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OPTIONS FOR THE REMEDIATION OF WINDERMERE:

IDENTIFICATION OF CURRENT NUTRIENT LOADS AND FUTURE LOADS TO MEET ECOLOGICAL TARGETS

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Executive Summary

1. The purpose of this report was to evaluate the current sources and load of nutrients, particularly phosphorus, to Windermere and to identify the reduction in load necessary to meet different phosphorus targets.
2. Discharge data provided by the Environment Agency from eleven years between 1997 and 2007 (inclusive) were analysed. These data included mainly daily estimates for four major inflows and the outflow at Newby Bridge. The ungauged part of the catchment was estimated to contribute about 22% of the theoretical water yield and this was added into the water-budget. For the period analysed, the average discharge from Windermere was 457 Mm^3 y^{-1}.
3. Roughly monthly nutrient chemistry data were provided by the Environment Agency for six sites on inflowing streams of which two, Blelham Beck and Mill Beck, did not have discharge data. Concentrations of ammonium, oxidised nitrogen, orthophosphate-phosphorus, total phosphorus and silica were analysed. Some sites, such the River Rothay and Mill Beck, had no total P data and at other sites, e.g. Blelham Beck, the data were of low frequency so loads of total P were estimated from orthophosphate. The concentration data were evaluated 'lightly' and the major outliers removed. Between 58% (ammonium) and 1% (silica) of the values were less than the limit of detection and these values were replaced by a concentration equal to half the detection limit.
4. Nutrient load from the catchment was estimated as the product of discharge and concentration, including estimates for the unmeasured part of the catchment. Nutrient load from the two wastewater treatment works (WwTW) that discharge directly to the lake were based on values in Maberly (2008). Analysis of concentration data and relationship between concentration and flow suggests that there is a significant point source upstream of the Mill Beck sampling site (and the known WwTW on the River Rothay).
5. The total average load of total phosphorus to Windermere was estimated to be 14.17 Mg y^{-1}, of which 71% entered via the inflowing streams (some of which could have derived from small WwTWs in the subcatchments) and 29% from the two major WwTWs. The total average load of orthophosphate-P was 7.86 Mg y^{-1}, of which 49% derived from the inflowing streams and 51% from the two major WwTWs. These estimates are higher than some previous estimates but the data do not allow the reason for this to be evaluated. The total average load of dissolved inorganic nitrogen was 294 Mg y^{-1} (80% from the inflowing streams) and that for silica was 927 Mg y^{-1} (all from the inflowing streams).

6. Interannual variation in load in the eleven years between 1997 and 2007 was 42% for total phosphorus and there was no correlation between annual load and annual discharge for this nutrient, consistent with a mainly point source.
7. The loads were converted to in-lake concentrations using five different approaches. The equation of Kirchner & Dillon (1975) was the only one where the estimated concentration fell within the observed concentrations. Although there is no way of judging whether this has any underlying mechanistic basis, this equation was used to estimate the loads needed to produce different lake concentrations of total phosphorus. Using this equation, the total load of total P from the catchment and the two directly-discharging WwTWs would be equivalent to an average in-lake concentration of 18 mg m^{-3}. The load from the inflowing streams alone would produce an in-lake total P concentration of 13 mg m^{-3} which exceeds the target concentration for the lake of 10 mg m^{-3}. Consequently, this target is not achievable by just removing the total P load at the WwTW. A target concentration of 15 mg total P m^{-3} could be achieved with the current load from the catchment and a 53% reduction in load from the two major WwTWs.
8. Loads of phosphorus from the catchment, the small WwTw and the two major WwTw on the shores of Windermere will all need to be reduced if the lake is to reach its ecological target for phosphorus and good ecological status or potential under the terms of the EU Water Framework Directive, especially in the face of current and future climate change.

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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 records extending back to the 1930s for some types of information. However, the more consistent data that formed what became the long-term monitoring programme was 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, 199) 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 Man's 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 wastewater treatment works (WwTW) on the lake shore (Maberly 2008) and a review 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 (excld North 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	-

2. Objectives

The first objective of this part of the project was to analyse the available nutrient and hydraulic discharge data plus the data from the WwTW to estimate a current phosphorus load to Windermere. The second objective was to estimate the nutrient loads to the lake that would meet different ecological targets.

3. Data provided

Data were provided by the Environment Agency for a number of sites within the Windermere catchment between January 1997 and December 2007. The sites location and broad types of data provided and used in this report are shown in Table 2. Estimates of nutrient load from the two WwTW were based on Maberly (2008).

Table 2. Location of sites with discharge and water quality data used in this report.

Station name	Station number	River	National Grid Reference	Data provided
Miller House Bridge	735022	Rothay	NY3712504195	Discharge & water quality
Jeffy Knots	735123	Brathay	NY3596503406	Discharge & water quality
Calgarth	735328	Trout Beck	SD3961299883	Discharge & water quality
Eel House	735226	Cunsey Beck	SD3695694055	Discharge & water quality
Newby Bridge Fms	735430	Leven	SD3660086264	Discharge & water quality
Blelham Beck			NY37090098	Water quality
Mill Beck			SD40209766	Water quality

4. Discharge

Discharge data were provided by the Environment Agency for five gauging stations in the Windermere catchment: four on inflows and one on the outflow on the River Leven (Table 2). The raw discharge data are shown in Figure 1. There is a period of data for Calgarth from December 2002 to July 2003 when level did not change indicating a malfunction in the equipment. These data were coded as complete, good and apportioned/ interpolated on the data from the EA problems were noted for this site (Appendix 1) and this section of the results but were excluded from the analysis.

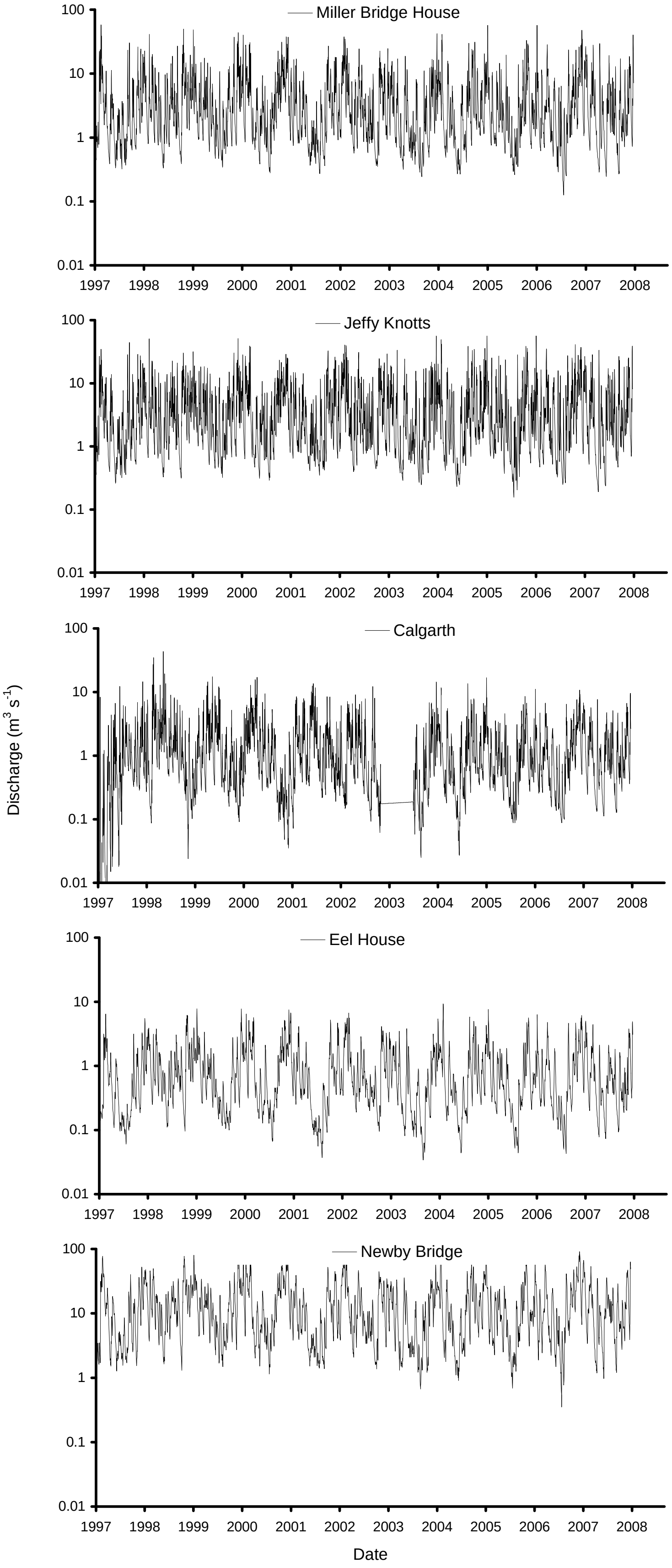

Figure 1. Raw discharge data (m^3 s^{-1}) for the five gauging stations from 1/1/1997 to 31/12/ 2007 (note the log scale).

Table 3. Mean discharge, catchment area, estimated mean precipitation and theoretical and estimated water yield for different subcatchments in the Windermere catchment. Catchment area and estimated precipitation were derived from the CEH Flood Estimation Handbook (Institute of Hydrology 1999). Discharge was the mean of values between 1977 and 2007, water yield was calculated from catchment area and mean precipitation for theoretical yield and mean discharge for estimated water yield. Values in parenthesis for theoretical yield represent the percent contribution to the catchment yield. Values in parenthesis for estimated yield represents the percent of estimated compared to theoretical yield.

				Water yield (Mm^3 y^{-1})	
Station name (River)	**Mean discharge (m^3 s^{-1})**	**Catch-ment area (km^2)**	**Estimated precipitation (1961-1990) (m y^{-1})**	**Theor-etical**	**Estimated**
Miller House Bridge (Rothay)	4.3	61.65	2.390	147.3 (27.1%)	135.6 (92%)
Jeffy Knots (Brathay)	4.6	57.69	2.745	158.4 (29.1%)	145.1 (92%)
Calgarth (Trout Beck)	1.4	24.34	2.172	57.7 (10.6%)	44.2 (77%)
Eel House (Cunsey Beck)	1.0	20.78	1.877	39.0 (7.18%)	31.5 (66%)
Blelham Beck	-	6.21	1.923	11.9 (2.19%)	-
Mill Beck	-	5.4	1.649	8.9 (1.64%)	-
Total subcatchments		176.07	2.404*	423.2 (77.9%)	-
Newby Bridge (Whole lake)	**14.5**	**250.2**	**2.172**	**543.4**	**457.3 (84%)**
Missing catchment	-	74.13	1.642*	120.1 (22.2%)	-

* Estimated from theoretical water yield and catchment area.

There is a very close correlation between daily discharge for Eel House and Newby Bridge, presumably because Eel House also has a major lake, Esthwaite Water, upstream in its catchment causing a lag in change in discharge as water level changes in both outflows (Fig. 2). The correlation between the two major northern inflows on the Rothay and Brathay is increased considerably if the Newby Bridge data are lagged by one-day partially to account for the delayed response of the lake where water levels can change dramatically (Fig. 2). However, there appears to be gauging problems at Calgarth on the Trout Beck and these have also been noted by the EA (Appendix 1), since the correlation between Calgarth and Newby Bridge was low for both lagged and unlagged discharge. Removing the apparently incorrect data from the record from Calgarth has virtually no effect on this relationship (not shown). Although it is not impossible for a subcatchment to have a different pattern of discharge, for example caused by different hydrology, altitude and total rainfall or local rainfall patterns, the extent of the difference suggests that these data are unreliable.

The average discharge values from each gauged sub-catchment appear to be reasonable since the estimated yield is between 66% and 92% of the theoretical yield; the difference presumably being accounted for by evapotranspiration plus possible differences in precipitation between the reference period 1961 to 1990 and the actual precipitation in 1997 to 2007. The metered discharges in aggregate comprised about 66% of the total catchment area and about 74% of the total catchment water yield, where this is calculated as the product of catchment area and mean annual precipitation taken from the CEH Flood Estimation Handbook for the period 1961 to 1990 (Table 3). Discharge data are needed for Blelham Beck and Miller Beck since these have recorded water quality data. These discharges were calculated using the real outflow data from Newby Bridge, reduced by the proportion of water yield for each catchment: 2.19% for Blelham Beck and 1.64% for Mill Beck (Table 3). A similar procedure was used for the rest of the catchment that was not monitored and this comprised 22.2% of the Outflow at Newby Bridge. In both cases, the data were lagged by one day- i.e. the inflow data were 1 day before the corresponding outflow data. The discharge data for Trout Beck were also calculated from the Newby Bridge outflow data using the same approach.

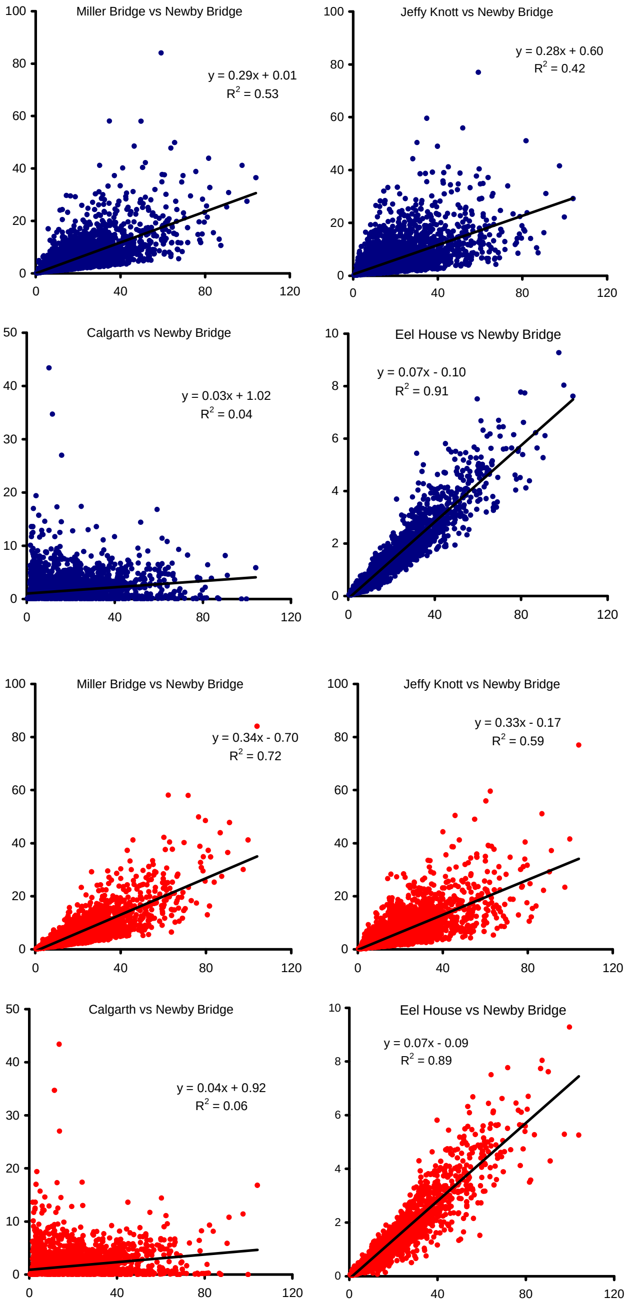

Figure 2. Correlations between daily discharge (m^3 s^{-1}) from the four named inflows and the outflow at Newby Bridge for unlagged data (upper panel, blue) and the outflow lagged one day after the inflows (lower panel, red).

5. Water chemistry

Water chemistry data were provided by the EA for eight sites in the Windermere catchment from January 1997 to December 2007. Of these, one (Black Beck) was not used as it is the inflow to Esthwaite Water and so not relevant. The variables that were analysed included those needed to estimate the load of phosphorus to the lake, orthosphosphate-P and total phosphorus, and other nutrients needed for subsequent simulations with the lake model PROTECH, namely silica, ammonium and oxidised nitrogen (i.e. the sum of concentrations of nitrate and nitrite). Many values in the dataset were below the limit of detection and these were replaced by a value equal to half the limit of detection: 0.015 g m^{-3} for ammonium-N, 0.1 g m^{-3} for oxidised nitrogen, 0.0005 g m^{-3} for orthophosphate-P, 0.01 g m^{-3} for phosphorus and 0.1 g m^{-3} for silica. The number of samples for each site and the number that were below the limit of detection are shown in Table 4. Overall, percent values below the detection limit were 58% for ammonium, 36% for total phosphorus, 8% for oxidised nitrogen, 5% for orthophosphate and 1% for silica.

*Table 4. Summary of water chemistry data used in this report. The header numbers are the EA methods codes. Concentrations are in g m^{-3}. The number in parenthesis is the number of samples less than the detection limit. The correlation of long-term change is shown. Significant correlations are shown: * P<0.05, ** P<0.01, *** P< 0.001.*

Site	**Statistic**	**0111 Ammonia (N)**	**0116 N Oxidised**	**0180 Orthophospht-P**	**0182 SiO2 Rv Filt**	**0348 Phosphorus-P**
Brathay	*Number of samples*	*128 (98)*	*128 (11)*	*128 (10)*	*128 (0)*	*127 (66)*
	Mean	**0.022**	**0.432**	**0.005**	**1.913**	**0.026**
	Correlation	0.151	0.113	0.305***	-0.076	0.132
Rothay	*Number of samples*	*128 (83)*	*128 (17)*	*128 (7)*	*116 (0)*	*0*
	Mean	**0.029**	**0.387**	**0.013**	**1.756**	**-**
	Correlation	0.003	0.102	0.080	-0.062	-
Rothay downstream of WwTW	*Number of samples*	*125 (41)*	*125 (7)*	*127 (0)*	*12 (0)*	*92 (33)*
	Mean	**0.611**	**0.569**	**0.036**	**1.852**	**0.087**
	Correlation	-0.003	0.024	-0.094	-0.062	0.000
Trout Beck	*Number of samples*	*128 (106)*	*128 (5)*	*127 (9)*	*114 (0)*	*11 (8)*
	Mean	**0.020**	**0.584**	**0.005**	**2.373**	**0.015**
	Correlation	0.124	0.126	0.016	0.087	-0.358
Cunsey Beck	*Number of samples*	*133 (65)*	*132 (14)*	*132 (5)*	*124 (5)*	*129 (32)*
	Mean	**0.040**	**0.595**	**0.011**	**1.867**	**0.033**
	Correlation	-0.090	-0.094	-0.296	-0.079	0.004
Blelham Beck	*Number of samples*	*133 (43)*	*132 (14)*	*128 (15)*	*38 (0)*	*29 (1)*
	Mean	**0.049**	**0.646**	**0.006**	**1.821**	**0.026**
	Correlation	-0.060	-0.225**	-0.100	-0.155	-0.083
Mill Beck	*Number of samples*	*131 (88)*	*131 (0)*	*127 (0)*	*116 (1)*	*0*
	Mean	**0.032**	**1.934**	**0.059**	**3.493**	**-**
	Correlation	-0.215*	-0.011	-0.157	-0.177	-

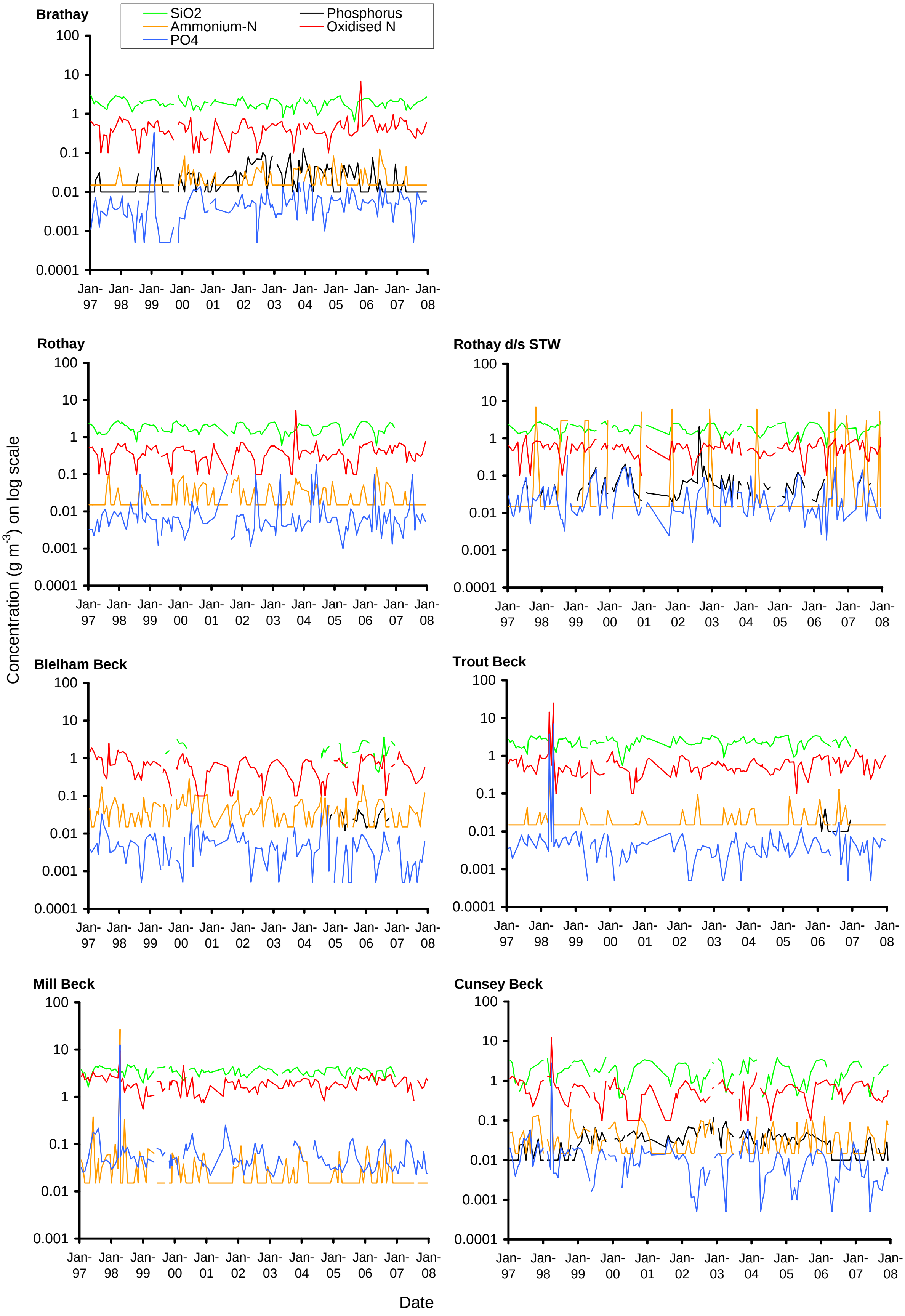

Figure 3. Time courses for raw data (limits of detection adjusted) to identify major problems with water chemistry data. Note the logarithmic concentration scale.

It is beyond the scope of this project to assess the quality of the data, however, at least some of the readings are likely to be inaccurate: for example in cases where the concentration of orthophosphate-P is more than that of total phosphorus. However, in an attempt to identify major outliers that will have a large influence on the estimated load, the raw data, with values less than the limit of detection replaced by half that concentration, were plotted on a logarithmic scale, so only the major excursions are obvious, and inspected visually. There is no simple fully objective way of assessing data quality so only the major discrepancies were adjusted using ‘expert judgement’. These are described in detail in Appendix 2. Overall, 15 apparent outliers were altered, representing less than 0.4% of the 3856 values used in this analysis.

It is likely that a number of the other orthophosphate concentrations were also high but there is no way to identify these.

A large number of samples had values below the detection limit, particularly for ammonium which tends to be very low at most times of the year (Table 4). In contrast, silica was above the detection limit on most occasions. Total phosphorus was not recorded from the Rothay or Mill Beck and there was only a partial record for Trout Beck and Blelham Beck so this chemical variable was not analysed further in this report. There was little evidence for long-term changes in concentration. There was a statistically significant increase in concentration of phosphate in the Brathay, a decrease in concentration of oxidised nitrogen in Blelham Beck and a decrease in concentration of ammonium in Mill Beck (Table 4. Consequently, the data were analysed in total and no time trends were taken into account.

Comparing the mean nutrient concentrations in the six inflow sites, Mill Beck had the highest average concentration of phosphate, oxidised nitrogen and silicate (Table 4). The former two chemicals indicate a possible nutrient source, presumably linked to the town of Windermere that falls in this catchment. The concentration of phosphate was about ten-times that of the River Brathay and Trout Beck. The highest concentration of ammonium occurred downstream from the sewage treatment works on the River Rothay.

The ecological targets are set for total phosphorus, however, no total phosphorus data were available for the River Rothay upstream of the WwTW or Mill Beck (Table 4). At these sites, loads of SRP were converted to loads of TP by multiplication by 1.7 (Hilton et al. 1993).

6. Nutrient load

The main aim of this section of the report was to estimate nutrient loads to Windermere. This was done simply by calculating load as the product of the daily mean discharge ($m^3 s^{-1}$) and the nutrient concentration ($g m^{-3}$). This number was multiplied by 86 400 ($s d^{-1}$) to produce a load in kg d^{-1}. It is understood that loads are difficult to estimate accurately from spot samples for a number of reasons including non-linear changes in concentration with flow (Johnes 2007). However, correlations were calculated to assess roughly what effect discharge had on the concentrations of nutrients. For many of the nutrients, there was no statistically significant correlation between discharge and concentration (Table 5). The River Rothay downstream of the sewage works had strong negative relationships between concentration and discharge for ammonium, oxidised nitrogen and orthophosphate-P, which is consistent with dilution of a point source (Table 5). A similar relationship was apparent on the River Brathay for orthophosphate-P. Although the average concentrations were low the reduction in concentration with flow suggests there may be a point source contribution-possibly from Elterwater WwTW, but this would need to be confirmed. Mill Beck also had significant negative relations between concentration and flow for oxidised nitrogen and for orthophosphate-P which further indicates a point source within this subcatchment. Cunsey Beck exhibited a different pattern with significant increase in concentrations of ammonium, oxidised nitrogen and silica with flow. This difference probably reflects changes brought about by Esthwaite Water, upstream of the sampling point.

The calculated loads as the product of discharge and concentration are shown in Table 6. Loads were also estimated for the missing part of the catchment. The changes in discharge were calculated as already described to complete the hydrological balance. The concentration of each variable used was the average of those on the River Brathay, River Rothay, Trout Beck, Blelham Beck, and Cunsey Beck. Mill Beck was excluded since it had high concentrations of phosphorus suggesting a non-catchment source.

*Table 5. Correlation between nutrient concentration and discharge. The header numbers are the EA methods codes. Significant correlations are shown: * P<0.05, ** P<0.01, *** P< 0.001.*

Site	0111 Ammonia (N)	0116 N Oxidised	0180 Ortho-phospht-P	0182 SiO2 Rv Filt	0348 Phosphorus-P
Brathay	-0.131	-0.109	-0.244**	-0.032	0.061
Rothay	0.155	0.011	-0.007	0.149	-
Rothay d/s WwTW	0.184*	-0.340***	-0.319***	0.091	-0.102
Trout Beck	-0.027	-0.139	0.220*	0.050	0.089
Blelham Beck	-0.134	0.214*	-0.090	0.271**	-0.135
Mill Beck	0.034	-0.268**	-0.361***	-0.177*	-
Cunsey Beck	0.195*	0.179*	0.082	0.417***	-0.040

Table 6. Loads of nutrients to Windermere (kg d^{-1}). The header numbers are the EA methods codes.

Site	0111 Ammonia(N)	0116 N Oxidised	0180 Orthophospht-P	0182 SiO2 Rv Filt	0348 Phosphorus-P
Brathay	6.36	131.27	1.36	613.3	9.35
Rothay	10.85	125.45	3.94	630.4	6.70*
Rothay d/s of WwTW	320.79	147.99	4.95	617.8	15.31
Trout Beck	2.60	71.54	0.69	330.5	3.01
Blelham Beck	1.24	20.72	0.16	55.0	0.56
Mill Beck	0.72	36.09	0.91	72.3	1.55*
Cunsey Beck	4.36	60.73	1.12	228.0	2.90
Missing Becks	10.77	160.58	2.27	609.4	8.19
Total (excluding WwTW)	**36.38**	**606.39**	**10.46**	**2538.86**	**32.25**
Contribution of Ambleside WwTW	309.94	22.54	1.01	0	8.61

* Estimated from SRP load multiplied by 1.7 (see text).

To estimate the total external load of nutrient to the lake, the previously estimated loads from the two WwTW that discharge directly into the lake, Ambleside in the North Basin and Tower Wood in the South Basin, were added into the budget using values recently calculated in Maberly (2008). Loads were converted to Mg y^{-1}.

Table 7. Load of nutrients to Windermere between 1997 and 2007 from different sources (Mg y^{-1}). Values in parentheses are the percent contribution to the total. DIN (dissolved inorganic nitrogen) equals the sum of ammonium and oxidised nitrogen.

Source	Orthophosphate -P	Total P	DIN	SiO_2
Total from catchment	3.82 (49%)	10.13 (71%)	234.6 (80%)	926.7 (100%)
Ambleside WwTW*	1.29 (16%)	1.29 (9%)	17.83** (6%)	0
Tower Wood WwTW*	2.75 (35%)	2.75 (19%)	41.10** (14%)	0
TOTAL	7.86	14.17	293.5	926.7

* *Derived from values in Maberly (2008) but differs slightly from tabulated values there as calculated for a different time period.*

** *DIN loads for the WwTW were estimated from the average ratio of ammonia plus oxidised nitrogen to soluble reactive phosphorus from the EA measurements at the discharge from the WwTW: these were 13.87 at Ambleside and 14.95 at Tower Wood.*

The estimated load of total P in Table 7 is 33% greater than the load estimated in Maberly (2008; Table 5) of 10.65 Mg y^{-1}. The main reason for the difference is the greater load estimated from the catchment. In this report this was estimated to be 10.13 Mg y^{-1} whereas in Maberly (2008) it was estimated to be 6.32 Mg y^{-1} (sum of catchment and indirect WwTW). This estimate was based on the figures presented in Reynolds & Irish (2000) which in turn was derived from Reynolds (1995). The catchment portion of this load estimate was estimated from winter concentrations measured in the lake in the mid-1940s, on the assumption that this reflected historical inflow concentrations. It is possible: a) that this assumption is incorrect and b) that diffuse catchment sources have increased since then or both these possibilities are true. However, the two estimates probably lie within the uncertainty involved in these types of estimates of load. Finally, Reynolds & Irish (2000) included an additional P-load to the lake of 0.42 Mg y^{-1} attributed to a rainfall input directly on the lake. I have not included this here, which in theory increases the discrepancy in the two phosphorus loads.

7. Assessing the accuracy of the estimated loads

Loads of nutrients to a lake are notoriously difficult to estimate accurately as a result of a number of factors associated with error of measurement, missing values and low-frequency of measurement. Johnes (2007) suggested that loads estimated from monthly measurements may differ from the true value by a factor of two. Some of the reasons for this are outlined below.

1. There is an inevitable error associated with the measurement of the discharge and nutrient concentration from which the load is calculated. Some of the problems with the discharge data are noted in Appendix 1 and the major outliers in nutrient concentration representing, for example, 1000-fold increases in concentration from one date to another that were identified as outliers by expert judgement are noted in Appendix 2. Associated with this, although probably of lesser importance in this work, is the detection limit: a total of 107 out of the 286 concentrations of total phosphorus analysed and used (i.e. excluding the data downstream from the WwTW on the River Rothay; Table 4) were below the limit of detection. Thus 37% of the total phosphorus concentrations used to estimate load were estimated as half the limit of detection, 0.01 g m^{-3}.
2. The data set provided for the nutrient chemistry was incomplete. Focussing on total phosphorus, which was the nutrient of major interest in this report, no values were available on the R. Rothay upstream of the WwTW or on Mill Beck. For these two sites, total phosphorus concentration had to be estimated using a factor of 1.7-times the concentration of orthophosphate which will introduce an unknown error into the subsequent estimate of concentration.
3. The frequency of concentration measurement was very low. The average number of total phosphorus concentrations analysed per year was 11.5 on the River Brathay and Cunsey Beck, but only 2.6 on Blelham Beck and 1 on Trout Beck. It is becoming accepted that daily or even-subdaily measurements of concentration are needed to provide accurate estimates of load because of the highly non-linear relationship between concentration and discharge with high loads associated with short-lived flood episodes, especially for nutrients associated with particulate material such as total phosphorus (e.g. Johnes 2007).
4. Not only were some of the gauged streams lacking measurements of total phosphorus, some of the catchment input streams were not measured. Comparison of the measured inflow and outflow suggested that 22.2% of the inflow was not gauged (Table 3) and the load of total phosphorus was therefore estimated from that of the other inflows which of course is an assumption of unknown magnitude.

It is not possible to assess directly the magnitude of any error in load estimates but yearly variation can be calculated to estimate the variance around the mean load. Table 4 shows that there have been no statistically significant long-term changes in concentration of total P at any of the sites, but a significant increase in orthophosphate on the River Brathay, a decline in concentration of oxidided nitrogen on Blelham Beck and a decline in concentration of ammonium on Mill Beck, so this approach is probably valid.

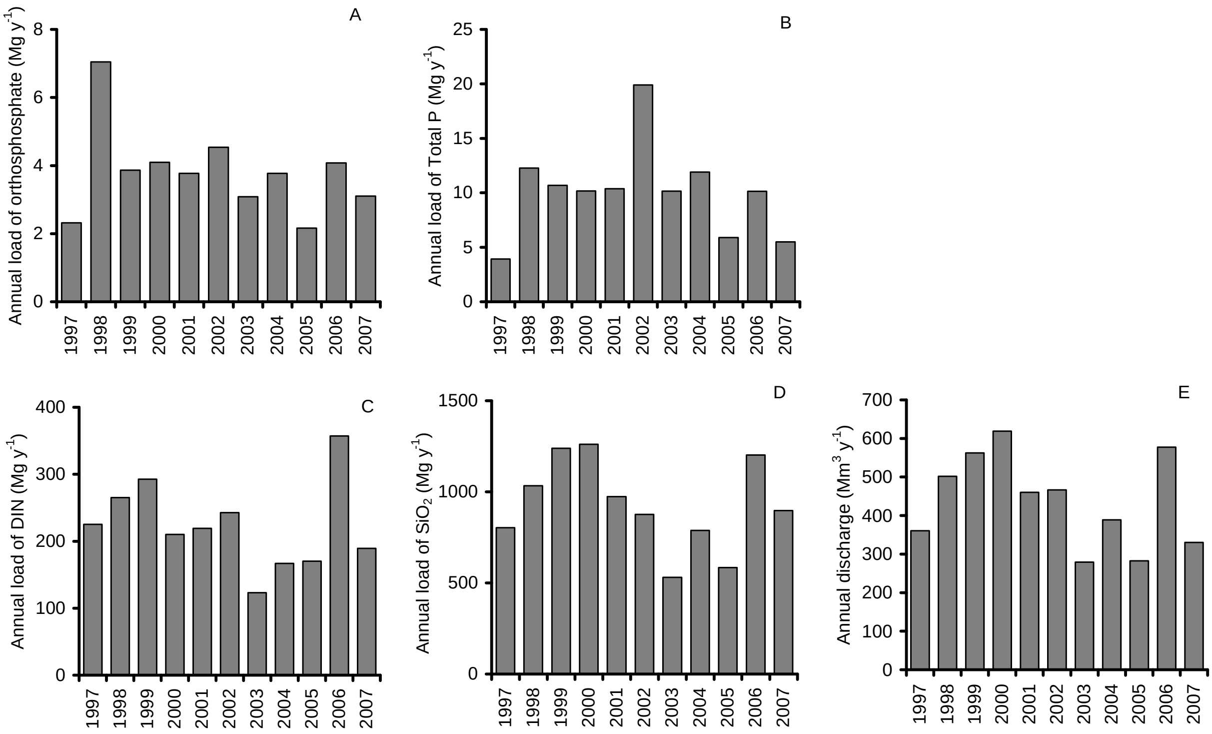

Figure 4. Inter-annual variation in loads of A. orthophosphate-P; B, total phosphorus; C, dissolved inorganic nitrogen; D, silica and E, discharge.

Figure 4. Shows that there is a large inter-annual variation in the estimated loads of nutrient and also total discharge. To try to understand the causes of this variation, correlations were calculated between the annual load of each nutrient and annual discharge. Figure 5 shows that there is a strong relationship between annual load and discharge for some of the nutrients. The strongest correlations were shown for silica (Fig. 5) with a highly statistically significant correlation ($P<0.001$) and for DIN ($P<0.01$). In contrast the correlations for orthophosphate and total phosphorus were not statistically significant. Although it is possible that these correlations could be an artefact caused by the method used to calculate load, the responses

shown by silica and DIN are those expected of a nutrient supplied primarily from diffuse sources, while the low correlation for the two forms of phosphorus are what would be expected from nutrients supplied primarily from point sources. This is therefore in rough accordance with what would be expected for the four nutrients.

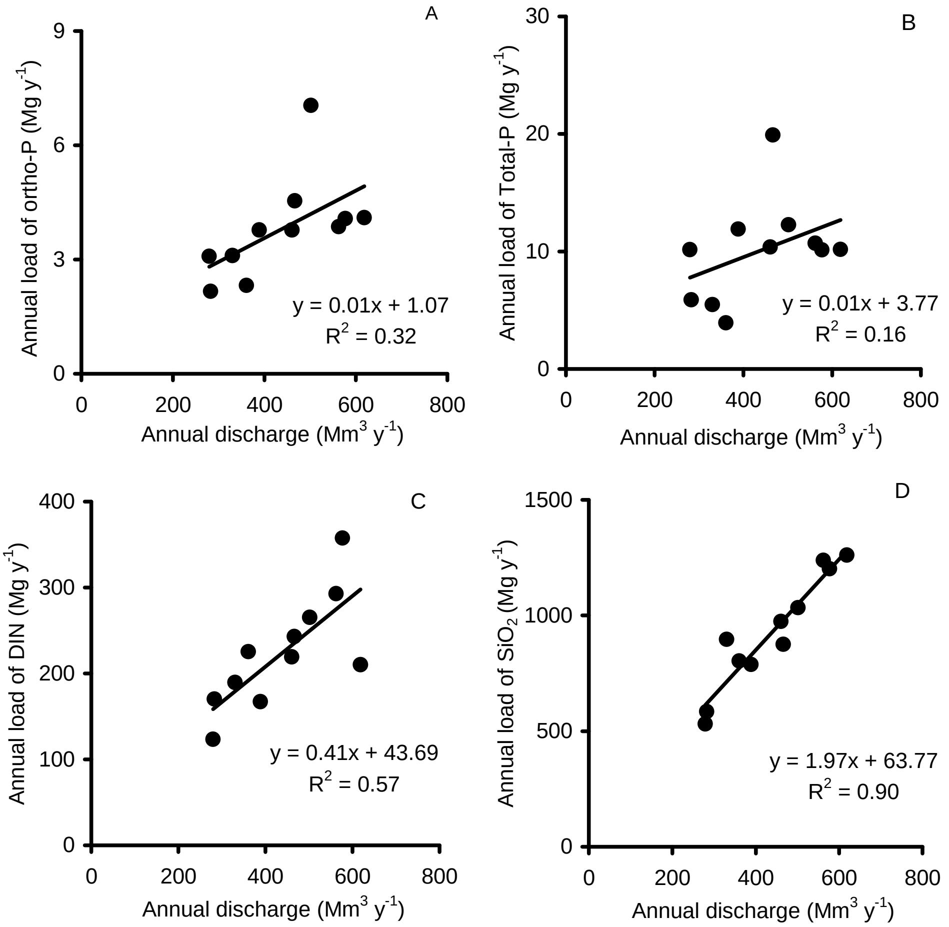

Figure 5. Relationship between annual load and discharge for A, orthophosphate-P; B, total phosphorus; C dissolved inorganic nitrogen and D, silica.

Table 8 quantifies the variation in inter-annual load of nutrients. This shows that interannual-variation in load or discharge is of the order of 27 to 42%. While this does not equate to the possible inaccuracies mentioned above, it gives an impression of the likely envelope of variation about an annual load-estimate.

Table 8. Mean, standard deviation and standard deviation as a percent of the mean for interannual variation in discharge ($Mm^3\ y^{-1}$) and loads of four nutrients ($Mg\ y^{-1}$). Note that the loads estimated here are slightly different from those in Table 7 because they have been aggregated by year while those in Table 7 are for the entire time-period.

Statistic	**Discharge**	**Orthophosphate-P**	**Total P**	**DIN**	**SiO_2**
Mean	438.9	3.80	10.08	224.0	926.7
SD	119.3	1.31	4.26	65.0	247.1
%SD	27.2	34.4	42.3	29.0	26.7

8. Relationship between load and lake concentration

It may be possible to check if these loads of nutrients estimated in this report are roughly correct by comparing them to the measured concentrations in the lake. The annual average concentrations of TP between 1997 and 2007 inclusive were calculated and the values for the two basins were averaged. Lake concentration was calculated simply as the quotient of load over hydraulic discharge and for phosphorus also using the OECD model of Vollenweider & Kerekes (1980; Equn 1) which is an average relationship for a population of lakes and does not necessarily apply to a given lake as it will depend, for example, on the proportional loss of a nutrient to the sediment.

$$P = a\left[\frac{L_p / q_s}{(1+\sqrt{\tau_w}}\right]^b \qquad \text{Equn 1}$$

Where: P = in-lake concentration of TP ($g\ m^{-3}$)

L_p = annual P load ($g\ m^{-2}\ y^{-1}$)

qs = water discharge height ($m\ y^{-1}$)

τ_w = water retention time (y)

a and *b* are coefficients obtained by fitting the data to different data sets.

In the OEDC model (Vollenweider & Kerekes 1980) three different data sets were modelled, yielding three different coefficients for *a* and *b*: 1.55 and 0.82 for the complete data set, 1.12 and 0.92 for the Nordic data set and 1.02 and 0.88 for the shallow lakes and reservoirs data set respectively.

An alternative way of estimating in-lake concentrations of phosphorus from phosphorus loads was suggested by Kirchner & Dillon (1975). This is shown in Equn 2 written in similar notation to the OEDC equation.

$$P = (L_p / q_s) * (1 - R) \qquad \text{Equn 2}$$

Where R is a dimensionless retention rate calibrated using the following equation:

$$R = 0.426e^{-0.271 * Zm / qs} + 0.574e^{-0.00949 * Zm / qs} \qquad \text{Equn 3}$$

Where Z_m is mean depth (m).

The various relationships between TP concentration in the lake and TP load are shown in Figure 6. For a given load there is a very large range of possible TP concentrations and so this approach cannot be used to check the accuracy of the estimates of TP load. Of the different equations used, that of Kirchner & Dillon (Equn 2) was the only one where the predicted total load accorded with the average concentrations of total phosphorus measured in the lake, but of course there is no way of checking objectively if this is caused by a correct underlying mechanism or an incorrectly estimated load. Nevertheless, this model was subsequently used to estimate the effect of the different external loads on phosphorus concentration to Windermere.

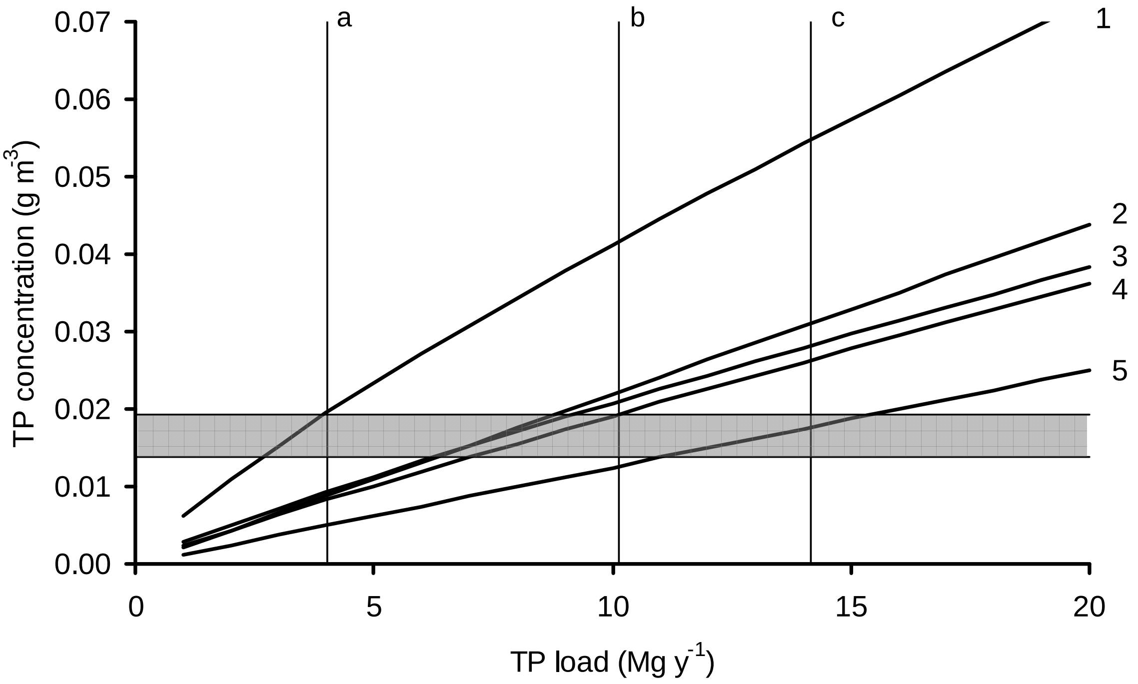

Figure 6. Comparison of average concentration of TP in Windermere and TP load. Curves show relationship based on: 1- OECD all datasets, 2- load divided by discharge, 3- OECD shallow lakes, 4- OECD Nordic lakes and 5- Kirchner & Dillon. The horizontal grey band is the observed annual average concentrations of TP in Windermere between 1997 and 2007 averaged over both basins. The three vertical lines are the estimated load based on: a- WwTW, b- the catchment and c- both WwTW and catchment.

9. Phosphorus loads for different lake phosphorus targets

The Kirchner & Dillon equation was used to estimate lake concentration from annual load. Using values of mean depth and water discharge height applicable to Windermere, R equals 0.431, 1-R equals 0.569 and q_s is 30.8, and 14.8 is the lake area in km^2, so Equn 2 becomes:

$$P = Load \ * \frac{0.569}{(30.8 * 14.8)} \qquad \text{Equn 4}$$

Where load is TP load in Mg y^{-1}.

Thus, the estimated total load in Table 7 of 14.17 Mg y^{-1} produces an in-lake TP concentration of 0.018 g m^{-3} (18 mg m^{-3}, equivalent to 18 µg L^{-1}; Table 8). Lake concentration based on load from catchment alone (10.13 Mg y^{-1}) is 0.013 g m^{-3} (i.e. 13 mg m^{-3}) and the lake concentration relating to the input from the two WwTW discharging directly to the lake (4.04 Mg y^{-1}) would produce an average TP concentration of 0.005 g m^{-3} (i.e. 5 mg m^{-3}). The TP concentration measured in the inflowing streams potentially include inputs from WwTWs upstream, such as at Hawkshead and Elterwater, although the amount of phosphorus that is removed in the streams and lakes upstream, and hence the amount that reaches Windermere, is unknown.

The loads estimated here from the water chemistry provided for the streams and, in an earlier project, for the WwTWs, suggest that the catchment, in the broadest sense, is the largest source of total phosphorus to Windermere. A target of 0.01 g TP m^{-3} is not achievable by reducing, or even totally removing, the load from the two major WwTW discharging to the lake (Table 9). A target of 15 mg TP m^{-3} would be achievable if the catchment load remained constant and the load from the two WwTWs reduced by about 53% from 4.04 to 1.9 Mg y^{-1}. While further reductions in phosphorus load from the WwTWs is highly desirable, as it is a relatively simple end-of-pipe solution, substantial further reductions in the phosphorus reaching the lake can only be achieved by reducing loads from the catchment. Some provisos need to be made for this conclusion. First, the TP load from the catchment is based on water chemistry data which appear not to be of very high quality. Although major outliers were not included in the analysis, it is possible that some of the values remaining are still too high. Some sites had no, or patchy, TP data and for these, concentration of TP was estimated by multiplying the SRP concentrations by a factor: this may not necessarily be applicable. Secondly, monthly estimates of nutrient concentration is known to be an inaccurate way of estimating load, although this usually underestimates rather than overestimates the load because it misses high concentrations produced during short-lived events such as floods. thirdly, although TP is traditionally used as an overall measure of lake productivity and trophic status, an unknown proportion of the TP will be unavailable to the phytoplankton. If the analysis of contribution of SRP from the WwTW and the catchment is based on SRP, both supply about equal amounts of phosphorus which suggests that further reduction of load from the WwTW (Table 7) will be beneficial.

Table 9. Relationship between loads of total P and in-lake concentrations of total P estimated using the equation of Kirchner & Dillon (1975).

TP concentration		**Load (Mg y^{-1})**			
(mg m^{-3})	**(g m^{-3})**	**Total**	**Catchment**	**WwTW**	**Comments**
18	0.018	14.2	10.1	4.1	Current estimate
5	0.005	4.1	0	4.1	WwTW alone
13	0.013	10.1	10.1	0	Catchment alone
10	0.01	8.0	10.1	-2.1	Not achievable by removing load from WwTW alone
15	0.015	12.0	10.1	1.9	Achievable
20	0.02	16.0	10.1	5.9	Higher than current load

10. Conclusions

In conclusion, this study reinforces the view that action needs to be taken to reduce loads of phosphorus, and especially the more biologically available soluble reactive phosphorus or orthophosphate, both from the catchment including the small WwTWs therein, and the two major WwTWs on the shores of Windermere. A reduction in phosphorus load appears to be increasingly critical because, although the initial reduction in 1992 at the onset of P-stripping had rapid beneficial effects, water quality has subsequently decreased, possibly as a result of trophic interactions within the food chain induced by climate change (Maberly et al. 2008). The consequences of these reductions in load for the lake phytoplankton will be addressed in a subsequent report. However, good ecological status under the EU Water Framework Directive is unlikely to be achieved without substantial further reduction in the amount of phosphorus entering the lake.

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12. Appendices

Appendix 1. Environment Agency – NW Region – North Area Flow Sites Data Quality Updated – October 2008

Station number	**Station name**	**Flow Data Quality Comments**
735022	Miller Bridge House	Low flows – Poor prior to 1991. Reasonable from 1991 to date. High flows - Do not use prior to 1991. From 1991 to date, uncertain above 2m and significant out of bank flow not measured. • Flows contained to bank full on left bank at 3.7m. Flows on to road on right bank above approx 2m. • Highest level/flow validated: 3.432m / 141.3m^3/s (08/01/2005) • Lowest level/flow validated: 0.321m / 0.127m^3/s (21/09/1995) • Highest gauging: 2.104m / 60.9m^3/s (02/12/1992) • Lowest gauging: 0.209m / 0.112m^3/s (27/07/1989) • Rating 06 currently valid from 20/07/06 to date. 6 ratings are valid over the period of record. Originally informal boulder control until a low timber bed control was installed in Feb 1991. That bed control deteriorated over the years and was completely rebuilt on 20/07/06 from when the current rating applies. Low flow records prior to 1991 are quite poor with gauging deviations ±50% on occasions. Since the timber control was constructed the record is much improved with rating changes allowing for the deterioration of the control prior to 2006. High flows are problematic. A flood bank was built in 1982 and prior to that date it is believed there would have been substantial bypass flow on the left bank somewhere above 2m stage. Since 1982 bank full at the station is at 3.7m although there is still bypass flow on the left bank, somewhere above 3m. There is also substantial flow along the road on the right bank which effectively bypasses the station. High flow ratings since 1991 are quite consistent although the extrapolation above highest gauging is uncertain and bypass flow is not taken into account. The high flow rating prior to 1991 appears to significantly overestimate flows above 1.5m, particularly for the period 1982 to 1991, and should not be used.
735123	Jeffy Knotts	Low flows – Reasonable considering the weed affected site. High flows – Use with extreme caution up to highest gauged level. Do not use above highest gauged level. • All flows contained. • Highest level/flow validated: 3.892m / 59.2m^3/s (03/01/1982) • Lowest level/flow validated: 0.312m / 0.144m^3/s (23/09/1995) • Highest gauging: 1.935m / 21.5m^3/s (28/11/2003) • Lowest gauging: 0.329m / 0.170m^3/s (19/09/1996) • Rating 14 currently valid from 01/10/05 to date. 40 ratings are valid over the period of record. Open channel site severely affected by weed growth and bed movements. Hence the high number of rating changes. Up to 2000 the site tended to have one rating for summer and one for winter but since 2000 this method has been considered too

		time consuming and a single rating has been applied from that date apart from summer 2005 when weed was particularly bad warranting a separate rating. Low flow data from 2000 tends to be within +/-20% depending on the state of the weed. There are no known problems with historic low flow data although it is likely to be poor in places. High flow ratings show large discrepancies at max gauged level (up to 50%) and over 100% discrepancies at max recorded levels. Some discrepancy can be expected due to vegetation growth in the channel. High flow gauging very difficult and hence large extrapolation involved. High flow ratings should be considered suspect up to highest gauged level and should be used with extreme caution. Above highest gauged level, flows should not be used. The site was considered under the HiFlow project and it was recommended that rating 07 be used as the high flow rating through the period of record for consistency.
735328	Calgarth	Low flows – Reasonable. High flows – Very suspect. Do not use. • Flows contained to bank full at 2.5m. • Highest level/flow validated (post control): 1.986m / 31.5m^3/s (08/01/2005) • Lowest level/flow validated (post control): 0.236m / 0.085m^3/s (28/07/2006) • Highest gauging (post control): 0.628m / 3.04m^3/s (22/05/2006) • Lowest gauging (post control): 0.238m / 0.078m^3/s (26/07/2005) • Rating 09 currently applies from 08/01/05 to date. 9 ratings are valid over the period of record. Originally open channel site that has a very mobile bed necessitating frequent rating changes. A low bed control was installed on 10/09/04 which has improved low flows although the flood in Jan 2005 caused large channel changes resulting in the current rating. There have also been problems with water level measurement making some level data and hence flow data suspect. Low flow data prior to Sept 2004 is not great with frequent minor bed movements. Low flow data since Sept 2004 is reasonable. Mainly because the site is for low flows only, medium to high flow data is very suspect throughout. There are significant differences between the 9 valid ratings at higher levels which appear unrealistic. The older ratings tend to significantly overestimate high flows compared to more recent ratings. Do not use high flow data or use with extreme caution.
735226	Eel House Br	Low flows – Suspect prior to 1978. Use with caution from 1978-1999. High flows – Suspect prior to 1999. Use with caution from 1999 onwards. • Flows contained to bank full at 1.5m • Highest level/flow validated (post control): 1.586m / 17.83m^3/s (04/01/1982) • Lowest level/flow validated (post control): 0.244m / 0.004m^3/s (18/07/1989) • Highest gauging (post control): 1.289m / 9.264m^3/s (29/12/1987) • Lowest gauging (post control): 0.248m / 0.004m^3/s (18/07/1989)

		• Rating 11 currently valid from 09/01/05 to date. 11 ratings are valid over the period of record. Non standard low control site that does suffer from weed growth and changes to the channel. As a result there is a very large spread of gaugings at all levels although the various rating changes have attempted to allow for this. Archived flows begin in 1976 although there are gaugings back to 1966 and it should be possible to produce rating equations for the period prior to 1976. Prior to the control being installed in 1978, the rating can give zero flow and this period needs reviewing at the low end. From 1978 to 1999 there are no known major problems with low flows although because of the various site issues and until a full review is completed, low flows should be treated with caution. There is more confidence with low flows from 1999 onwards. There is a very large spread of high flow ratings with little consistency and over 30% difference in some cases. High flow gaugings since 1999 have given more confidence to the high flow rating since then although there is still some uncertainty due to difficulty of gauging. Although some differences at high levels over time might be expected, the spread of high flow ratings appears suspect and caution should be used with all high flow data. The site was considered under the HiFlow project and it was recommended that rating 10 be used as the high flow rating through the period of record for consistency.
735430	Newby Bridge	Low flows – Good. High flows – No known problems although needs further work to confirm. • Flows contained to bank full at 2.5m. • Highest level/flow validated: 2.009m / 130m^3/s (04/01/1982) • Lowest level/flow validated: 0.107m / 0.245m^3/s (12/06/1984) • Highest gauging 1.983m / 122m^3/s (04/01/1982) • Lowest gauging: 0.124m / 0.280m^3/s (03/10/1972) • Rating 02 currently applies through period of record (from 14/06/71 to date). This is a good flow site through the range with all flows contained within the wing walls. The single rating has remained accurate since construction of the weir in 1971. Because there is no cableway, there is an element of doubt over the high flow rating. Some high flow gaugings have been achieved in the past and the rating is based on these but their quality is unknown. There is reasonable confidence to bank full although more work is required to confirm the high flow rating. The site was considered under the HiFlow project and it was recommended that rating 02 be used as the high flow rating through the period of record.

Appendix 2. Details of apparent outliers altered using expert judgement.

			Concentration (g m^{-3})		
Site	**Date**	**Determinand**	**Original**	**Replacement**	**Comment**
Brathay	3/2/1999	Orthophosphate-P	0.331	0.004	Changed to mean value on two adjacent dates
Brathay	27/10/2005	Oxidised N	6.78	0.416	Changed to mean value on two adjacent dates
Rothay	2/10/2003	Oxidised N	5.27	0.52	Divided by ten to make similar to subsequent date
Trout Beck	30/3/1998	Orthophosphate-P	3.78	0.0038	Divided by 1000 to bring into range
Trout Beck	13/5/1998	Orthophosphate-P	7.05	0.0071	Divided by 1000 to bring into range
Trout Beck	30/3/1998	Oxidised-N	14.6	0.851	Changed to mean value on two adjacent dates
Trout Beck	13/5/1998	Oxidised-N	25.0	0.690	Changed to mean value on two adjacent dates
Trout Beck	30/3/1998	Ammonium-N	0.449	0.15	Changed to mean values on adjacent dates = limit of detection
Trout Beck	13/5/1998	Ammonium-N	0.637	0.15	Changed to mean values on adjacent dates = limit of detection
Mill Beck	16/4/1998	Orthophosphate-P	12.6	0.053	Changed to mean value on two adjacent dates
Mill Beck	16/4/1998	Oxidised N	9.51	2.27	Changed to mean value on two adjacent dates
Mill Beck	16/4/1998	Ammonium-N	26.6	0.023	Changed to mean value on two adjacent dates
Cunsey Beck	30/3/1998	Orthophosphate-P	2.83	0.052	Changed to mean value on two adjacent dates
Cunsey Beck	30/3/1998	Oxidised N	12.5	1.10	Changed to mean value on two adjacent dates
Cunsey Beck	30/3/1998	Ammonium-N	1.07	0.015	Changed to mean value on two adjacent dates