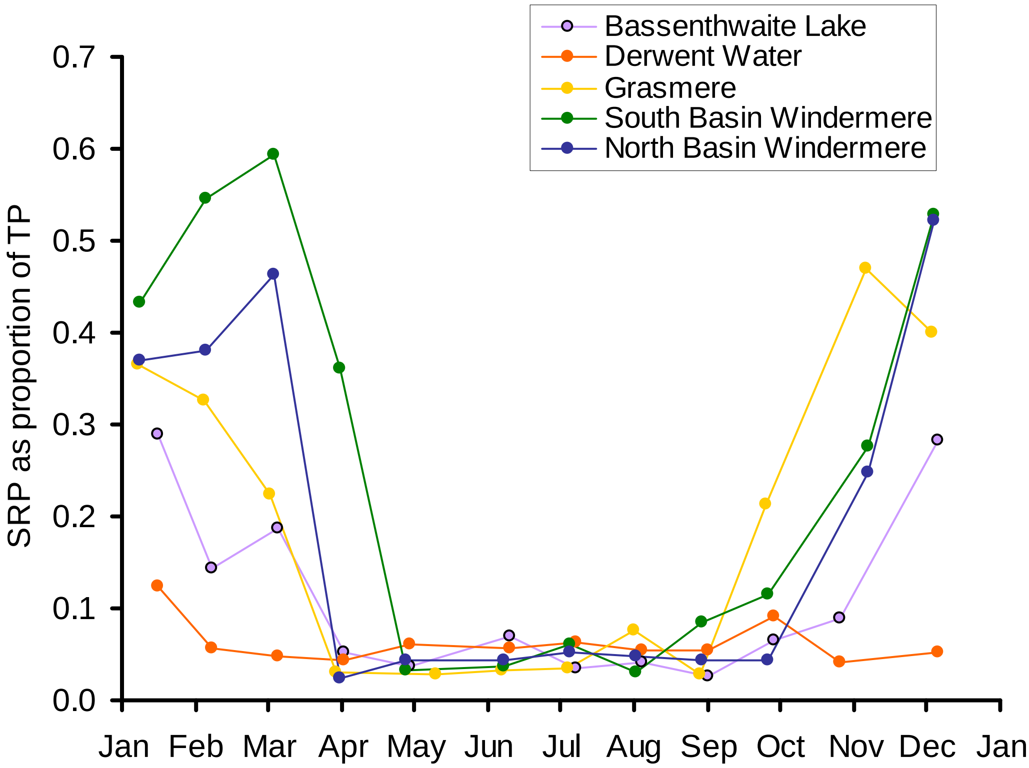

Figure 7. SRP as a proportion of TP in the five lakes during 2007.

8. SECCHI DEPTH

Secchi depth is traditionally used in limnology to quantify water clarity. Secchi depth can be affected by phytoplankton, non-living particles such as sediment, and also dissolved organic carbon, although this latter factor is of small importance in the five lakes in this report.

Secchi depth was rather variable across lakes and seasons. Bassenthwaite Lake tended to have the shallowest Secchi depths (i.e. lowest water clarity) and this is probably linked to the high amount of suspended sediments in this lake (Thackeray *et al*. 2004, 2006). Derwent Water tended to have the greatest Secchi depths and this is probably linked to the generally low phytoplankton biomass in this lake. The greatest Secchi depths in a given lake occurred in February in most lakes at a time of low phytoplankton biomass.

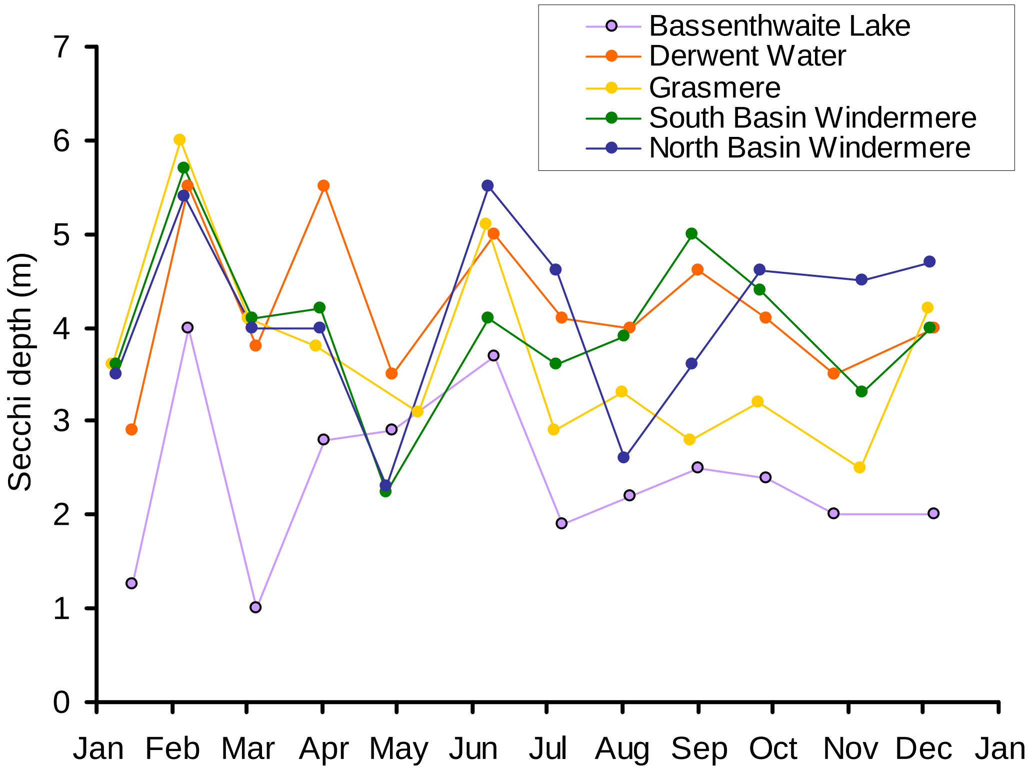

Figure 8. Seasonal changes in Secchi depth in the five lakes in 2007.

9. PHYTOPLANKTON CHLOROPHYLL *A* CONCENTRATION & SPECIES COMPOSITION

Growth of phytoplankton is often one of the most obvious symptoms of high nutrient availability, natural or man-made, and can have a large effect on water quality and the ecology of a lake. The overall abundance of phytoplankton is quantified as the concentration of the ubiquitous green, photosynthetic pigment chlorophyll *a*. This is supplemented by counts of the species that contributed to the phytoplankton chlorophyll *a*.

Generally, the five lakes produced typical 'diacmic' patterns of phytoplankton chlorophyll *a* (Talling 1993) with a spring peak in April or May and a summer peak in August or September (Fig. 9). Derwent Water, the least productive of the five lakes had the lowest phytoplankton population and smallest peaks. The other lake basins showed a large variability in chlorophyll concentrations (note that the measured fortnightly samples showed a larger range than the monthly data reported here).

Bassenthwaite Lake produced a spring peak of 19.3 mg Chl *a* m^{-3} in April 2007 (Fig. 9) which is slightly higher than the average produced in previous years. This was dominated by the diatom *Aulacoseira subarctica* (2544 cell cm^{-3}), the green algae *Chlorella* sp. (2556 cell cm^{-3}) and *Koliella longiseta* (256 cell cm^{-3}), the cryptophytes *Rhodomonas* sp. (966 cell cm^{-3}) and *Cryptomonas* sp. (230 cell cm^{-3}) and the haptophyte *Chrysochromulina parva* (238 cell cm^{-3}). Phytoplankton chlorophyll *a* was lower in May and June and then increased during the summer reaching a peak in September of 18.7 mg Chl *a* m^{-3} which comprised the diatom *Urosolenia* sp. (682 cell cm^{-3}), the cryptophyte *Rhodomonas* sp. (509 cell cm^{-3}) and the green alga *Chlorella* sp. (444 cell cm^{-3}). The late summer phytoplankton was slightly lower than the average in previous years which probably resulted from the cool wet weather which will have reduced growth rates and increased flushing losses.

In Derwent Water there was a gradual build up of phytoplankton populations from an overwintering population of about 1 mg Chl *a* m^{-3} to a peak in May of 7.0 mg Chl *a* m^{-3} (Fig. 9). This was dominated by a small unidentified flagellate (2166 cell cm^{-3}), the green alga *Chlorella* sp. (890 cell cm^{-3}), the haptophyte *Chrysochromulina parva* (233 cell cm^{-3}) and the centric diatom *Cyclotella* sp. (73 cell cm^{-3}). Following a very slight decline, the phytoplankton built up again to a peak in August of 5.9 mg Chl *a* m^{-3} which comprised the green alga *Chlorella* sp. (509 cell cm^{-3}), the cryptophyte *Rhodomonas* sp. (125 cell cm^{-3}), an unidentified flagellate (108 cell cm^{-3}) and the chrysophyte *Bitrichia chodatii* (33 cell cm^{-3}). There was a late relatively large population in November of 5.8 mg Chl *a* m^{-3} which comprised the centric diatom *Urosolenia* sp. (336 cell cm^{-3}), the green alga *Chlorella* sp. (292 cell cm^{-3}), the diatom *Asterionella formosa* (77 cell cm^{-3}) and the haptophyte *Chrysochromulina parva* (70 cell cm^{-3}).

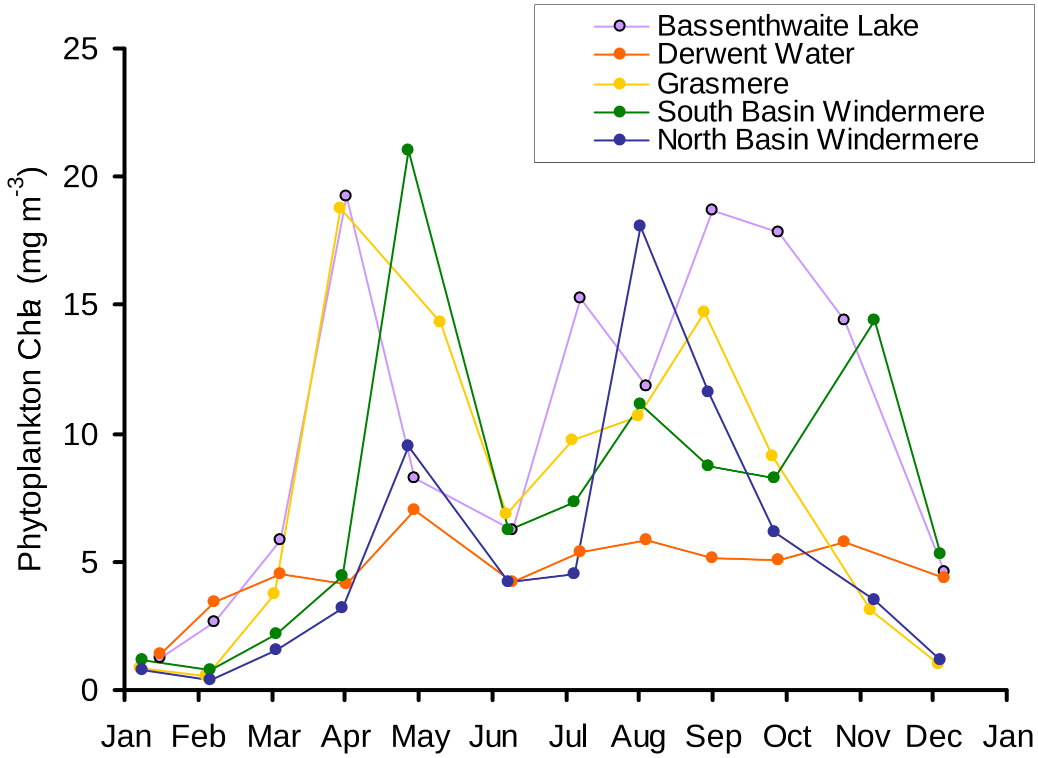

Figure 9. Seasonal changes in concentration of phytoplankton chlorophyll a in the five lakes in 2007.

Grasmere produced a large spring bloom in April of 18.8 mg Chl *a* m^{-3} comprising the green alga *Chlorella* sp. (3372 cell cm^{-3}), the haptophyte *Chrysochromulina parva* (1654 cell cm^{-3}), the chrysophytes *Ochromonas* sp. (763 cell cm^{-3}) and *Kephyrion* sp. (140 cell cm^{-3}) and the diatom *Asterionella formosa* (329 cell cm^{-3}). *A. formosa* went on to produce a large population in the subsequent fortnight that was above the average for this time of year. Following a decline in early summer the phytoplankton increased to a second peak of 14.8 mg Chl *a* m^{-3} in August comprising a diverse assemblage including the haptophyte *Chrysochromulina parva* (3457 cell cm^{-3}), the green algae *Chlorella* sp. (3156 cell cm^{-3}), *Coenochloris* sp. (190 cell cm^{-3}), and *Golenkinia* sp. (107 cell cm^{-3}), the cryptophyte *Plagioselmis nannoplantica* (429 cell cm^{-3}) and the chrysophytes *Synura* sp. (408 cell cm^{-3}) and *Ochromonas* sp. (236 cell cm^{-3}). Like other lakes the summer population was lower than the average in previous years which was probably a result of the wet, cool weather.

The North Basin of Windermere produced a peak phytoplankton population in early May of 9.5 mg Chl *a* m^{-3} (Fig. 9) that comprised the diatom *Asterionella formosa* (1812 cell cm^{-3}), the haptophyte *Chrysochromulina parva* (1159 cell cm^{-3}), the green alga *Chlorella* sp. (856 cell cm^{-3}) and the cryptophyte *Rhodomonas* sp. (303 cell cm^{-3}). Following lower population of phytoplankton in June and July the concentration of chlorophyll *a* increased to a peak of 18.1 mg Chl *a* m^{-3} comprising the diatoms *Tabellaria* sp. (138 cell cm^{-3}) and *Urosolenia* (190 cell cm^{-3}), the cyanobacteria *Pseudanabaena limnetica* (1.19 mm filament cm^{-3}) and *Planktothrix mougeotii* (0.92 mm filament cm^{-3}), the cryptophyte *Rhodomonas* sp. (206 cell cm^{-3}) and the green alga *Chlorella* sp. (255 cell cm^{-3}) and then declined steadily throughout the rest of the year.

The South Basin of Windermere produced a large spring bloom in early May of 21 mg Chl *a* m^{-3} that exceeded the average amount produced at this time of year. The population comprised the diatoms *Fragilaria crotonensis* (246 cell cm^{-3}) and *Asterionella formosa* (123 cell cm^{-3}) along with the green alga *Chlorella* sp. (1661 cell mL^{-1}), the haptophyte *Chrysochromulina parva* (314 cell cm^{-3}) and the cryptophyte *Rhodomonas* sp. (146 cell cm^{-3}). Following a decline, the population increased again to 11.2 mg Chl *a* m^{-3} in August which is lower than the average summer populations at this time of year as noted for a number of other lakes. There was an unusually late peak in November of 14.4 mg Chl *a* m^{-3} which was mainly composed of the diatom *Aulacoseira subarctica* (232 cell cm^{-3}).

10. COHERENCE AMONG LAKE BASINS

If year-to-year changes in lake features vary coherently this indicates that they are being influenced by the same driving factor such as the weather. In a number of places in this report similar patterns have been noted, such as the low summer phytoplankton chlorophyll *a* concentration. The extent of this coherent pattern was tested in a simple way here by correlating annual means across lakes for the long-term data from 1995 to 2007. Note that fortnightly samples were used for the 2007 data to make them comparable with previous years.

Overall there were many more positive correlations than negative correlations and the only significant correlations were positive (Table 2). This suggests that lakes are varying together and that there is a pattern of coherence across the lakes.

The North and South Basin of Windermere were the two lake basins which behaved most similarly (Table 2) which is not surprising given that they are directly connected to one another. However, year-to year changes in phytoplankton chlorophyll *a*, TP and SRP were not significantly coherent in the two basins of Windermere suggesting that they are influenced more by local or in-lake processes than by the weather. Bassenthwaite Lake and Derwent Water are also linked by a short stretch of river and they behaved coherently for surface temperature, secchi depth and phytoplankton chlorophyll *a*.

Mean oxygen concentration at depth was only significantly correlated for the two basins of Windermere. Mean surface water temperature was the most correlated of all the variables with four of the ten comparisons being significant and all being positive with correlation coefficients exceeding 0.33. Mean water temperature at depth was correlated for the two basins of Windermere, as might be expected, but there was also a correlation, just significant, between water temperature at depth in North Basin Windermere and Derwent Water. The depth of the Secchi disk was positively correlated between Bassenthwaite Lake and Derwent Water and also between the two basins of Windermere. There is a hint of a negative correlation between year-to year changes in Secchi depth in Derwent Water and the South Basin of Windermere, indicating that the weather affects Secchi depth in these two lakes in opposite ways. This can also be seen for this pair of lakes, although to a much lesser extent, for chlorophyll *a*. However, neither the correlation for Secchi depth nor phytoplankton chlorophyll *a* was statistically significant.

Table 2. Coherence (correlation coefficient) in annual mean for different variables across all five lakes using fortnightly data from 1995 to 2007. Unshaded cells, not significant; green shaded cells P<0.05, yellow shaded P<0.01; Red shaded P<0.001. Positive correlations have a black font and negative correlations have a blue font.

Variable	Lake	Derw	Gras	Nbas	Sbas
Bottom-Oxygen	Bass	0.507	0.469	-0.072	0.229
	Derw		0.527	0.044	0.316
	Gras			0.123	0.383
	Nbas				0.776
Surface temperature	Bass	0.909	0.792	0.378	0.335
	Derw		0.765	0.453	0.426
	Gras			0.462	0.397
	Nbas				0.979
Bottom temperature	Bass	0.215	0.247	0.180	0.121
	Derw		0.360	0.558	0.509
	Gras			0.241	-0.006
	Nbas				0.942
Secchi depth	Bass	0.645	-0.277	0.088	0.000
	Derw		-0.150	0.059	-0.407
	Gras			0.198	0.326
	Nbas				0.647
Chl a	Bass	0.657	0.588	0.121	0.125
	Derw		0.295	0.217	-0.115
	Gras			0.016	-0.008
	Nbas				0.086
TP	Bass	0.089	0.432	-0.193	0.234
	Derw		0.250	0.630	0.479
	Gras			0.234	0.758
	Nbas				0.494
SRP	Bass	0.041	0.091	0.392	0.369
	Derw		0.422	0.218	-0.090
	Gras			0.589	0.158
	Nbas				0.271

Mean concentrations of phytoplankton Chl *a* in Bassenthwaite were positively correlated with nearby Derwent Water but also to more distant Grasmere (Table 2). The link with Grasmere may be caused by the susceptibility of both lakes to hydraulic loss since they have the shortest mean retention times of the five lakes studied (Table 1). Year to year changes in TP were correlated for Derwent Water and North Basin Windermere and for Grasmere and South Basin Windermere. The correlation between Grasmere and South Basin Windermere was particularly strong and not necessarily caused by hydraulic linkage since correlations with the intervening North Basin were not significant. SRP is particularly labile since it is used rapidly by phytoplankton during the growing season. Nevertheless, there was a positive correlation between North Basin Windermere and Grasmere.

Overall there is strong evidence that some variables change coherently among lakes which is an indication of the importance of the weather in controlling lake properties.

11. LONG TERM TRENDS

Year-to-year variation caused by the weather notwithstanding, long-term trends in the data were checked for annual minimum, mean and maximum values of the various lake properties by simple correlation. Note that the full fortnightly dataset were analysed for 2007 in order to make the results comparable. The results will be discussed on a lake-by-lake basis.

North Basin of Windermere

There was a significant increase in mean TP and an increase that was not quite significant in maximum TP (Table 3). Mean and maximum concentrations of chlorophyll *a* also showed signs of increasing but the correlation was not statistically significant. Mean Secchi depth decreased significantly as did the mean and minimum oxygen concentration at depth. Overall the data for the North Basin of Windermere show a worrying decline in water quality.

Table 3. Long term trends in annual minimum, mean and maximum values of six properties for the five lakes from 1995 to 2007 based on fortnightly data. Results are presented as the correlation coefficient: non-significant cells are not shaded, green shading indicates P<0.05, yellow shading indicates P<0.01. Positive correlations have a black font and negative correlations have a blue font.

Variable	Annual statistic	North Basin of Windermere	South Basin of Windermere	Grasmere	Derwent Water	Bassenthwaite Lake
TP	Max	0.432	0.098	-0.518	-0.241	-0.637
	Mean	0.564	0.002	-0.261	0.242	-0.760
	Min	0.166	-0.230	0.085	0.304	-0.278
SRP	Max	-0.416	-0.700	-0.343	0.159	-0.665
	Mean	0.189	0.127	0.628	0.327	-0.328
	Min	0.044	0.518	0.377	-0.483	-0.495
Chlorophyll a	Max	0.539	-0.035	-0.289	0.553	0.030
	Mean	0.445	0.176	-0.294	0.384	-0.196
	Min	-0.280	-0.376	-0.110	-0.223	-0.556
Secchi disc	Max	-0.342	-0.528	-0.727	0.102	0.331
	Mean	-0.607	-0.673	-0.503	0.202	0.215
	Min	-0.115	-0.560	-0.135	0.198	0.106
Oxygen at depth	Max	0.085	-0.022	0.532	0.425	-0.154
	Mean	-0.701	-0.389	0.038	0.249	0.163
	Min	-0.732	-0.256	0.424	0.312	0.467

South Basin of Windermere

The South Basin of Windermere showed a number of significant long-term trends. The maximum concentration of SRP has declined significantly: the SRP maximum typically occurs early in the year and represents the pool of available phosphorus for subsequent phytoplankton growth so this decrease is an encouraging sign. However, there have been no changes in the concentration of either TP or phytoplankton chlorophyll *a* (Table 3). In contrast, the mean and minimum depth of the Secchi disc has decreased indicating worsening water clarity which could be caused by changes in phytoplankton populations or by input of non-living material from the catchment (see Grasmere below). There has also been a decline in mean and minimum oxygen concentration at depth although, unlike the North Basin, the change is not statistically significant.

Grasmere

Grasmere appears to be relatively stable with only two statistically significant long term trends (Table 3). Although the mean concentration of SRP has increased, this has not resulted in increases in phytoplankton chlorophyll *a* and there is no evidence for an increasing concentration of TP: in fact, both these variables show a weak, but non-significant, downward trend. The maximum Secchi depth has declined, however, and this reduction in Secchi depth is a feature of the three lakes in the Windermere catchment which may suggest it is not necessarily linked to increasing phytoplankton populations but to other factors that reduce water clarity such as increases in suspended solids or dissolved organic carbon. This idea, however, has not been tested.

Derwent Water

Derwent Water is also relatively stable. The only statistically significant trend is an increase in maximum concentration of phytoplankton chlorophyll *a* (Table 3). This may be a sign of some concern since it is associated with trends for increasing average concentrations of SRP and TP. If any nutrient enrichment is occurring, however, it has not yet translated into either a decreased light climate or a greater depletion of oxygen at depth since neither of these features show a statistically significant trend.

Bassenthwaite Lake

Alone of the five lakes reported on here, the water quality in Bassentwaite Lake is showing some signs of improvement. The maximum and mean concentration of TP show a statistically significant decline (Table 3), although closer analysis suggests that this has been strengthened by particularly low concentrations in 2007, possibly as a result of dilution of point-source inputs by high rainfall. Nevertheless, this trend has been reported before (e.g. Maberly *et al*. 2006a) and there is a statistically significant decline in maximum concentration of SRP and some decline in all six of the phosphorus statistics. To date, the effect of this reduction in phosphorus on other aspects of the ecology of the lake have been marginal. The minimum concentration of phytoplankton chlorophyll *a* has declined significantly but there have been no change in mean or maximum concentration of chlorophyll *a*. There is some weak evidence that Secchi depth is improving but the changes are not yet significant. The minimum concentration of oxygen at depth is not such a big issue in the weakly and intermittently stratified Bassenthwaite Lake, but there are some indications that this too is improving. Overall if the current trends on Bassenthwaite continue the lake may be poised for tangible future improvements in water quality.

12. COMPLIANCE & STATUS FOR THE WATER FRAMEWORK DIRECTIVE

The accumulating data on how these contrasting lakes operate gives an increasingly refined picture of the trends of improvement or deterioration in the status of each lake. These patterns are summarised on a lake-by-lake basin below. Each lake is also given a preliminary ecological status based on the current Water Framework Directive (WFD) classifications using the appropriate lake typology depending on their alkalinity and mean depth. The site specific boundaries for TP and chlorophyll *a* are as described in Maberly *et al.* (2006b). Note that these have not yet been completely finalised and so the ecological quality ratio (EQR) boundaries used here may not be the final versions.

North Basin of Windermere

The initial modest improvement in the North Basin of Windermere seen following the implementation of tertiary wastewater treatment has now stalled and there are clear signs of deterioration. This does not appear to be caused by a reduction in the efficiency of phosphorus removal from the Ambleside WwTW (Maberly 2008) and must, therefore, be caused by some other factor or factors. Good ecological status was last seen for TP in 2001 and for chlorophyll *a* in 1995 (Fig. 10). Currently the North Basin of Windermere is in the middle of the moderate ecological status for both features and will clearly need a Programme of Measures to improve the condition of the lake. Further evidence for deterioration in the condition of the lake is the statistically significant decrease in average Secchi depth and reduction in oxygen concentration at depth. The ecological status for the North Basin of Windermere in 2007 is almost identical to the status in 2006.

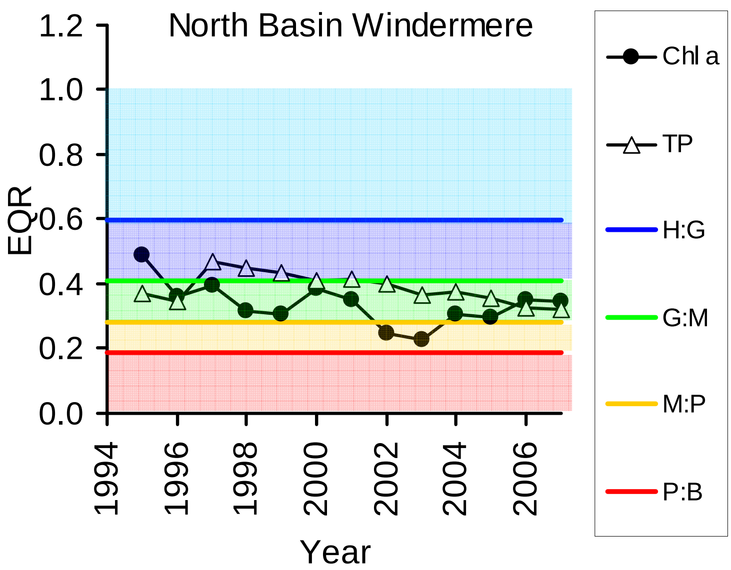

Figure 10. Long-term changes in the ecological status of the North Basin of Windermere in relation to the Water Framework Directive.

South Basin of Windermere

As for the North Basin, there was an immediate improvement in the lake following the implementation of tertiary wastewater treatment in 1992, followed by a subsequent decline that does not appear to be caused by a reduction in the efficiency of phosphorus removal by either of the two WwTW that feed directly into the South Basin (Maberly 2008). The ecological status in 2007 is similar to that in 2006 and is moderate, tending to poor for both chlorophyll *a* and total phosphorus (Fig. 11). There are signs of continuing decline in the lake with statistically significant reductions in mean Secchi depth and the hypolimnetic concentration of oxygen (Sections 5, Table 3).

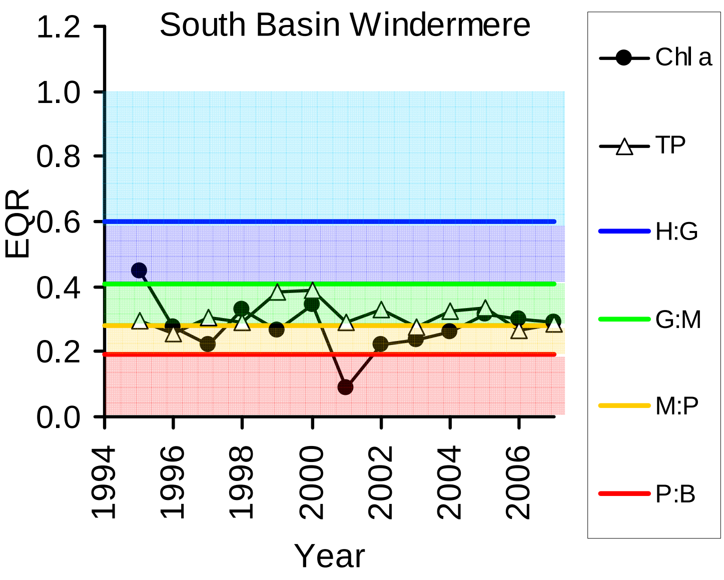

Figure 11. Long-term changes in the ecological status of the South Basin of Windermere in relation to the Water Framework Directive.

Grasmere

Grasmere also fails good ecological status and in 2007 was in the middle of moderate ecological status for total phosphorus and chlorophyll *a* (Fig. 12). The chlorophyll *a* value has oscillated around the moderate:poor boundary and in 2007 was lower (and EQR higher) than in the recent past, possibly because of the wet summer, or alternatively because of a recovery in ecological status. Generally, the lake is relatively stable although, as for the two Windermere basins, there is evidence for declining Secchi depth (Table 3). A more detailed understanding of why this lake is failing good ecological status is needed.

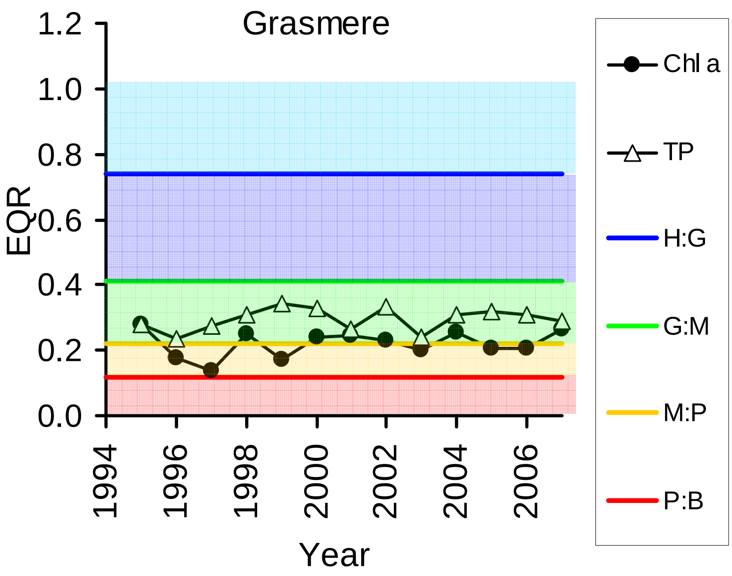

Figure 12. Long-term changes in the ecological status of Grasmere in relation to the Water Framework Directive.

Derwent Water

The ecological status of Derwent Water has varied considerably over the last 14 years (Fig. 13). Generally, the ecological status for TP is better than the status for chlorophyll *a* which indicates that this lake produces more chlorophyll per unit TP than the average in the WFD calibration data sets, perhaps because it is relatively shallow. Between 2002 and 2006 there was a steady decline in ecological status, and for chlorophyll *a* this fell into moderate status. In 2007 the status of both TP and chlorophyll *a* had improved and both are now in good ecological status. Nevertheless, the average concentration of TP and SRP is increasing slightly, albeit not statistically significantly (Table 3), so action is recommended especially as there are clear point sources providing phosphorus to this lake which gives relatively easy options for a successful Programme of Measures (Maberly Elliott & Thackeray 2006).

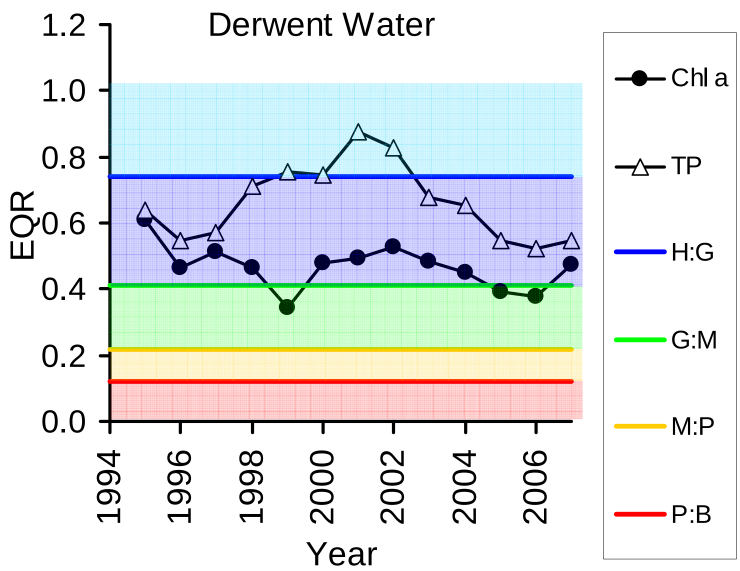

Figure 13. Long-term changes in the ecological status of Derwent Water in relation to the Water Framework Directive.

Bassenthwaite Lake

Bassenthwaite Lake falls on the low-alkalinity: moderate-alkalinity boundary. In the report of Maberly *et al*. (2007) on 2006 data it was just in the moderate alkalinity boundary but in 2007 it is in the low alkalinity category and this is the category used in this report. Looking back from 1995 to 2007 the average alkalinity is 9.9 mg $CaCO_3$ m^{-3} also placing it just in the low alkalinity category. Note that the suggested EQR boundaries are slightly more stringent for low-alkalinity shallow compared to moderate-alkalinity shallow lakes. There has been an upward trend in ecological status, judged using TP, caused by the reduction in average TP concentrations. In 2007, Bassenthwaite Lake was on the good:moderate boundary for TP. The ecological status judged from the more critical concentration of phytoplankton chlorophyll *a* has oscillated between moderate and poor but lies within the moderate band in 2007. Future

Programmes of Measures are needed to identify the sources of phosphorus in addition to that from the Kewsick WwTW such as smaller WwTW works, septic tanks and the contribution from internal loading from the sediments.

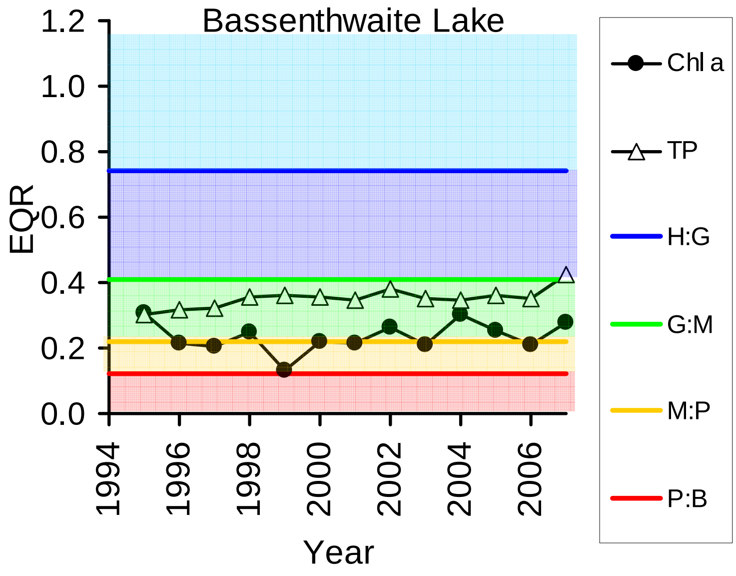

Figure 14. Long-term changes in the ecological status of Bassenthwaite Lake in relation to the Water Framework Directive.

12. RECOMMENDATIONS FOR FURTHER RESEARCH

The long-term, detailed monitoring reported on here is a valuable exercise that provides further fundamental understanding of how lakes operate, a way of assessing the effectiveness of management procedures and warning of deterioration in lake ecological status. The co-funding provided by this project is a valuable way of maintaining this data-set. Specific topics that this study has highlighted as needing more attention are described below.

A specific project studying the effects of nutrient enrichment, climate change, invasion of non-native species and changing trophic interactions on the water quality of Windermere using long-term data is currently underway. This could usefully by complemented by ***a comprehensive literature review on Windermere***. Windermere is perhaps the best studied lake in the world but a modern literature review is needed that includes both published work and the unpublished work that exist in many reports. This will produce a firm basis for future management decisions and support the new Windermere Restoration Programme.

Grasmere is failing to improve and appears to be 'stuck' in moderate ecological status. ***An assessment is needed of the nutrient sources to Grasmere, the causes of the failure to improve and practical suggestions on ways to manage the lake to bring it to good ecological status.***

Although Derwent Water is at good ecological status, it has shown signs of recent deterioration but ways of remediating this have recently been identified (Maberly, Elliott & Thackeray 2006). Of potentially greater long-term concern is the invasion of the non-native macrophyte *Crassula helmsii*. This could conceivably interfere with the spawning of the last healthy population of Vendace in The British Isles. ***We suggest a baseline study is undertaken to identify the current distribution of* C. helmsii *so that any future changes in abundance or spread of this species can be assessed.***

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