Centre for Ecology & Hydrology

Lancaster Environment Centre

Library Avenue

Bailrigg

Lancaster LA1 4AP

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THE RESPONSE OF WINDERMERE TO EXTERNAL STRESS FACTORS:

PHOSPHORUS LOAD FROM WASTEWATER TREATMENT WORKS

Prepared by:

S.C. Maberly

Project Leader: S.C. Maberly
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CONFIDENTIALITY STATEMENT

Executive Summary

1. The input from the wastewater treatment works (WwTW) that discharge directly into Windermere at Ambleside and Tower Wood contribute a large amount of the total phosphorus load to the lake. In 1992 this load was reduced by establishment of tertiary treatment at each works. This elicited a rapid improvement in water quality but this started to deteriorate subsequently. This report analyses the output phosphorus loads from the two WwTW to establish to what extent the deterioration might be caused by any increases from the WwTW.
2. Data were available from 1978 with, on average, weekly sampling or better from the two WwTW. Before 1987 there were infrequent measurements of P-load. Since 1995 there have been one or two load measurements per week from each plant.
3. The average seasonal pattern of flow is relatively even, but higher values in winter suggest input from non-domestic sources. There are large seasonal changes in the concentration of phosphorus leaving the WwTWs, with highest concentrations in summer, possibly as a result of higher tourist numbers and slightly lower flow. The load of phosphorus also varies seasonally: monthly load is highest in summer.
4. In 1991 the average concentration of phosphorus leaving the WwTW was 3.2 and 3.8 mg L^{-1} at Ambleside and Windermere Tower Wood respectively. There was a step-reduction in the concentration of phosphorus leaving the two WwTW in 1992 and no evidence for a return to the higher values of pre 1992, apart from transiently higher values at Ambleside in 1999 and 2000 (around 2.5 mg L^{-1}). Between 1993 and 2007 the annual average concentration of phosphorus leaving the WwTWs was 1.48 mg L^{-1} and 1.26 mg L^{-1} for Ambleside and Windermere Tower Wood respectively.
5. Annual phosphorus load has fallen by about 50% in 1993-2007 compared to 1978-1991 at both WwTWs. At Ambleside it has fallen from 2.2 to 1.09 Mg y^{-1} and at Windermere Tower Wood it has fallen from 5.85 to 2.82 Mg y^{-1}. Loads from storm overflows are not included in these estimates since no data appear to exist.
6. It is difficult to estimate catchment loads of phosphorus, nevertheless the data suggest that the WwTW contribute about 37% of the total phosphorus and 66% of the soluble reactive phosphorus load to the lake. The percentages for the North Basin are slightly lower, and the percentages for the South Basin are slightly higher, than this average. The WwTW are still the largest source of available phosphorus to the lake.
7. Any more recent deterioration in water quality in the two basins of Windermere are unlikely to be cause by increased phosphorus loads from the two WwTWs.

Introduction

Windermere is the largest natural lake in England and has one of the longest scientific records in the world. The limnological history of its changing water quality was outlined in Pickering (2001) and will be analysed in more detail elsewhere in this report. This part of the report will analyse how one of the main sources of phosphorus to the lake, the input from the wastewater treatment works (WwTW) have varied historically to establish to what extent this might be the cause of the recorded change in water quality. In the analysis of Reynolds & Irish (2000) for 1991, WwTWs in the catchment (Fig. 1) were estimated to contribute 70% of the total phosphorus (TP) and 93% of the soluble reactive phosphorus (SRP) to the lake as a whole, with the two sewage works that discharge directly to the lake at Ambleside and Tower Wood contributing the great majority of the load. Since 1992, tertiary treatment at these two works has reduced the phosphorus load to the lake but although there was an immediate improvement (Pickering 2001) there has more recently been a deterioration in water quality (Maberly et al. 2007).

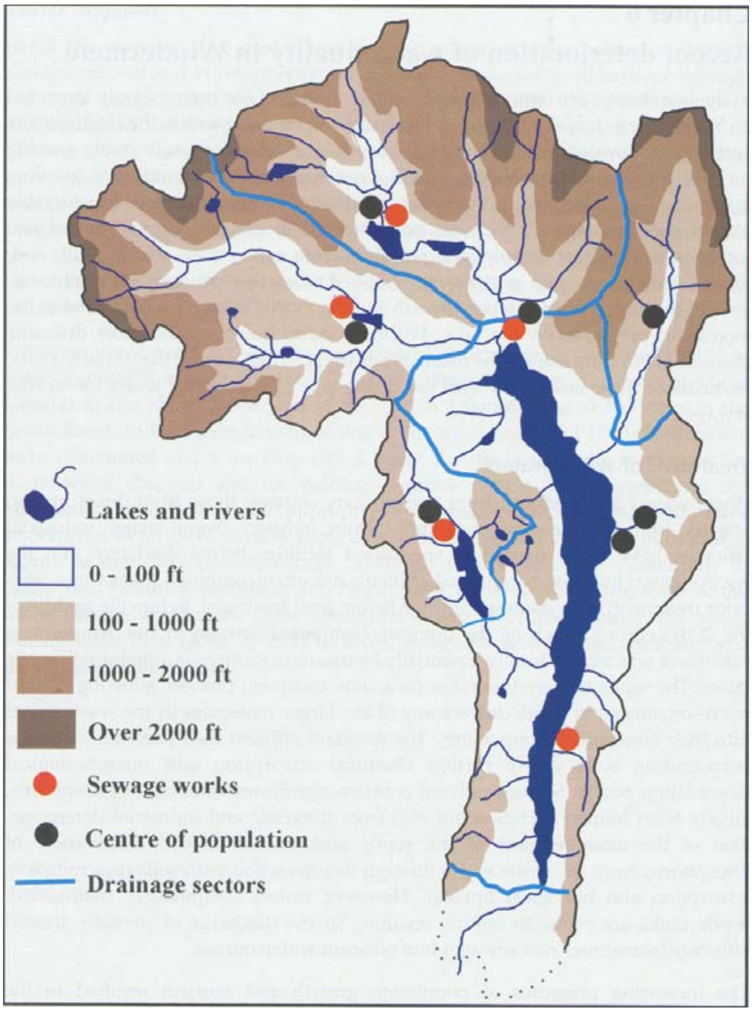


Figure 1. Map of Windermere catchment showing the location of sewage works (Wastewater treatment Works). The two works feeding directly into the lake are at Ambleside at the north end and at Tower Woods at the sout- eastern shore. Based on Pickering (2001).

Data preparation and analysis

Data from the Ambleside and Windermere Tower Wood wastewater treatment works that discharge directly into Windermere were provided by the Environment Agency. The extent of the data is shown in Table 1. The average frequency of data from the two WwTWs was better than weekly.

Table 1. Summary of temporal extent and number of samples from the Ambleside and Windermere Tower Wood Wastewater Treatment Works (WwTW).

Location	Start date	End date*	Number of dates	Average dates per year
Ambleside WwTW	25/01/1978	28/12/2007	2085	70
Ambleside WwTW (Storm)	13/10/1982	20/03/1996	30	2
Windermere Tower Wood WwTW (Old Outfall)	08/02/1978	28/12/2007	2164	72
Windermere Tower Wood WwTW (New Outfall)	26/10/1993	17/12/2007	383	27
Windermere Tower Wood WwTW (Storm)	01/10/1984	20/08/1985	2	2

*Excluding a few dates in early 2008 (data analysis stopped at end 2007).

Analysis was focussed on estimating phosphorus load to the lake. In order to calculate this, an estimate is needed of hydraulic flow and phosphorus concentration on a given date. Within the dataset, flow was recorded using six different methods. To maximise the number of dates with some form of flow record, the six different measurements of flow were aggregated. Table 2 shows the number of dates for each type of flow measurement and the number of dates after the flows were aggregated (taking units into account where necessary). The aggregated data are not averages but are values from the most frequent measurement or the second most frequent measurement etc., if the most frequent or next most frequent type of measurement was not made on a particular date. The aggregated flow data were inspected visually and high values checked. In some cases the numbers appeared to be incorrectly entered, often as multiples of 10, 100 or 1000. A conservative approach was taken to altering these data by inspection of values on adjacent dates. Table 3 list the number of flow data that were altered for each site.

A similar procedure was used to estimate phosphorus concentration. Three different types of phosphorus measurements were made of which unfiltered orthophosphate (method 0180) was the most frequent and total phosphorus (method 0348) the second most frequent (Table 2). Although the total phosphorus measurement in theory includes fractions not measured by the two other measures, in practice most of the phosphorus from a WwTW will be available to organisms in the lake and there were only small differences between mean values of unfiltered orthophosphate and total phosphorus across the data sets (orthophosphate as a percentage of total phosphorus was 105%, 86% and 87% for the Ambleside, Windermere Tower Wood old outfall and Windermere Tower Wood new outfall sites respectively). Consequently, the different forms of phosphorus were used interchangeably in this analysis. A number of P concentrations were noted as less than a limit of detection (normally less than 0.1, 0.2 or 0.5 mg L^{-1}). These values were converted to half-the limit of detection values in the analyses. The number of samples that were converted is shown in Table 3.

There are two sampling datasets for the Windermere Tower Wood WwTW: the “Old outfall” is provided by United Utilities while the “New Outfall” dataset is measured by the Environment Agency and starts in 1993 (Table 1). Since both sets of data were from the same outfall they were combined. When data were collected on the same date there was generally a reasonable agreement with Pearson correlation coefficients of 0.80 for discharge, 0.71 for P-concentration and 0.57 for P-load (in each case with $n = 149$, $P<0.001$). The combined dataset comprised the individual values from one or other of the datasets or the average of both on the dates where duplicate analyses existed.

Table 2. Number of flow and phosphorus concentration measurements of different types for the different sites. The header numbers are the EA methods codes and values in bold are the aggregated number. The final row gives the total number of measurements for each measurement.

	0037 Flow (m3/s)	0038 Flow Mean Dly (Ml/d)	0047 Flow Instant (Ml/d)	3527 Flow (l/s)	9200 Flow24 HrFT (Ml)	9947 FlowInst Est (Ml/d)	**Aggregated flow (Ml/d)**	0180 Orthophospht (mg/l)	0191 OrthophsFilt (mg/l)	0348 Phosphorus-P (mg/l)	**Aggregate P**	**Load**
Ambleside WwTW	1	9	166	11	807	35	**1008**	1319	17	261	**1437**	**920**
Ambleside WwTW (Storm)	0	0	1	0	0	0	**1**	25	0	7	**25**	**1**
Windermere Tower Wood WwTW (Old Outfall)	0	0	87	0	1127	49	**1263**	1469	16	179	**1592**	**1147**
Windermere Tower Wood WwTW (New Outfall)	3	11	268	28	0	0	**294**	369	1	251	**375**	**292**
Windermere Tower Wood WwTW (Storm)	0	0	0	0	0	1	**1**	0	0	0	**0**	**0**
TOTAL	4	20	522	39	1934	85	**2567**	3182	34	698	**3429**	**2360**

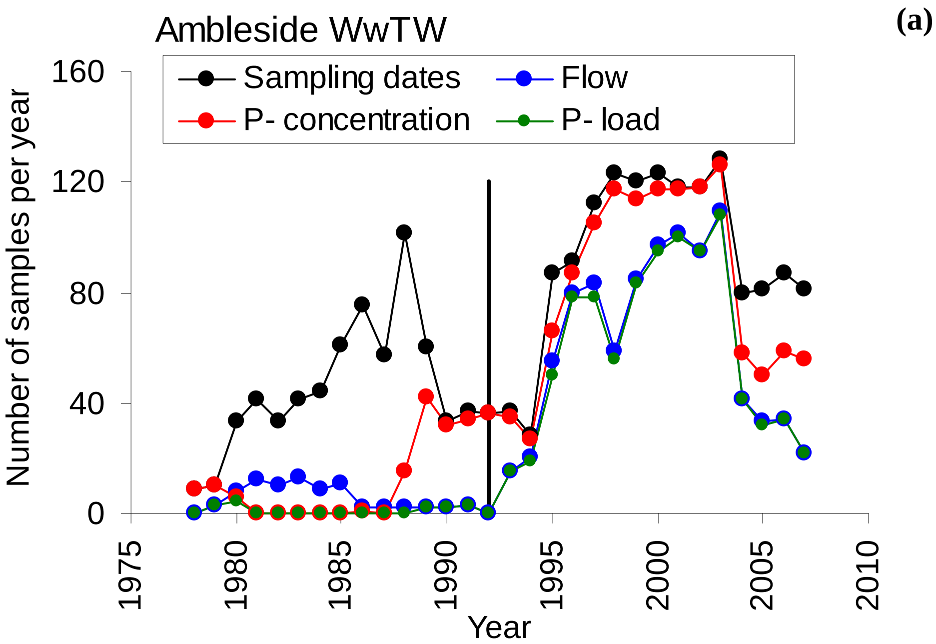
Table 3. Number of values of flow and phosphorus concentrations altered for each site.

	No. flow values altered	No. P values altered
Ambleside WwTW	9	59
Ambleside WwTW (Storm)		
Windermere Tower Wood WwTW (Old Outfall)	14	57
Windermere Tower Wood WwTW (New Outfall)	8	41
Windermere Tower Wood WwTW (Storm)		

The number of samples per year and the number of samples of aggregated flow, phosphorus concentration and phosphorus load for the different sites are shown in Figure 2. Estimates of flow were infrequent before 1992 and estimates of load are consequently also low before then. From 1989 onwards there are at least 30 to 40 measurements of phosphorus concentration per year. Estimates of load per year increased between 1993 and 2003 upto over 100 a year at both WwTWs. At the Ambleside WwTW there was a marked reduction in sampling from 2004 onwards with estimates of phosphorus concentration and particularly flow and load falling back to 20 to 40 per year while at the Windermere Tower Wood WwTW sampling frequency remained at around 100 samples per year.

Seasonal patterns

The dataset between 1987 (the start or relatively frequent measurements, see Fig. 2) and 2007 was analysed to determine overall seasonal patterns of discharge from the two WwTW. At both WwTW there was an expected seasonal pattern of flow with minimum values between June and July (Fig. 3). The flow from the Windermere Tower Wood WwTW was on average about 2.9-times that from the Ambleside WwTW. There were also clear seasonal patterns in the phosphorus concentration leaving the WwTW with lowest values, around 1 mg L^{-1} in winter increasing to between 2 and 3 mg L^{-1} in summer. The mean monthly concentrations leaving the two WwTW were very similar. Phosphorus load also showed a seasonal pattern with higher values between April and November than in December and January to March. The load from the Windermere Tower Wood WwTW was on average about 3.0-times greater than that from Ambleside.



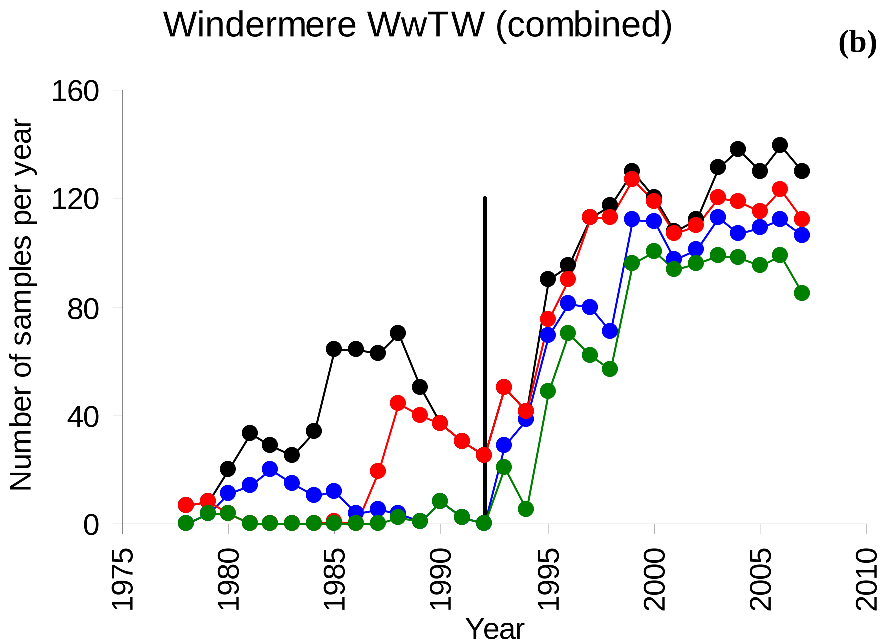


Figure 2. Number of dates with some kind of sample, flow measurement, phosphorus concentration or calculated load for (a) the Ambleside WwTW and (b) the Windermere Tower Wood WwTW based on combined samples. The vertical line shows 1992, the year of the implementation of the tertiary treatment plants.

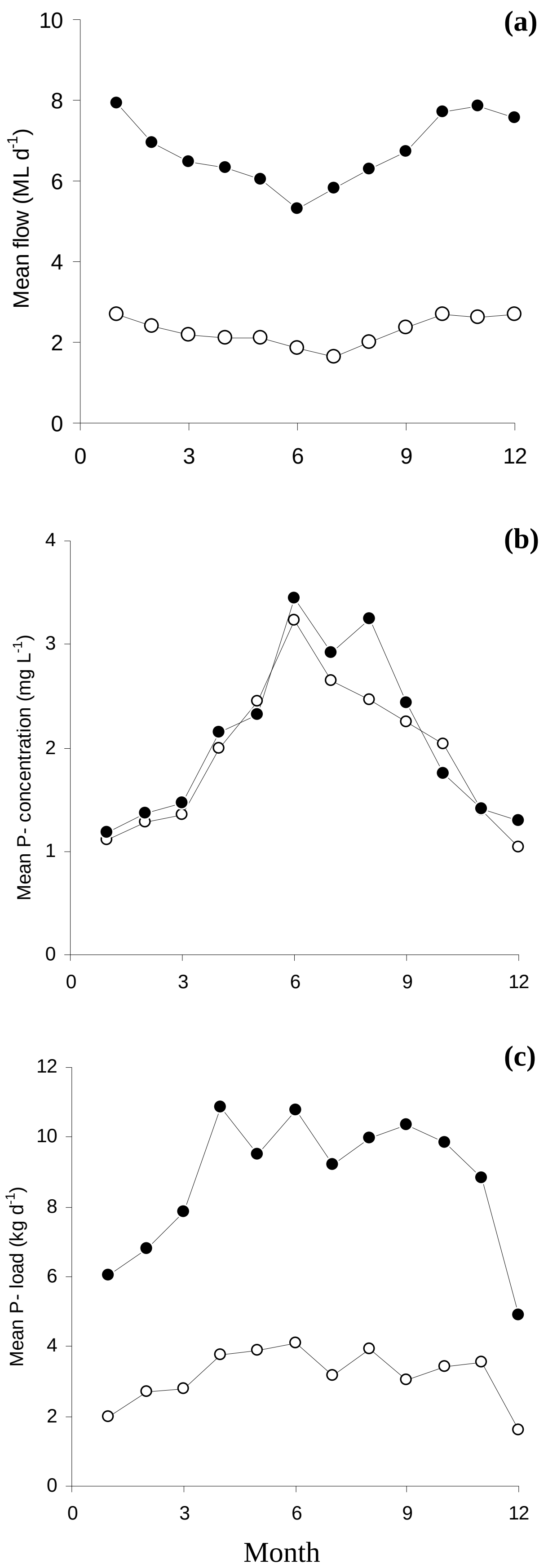


Figure 3. Monthly mean values for (a) flow, (b) phosphorus concentration and (c) phosphorus load over the period 1978 to 2007 for the WwTW at Ambleside (○) and Windermere Tower Wood (●).

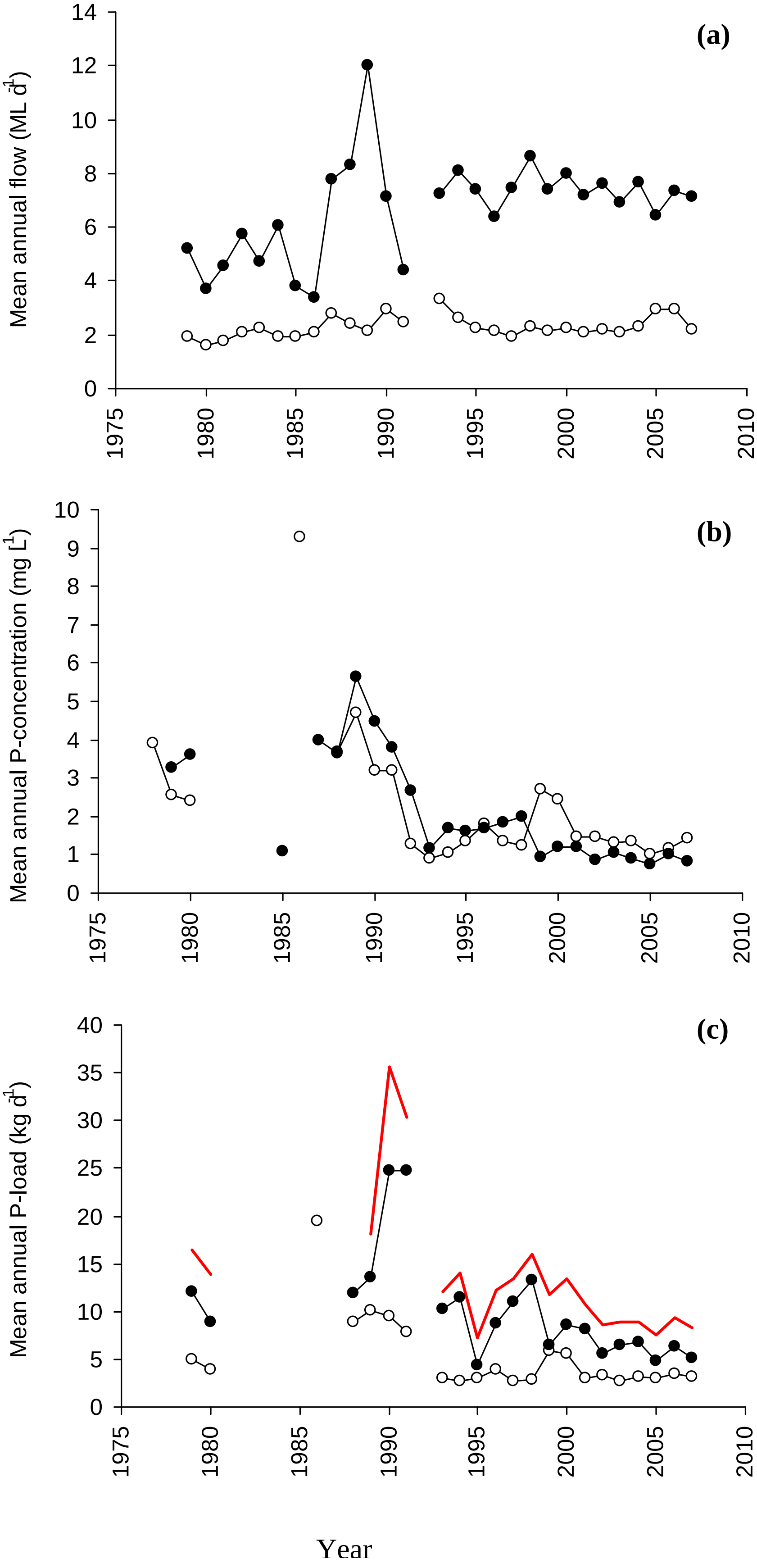


Figure 4. Annual mean values for (a) flow, (b) phosphorus concentration and (c) phosphorus load over the period 1978 to 2007 for the WwTW at Ambleside (○) and Windermere Tower Wood (●). The total load from the two WwTW is also given (red line).

Long-term changes

There has been a tendency for the annual mean flow from the two WwTW to increase over time (Fig. 4), although the change is not quite statistically significant at the Ambleside WwTW. Before 1993, the annual mean concentration of phosphorus was generally between 2 and 6 mg L^{-1}, although there was one very high value from Ambleside in 1986 (based on a single value in that year) and a low value from Windermere Tower Wood in 1985 (again based on a single value in that year). In 1991, the mean phosphorus concentration leaving the two plants was 3.2 mg L^{-1} at Ambleside and 3.8 mg L^{-1} at Windermere Tower Wood. In 1992, the year in which the tertiary treatment started, this had fallen to 1.3 mg L^{-1} at Ambleside and 2.7 mg L^{-1} at Windermere Tower Wood. In 1993 the annual means had fallen to 0.9 and 1.2 mg L^{-1} at Ambleside and Windermere Tower Wood respectively (Fig. 4). The detailed time-course of changing concentration of phosphorus from the two WwTWs is shown in Figure 5. There has been a marked reduction in the minimum concentration of P since the end of 1991 but there are still occasional peaks of high phosphorus concentration, although lower than those that occurred before the tertiary treatment started. Between 1993 and 2007, the annual mean concentration of phosphorus leaving the WwTWs was 1.48 mg L^{-1} at Ambleside and 1.26 mg L^{-1} at Windermere Tower Wood. The slightly higher mean at Ambleside was largely the result of the discharges in 1999 and 2000 which were 2.69 and 2.44 mg L^{-1} respectively, suggesting some malfunction in the treatment process during this time. Since 2001, both plants appear to have been operating well with average P-concentrations between 2001 and 2007 of 1.32 mg L^{-1} at Ambleside and 0.95 mg L^{-1} at Windermere Tower Wood. Figure 4 shows that the reduction in phosphorus load from the two WwTW achieved in 1993 has, by and large, been maintained subsequently.

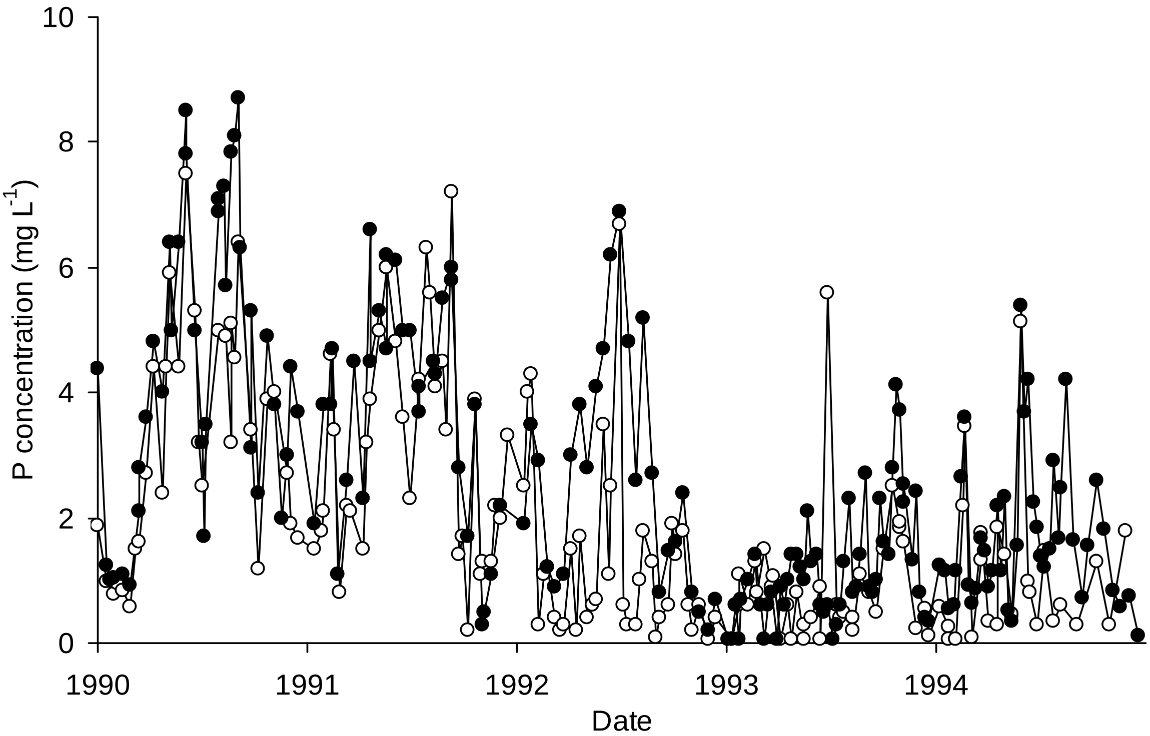


Figure 5. Time-course of changing concentration of phosphorus from the WwTW at Ambleside (○) and Windermere Tower Wood (●) before and after the implementation of the tertiary P-removal process in 1992.

Although concentration of phosphorus is the variable that is relevant to the consent for the operation of the WwTW, for the ecology of the lake the load of phosphorus is the relevant factor. Figure 4 shows the estimated annual loads of phosphorus from the two WwTW and the total load from both. Estimates of load before 1993 are relatively scarce but, based on annual means, they averaged about 6.0 kg d^{-1} at Ambleside and 16.0 kg d^{-1} at Windermere Tower Wood. The equivalent averages between 1993 and 2007 were 2.99 kg d^{-1} at Ambleside (50% of earlier mean) and 7.84 kg d^{-1} at Windermere Tower Wood (49% of earlier mean). From 2001 to 2007 the average loads were slightly lower at 2.69 kg d^{-1} at Ambleside (45% of earlier mean) and 6.21 kg d^{-1} at Windermere Tower Wood (39% of earlier mean).

Estimated loads

The data presented above were used to estimate overall annual loads to Windermere from the Ambleside and Windermere Tower Wood WwTWs and the total load to the lake. It is important to note that there are missing loads of phosphorus from the storm overflows at both WwTW but very few data are available (Table 3) so the magnitude of the load is unknown.

Compared to the period between 1978 to 1991, there has been a mean reduction of 1.09 Mg P y^{-1} from the Ambleside WwTW, 2.82 Mg P y^{-1} from the Windermere Tower Wood WwTW and 3.91 Mg P y^{-1} from these two WwTW in total. This represents a reduction of phosphorus load from the WwTW of about 50%.

Table 4. Estimated Phosphorus loads from the Ambleside and Windermere Tower Wood WwTW and the combined load to the lake for three time periods and the reduction 1993-2007 vs 1978-1991 with % reduction in parentheses.

	Phosphorus load Mg y^{-1}		
Period	Ambleside	Windermere Tower Wood	Combined from WwTWs
1978-2007	1.37	3.72	5.09
1978-1991	2.20	5.85	8.05
1993 -2007	1.09	2.82	3.91
Reduction 93-07 vs 78-91	1.11 (50%)	3.03 (52%)	4.14 (51%)

The estimated loads from the two WwTW are lower than those estimated by Reynolds & Irish (2000) (5.07 Mg y^{-1} from Ambleside and 7.69 Mg y^{-1} from Windermere Tower Wood) but these latter values were based on estimates of P-inflow, not discharge and this probably accounts for the discrepancy. However, the loads estimated here are very similar to that estimated in Talling et al. (1986) based on resident and visitor numbers. The 1978-1991 load from the Ambleside works is 2.2 Mg y^{-1} compared to 1.97 Mg y^{-1} in Talling et al. (1986). The 1978-1991 load from the Windermere Tower Wood works is 5.85 Mg y^{-1} compared to 6.01 Mg y^{-1} in Talling et al. (1986).

The contemporary loads from the Ambleside and Windermere Tower Wood WwTW can be put into context by comparison with loads from other sources. It should be noted that making estimates of phosphorus load to a lake is extremely difficult and we follow the approach in Reynolds & Irish (2000) where calculations are made using historic data on lake concentrations to estimate catchment loads. Such an approach does not take changes in fertiliser use or changed inputs from septic tanks into account and so may underestimate the diffuse catchment input. Nevertheless a calculation suggests that the total load to the lake is roughly correct. If the total load of total phosphorus is 10.65 Mg y^{-1} and the hydraulic discharge is 437 10^6 m^3 y^{-1} (Reynolds & Irish 2000), then the average concentration of total phosphorus is 24 mg m^{-3}. This is similar to the mean total phosphorus concentration measured in the South Basin of Windermere between 1995 and 2006 of 20 mg m^{-3} suggesting that the estimates are broadly correct

Table 5 indicates that the Ambleside WwTW contributes 17% of the total phosphorus and 48% of the soluble reactive phosphorus to the North Basin (Table 5). In the South Basin, the Windermere Tower Wood WwTW contributes 67% of the total phosphorus and 78% of the soluble reactive phosphorus. The values from the two WwTWs to the lake as a whole are 37% for total phosphorus and 66% for soluble reactive phosphorus.

Table 5. Phosphorus loads (Mg y^{-1}) from the Ambleside and Windermere Tower Wood WwTWs for the period 1993 to 2007 compared to loads from other sources.

	North Basin		South Basin		Whole Lake		
Source	TP	SRP	TP	SRP	TP	SRP	Note
Catchment	4.82	0.88	0.66	0.22	5.48	1.10	A
Direct rain	0.23	-	0.19	-	0.42	-	A
Indirect WwTW	0.28	0.28	0.56	0.56	0.84	0.84	B
Direct WwTW	1.09	1.09	2.82	2.82	3.91	3.91	C
Direct WwTW (%)	17	48	67	78	37	66	-
TOTAL	**6.42**	**2.25**	**4.23**	**3.60**	**10.65**	**5.85**	**-**

A. Reynolds & Irish (2000).
B. Include Grasmere and Elterwater WwTW for the North Basin, Hawkshead WwTW for the South Basin. Reynolds & Irish (2000).
C. 1993-2007 data from Table 4, this report.

Conclusions

There has been a significant and sustained reduction in the amount of phosphorus entering Windermere from the two WwTWs. Nevertheless, these still appear to be the largest single source of available (largely soluble reactive) phosphorus to the lake.

If a reduction in water quality in the last ten years can be established, the data analysed here suggest that it is not caused by worsened performance of the WwTW and increased phosphorus loads to the lake from these sources.

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