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OPTIONS FOR THE REMEDIATION OF WINDERMERE:

PROTECH MODELLING OF THE EFFECTS OF DIFFERENT MANAGEMENT SCENARIOS

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Executive Summary

1. The purpose of this report was to establish the effect of reduced nutrient loading from the two wastewater treatment works (WwTW) at Ambleside and Tower Wood on the amount and types of phytoplankton in the two basins of Windermere. A secondary objective was to assess the likely impact of reduced grazing pressure by zooplankton on phytoplankton amount.
2. The nutrient loads from the catchment and the WwTWs were estimated in previous reports for the whole lake (Maberly 2008, 2009) but basin-specific loads were calculated here. The modelling work was carried out using the algal lake model PROTECH based on the year 1998. The model produced a good representation of the seasonal changes in phytoplankton chlorophyll *a* and also successfully simulated the types of algae present.
3. The mean contribution of direct discharge of SRP from WwTW between 1997 and 2007 was 30% of the total load in the North Basin but 52% of the total load in the South Basin of Windermere. In 1998, the year used for the modelling exercise, this difference was even greater at 15% and 62% for the North and South Basin respectively.
4. The differential contribution of the WwTWs to their respective basin translated across to the responsiveness of each basin to reductions in SRP loading from the WwTW. In the North Basin, even complete removal of the SRP load from the WwTW at Ambleside only caused an 11% decrease in annual mean phytoplankton chlorophyll *a*. In contrast, in the South Basin complete removal of the SRP load from the Windermere WwTW would cause a 54% decrease in annual mean phytoplankton chlorophyll *a*. However, these differences are consistent with the observed minimal reduction in winter concentrations of SRP and TP in the North Basin following tertiary treatment in 1992, while substantial reductions have been recorded in the South Basin.
5. Further removal of SRP from the Ambleside WwTW, while beneficial, will not be sufficient to cause a marked further improvement in water quality in the North Basin. More effort will be needed to tackle other sources of phosphorus including smaller point sources and diffuse sources from the catchment. In contrast, severely reducing the SRP load from WwTW discharging to the South Basin should have a further benefit in reducing phytoplankton.
6. The limited modelling of the effect of zooplankton grazing on phytoplankton did not show a large effect but a more sophisticated zooplankton grazing module is needed (and is currently being developed) before we can be confident about the magnitude of this effect. Further work addressing the effect of climate change will also need to be included in future models and the forecasts could be made more robust by modelling additional years.

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1. Introduction

Windermere is England's largest lake and is situated in the English Lake District. It is among the most intensively studied lakes in the world with some records extending back to the 1930s. However, the more consistent data that formed what became the long-term monitoring programme were initiated by John W.G. Lund in 1945. For a description of the history of the long-term monitoring programme see Elliott (1990). The earliest data were collected by the Freshwater Biological Association at their laboratories based at Wray Castle and, from about 1950, The Ferry House. Since 1989, the monitoring work has been undertaken by the directly NERC-controlled Institute of Freshwater Ecology which later became a component of the Centre for Ecology & Hydrology.

Windermere lies at an altitude of 39 m (Talling, 1999) and comprises two basins, the North Basin and the South Basin, that are partially separated by several islands and an area of shallow water. The two basins differ in size and depth: the North Basin has a larger area, volume, maximum depth and mean depth than the smaller South Basin (Table 1). The catchment of the North Basin has a higher altitude than the catchment that links directly to the South Basin (mean altitude 270 vs 116 m Table 1) and the preponderance of upland, nutrient-poor land is one of the reasons for the lower nutrient status of the North Basin which is currently mesotrophic, while the South Basin is mesotrophic to eutrophic. With a palaeolimnological perspective, however, both basins were oligotrophic in the period before human activity had a major effect on the lake ecology (Pennington 1943). A major review of Windermere was undertaken by Talling (1986) that documents, *inter alia*, the response of the two basins to nutrient enrichment. Since then a number of major changes have taken place. These include implementation of phosphate stripping (tertiary treatment) at the two wastewater treatment works (WwTW) that discharge directly into the lake, detectable effects of climate change and major increases in a non-native fish, the roach. Numerous scientific papers and reports have been written on Windermere: the two most recent being a review of the phosphorus inputs from the two WwTW on the lake shore (Maberly 2008) and an analysis of long-term changes in the lake (Maberly et al. 2008).

Table 1. Key physical and geographical features of the two basins of Windermere and the whole lake (largely based on Talling 1999).

Feature (unit)	**Windermere North Basin**	**Windermere South Basin**	**Whole Lake**
Catchment area (km^2)	187	63	250
Mean catchment altitude (m)	270	116	231
Lake length (km)	7.0	9.8	16.8
Max. width (km)	1.6	1.0	1.6
Area (km^2)	8.1	6.7	14.8
Volume (m^3 x 10^6)	201.8	112.7	314.5
Mean depth (m)	25.1	16.8	21.3
Max. depth (m)	64.0	42.0	64
Approx. mean retention time (days)	180	100	280
Mean total phosphorus (2007, mg m^{-3})	16	21	-

Like most lowland lakes in this region, phosphorus is the main resource that limits productivity. For example, the 2005 Lakes Tour showed that the mean concentration of phytoplankton chlorophyll *a* was strongly related to mean concentration of total phosphorus (Fig. 1). Although part of this relationship is the result of chlorophyll contributing to total phosphorus, the strong relationship is good evidence for the potent controlling effect of phosphorus on phytoplankton.

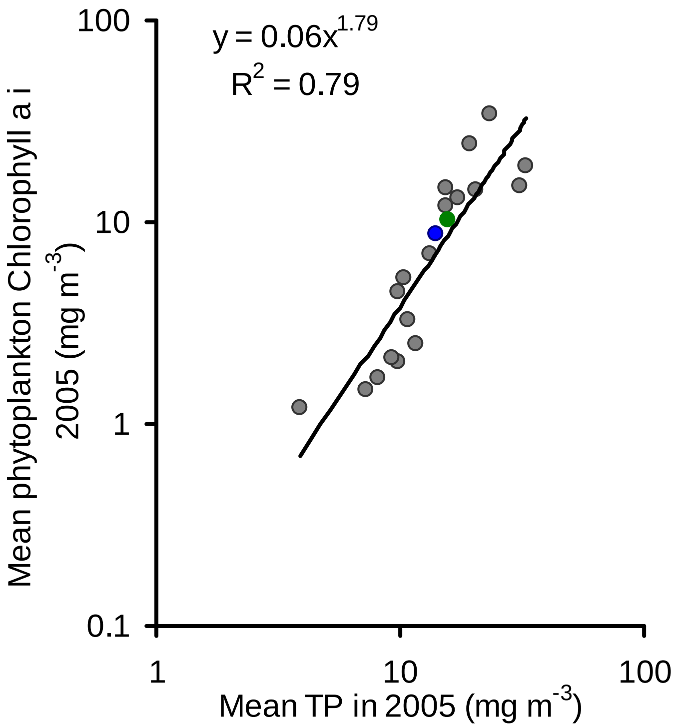


Figure 1. The relationship between mean phytoplankton and mean total phosphorus in the 20 lakes that constitute the Lakes Tour. Note that both scales are logarithmic and that Windermere North Basin is indicated as a blue and the South Basin as a green circle. Redrawn from Maberly et al. (2006).

The report of Maberly *et al.* (2008) undertook a detailed analysis of the patterns of long-term change in Windermere. It demonstrated the beneficial effect that the tertiary phosphorus removal had had when it was first instigated in 1992 (Fig. 2).

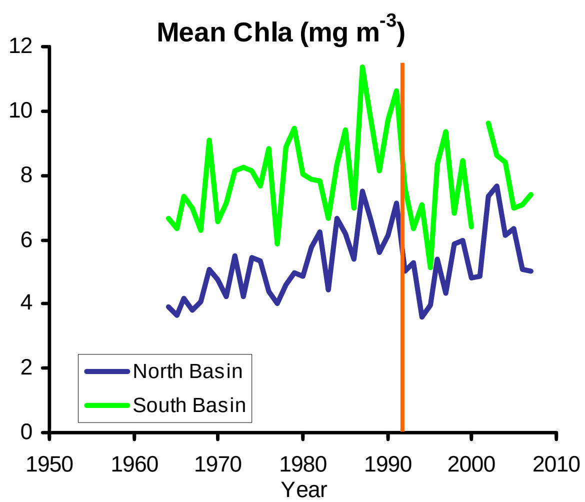


Figure 2. Changes in annual mean concentration of phytoplankton chlorophyll a *in Windermere. The vertical line shows the start of the tertiary treatment in 1992 at the two WwTWs that discharge directly into the lake. Figure derived from Maberly* et al. *(2008).*

The analysis identified an increase in concentrations of phytoplankton chlorophyll *a* in recent years that occurred despite no apparent change in the in-lake concentrations of total phosphorus or in external loading from the two directly-discharging WwTW (Maberly 2008).

As a consequence, the amount of chlorophyll per unit of total phosphorus has increased (Fig. 3a). The density of summer zooplankton has decreased (Fig. 3b), suggesting that the increase in phytoplankton may have resulted from decreasing density of zooplankton. In recent years, roach, which are zooplanktivorous, have increased and this could, in turn, be the cause of the lower summer zooplankton.

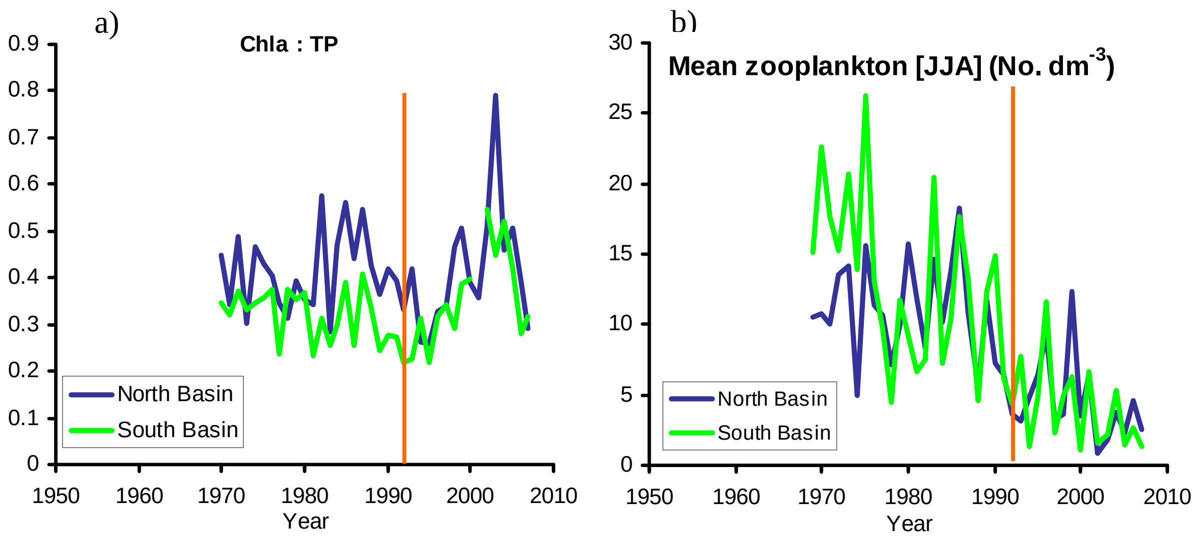


Figure 3. Long-term changes in the annual mean ratio of phytoplankton chlorophyll a to concentration of total phosphorus (a) and zooplankton density in summer (JJA) (b) in the North and South Basins of Windermere. The vertical line shows the start of the tertiary treatment in 1992 at the two WwTWs that discharge directly into Windermere. Figure derived from Maberly et al. *(2008).*

2. Objectives

The first objective of this work was to undertake PROTECH modelling of Windermere for three scenarios of phosphorus removal:

- Phosphorus removal to 1 mg L^{-1} (g m^{-3}) at the Windermere (Tower Wood) and Ambleside WwTW

- Phosphorus removal to 0.5 mg L^{-1} at both WwTW
- Complete removal of WwTW discharge outside the Windermere catchment

Secondly, PROTECH will be used to explore the effect of zooplankton grazing on phytoplankton populations.

3. PROTECH simulation procedure

PROTECH (**P**hytoplankton **R**esp**O**nses **T**o **E**nvironmental **CH**ange; Reynolds *et al.* (2001)) is a process-based model that simulates the daily growth of multiple phytoplankton species throughout the water column. The model has been developed and tested on a wide range of lakes and reservoirs around the world over the last two decades (e.g. Elliott *et al*. 2000; Lewis *et al.* 2002; Elliott & Thackeray 2004; Elliott *et al.* 2005, 2007; Bernhardt *et al*. 2008) and been used in over 20 peer-reviewed publications. Full details of the equations within the model can be found in Reynolds *et al.* (2001).

In simulating Windermere, the approach was taken to model the two basins separately and therefore specific driving data files were created for each basin. The year 1998 was chosen as a baseline for testing because the seasonal pattern of phytoplankton development was typical of that seen in the last few decades e.g. with a bimodal bloom response. Meteorological data for this year, drawn from both Ambleside and Keswick, were used to provide observed values for daily cloud cover, wind speed and air temperature to drive the model. For each basin, daily estimates of loads were needed of soluble reactive phosphorus (SRP), dissolved inorganic nitrogen (DIN: the sum of ammonium, nitrate and nitrite) and silica (SiO_2). Therefore, for the North Basin, the inflowing concentrations used were those from the rivers Brathay and Rothay, Trout Beck, Mill Beck and Blelham Beck plus 0.43 times the total 'missing catchment' attributed to the North Basin (judged on the basis of area). These concentrations were converted to loads by multiplying each by their appropriate discharge, and linear interpolation was used to produce daily estimates. For the WwTW at Ambleside, daily loads of SRP were generated by apportioning the annual load according to the mean proportion delivered each month. Loads of DIN were estimated as 13.87-times the load of SRP. No SiO_2 load was assumed from the WwTW.

For the South Basin, the main input was derived from water moving down from the North Basin. Inflow data for the North Basin could not be used for this, since the plankton will have processed some, or most, of these nutrients and modelled nutrient concentrations from PROTECH could not be used as this risked propagating model errors and so the fortnightly concentrations in the lake, measured by CEH, were interpolated to provide daily inflow concentrations. Daily loads were calculated from these concentrations and the measured daily Newby Bridge outflow multiplied by 0.8, the proportion of the hydraulic discharge of the South Basin deriving from the North Basin. To these loads were added the estimated loads from Cunsey Beck and that estimated from the missing part of the catchment (0.57 of the total from the missing catchment). Finally, the loads from the WwTW from Tower Woods were calculated using the same approach as outlined for the Ambleside WwTW but DIN was estimated at 14.95-times the SRP load (see Maberly 2009).

The main focus of this report is the ecological effect of the main limiting nutrient, phosphorus. The calculated daily load of SRP to each basin is shown in Figure 4. Loads of SRP were generally slightly greater in the South than the North Basin. The values in the North Basin showed a very large peak (Fig. 4a) reaching nearly 130 kg d^{-1} on 10 September 1998. This derived wholely from the R. Brathay where the estimated load on that date was 122 kg d^{-1}. In turn, this derived from a relatively high concentration (0.1 g SRP m^{-3}, Maberly

2009), about 10-times higher than the long-term mean, at a time of relatively high hydraulic discharge. These peaks of elevated SRP are seen consistently in the data record (Maberly 2009, Fig. 3). However, it is possible that because PROTECH needs data to be derived from these roughly monthly data, the interpolated, daily values will have exaggerated the effect of this peak on annual load. However, no data are available to check this possibility and we take this into account in our later interpretation of the model outputs.

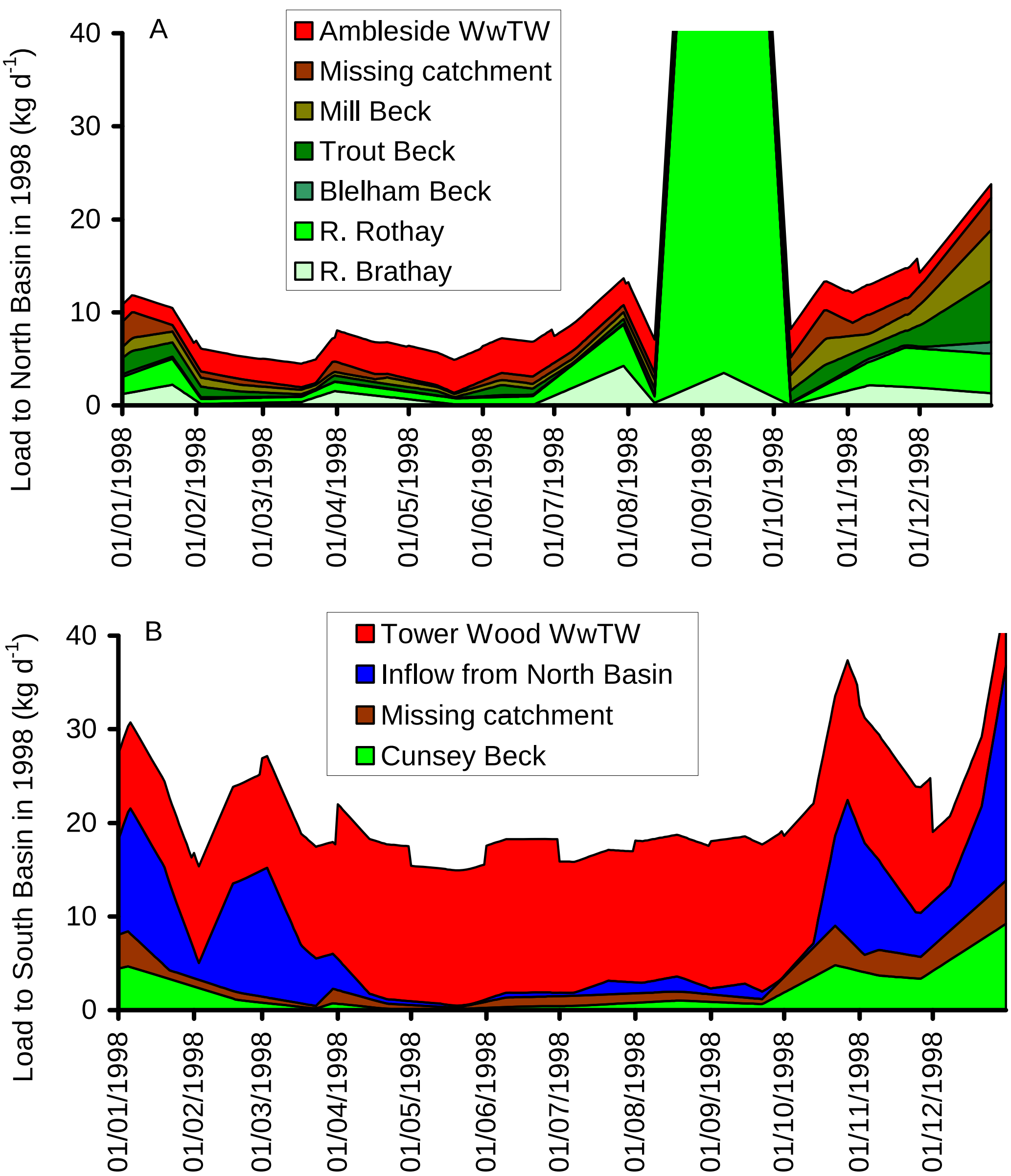


Figure 4. Calculated daily load of soluble reactive phosphorus (SRP) from various sources to the North Basin (A) and South Basin (B) of Windermere in 1998. Note the peak of the very high load to the North Basin from the R. Rothay is truncated for reasons of scaling (see text).

Table 2 estimates daily loads of SRP to the North Basin and South Basin of Windermere separately using mean data from the eleven years between 1997 and 2007 (Maberly 2009) and the data calculated here for 1998. In the North Basin, the load of SRP contributed by the WwTW was 30% of the total load in the eleven year period and 15% of the total load in 1998. The lower value in 1998 was caused by the higher catchment load, mainly from the R. Rothay, as discussed above, but partly because of a slightly lower annual load from the Ambleside WwTW. In the South Basin of Windermere, SRP inputs from WwTW were larger both in absolute terms and as a percentage of total load. The total SRP load contributed by the Tower Wood WwTW was 52% in the eleven-year period and 63% in 1998.

Table 2. Estimate of daily load of SRP (kg d^{-1}) to the North and South Basins of Windermere as a mean over eleven years between 1997 and 2007 and for 1998. Values in parentheses for the WwTWs are the contribution of each WwTW to the total SRP load to the basin.

North Basin			South Basin		
Site	1997-2007	1998	Site	1997-2007	1998
R. Brathay	1.36	1.26	Inflow from North Basin	4.57	4.57
R. Rothay	3.94	11.07	Cunsey Beck	1.12	1.92
Blelham Beck	0.16	0.17	‘Missing catchment’	1.29	1.47
Trout Beck	0.69	1.15	Tower Wood WwTW	7.53 (51.9%)	13.29 (62.6%)
Mill Beck	0.91	1.15	**TOTAL**	**14.51**	**21.24**
‘Missing catchment’	0.98	1.11			
Ambleside WwTW	3.52 (30.4%)	2.87 (15.3%)			
TOTAL	**11.56**	**18.79**			

To estimate loads for the reduced load-scenarios from the two WwTW, SRP load was reduced proportionally in relation to the outflowing SRP concentration. In 1998, the annual mean concentration was 1.26 g m^{-3} from the Ambleside WwTW and 1.99 from the Tower Wood WwTW. These were larger than the mean concentration in the eleven years between 1997 and 2007 which were 1.55 and 1.15 g m^{-3} at Ambleside and Tower Wood respectively. For the 1 g

m^{-3} (1 mg L^{-1}) scenario, loads from the WwTW were reduced by 1.256-times and 1.994-times for Ambleside and Tower Wood respectively. For the 0.5 g m^{-3} scenario loads from the WwTW were reduced by 2.512-times and 3.988-times for Ambleside and Tower Wood respectively. For the complete removal scenario, loads of P from the two WwTWs were set to zero. For all scenarios, loads of DIN from the two WwTWs and loads of all nutrients from the catchment were not altered. However, since for the South Basin the load from the North Basin inflow was derived from monitoring data and there is no way to predict how reductions in load from the Ambleside WwTW will affect this, the SRP load reduction scenarios were operated independently i.e. the reductions in the South Basin did not include any reduction in load from the North Basin and so this might slightly underestimate the effect on the South Basin of running, for example, the 0.5 g m^{-3} scenario at both WwTWs.

4. PROTECH validation procedure

For validation, fortnightly observed total chlorophyll *a* concentrations and counted species data were used. The most dominant (i.e. greatest contributors to the biomass throughout the year) 8 species in these data were selected to be simulated by PROTECH. As the model predicts ecological strategy types more successfully than individual species, both the observed species data and the PROTECH species output were classified according to their strategy group. This classification is based on Reynold's (1989) proposed groupings established using the morphological dimensions of the phytoplankton (Fig. 5).

In the classification, C-strategists are fast growing and small sized, favoured by high light and nutrients availability; interestingly, there are no representatives in this study as few such types produced any significant biomass in 1998. S-strategists are very slow growing, but tolerate relatively low nutrient availability and strong stratification (most are motile). The Rstrategists, which tend to be long and thin, are adapted to low light and a mixed water column. In between these main groups there are sub-groups defined; e.g. CS-strategists, which have some characteristics of both C- and S-strategists and CR-types which straddle the C and R divide. Finally, because PROTECH expresses the species specific biomass in its simulations as a chlorophyll concentration and not cell counts, the observed count data were approximated as a relative proportion of the total cell numbers for each strategy group. These proportions where then used to estimated what proportion of the observed total chlorophyll was due to each strategy group.

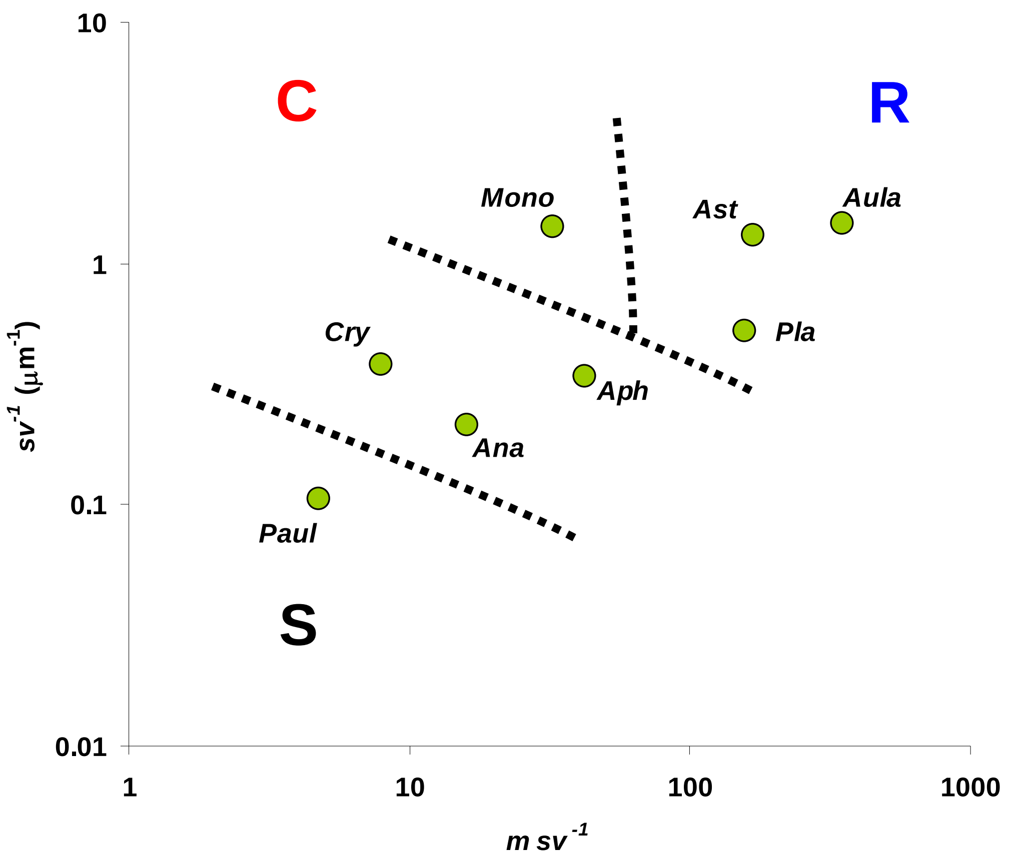


Figure 5. CSR strategy classification for the eight PROTECH species simulated. Ana = Anabaena (CS); *Aph = Aphanizomenon* (CS); *Ast = Asterionella* (R); *Aula = Aulacoseira* (R); *Cry = Cryptomonas* (CS); *Mono = Monoraphidium* (CR); *Paul = Paulschulzia* (S) and *Pla = Planktothrix* (R).

5. Model validation

The model was run for both Windermere basins and the output compared to the observed data. The North Basin simulation of total chlorophyll *a* compared favourably to the observed total chlorophyll *a* (Fig. 6) simulating the timing of the spring and summer peak. However, the simulated spring peak was a little lower for one observation (day 118) and the in the early autumn, there was an over estimate of biomass (around day 245). This latter point reduced the statistical correlation between the two data sets ($R^2 = 0.51$; $P < 0.01$), but with its removal, the correlation increased markedly ($R^2 = 0.75$; $P < 0.01$), indicating the overall good agreement between observation and simulation.

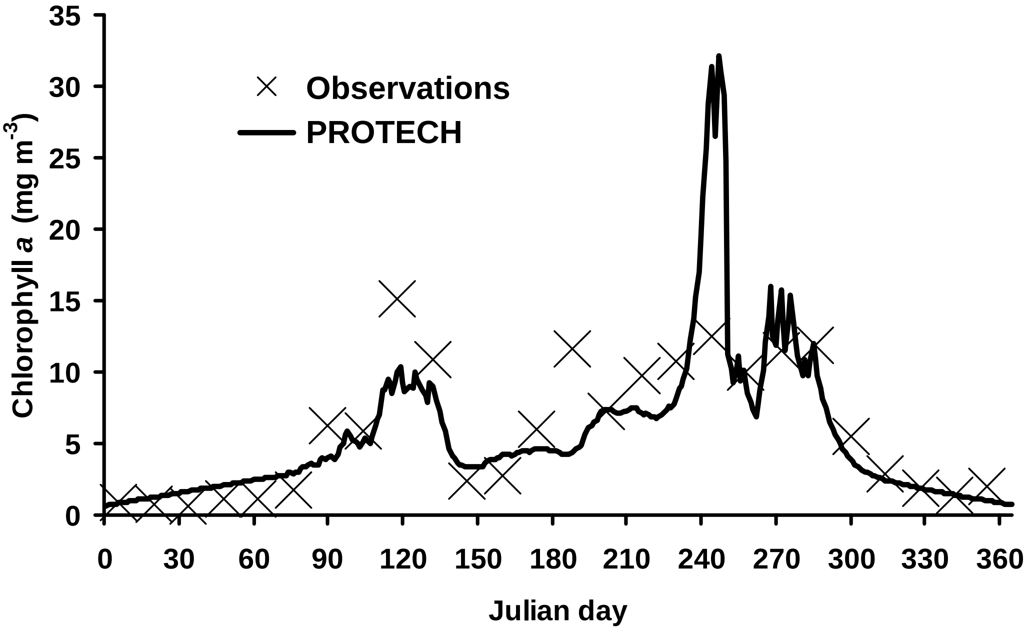


Figure 6. Comparison between observed (crosses) and PROTECH simulated (solid line) chlorophyll a concentrations (mg m^{-3}) for Windermere North Basin, 1998.

At the CSR strategy level, there was also good agreement during the two blooms periods (Fig. 7) with R-type diatoms dominating in the spring and CS-types dominating the summer/autumn bloom (consisting mainly of Cyanobacteria species), although PROTECH did simulate an unobserved increase in R-types at the end of the bloom (from day 258 onwards).

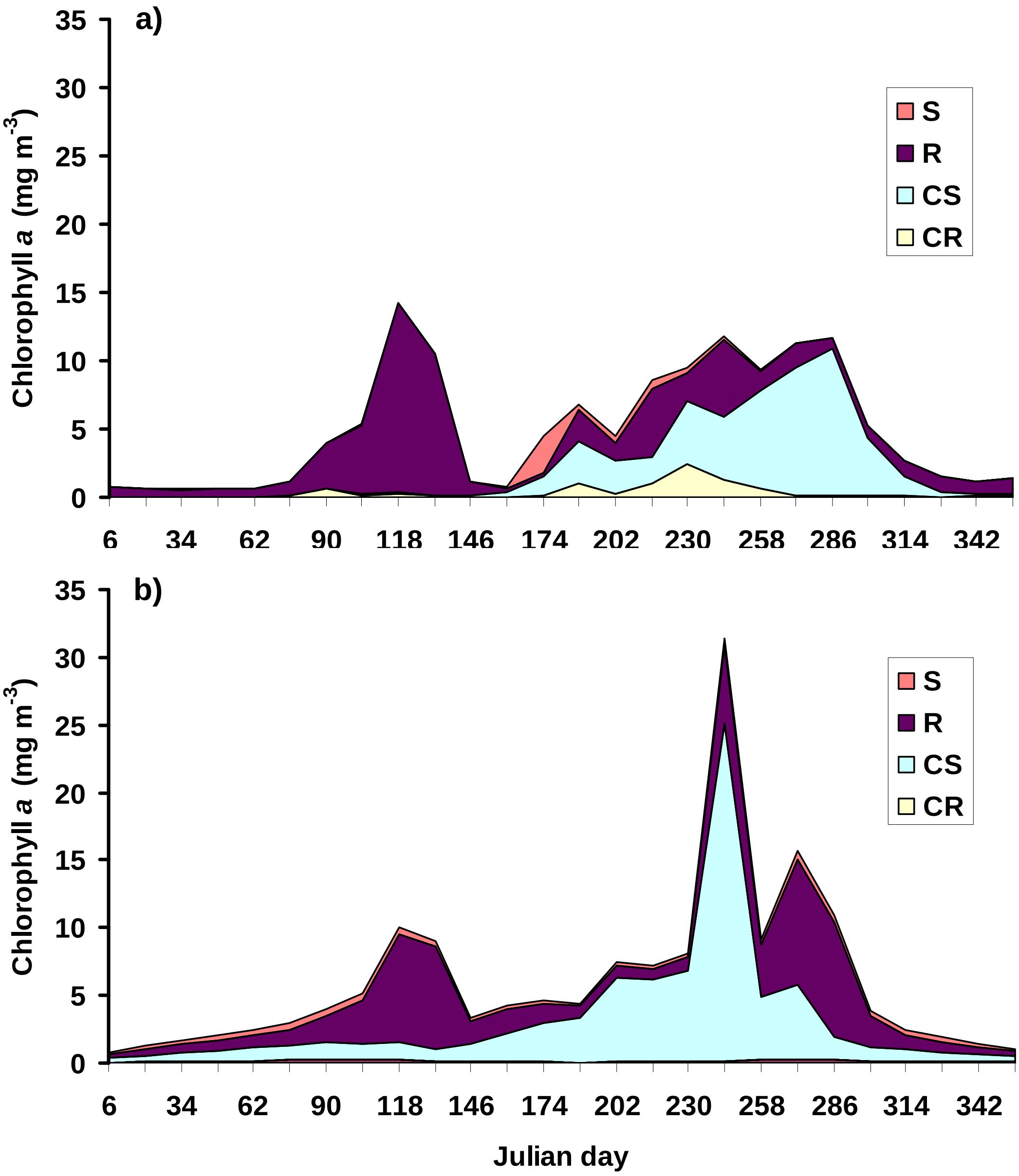


Figure 7. Comparison between (a) observed and (b) simulated function groups, expressed as chlorophyll a, in Windermere North Basin, 1998.

The South Basin simulation was also compared to observations to validate PROTECH (Fig. 8) and it showed a reasonable fit for total chlorophyll *a* (R^2 = 0.60; P < 0.01).

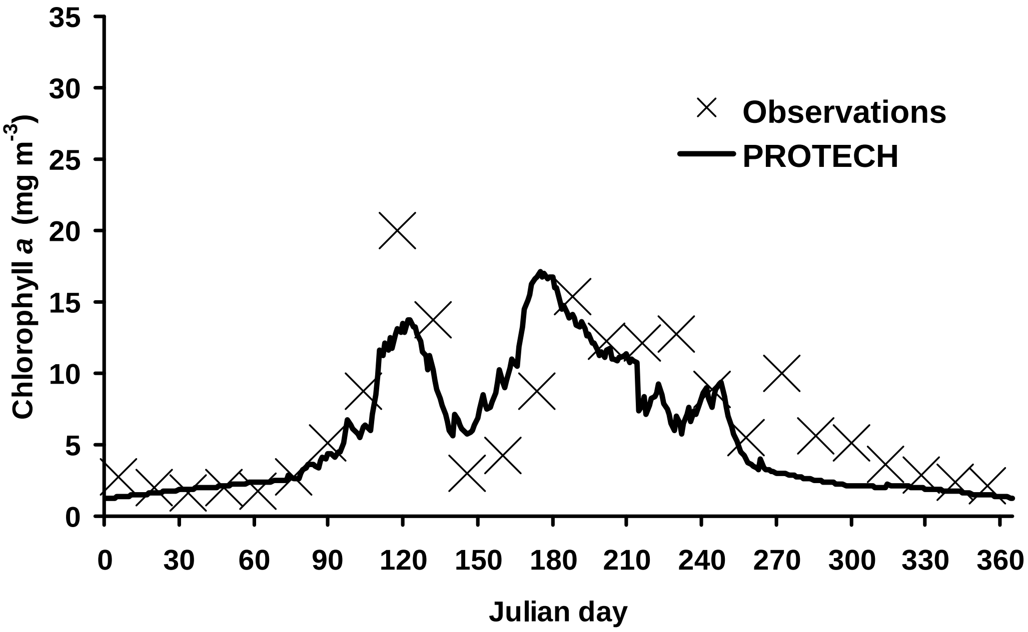


Figure 8. Comparison between observed (crosses) and PROTECH simulated (solid line) chlorophyll a concentrations (mg m^{-3}) for Windermere South Basin, 1998.

The main areas of greatest deviation from the observed total chlorophyll *a* were the underestimated biomass during the spring peak (day 118) and the underestimate of biomass at the end of the summer/autumn bloom (particularly around day 272).

Species strategy group comparison demonstrated that, although the observed overall pattern of total chlorophyll *a* was similar in timing and magnitude between the two basins, the functional characteristics greatly varied during the summer/autumn bloom. During this period, R-types dominated in the South Basin (Fig. 9a), compared to the dominance of CS-types in the North Basin (Fig. 7a). It was therefore encouraging that PROTECH also simulated the same pattern of dominance by R-types throughout the year (Fig. 9b). Furthermore, PROTECH captured the observed change in the R-types with diatoms dominant in the spring and *Planktothrix* dominating throughout the duration of the second bloom.

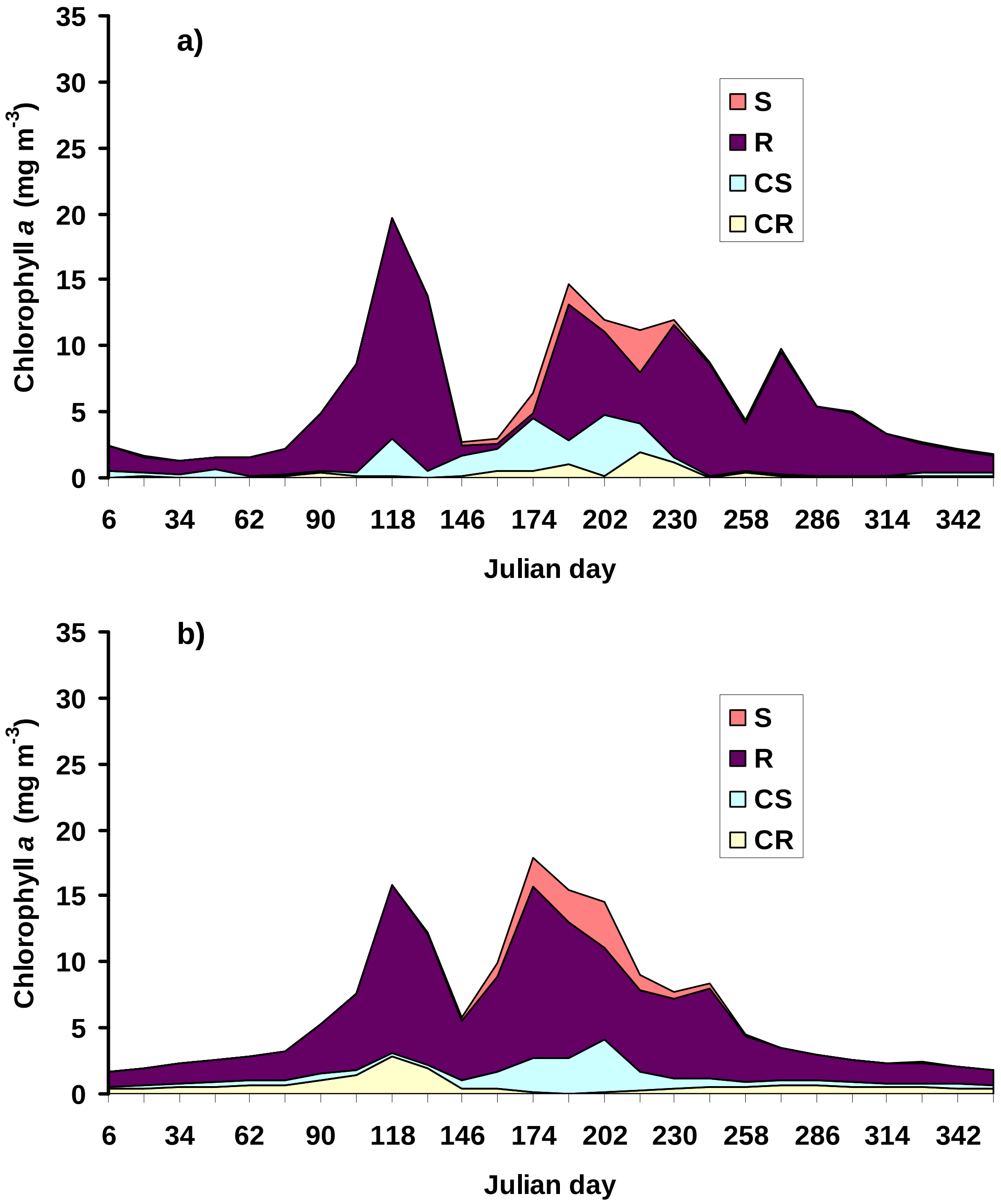


Figure 9. Comparison between (a) observed and (b) simulated function groups, expressed as chlorophyll a, in Windermere South Basin, 1998.

6. Phytoplankton response to nutrient-reduction scenarios

The three nutrient scenarios created for each basin (annual mean SRP concentration from the WwTW of 1, 0.5 and 0.0 g m^{-3}) that characterized different hypothetical conditions of phosphorus loading to the lake via sewage inputs were used to drive PROTECH, using the

1998 simulations as their baseline. The differences between the two basins' SRP inputs was marked (Fig. 10), reflecting the relative importance of the sewage input to the overall load. Thus, North Basin's SRP input changed very little, compared to the South Basin. Note that the South Basin scenario assumes no beneficial effect of P-load reduction from the North Basin and so may underestimate the real response of the South Basin to reduction at both WwTWs.

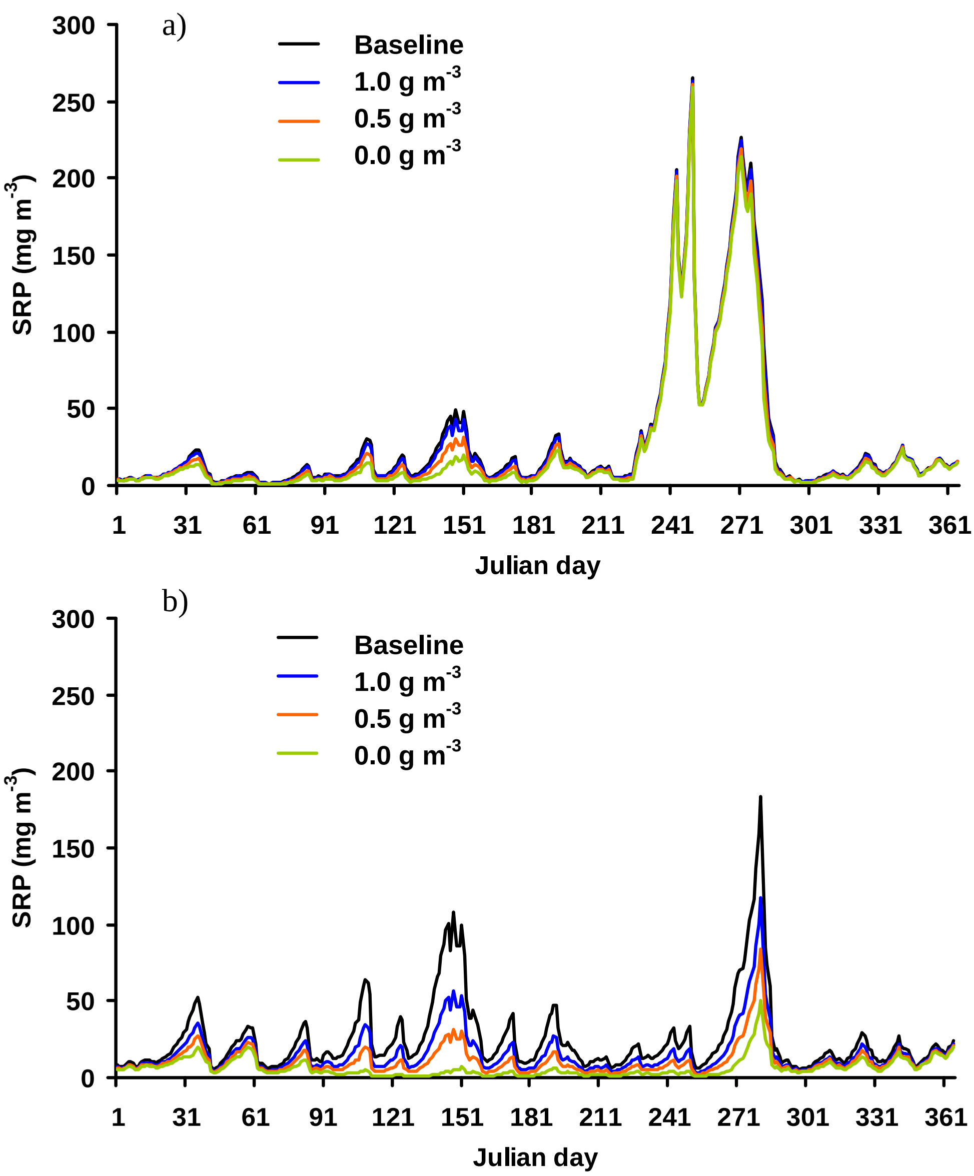


Figure 10. Mean daily SRP inflow concentrations for the baseline (black line) and for the three scenarios: 1, 0.5 and 0.0 g m^{-3} SRP from the two WwTW (blue, orange and green respectively) in (a) Windermere North Basin, 1998 and (b) Windermere South Basin, 1998.

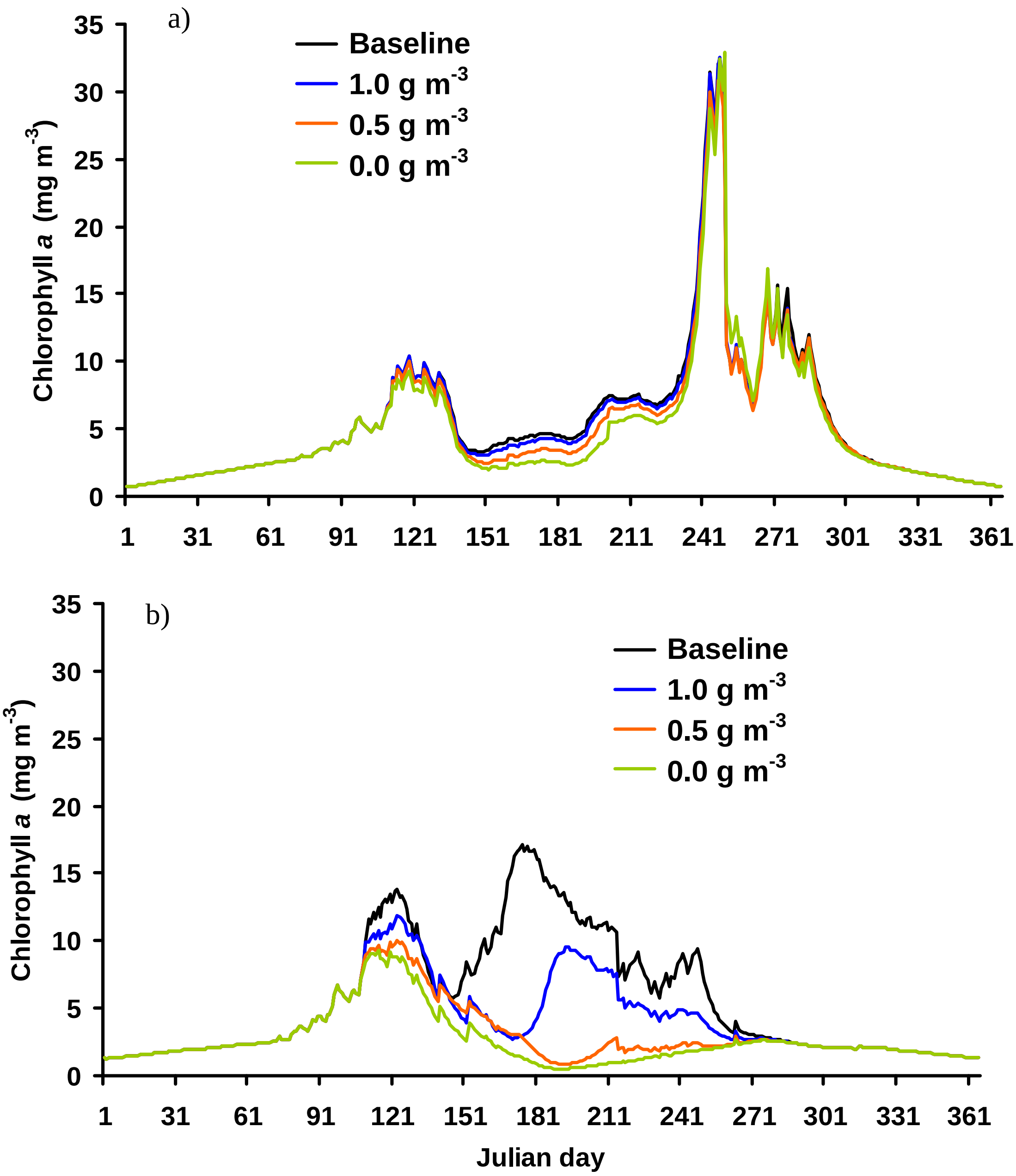


Figure 11. Comparison between the baseline (black line) PROTECH total chlorophyll a and for the three scenarios: 1, 0.5 and 0.0 g m^{-3} SRP (blue, orange and green respectively) in (a) Windermere North Basin, 1998 and (b) Windermere South Basin, 1998.

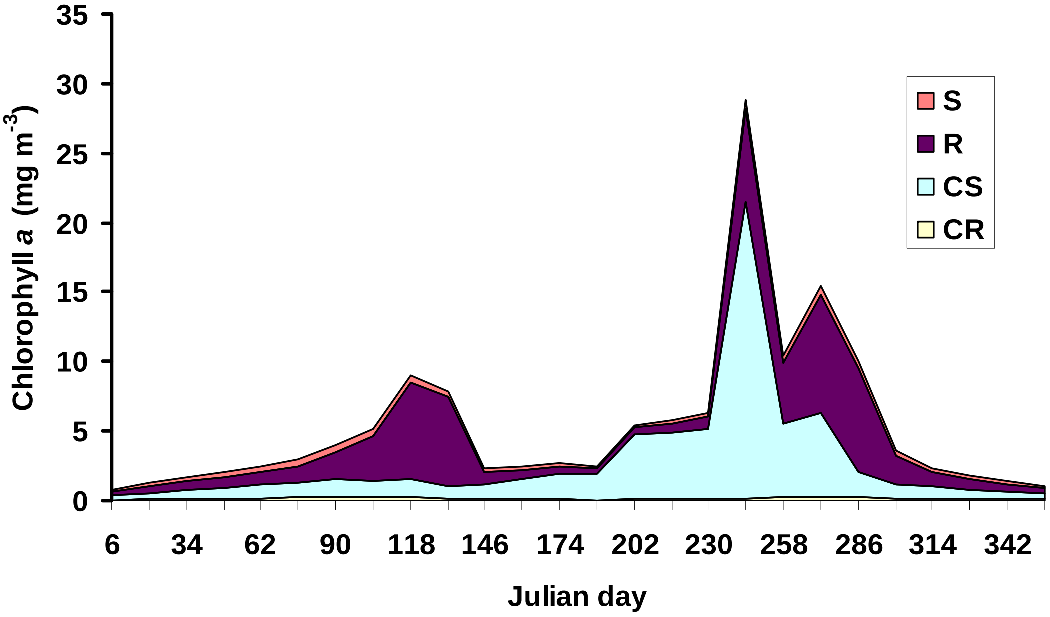
This difference between SRP inputs to the two basins was reflected in the PROTECH simulations of total chlorophyll *a* (Fig. 11). The North Basin total chlorophyll changed very little, with only a slight decline occurring in the summer (Fig. 11a). In contrast, the South

Basin chlorophyll *a* decreased markedly from the spring onwards, with very little phytoplankton biomass being simulated in the summer particularly in the 0.5 and 0.0 g m^{-3} scenarios (Fig. 11b). Thus, the contrast in the nutrient inputs for the two basins was readily expressed in the phytoplankton biomass simulated, showing that the South Basin was considerably more sensitive to the decreased sewage input scenarios than the North Basin. Note again that this is a worse-case scenario as any possible benefits of reduced P-load from the North to the South Basin were not taken into account.

There were also some shifts in the phytoplankton strategy groups simulated. For example in the North Basin of Windermere, for the most extreme nutrient-reduction scenario where the WwTW works ourflow was set to zero, there was an increase in the proportion of CS algae such as *Aphanizomenon* (Fig. 13a) compared to baseline conditions (Fig. 9a). In the South Basin of Windermere, where a reduction in phosphorus loading from the WwTW had a large effect on phytoplankton abundance, the phytoplankton became dominated by R-types such as *Asterionella* and *Aulacoseira* (Fig. 13b) whereas in the baseline runs (Fig. 9b), there was a contribution from other strategy groups.

The annual mean concentrations of phytoplankton chlorophyll *a* for the different scenarios and the two basins are shown in Table 3. The mean concentration in the baseline simulation is close to that measured during the fortnightly sampling by CEH (Reynolds et al. 1999) in the North Basin. The measured concentrations in the South Basin were slightly greater than those modelled by PROTECH (6.8 vs 5.6 mg m^{-3}, Table 3) which could indicate an additional source of phosphorus to this basin. This could result from internal load from phosphorus released from the sediment during summer anoxia since elevated concentrations of SRP are often measured in the South Basin at depth in summer (CEH unpublished information). Table

3 also shows that the South Basin is more responsive to P-removal from WwTW than is the North Basin.



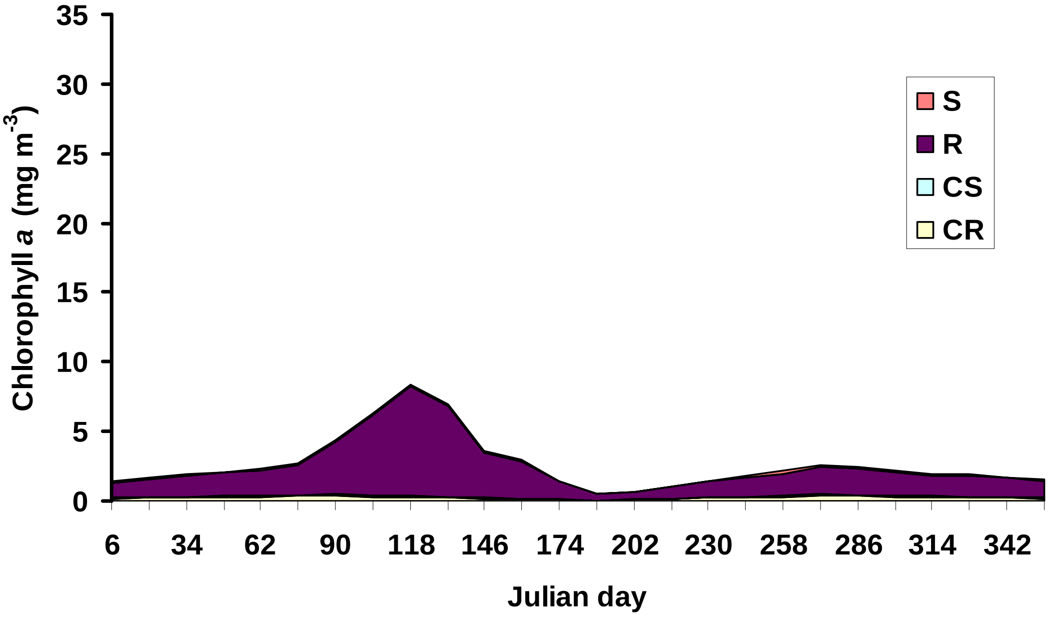


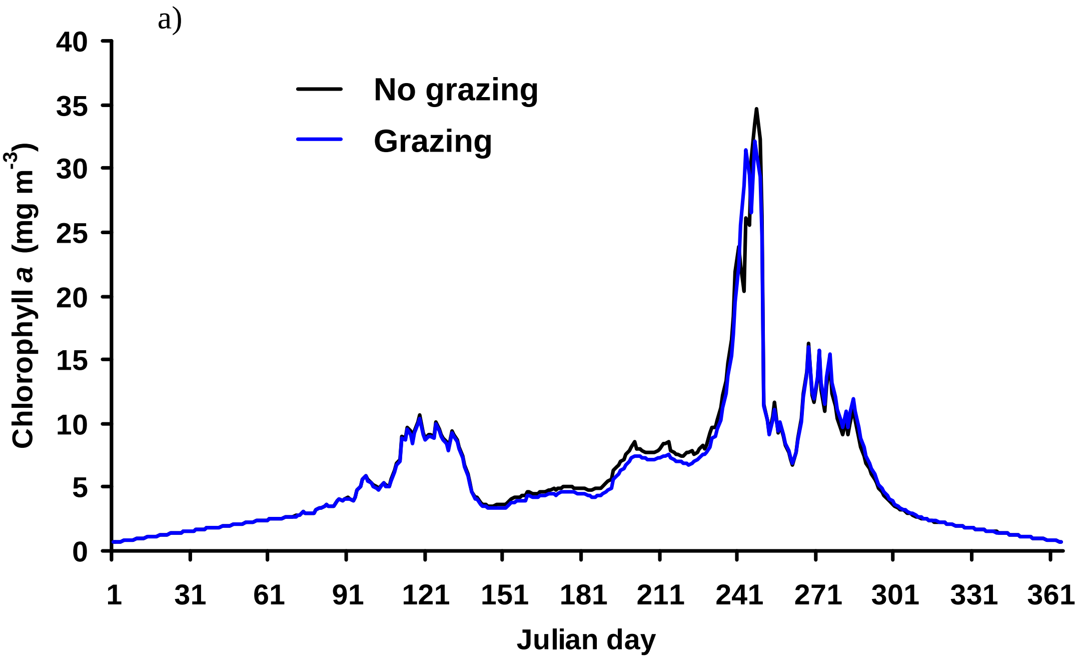
Figure 12. Simulated strategy groups for the 0.0 g m^{-3} SRP scenario for (a) Windermere North Basin 1998 and (b) Windermere South Basin, 1998.

Table 3. Measured and simulated annual mean phytoplankton chlorophyll a *concentration (mg m^{-3}) for the different modelling scenarios in the North and South Basins of Windermere in 1998. Values in parenthesis are the percentage of the chlorophyll a concentration relative to the baseline concentration (see text for discussion). Also shown are approximate estimates for 1997- 2007 based on mean SRP loads in Table 2 and the regressions in Figure 14.*

	North Basin		South Basin	
Scenario	1998	Estimated mean 1997-2007	1998	Estimated mean 1997-2007
Measured	6.0	-	6.8	-
Baseline	5.6 (100%)	4.0 (100%)	5.6 (100%)	4.0 (100%)
1.0 g m^{-3} SRP	5.4 (97.8%)	3.9 (96.2%)	4.1 (73.2%)	3.1 (78.0%)
0.5 g m^{-3} SRP	5.2 (93.4%)	3.6 (88.9%)	3.0 (53.6%)	2.7 (67.0%)
0 g m^{-3} SRP	5.0 (89.1%)	3.3 (81.5%)	2.6 (46.4%)	2.2 (55.9%)

7. Phytoplankton responses to removal of grazing pressure

The effect of removing zooplankton grazing pressure was limited in these PROTECH simulations (Fig. 13). There was almost no response in spring and autumn in either basin and only a small effect in summer that was slightly greater in the South (Fig. 13b) than the North (Fig. 13a) Basin of Windermere.



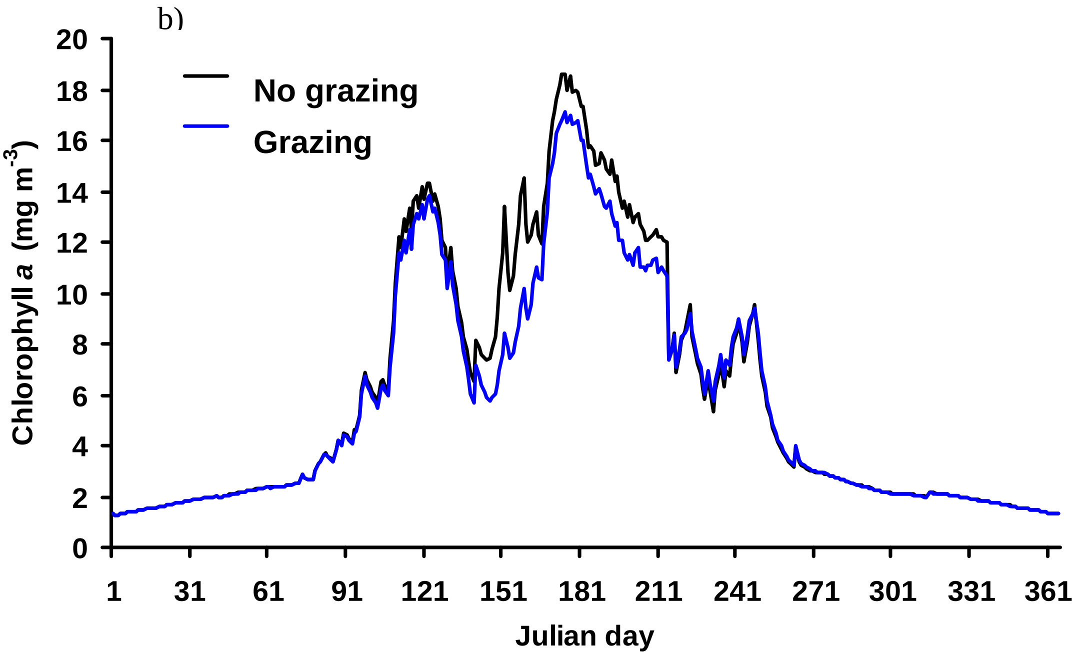


Figure 13. Comparison between chlorophyll a concentrations (mg m^{-3}) baseline simulation with (blue line) and without zooplankton (black line) grazing functions active for (a) Windermere North Basin, 1998 and (b) Windermere South Basin, 1998.

8. Interpretation of model results

The analysis of SRP loads to each basin from different sources show that the North and South Basin of Windermere are differentially influenced by SRP from WwTW. On average (1997 to 2007) 30% of the SRP load to the lake was derived from WwTW in the North Basin but the equivalent figure for the South Basin was 52% (Table 2). This difference results in part from the much greater catchment area for the North Basin (187 km^2) compared to the South Basin (63 km^2, Table 1). This difference in the contribution of the two WwTWs to the total load of SRP to each basin causes a crucial difference in the degree of phytoplankton response to reduced SRP load from the WwTWs. In the North Basin, even complete removal of the SRP input from the Ambleside WwTW only caused an 11% decrease in annual mean concentration of phytoplankton chlorophyll *a* (Table 3). In contrast, there was a forecast 54% decline in phytoplankton chlorophyll *a* in the South Basin (Table 3). This difference is not caused by a different sensitivity to phosphorus by the two basins, since if the annual mean chlorophyll *a* concentrations are plotted against daily SRP load for the different scenarios they show a very similar response (Fig. 14). The South Basin is slightly more responsive to increased SRP-load than the North Basin (a slope of 0.24 in South Basin vs 0.21 mg chlorophyll a m^{-3} kg^{-1} d in the North Basin). The greater intercept for the North Basin is probably an artefact caused by elevated summer chlorophyll resulting from an extreme pulse of SRP delivered in mid-summer (see above).

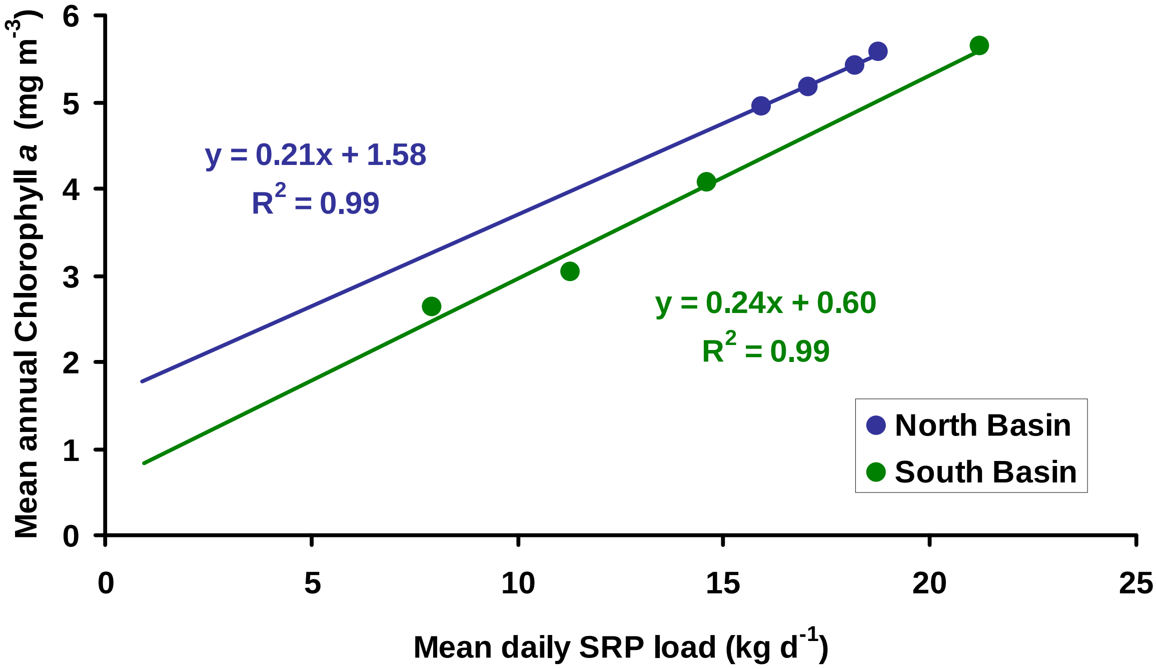


Figure 14. Modelled response of mean annual phytoplankton chlorophyll a *to mean daily SRP load resulting from the different nutrient load scenarios for operating the WwTW.*

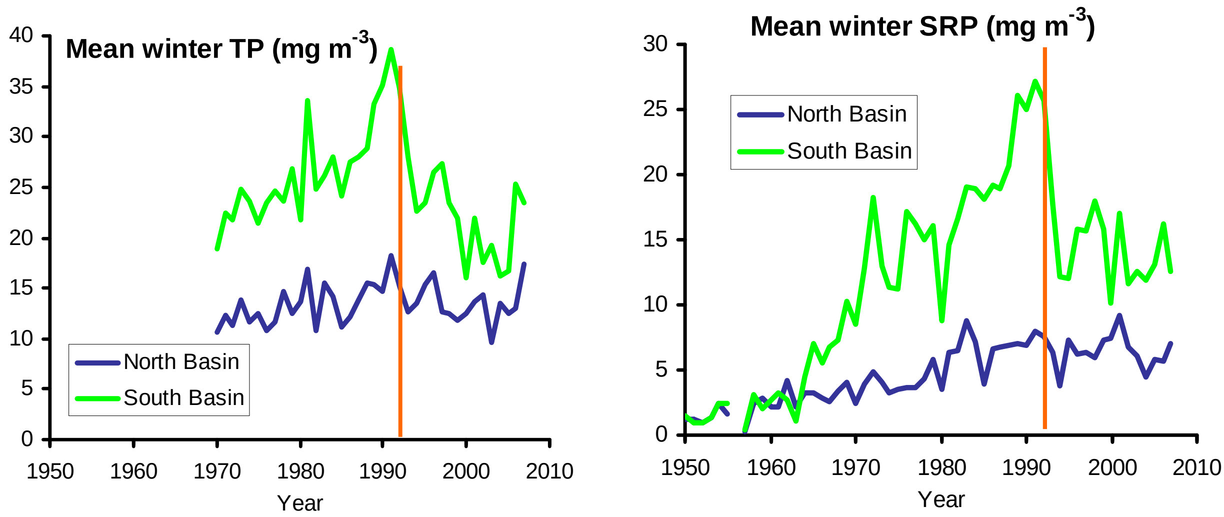


Figure 15. Long-term changes in the mean winter concentration of total phosphorus (TP) and soluble reactive phosphorus (SRP) in the North and South Basins of Windermere. The vertical line shows the start of the tertiary treatment in 1992 at the two WwTWs that discharge directly into Windermere. Figure derived from Maberly et al. *(2008).*

There were not sufficient resources to run model simulations for several years and running a simulation for an ‘average year’ is not appropriate and there could be a concern that the results found her are influenced by the particular year, 1998, that had higher than average catchment inputs in the North Basin and higher than average inputs from the WwTW in the South Basin. Partially to check for this, the regressions in Figure 14 were used to estimate annual mean chlorophyll *a* concentrations based on the average loads 1997-2007 and the proportions of SRP reduction from each WwTW scenario as outlined above. While the average concentration of chlorophyll *a* produced was less than in the properly simulated 1998, the percentage reductions for the SRP-reduction scenarios were rather consistent for the average loads in both North and South Basin (Table 3).

The recorded responses of the two basins to a reduction in SRP load on the initiation of tertiary treatment in 1992 also strongly supports the relatively low importance of WwTW to phosphorus load to the North Basin. There was a clear reduction in winter concentrations of TP and SRP in the South Basin but only a muted response in the North Basin (Fig. 15). However, a simulation of several other years with varying contribution from the catchment and the WwTW would further check the robustness of the conclusions.

The lack of effect of removing zooplankton grazing on the phytoplankton chlorophyll is very interesting. At face value this suggests that zooplankton do not control phytoplankton abundance. While the evidence to the contrary is largely circumstantial, based on correlations between reduced summer zooplankton and increased summer phytoplankton there is intuitive support for this. A second possibility is that zooplankton abundance is suppressed by lack of suitable food. At present, the grazing routine in PROTECH is quite simple and probably not able to distinguish between control of phytoplankton by zooplankton or control of zooplankton by phytoplankton.

9. Future work

Given the intriguing results highlighted in this study and the clear contrasting responses of the two basins, there are many possibilities for future work. Firstly, it would be perhaps wise to investigate other representative years using PROTECH, or at least review if the relative importance of SRP from the WwTW has changed for the two basins since 1998.

Secondly, the effects of climate change have not been assessed. It is quite possible that, at least in terms of the composition of the phytoplankton community, warmer temperatures could select for Cyanobacteria species. Ultimately, though, the overall biomass will be greatly dependent on the nutrient supply to the lake.

Thirdly, the secondary impacts of these changes have not been examined. For example, oxygen concentration will be added into PROTECH soon and this would allow the impact of these changes to be assessed on, for example, the habitat volume of the Arctic Charr.

Finally, we are currently developing a more sophisticated grazing routine within PROTECH that should be able to distinguish more clearly between top-down or bottom-up interactions between zooplankton and phytoplankton and hence whether the recent observed worsening of water quality in Windermere, despite maintained phosphorus loads, is caused by trophic interactions within the lake.

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