Institute of Freshwater Ecology

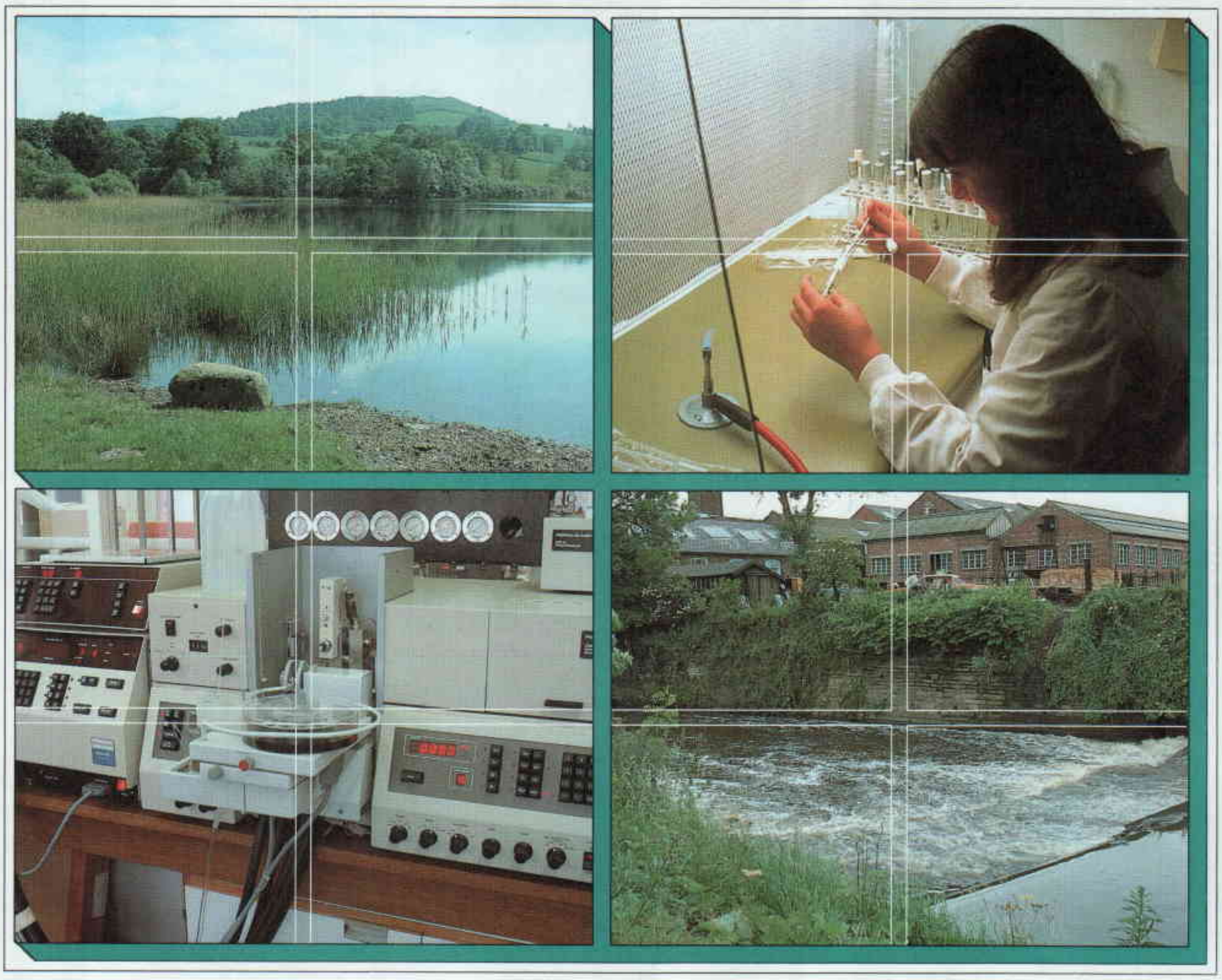
PLEASE RETURN TO:
DR LINDA MAY
IFE, BUSH ESTATE
PENICUIK, EH26 0QB

AN ASSESSMENT OF THE NUTRIENT LOADINGS FROM THE CATCHMENT TO BASSENTHWAITE LAKE.

Principal Investigators:

L May BSc PhD CBiol MiBiol
C J Place BSc
D G George Bsc PhD
J McEvoy

Report to Environment Agency, NW Region - December 1996



Natural Environment Research Council

Institute of Freshwater Ecology
Edinburgh Laboratory, Bush Estate, Penicuik,
Midlothian EH26 OQB, Scotland
Telephone 0131 445 4343; Fax 0131 445 3943

AN ASSESSMENT OF THE NUTRIENT LOADINGS FROM THE CATCHMENT TO BASSENTHWAITE LAKE

Report to Environment Agency, NW Region - December 1996

Principal Investigators:

L May BSc PhD CBiol MiBiol
C J Place BSc
D G George Bsc PhD
J McEvoy

Contract Completion Date: 31 March 1997
TFS Project No.: T11067b7
Report no.: ED/T11067b7/1

This is an unpublished report and should not be cited without permission, which should be sought through the Director of the Institute of Freshwater Ecology in the first instance: Windermere Laboratory, Far Sawrey, Ambleside, Cumbria LA22 OLP, UK. Tel: 015394 42468; Fax: 015394 46914.

The Institute of Freshwater Ecology is part of the Centre for Ecology and Hydrology of the Natural Environment Research Council.

SUMMARY

Bassenthwaite Lake has become increasingly eutrophic in recent years. This nutrient enrichment is thought to be threatening the survival of its vendace population, which is protected under the Wildlife and Countryside Act, 1981. In 1993, an intensive study was undertaken to determine the nutrient load to the lake from its catchment. The study concluded that the annual was about 16.7 t y^{-1} total phosphorus (TP), 8.7 t y^{-1} orthophosphate (OP), 128 t y^{-1} nitrate (NO_3-N) and 699 t y^{-1} silica (SiO_2).

By using the data collected to run a dynamic lake model, it was found that orthophosphate (OP) was the main nutrient limiting algal abundance in the lake. This suggested that any increase in OP would be reflected in a corresponding increase in algae, while a decrease in OP load would result in a decrease in algal abundance. NO_3-N and SiO_2 loads were less critical, in terms of reducing algal densities, as these were almost always available in excess of the quantities required for algal growth and even quite marked reductions in their availability would probably have little effect on algal abundance. It was, therefore, concluded that the most cost effective way of reducing eutrophication problems within the lake, and improving water quality, was to reduce the levels of TP entering the lake.

The main sources of TP within the catchment were determined. Sewage effluent contributed 41% of the TP load to the lake (ie 6.8 t TP y^{-1}). A further 39% (ie 6.5 t TP y^{-1}) was attributed to land cover sources within the surrounding catchment and a very small proportion (about 1%) probably originated from rain falling directly onto the lake surface. However, having taken into account all of these 'known' sources of TP, 19% of the measured TP load remained unaccounted for.

The catchment was found to support a fairly extensive and widely scattered rural population, most of whom rely on septic tanks for the disposal of household wastes. These were evaluated as a potential source of TP. The study found that there were approximately 1100 septic tanks within the catchment and that these, together, could have been responsible for about 14% of the TP load to the lake (ie about 2.3 t TP y^{-1}) leaving only 5% of the load unaccounted for.

In 1993, the Keswick sewage treatment works (STW) contributed about 80% of the TP output from all of the STWs within the catchment. However, this works was upgraded in 1995, reducing its TP output by 80% and the total TP load to the lake by about 26%. Following this upgrade, the main sources of TP entering the lake are now thought to be: land cover (52%), STWs 21%, septic tanks (18%).

The methods used in this study were based on annual values for TP losses within the catchment. Although this approach gives an overview of how much phosphorus is entering the lake, and where it is coming from, it is of limited use in predicting the effects of changes within the catchment on lake water quality. Such predictions can only be achieved by using the output from the catchment model as input to a dynamic lake model, such as PROTECH. However, this requires seasonal variation to be introduced into the TP load predictions. This could be achieved through the further development of existing rainfall/runoff models to include estimates of nutrient losses.

CONTENTS

1 Introduction

Bassenthwaite Lake (54°39'N, 3°13'W) is the fourth largest lake in the English Lake District, with a surface area of 5.11 km^2 and an estimated total volume of 27.9 x10^6 m^3. It is also the shallowest lake in this area, having a mean depth of 5.3 m, and a maximum depth of 19 m (Ramsbottom, 1976).

The lake lies at an altitude of 70 m above sea level, in a wide valley between the Thornthwaite and Skiddaw Fells. Its catchment is relatively large, extending over an area of some 347 km^2, and includes the catchments of Derwentwater and Thirlmere whose outflows, ultimately, drain into Bassenthwaite Lake. More than 60% of the catchment is covered by upland moor, rough grazing land and bare rock. Most of the remainder is used for forestry and improved pasture. However, there are some small villages scattered throughout the catchment and the lake itself lies 4 km north of Keswick, a town whose population is thought to double during the summer months due to tourism.

Table 1.1 Long-term records of nutrient chemistry and chlorophyll*a* in Bassenthwaite Lake. Multiple observations are shown as mean values, followed by the number of measurements (in parentheses).

Concentration ($\mu g\ l^{-1}$)	1928[a]	1949[b]	1971[c]	1984[d]	1987/88[e]	1993[f]
Total-P	--	--	19(3)	23(2)	35(12)	32(17)
PO_4-P	2.1(9)	1(10)	0.85(2)	1(4)	5(12)	6.7(17)
NO_3-N	91(9)	151(13)	--	390(4)	370(12)	253(17)
SiO_2	1200(9)	1900(13)	--	1220(4)	1540(12)	980(17)
Chlorophyll*a*	--	--	10.6(2)	--	15.3(12)	13.9(24)

Sources of data:

[a] Pearsall (1920)
[b] Mackereth & Lund, unpublished data
[c] Jones (1972)
[d] FBA, unpublished
[e] Mubamba (1989)
[f] IFE, unpublished

The lake is generally considered to be mesotrophic, but evidence from long-term water chemistry records suggests that it has become increasingly eutrophic in recent years (**Table 1.1** - after Atkinson *et al.*, 1989). This view is strongly supported by sediment analyses which have shown a distinct increase in the abundance of diatoms, which thrive in nutrient-rich water, since the early 1900s (Cranwell *et al.*, 1995). Cranwell *et al.* (1995) suggest that this eutrophication is probably due to a combination of factors, including (1) increases in resident and tourist population densities within the catchment, (2) the introduction of phosphorus-based detergents in the 1950s and (3) the more widespread use of fertilisers within the surrounding catchment.

In 1983, Bassenthwaite Lake was declared a Grade 1 Site of Special Scientific Interest (SSSI) under the provisions of the Wildlife and Countryside Act, 1981. This was partly due to the presence of vendace (*Coregonus albulus*) which, though common in Scandinavia, is listed as an endangered species in central Europe where its survival is thought to be threatened by eutrophication (Lelek, 1987). The vendace population of Bassenthwaite Lake, thought to be one of only two remaining populations in the United Kingdom (Maitland and Lyle 1991), is also thought to be threatened by eutrophication. Evidence suggests that, if this situation continues, the vendace population could become extinct due to (1) increased deep water anoxia, (2) greater competition from cyprinids, which might also prey on vendace eggs, and (3) degradation of its spawning areas, due to increased siltation and the loss of submerged vegetation through shading from phytoplankton blooms (Atkinson *et. al.*, 1989).

Although, by 1993, there was evidence of increasing eutrophication in Bassenthwaite Lake, itself, little was known about the nutrient load to the lake from the surrounding catchment. A series of studies (Hilton *et al.*, 1993; May *et al.*, 1995; Lawlor & Tipping, 1996; May *et al.*, 1996) were commissioned by the North-West Region of the Environment Agency (EA) [formerly the National Rivers Authority (NRA)] to rectify this situation. These studies aimed to:

(1) assess the nutrient load to the lake

(2) determine the main nutrient which is limiting algal abundance

(3) identify and quantify point sources of this nutrient

(4) identify and quantify diffuse sources of this nutrient

(5) determine the likely cause of increasing eutrophication in recent years.

This report summarises and updates the results of these earlier studies and provides some new information on septic tanks within the catchment, including their likely nutrient load to the lake.

2 The Geographical Information System (GIS)

2.1 Introduction

The successful management of eutrophication in lakes requires an integrated approach which takes into account not only the lake itself, but many aspects of its surrounding catchment. It is particularly important to address the problem of increasing nutrient loads from the catchment, as this, almost certainly, must be reduced if the trend of progressive nutrient enrichment is to be halted or reversed.

In order to do this, various sources of nutrients within the catchment must be identified and quantified. This process is relatively easy for point sources, such as industrial discharges or sewage effluents, but very much more difficult for non-point (diffuse) sources, such as agricultural runoff, which cannot be measured easily. This has encouraged water managers to develop methods of assessment which are based on catchment characteristics such as soil, vegetation and land cover. One such method of assessment is that known as the 'export coefficient' method. This estimates nutrient losses from the surrounding catchment on the basis of the areal extent of each land cover type and its associated nutrient export coefficient.

Although the nutrient export coefficients required for this approach are, largely, available from the literature, the land cover information required to support these calculations is more difficult to obtain. Historically, this information has been derived manually from paper-based maps which is a very labourious and time consuming process. However, recent improvements in Geographical Information Systems (GIS), and the increasing availability of map data in a machine readable (digital) form, have greatly improved the speed and accuracy with which this task can be carried out. GIS is now an extremely powerful tool which has many applications in the management of freshwater systems at the catchment and subcatchment level. This project takes full advantage of this.

In terms of the present study, a GIS allows us to analyse the catchment of Bassenthwaite Lake, and its subcatchments, and answer questions which relate not only to different attributes of the catchment (non-spatial data), but also to their extent and location (spatial data). For example, we can determine the areal extent of a particular land cover type, such as forest, and where that forest is. In this project, a GIS has been used to help us find out how much phosphorus (P) is coming off the catchment and where it is coming from.

A GIS can be defined as "An organised collection of computer hardware, software, geographic data and personnel designed to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced data" (ESRI, 1992). The project was carried out using ARC/INFO (v. 7.0), a Geographical Information System (GIS) which was developed by the Environmental Systems Research Institute Inc. (ESRI). In general, a GIS comprises 2 types of data. The first type of data is geographical or map data which describe the catchment in detail; these data include digital land cover maps and soils information. The second type of data is known as attribute data. This describes certain properties of the map data described above, such as nutrient export coefficients and hydrology of soils types (HOST) classes (see **Section 9.2**). Both types of data are used in combination to provide further information about the catchment, such as nutrient losses and hydraulic runoff (see **Sections 6 & 9**, respectively).

The GIS of the Bassenthwaite catchment comprised the following digital maps (coverages):

- lake outlines
- rivers
- catchment and subcatchment boundaries
- land cover
- soils
- sources of sewage effluent
- septic tanks
- rain gauges
- flow and water quality sampling sites

Most of these datasets are outlined below and described in detail by May *et al.* (1995, 1996). However, the derivation of the septic tanks coverage, which has not been used before, is described in **Section 7** of this report.

2.2 Description of datasets

2.2.1 *Lake outlines*

Lake outlines were derived from a 25m resolution land cover dataset provided by the Institute of Terrestrial Ecology (ITE). The original data were supplied in raster format and these were converted to a polygon coverage using the ARC/INFO command 'POLYGRID'. Areas of standing water were then extracted from the coverage to create a lake outlines coverage.

2.2.2 *Rivers*

A rivers centre line network for the catchment was provided by the Institute of Hydrology. This was converted into a rivers map for the area by erasing those links within the original drainage network which fell within the lake boundaries.

2.2.3 *Catchment and subcatchments*

The catchment of Bassenthwaite Lake was manually interpreted from the stream network and elevation contours on a 1:50,000 scale Ordnance Survey, Landranger Series, paper map. Subcatchments were defined in relation to the position of the water chemistry sampling sites on each inflow stream (see **Section 3**). The outlines of the catchment and subcatchments were entered into the GIS by digitising.

2.2.4 *Land cover*

Land cover data for 1972 and 1988 were supplied by the Lake District National Parks Authority, Kendal, in SPANS raster format, with a resolution of 20.03m per cell. These data had originally been compiled from 1:25,000 scale aerial photographs of the area which had been interpreted, digitised and converted into thematic maps for the Countryside Commission, by Silsoe College, Bedfordshire. The land cover maps were imported into ARC/INFO by the method described in May *et al.* (1995).

2.2.5 *Soils*

A digital soil map for the Bassenthwaite catchment was supplied, under licence, by the Soil Survey and Land Research Centre (SSLRC) of Cranfield University, England. The data were supplied in ASCII format, each data point consisting of an Ordnance Survey (OS) grid reference and an associated numeric soil code. These data were imported into a polygon representation of a 100m grid and clipped to the shape of the catchment using a digitised catchment outline. A key to allow cross-referencing between the soil codes and the published legend for the 1:250,000 soils map of England and Wales (SSEW, 1983) was also provided.

2.2.6 *Sources of sewage effluent*

The location of all known sources of sewage effluent within the catchment was provided by North West Water Limited in the form of a large scale sketch map. The OS grid reference of each site was obtained by reference to a 1:50,000 scale Ordnance Survey, Landranger Series, paper map. These data were entered into the GIS and converted into a map coverage using the ARC/INFO 'GENERATE' command for point data.

2.2.7 *Septic tanks*

See **Section 7**.

2.2.8 *Rain gauges, flow gauges and water chemistry sampling sites*

The location of rain gauges, flow gauges and water chemistry sampling sites within the catchment were provided by the EA in the form of OS grid reference data. These were incorporated into a map coverage using the ARC/INFO 'GENERATE' command for point data.

The Bassenthwaite GIS also contained attribute data associated with each map. These included the following:

- lake names
- subcatchment numbers
- land cover descriptions
- nutrient export coefficients
- soil descriptions
- hydrology of soil types (HOST) classes (see **Section 9**).

Identification codes for all septic tanks, sewage works, rain gauges, flow gauges and water chemistry sampling sites were also incorporated into the GIS.

3 Assessing the nutrient load to the lake

3.1 Introduction

Although it was well recognised that Bassenthwaite Lake had become more and more eutrophic in recent years, the evidence for this was based on observations of the lake itself rather than information on its nutrient load. These observations included an increase in nutrient and chlorophyll*a* concentrations in the open water, and more frequent de-oxygenation of the deeper waters. Little was known about the nutrient load to the lake until the EA began to monitor water chemistry and rate of flow for each of the main inflow streams, in January 1993. This work is described in detail by Hilton *et al.* (1993) and summarised below. The data collected were used to identify the main nutrient limiting algal abundance in the lake (see **Section 4**) and to validate output from the GIS-based runoff models (see **Sections 6-9**).

3.2 Methods

3.2.1 *Hydraulic load*

The net hydraulic load to the lake was calculated as the sum of the inputs from runoff and rainfall minus losses due to evaporation from the lake surface. Inputs from runoff and rainfall, and losses due to evaporation, were calculated as described below.

Inflows and direct runoff

Accurate estimates of the extent of the entire catchment, and its constituent subcatchments (defined as the drainage area upstream of the sampling sites shown in **Figure 3.1**), were obtained from the GIS. As some sampling sites were situated a significant distance from the mouth of the stream, a few small areas of land, near the shore of the lake, did not form part of the subcatchments as defined above. These were assumed to drain directly into the lake and are collectively referred to, below, as the 'ungauged' catchment. The area of this 'ungauged' was also obtained from the GIS.

Daily rates of flow for Site 1a for the period January to August, 1993, were provided by the EA. Corresponding values for the 10 remaining feeder streams (sites 2 - 11, see **Figure 3.1**) and the 'ungauged' catchment were generated from these data, as follows:

$$Flow_n = Flow_1 \times \frac{Area_n}{Area_1}$$

where: n is the number of the feeder stream

$Flow_n$ is the rate of flow in feeder stream n

$Area_n$ is the subcatchment area upstream of Site n.

Annual hydraulic loads were calculated to be 1.5 times that recorded during the 8-month monitoring period.

Rainfall

Daily rainfall figures for 3 rain gauges within the Bassenthwaite catchment (**Figure 3.1**) were provided by the EA. The hydraulic load to the lake from rain falling directly onto its surface was calculated by multiplying the average annual rainfall figures for 1993 by the surface area of the lake.

Evaporation

Hydraulic losses due to evaporation from the lake surface were calculated as follows:

$$AE_{lake} = PE_{land} \times r_1 \times r_2$$

where: PE_{land} = potential evapotranspiration losses from land (mm y^{-1})

r_1 = conversion factor for calculation of actual evapotranspiration losses from potential evapotranspiration losses

r_2 = conversion factor for calculating evapotranspiration losses from the lake surface from evapotranspiration losses over land

AE_{lake} = actual evapotranspiration from the lake surface (mm y^{-1})

The following values were used in the present study: PE_{land} = 425 mm y^{-1} (Meteorological Office map of Potential Evapotranspiration), r_1 = 1.00 (IH, 1978) and r_2 = 1.2 (Smith, 1974).

3.2.2 *Flushing rate and retention time*

Monthly flushing rates (loch volumes per month) were estimated as the ratio of lake volume and monthly net hydraulic load. Annual flushing rate (lake volumes y^{-1}) was calculated as the total net hydraulic load for 1993 (m^3 y^{-1}) divided by the lake volume (m^3) and the corresponding water retention time value (expressed in days) was calculated as the reciprocal of this.

3.2.3 *Nutrient loads*

Water chemistry information for each of the main inflows of the lake (**Figure 3.1**), for the period January to August 1993, was supplied by the EA. Data for total phosphorus (TP) and orthophosphate (OP) had been collected at 3 to 7 day intervals. Those for the nitrate (NO_3-N) and silicate (SiO_2) analyses had been collected at monthly intervals. In addition to the above, samples for TP, OP, NO_3-N and SiO_2 measurements were also available at 3 to 5 day intervals for site 1a, upstream of the STW effluent pipe on the River Derwent. This allowed the nutrient load from the sewage treatment works at Keswick to be estimated (see **Section 5**).

Annual nutrient loads were calculated for each inflow by the method of Rodda and Jones (1981):

$$L = K \sum_{i=1}^{n} \left(\frac{C_i Q_i}{n}\right)$$

where: L = load (kg y^{-1})

K = conversion factor for the time period involved (in this case, 365)

C_i = instantaneous nutrient concentration in individual water sample (kg m^{-3})

Q_i = instantaneous discharge at time of chemical sampling (m^3 d^{-1})

n = number of sampling occasions

Annual nutrient loads from the ungauged catchment were estimated using the GIS-based export coefficient approach described in **Section 7**. The land cover in this part of the catchment was similar to that of subcatchment 10. Nutrient export coefficients calculated from the field data for this catchment (ie 0.5 kg TP ha^{-1} y^{-1}, 0.25 kg OP ha^{-1} y^{-1}, 4.0 kg NO_3-N ha^{-1} y^{-1} and 36 kg SiO_2 ha^{-1} y^{-1}) were used for these calculations.

The nutrient load from rain falling directly onto the surface of the lake was calculated as the product of the annual hydraulic load from rainfall and the estimated concentration of each nutrient in freshly fallen rainwater. These values were as follows: 25 mg TP m^{-3} and 12 mg SRP m^{-3} (Bailey-Watts *et al.*, 1987), and 3.6 mg NO_3-N m^{-3} and 1 x 10^3 mg SiO_2 m^{-3} (Kirika, *pers. comm.*)

3.3 Results

3.3.1 *Hydraulic load*

The total hydraulic load to Bassenthwaite Lake during 1993 was estimated to be 5.2 x 10^8 m^3 y^{-1} (**Table 3.1**). This composed 8.68 x 10^6 m^3 (1.7%) from rainfall onto the lake surface, 2.0 x 10^7 m^3 (4%) entering the lake directly from the ungauged catchment close to the lake shore and 4.90 x 10^8 m^3 (93.6%) from the feeder streams. Slightly more than 88% of the total hydraulic load was accounted for by only 3 of the inflows, i.e. (1) River Derwent (69.4%); (2) Newlands Beck (12.8%); (8) Halls Beck (6%).

The evaporation corrected total input of water to the lake (*ie* the net hydraulic load) during 1993 was estimated to be 5.18 x 10^8 m^3. If matched by outflow losses, this corresponds to a flushing rate of 18.6 loch volumes y^{-1}, which is equivalent to a water residence time of about

19.7 days. Temporal variability in the rate of water input was considerable (**Figure 3.2**). Daily inputs varied from 2 x 10^5 m^3 d^{-1} on 12 February to 7 x 10^6 $m^3 d^{-1}$ on 18 January, with a mean of 1.4 x 10^6 m^3 d^{-1}, while monthly flushing rates ranged over an order of magnitude (inset **Figure 3.2**).

3.3.2 *Nutrient load*

The total phosphorus (TP) load to the lake during 1993, including that from rainfall and direct

Table 3.1 Estimated hydraulic load to Bassenthwaite Lake in 1993.

Source	Hydraulic load (x10^6 m^3 y^{-1})	Percentage of total
Inflow 1b	360.8	70.6
Inflow 2	66.4	13.0
Inflow 3	0.7	0.1
Inflow 4	1.7	0.3
Inflow 5	1.7	0.3
Inflow 6	16.8	3.3
Inflow 7	1.0	0.2
Inflow 8	31.5	6.2
Inflow 9	2.1	0.4
Inflow 10	4.1	0.8
Inflow 11	3.8	0.7
Direct runoff	20.5	4.0
Rainfall	8.7	1.7
Subtotal	519.8	100.0
Evaporation	-2.2	
Net hydraulic load	517.6	

runoff, was estimated to be about 16,679 kg (**Table 3.2**). The corresponding values for dissolved ortho-phosphate (OP), NO_3-N and SiO_2 were 8.7 x 10^3 kg, 128 x 10^3 kg and 699 x 10^3 kg, respectively. The River Derwent (inflow 1) accounted for approximately 80%

of the estimated TP and OP loads, 70% of the NO_3-N entering the lake and 64% of the incoming SiO_2. Individual values for each inflow, and for the contributions from rainfall and direct runoff, are shown in **Table 3.2.** Only inflows 1, 2, 6 and 8 individually contributed >2% of the total nutrient load to the lake.

Table 3.2 Estimated nutrient load to Bassenthwaite Lake during 1993.

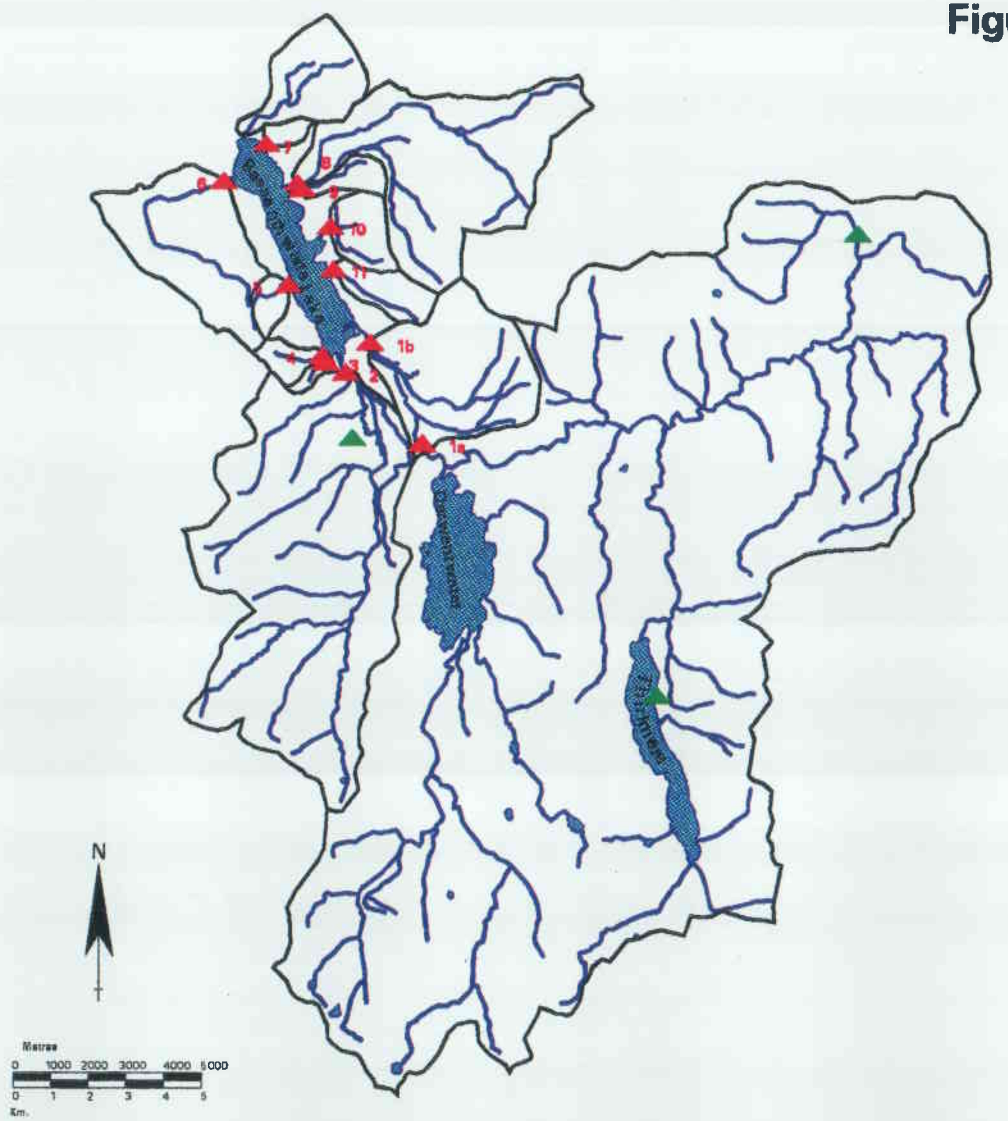
Source	Nutrient load ($kg\ y^{-1}$)				Percentage of total			
	TP	OP	NO_3-N	SiO_2	TP	OP	NO_3-N	SiO_2
Inflow 1b	13,004	7,010	90,890	447,767	77.96%	80.19%	70.90%	64.01%
Inflow 2	971	283	17,052	98,322	5.82%	3.24%	13.30%	14.06%
Inflow 3	108	81	675	1,562	0.65%	0.93%	0.53%	0.22%
Inflow 4	18	7	603	3,120	0.11%	0.08%	0.47%	0.45%
Inflow 5	19	9	389	2,973	0.11%	0.10%	0.30%	0.43%
Inflow 6	1,032	567	10,461	51,392	6.18%	6.48%	8.16%	7.35%
Inflow 7	204	147	960	3,210	1.22%	1.68%	0.75%	0.46%
Inflow 8	690	333	2,852	60,545	4.14%	3.81%	2.22%	8.66%
Inflow 9	78	38	1,076	5,634	0.47%	0.43%	0.84%	0.81%
Inflow 10	145	64	1,171	10,331	0.87%	0.73%	0.91%	1.48%
Inflow 11	122	63	1,457	8,576	0.73%	0.72%	1.14%	1.23%
Subtotal	16,390	8,602	127,584	693,430	98%	98%	100%	99%
Rainfall	217	104	31	869	1.30%	1.19%	0.02%	0.12%
Direct runoff	72	36	577	5,195	0.43%	0.41%	0.45%	0.74%
Total	16,679	8,742	128,193	699,494	100%	100%	100%	100%

3.3 Discussion

The total nutrient load to the lake was found to be relatively high compared to many other lakes of comparable size. As such, the lake would normally be expected to produce dense phytoplankton blooms with chlorophyll*a* levels in excess of 100 $\mu g\ l^{-1}$, as is the case in Loch Leven, which has a similar size and nutrient load. However, this is not the case. The reason for this is that the flushing rate of Bassenthwaite (18.6 loch volumes y^{-1}) is very high compared to that of Loch Leven (2 loch volumes y^{-1}). In spite of this, the recent nutrient enrichment of Bassenthwaite lake is thought to be threatening the survival of its resident vendace population.

In order to control and reduce the nutrient load to the lake, it is important not only to quantify the amount of nutrients entering the lake but also find out which is the main nutrient limiting algal abundance and where that nutrient is coming. **Sections 5** to **7**, below, address these problems.

Figure 3.1 Bassenthwaite Lake and catchment showing subcatchments, sampling sites and rain gauges.



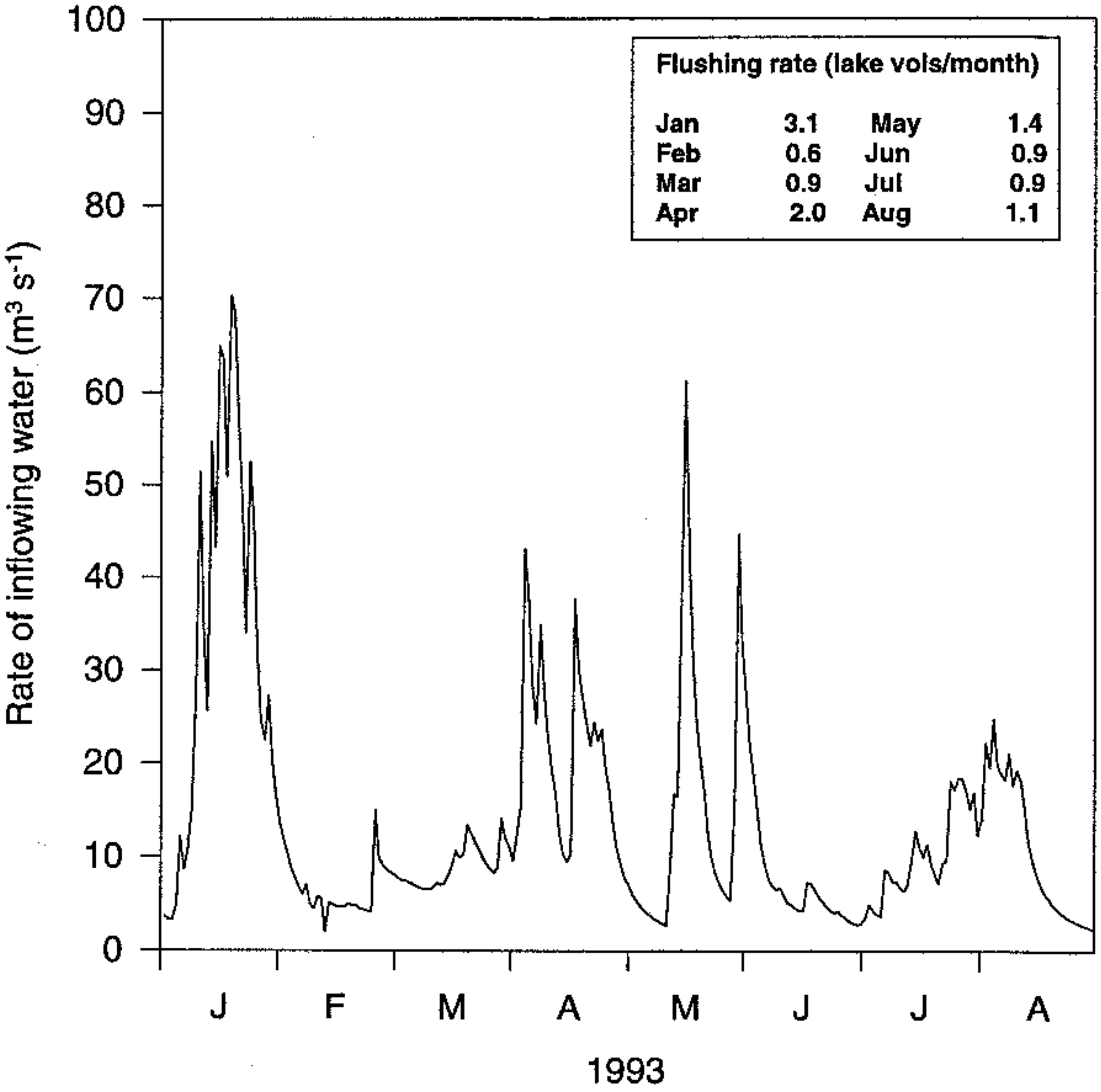
Catchment and subcatchment boundaries

Rivers and Streams

Sampling sites

Raingauge

Figure 3.2 Temporal variation in the hydraulic load to Bassenthwaite Lake between January and August, 1993. Inset shows variation in monthly flushing rates.



4 Identifying the main limiting nutrient

4.1 Introduction

Having quantified the nutrient load to the lake, the next stage of the work was to determine which nutrient, or combination of nutrients, was limiting algal growth and biomass accumulation within the lake for most of the year. This was important because it was only by decreasing the input of these nutrients that the adverse effects of eutrophication could be reduced. Also, this information would allow limited resources to be targeted more effectively in the management of the eutrophication problem.

The main nutrient limiting algal abundance in the lake was identified through the use of a dynamic lake model (PROTECH). This is a process-based model which applies limnological knowledge to the problems of enhanced algal growth and, in particular, biomass accumulation. It has many advantages over steady-state models, which cannot deal with dynamic situations, and statistical models, which require extensive calibration. The application of this model to Bassenthwaite Lake is described in detail by Hilton *et al.* (1993). The methods and main findings of this report are summarised below.

4.2 Methods

PROTECH 1 was used to simulate the observed dynamics of nutrients and phytoplankton within the lake during 1993 and to identify the main components driving algal growth and limiting the accumulation of algal biomass. This was achieved by mathematically 'switching off' the potentially limiting effects of flushing rate and nutrient concentrations, either singly or in combination, and re-running the model. The model outputs were compared to the 'natural' situation to determine which potentially limiting factor caused the greatest predicted increase in algal abundance when switched off. This was identified as the main limiting factor.

As input, the model requires estimated rates of flow and corresponding concentrations of OP, NO_3-N and SiO_2 in each of the main feeder streams (see **Chapter 3**). OP rather than TP concentrations were used because these represent the fraction of TP entering the lake which is immediately available for algal growth. As the model requires daily input data, discharges (m^3 s^{-1}) and nutrient concentrations (mg m^{-3}) for the 'non-sampled' days for each feeder water were generated from the field data as described in Hilton *et al* (1993). Information on the dynamics of in-lake nutrients, physical conditions and phytoplankton were used as validation data for the output. These were provided by the IFE.

4.3 Results

The simulations showed that 'switching off' the potentially limiting effects of flushing rate or NO_3-N and SiO_2 concentrations within the model had very little effect on predicted chlorophyll*a* levels. However, when OP limitation was switched off, there was a marked increase in predicted chlorophyll*a* levels compared to the observed values (**Figure 4.1**), especially during the summer months when chlorophyll*a* values of about 250 mg m^{-3}, ie more than 10 times the measured values, were predicted. The results strongly suggested that OP was the major factor limiting algal abundance in the lake.

4.4 Discussion

As OP was found to be the main nutrient limiting algal abundance within the lake, it was assumed that any reduction in OP load would similarly reduce algal abundance (*ie* chlorophyll*a* levels) and improve water quality. However, it was also noted that other forms of forms of phosphorus entering the lake could also become bioavailable OP under certain conditions. It was, therefore, assumed that any planned reduction in OP load should be undertaken as part of an overall reduction in all forms of phosphorus entering the lake. The next stage of this study was to identify and quantify all sources of TP entering the lake.

Figure 4.1 Output from lake model showing that OP availability limits algal biomass accumulation in Bassenthwaite Lake for most of the year.

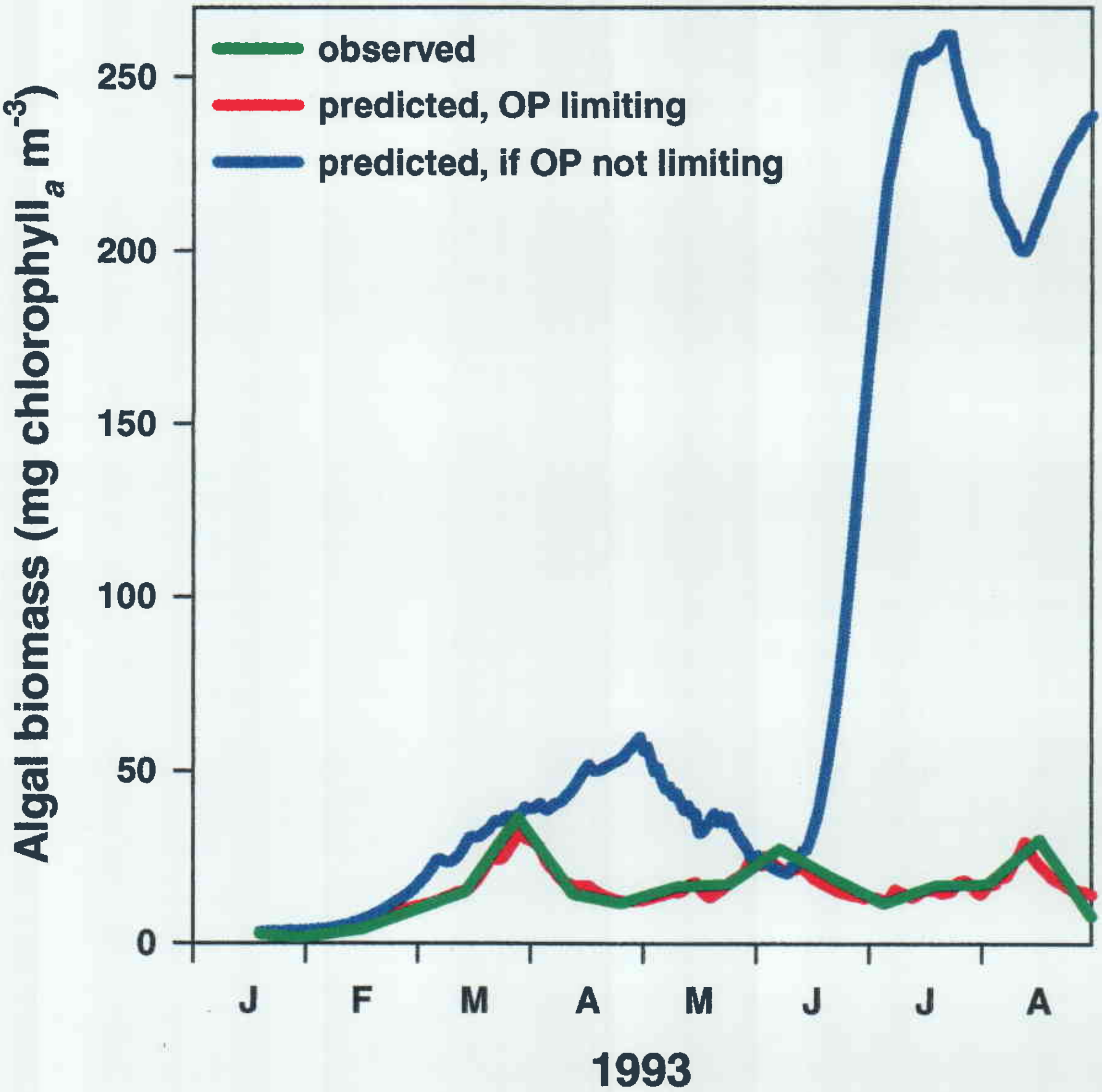


fig4_1.jnb

5 Estimating the TP load from point sources within the catchment

5.1 Introduction

Sources of TP within a catchment can be classified as *point sources*, such as industrial effluent or sewage treatment works discharges, and *non-point* (diffuse) *sources*, such as runoff. Point sources are usually addressed first, because they are easier to identify, quantify and control than non-point sources. This is also the case in the present study. Point sources of TP are quantified below and losses from non-point sources are considered separately (see **Sections 6** and **7**).

The most important point sources of TP within the Bassenthwaite catchment are discharges from sewage treatment works (STWs), which tend have high TP concentrations and are especially rich in bioavailable OP. The likely TP loads from these sources are assessed, in detail, below. As the lake is situated in a rural conservation area there is little industry and the TP load from industrial sources is thought to be negligible.

5.2 Methods

Information on the location of STWs within the catchment was provided by NWW, together with an estimate of their size (mostly expressed as population equivalents). These data were used to estimate the likely TP load from each STW, as described below. A range of methods were used as these STWs varied considerably in size and in the amount of information that was available concerning their effluent discharges. Some large hotels with private sewage treatment facilities are also included in the calculations.

5.2.1 *Keswick STW*

Effluent from the outfall and storm overflow pipes of the Keswick sewage treatment works (STW) enter the River Derwent between sampling sites 1a (upstream) and 1b (downstream) (**Figure 3.1**). These sites are less than 3 km apart and the subcatchment draining to site 1b is only marginally (5.4%) larger than that draining to site 1a. It was, therefore, assumed that the TP load from diffuse sources between sites 1a and 1b were minimal and that any increase in TP load to the River Derwent between sites 1a and 1b was due to the Keswick STW. As such, the TP load of this STW for 1993 was calculated as the difference in load between these two sites.

The Keswick STW was upgraded in early 1995 to reduce its TP output. Monitoring data provided by North West Water Limited (NWW) relating to effluent chemistry before and after the upgrade suggest that, in 1995, TP concentrations in the effluent had been reduced by 80% compared to 1993 levels.

5.2.2 *Bassenthwaite STW*

The Bassenthwaite STW discharges into Halls Beck. As rates of discharge were unknown, the average discharge consent of 0.175 Ml d^{-1} was used to calculate the TP load from this source. This was multiplied by the mean TP concentration in the effluent between February and August 1993 (ie 4.33 mg l^{-1}).

5.2.3 *Embleton STW*

The Embleton STW serves a population of about 250 people all year round and an additional 280 holiday makers from June to August. This works discharges into Dubwath Beck (inflow 6), but its TP output has never been measured. The annual TP load from this STW was, therefore, estimated assuming an annual population equivalent (PE) of 320 people and a *per capita* TP output of 0.56 kg y^{-1}.

5.2.4 *Thornthwaite STW*

The TP output from this STW was estimated as the product of the estimated discharge (0.1 Ml d^{-1}, see Hilton *et al.*, 1993) and the mean TP concentration of the effluent during 1993 (2.95 mg l^{-1}).

5.2.5 *Other small STWs*

Population equivalent figures for the small STWs at Bassenfell, Dubwath, Grange-in-Borrowdale, Rosthwaite, Seatoller, Stonethwaite, Threlkeld were provided by NWW. The TP load from these sources was estimated from these values by assuming a *per capita* TP output of 0.56 kg y^{-1}.

5.2.6 *Hotels*

Individual TP loads from the private sewage treatment systems of 8 hotels within the catchment were estimated from the number of bedrooms is each hotel (AA, 1990), as follows:

$$TP_{hotel}=2\times rooms_{hotel}\times occupancy_{hotel}\times TP_{export}$$

where:

$rooms_{hotel}$	=	number of rooms in each hotel
$occupancy_{hotel}$	=	occupancy rate of each bed
TP_{hotel}	=	TP load from hotel sewage effluent
TP_{export}	=	*per capita* export coefficient for sewage effluent

It was assumed that there were usually 2 beds per room and that the mean occupancy rate for each bed was 50%. A *per capita* TP export coefficient of 1 kg y^{-1} was also assumed.

5.3 Results

The locations of all known point sources of sewage effluent are shown in **Figure 5.1**. Estimated TP losses from these sources ranged from 36 kg y^{-1} to 5349 kg y^{-1} (inset **Figure 5.1**). The largest of these was the STW at Keswick which, in 1993, contributed almost 80% of the TP output from STWs and remote hotels within the catchment. Most of the remaining sources were relatively small by comparison. Even the largest of these, the Bassenthwaite (277 kg y^{-1}) and Threlkeld (248 kg y^{-1}) STWs, each contributed only 3-4% of the total output and TP losses from the remaining sites were even smaller. The total TP output from STWs was estimated to be about 6,830 kg y^{-1}. This accounted for 41% of the measured TP load to the lake.

5.4 Discussion

In 1993, 41% of the TP entering the lake could be attributed to point sources within the catchment, suggesting that the remaining 59% probably arose from diffuse sources (**Figure 5.2a**). Almost 95% of the TP losses from these point sources was found to be coming from a single large STW at Keswick.

The Keswick STW was upgraded in 1995 in response to a report by Hilton *et al.* (1993) which indicated that this would result in an improvement in lake water quality. The upgrade reduced the TP load from this STW by 80% (NWW, *pers. com.*) and the TP load to the lake by 26%. As a result, the TP load to the lake from point sources was reduced to 21% of the total load, while that from diffuse sources became relatively more important, accounting for 79% of the total load (**Figure 5.2b**). The next stage in the catchment management process was to identify and quantify TP losses from diffuse sources within the catchment.

Figure 5.1 Catchment of Bassenthwaite Lake showing main point sources of TP (sewage effluent).

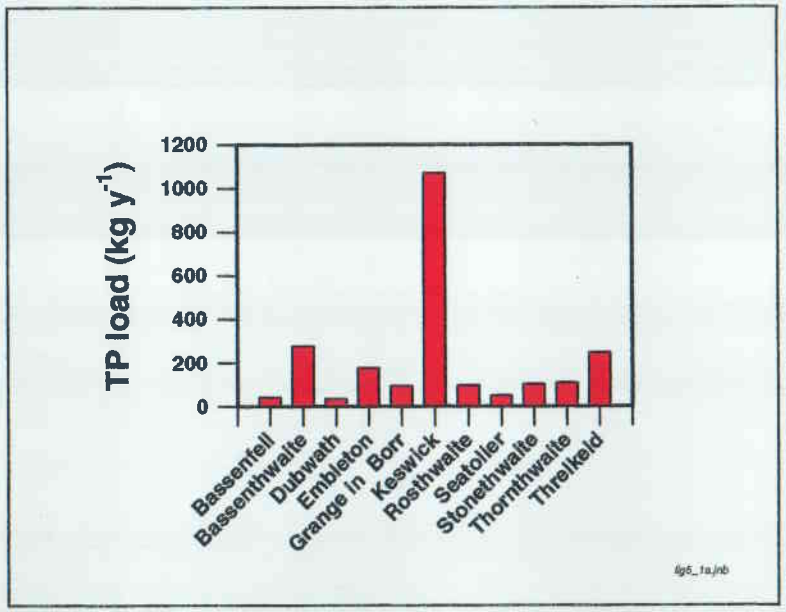
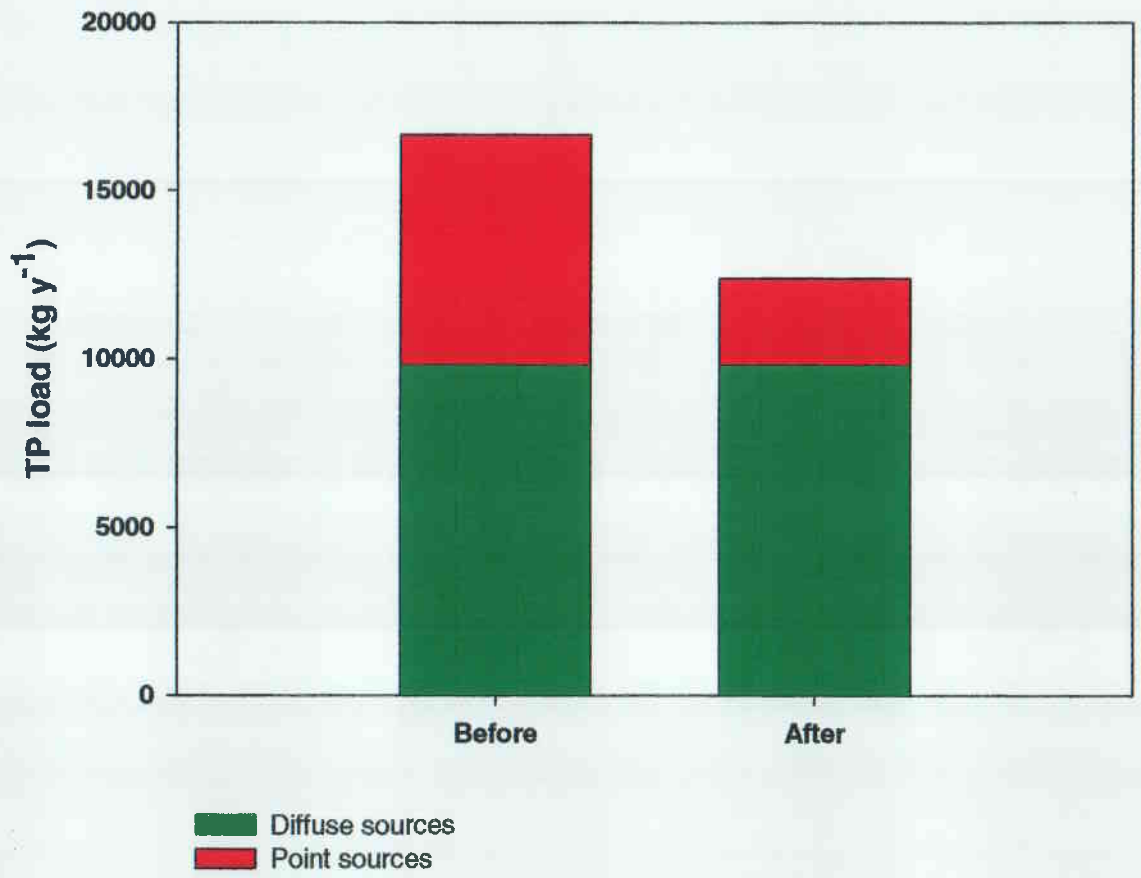


Figure 5.2 TP load from point sources (STWs) and diffuse sources, before and after the STW upgrade.



sepa02.jnb

6 Estimating TP losses from diffuse sources: land cover

6.1 Introduction

Preliminary estimates of the TP load from land cover sources within the Bassenthwaite catchment are given by May *et al.* (1995) who describe the methods in detail. However, these authors found that the TP export coefficients used tended to overestimate measured losses in heavily forested areas. For the purposes of the present study, it was assumed that TP loss rates for forestry had been drastically reduced from those measured in the 1970s and used in the earlier study. The likely explanation of this was recent changes in forestry practices which had been aimed at reducing nutrient losses and soil erosion. In view of this, the TP loss rate for mature coniferous forest in the present study was updated to those of broadleaved and mixed forest (*ie* 0.15 kg $ha^{-1} y^{-1}$); that of new/cleared forest was set slightly higher, at 0.2 kg $ha^{-1} y^{-1}$. In addition, the TP export values for improved pasture were updated to 0.38 kg $ha^{-1} y^{-1}$ in the present study. This value was derived from the measured values of Lawlor & Tipping (1996), assuming that TP loss rates were twice as high as OP loss rates for this land cover type.

6.2 Methods

The original land cover data set for the area, as supplied by LDNPA, contained 38 classes of land cover. For the present study, these were reduced to 12 land cover groups (May *et al.*, 1995) which were then summarised in terms of absolute area and percentage cover for the entire catchment. The TP load from each land cover category within the catchment was then predicted by multiplying the areal extent of each land cover type by the relevant TP export coefficient shown in **Table 6.1**. It should be noted, however, that the value given for urban/rural settlement in **Table 6.1** refers to runoff from these areas and excludes TP output from STWs.

The TP loss estimates were compared to the measured annual loads given in **Section 3.** For the purposes of this study, it was assumed that there had been very little change in land cover between 1988, when the aerial photographs were taken, and 1993, when the water quality data were collected.

Table 6.1 Land cover categories and related export coefficients.

Land cover code	Land class category	TP Export Coefficient	Reference
100	Urban/rural settlement (runoff only)	0.83	*Bailey-Watts, Sargent, Kirika & Smith (1987)*
200	Upland moor	0.1	*Harper & Stewart (1987)*
300	Improved pasture	0.38	*This study*
400	Coniferous forest	0.15	*This study*
500	Cleared/new forest	0.2	*This study*
600	Broadleaved forest	0.15	*Dillon & Kirchner (1975)*
700	Mixed forest	0.15	*Hancock (1982); Dillon & Kirchner (1975)*
800	Bogs & peat	1.0	*Casey, O'Connor & Green (1981)*
900	Inland bare rock	0.1	*May et al., 1995*
1000	Rough grazing	0.07	*Cooke & Williams (1973)*
1100	Arable	0.25	*Cooke & Williams (1973)*
1200	Other	0.1	*May et al., 1995*

6.3 Results

6.3.1 *Land cover*

The total area of the Bassenthwaite catchment, excluding areas of standing water, is 34,741 ha. Land cover for the catchment in 1988 is shown in **Figure 6.1**. More than half of the catchment (53%) is covered by upland moor, 21% by improved pasture and 12% by forestry (**Table 6.2, Figure 6.2a**). There are also small scattered areas of 'other' land cover types, including rough grazing (5.2%), inland bare rock (4.8%) and urban/rural settlement (1.8%).

Table 6.2 Areal extent of different land cover types within the catchment of Bassenthwaite Lake.

Land Cover	Area (ha.)	Area (%)
Urban/rural settlement (runoff only)	614	2
Upland moor	18,560	53
Improved pasture	7,233	21
Coniferous forest	1,628	5
Cleared/new forest	465	1
Broadleaved forest	923	3
Mixed forest	1,189	3
Bogs & peat	398	1
Inland bare rock	1,668	5
Rough grazing	1,790	5
Arable	74	0
Other	199	1
Total	34,741	100

6.3.2 *Predicted TP losses*

Estimated TP losses from each land cover type within the Bassenthwaite catchment are given in **Table 6.3** and **Figure 6.2b**. Most of the TP comes from upland moor (29%), improved pasture (42%) and forests (10%). A further 8% comes from urban/rural settlement runoff, while 11% is attributable to the remaining land cover types. In total, an estimated 6,497 kg TP yr^{-1} is lost in runoff from this catchment. This accounted for 39% of the measured TP load to the lake in 1993, and 52% of the predicted TP load after the Keswick STW upgrade.

TP losses from the catchment can also be expressed as a TP loss rates map (**Figure 6.3**). Visual comparison with the land cover map (**Figure 6.1**) suggests that, for the most part, the highest TP loss rates occur on the fertile soils of the valley bottoms, while much lower TP loss rates are found on the upland moors, with the exception of small areas of bogs and peat.

Table 6.3 TP losses from different land cover types within the catchment of Bassenthwaite Lake.

Land Cover	TP Losses ($kg\ y^{-1}$)	TP Losses (%)
Urban/rural settlement (runoff only)	510	7.9
Upland moor	1,856	28.6
Improved pasture	2,749	42.3
Coniferous forest	244	3.8
Cleared/new forest	93	1.4
Broadleaved forest	138	2.1
Mixed forest	178	2.7
Bogs & peat	398	6.1
Inland bare rock	167	2.6
Rough grazing	125	1.9
Arable	19	0.3
Other	20	0.3
Total	6,497	100

6.4 Discussion

The results outlined above suggest that, in 1993, 6,497 kg TP (*ie* 39% of the measured TP load to the lake) arose from runoff related to land cover in the catchment. These values were calculated using land cover data and related TP export coefficients. May *et al.* (1996) also considered the use of soils data to improve estimates of annual nutrient losses from the catchment, using TP export coefficients for different soil types as determined by Lawlor & Tipping (1996). However, May *et al.* (1996) found that this approach did not improve on TP runoff predictions based on land cover and published export coefficients because land cover tended to reflect the underlying soil type. As TP export coefficients for different land cover types are more widely available than for soil types, the authors concluded that the land cover/export coefficient approach was more widely applicable to different catchments than the soils/nutrient export coefficient approach.

The TP load from point sources within the catchment was estimated to be 6,830 kg during 1993 (see **Section 5.3**). An additional 6,497 kg TP appears to be attributable to land cover sources and a small amount (217 kg TP) enters the lake in rain falling directly onto the surface of the lake (see **Section 3.3.2**). These account for only 81% of the measured TP load to the lake. A further 3,135 kg TP (19% of the total load) remains unaccounted for (**Figure 6.4**).

Some consideration was given to the likely sources of this apparent 'error'. The influence of storm events, which tended to wash additional phosphorus laden material into the streams, had not been considered. Also, the methods used to interpolate and extrapolate missing values from the field measurements may have introduced some additional errors. However, preliminary results from May *et al.* (1995) suggested that seepage from septic tanks may make a significant contribution to TP losses from the catchment in some areas. An attempt was, therefore, made to quantify TP losses from septic tanks within the catchment.

Figure 6.1 Catchment of Bassenthwaite Lake showing land cover for 1988.

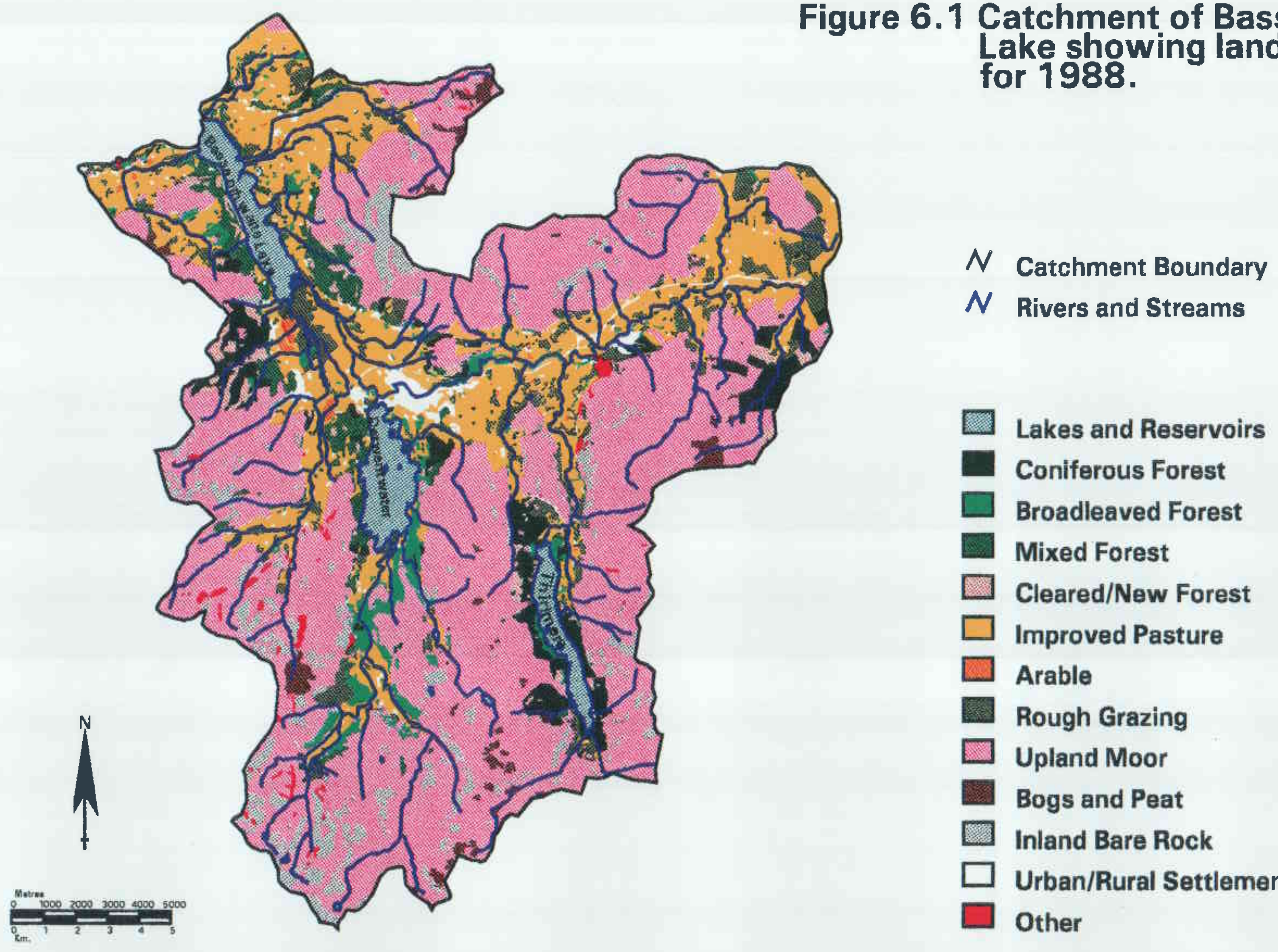
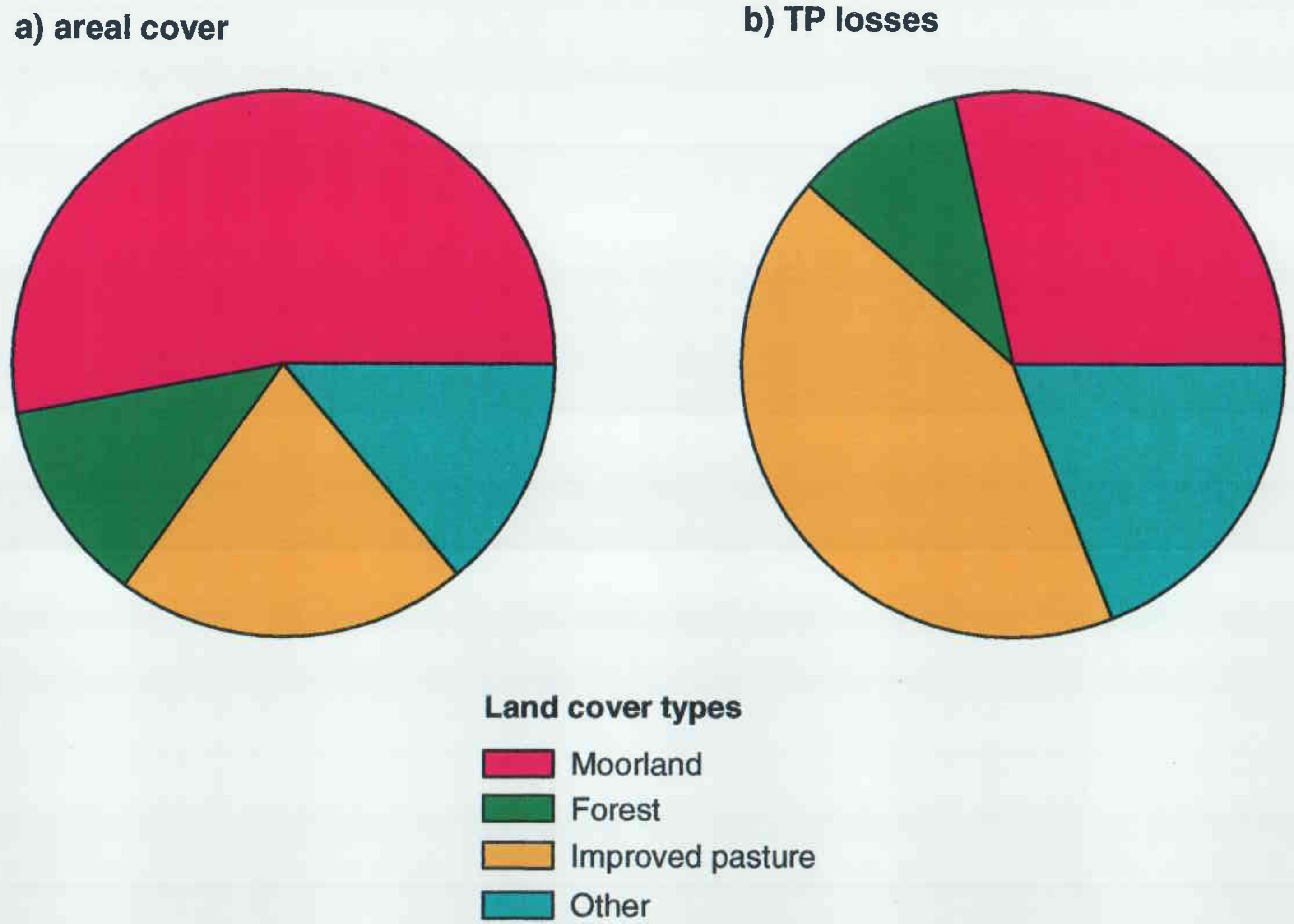


Figure 6.2 Proportion of catchment covered by each land cover type and their associated TP losses.



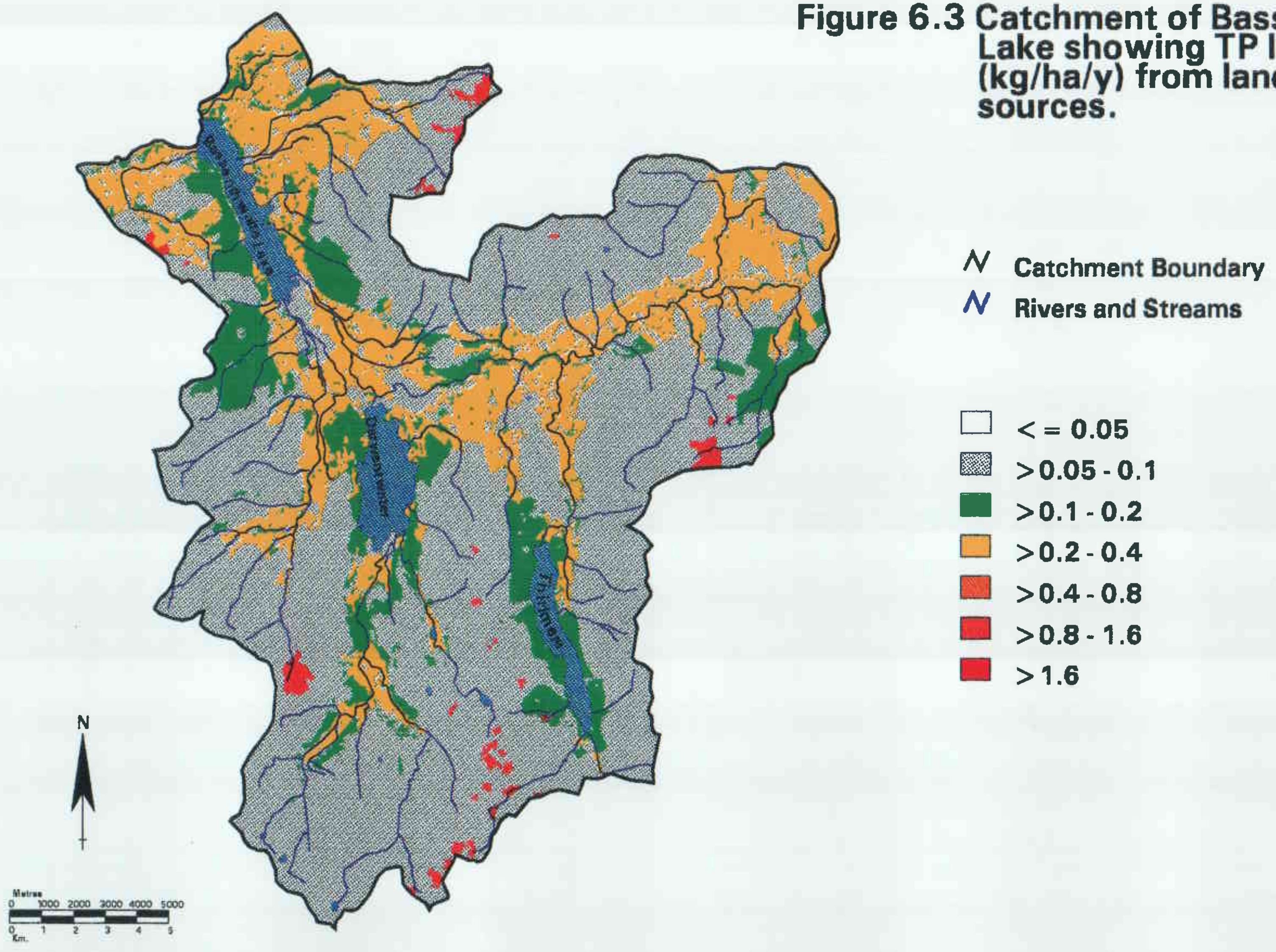


Figure 6.3 Catchment of Bassenthwaite Lake showing TP loss rates (kg/ha/y) from land cover sources.

Figure 6.4 Relative importance of TP losses from different sources within the catchment of Bassenthwaite Lake during 1993.

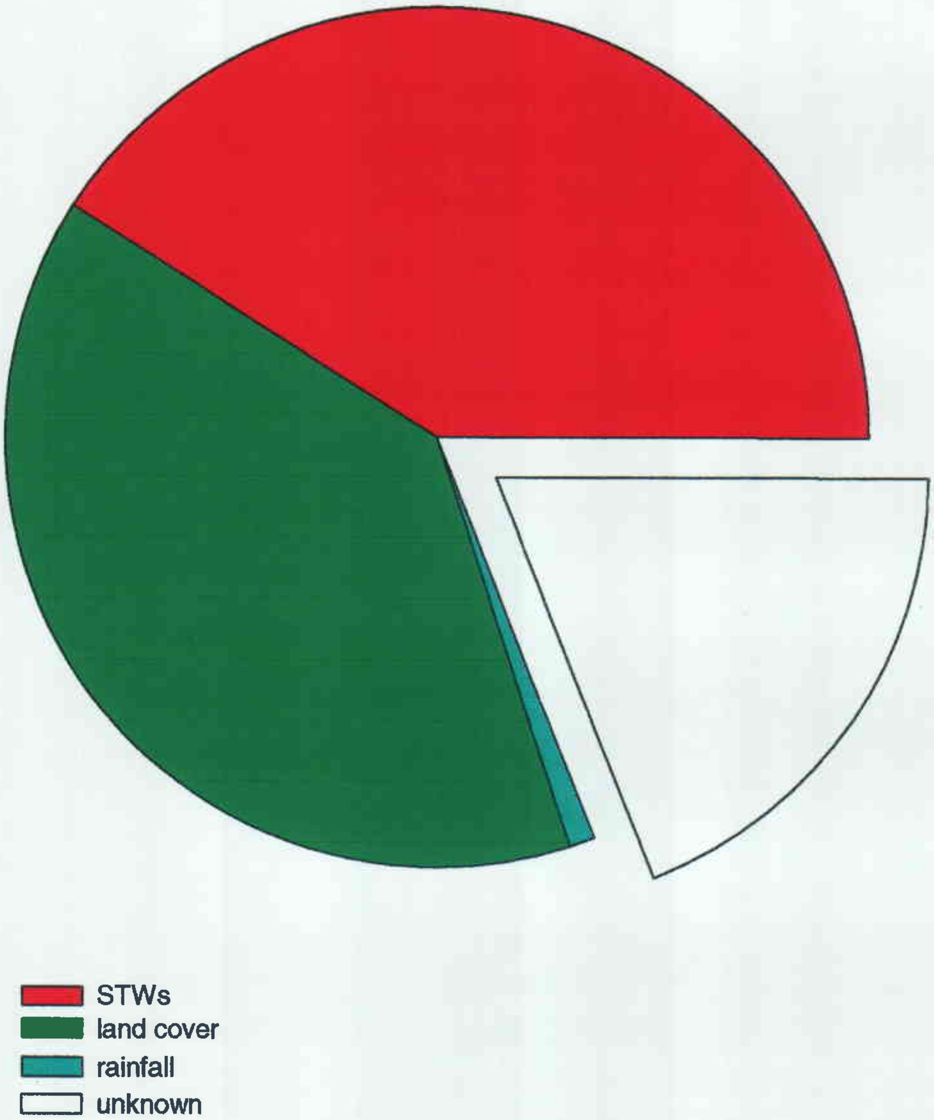


fig6_4.jnb

7 Estimating the TP load from diffuse sources: septic tanks

7.1 Introduction

In a rural catchment, such as that around Bassenthwaite Lake, many of the local population rely on septic tanks for the disposal of domestic wastes. However, there is little information on the number and location of these tanks within the catchment and little is known of the fate of the phosphorus (P) which enters the septic tank system. In general, the amount of this P which enters local watercourses depends on the age and type of each septic tank, and the P adsorption properties of the surrounding soils but this information is not available, in detail, for this area. This section of the report uses existing data to estimate the number and location of septic tanks within the catchment, and assess the likely TP load to the lake from this source.

7.2 Methods

The number of septic tanks within the catchment was estimated by assuming that all premises within the catchment which did not receive bills for sewerage connection were connected to septic tanks. These were identified by subtracting the postcodes of all premises receiving bills for sewerage connection (as supplied by NWW) from the list of all premises within the catchment, as determined from the Ordnance Survey (OS) Address-Point dataset for the area. As the address-point dataset also contains the location of each of these premises, expressed as OS coordinates, it was also possible to map the exact locations of these septic tanks (**Figure 7.1**).

The likely TP output from these septic tanks was determined by assuming an average of 3 people per household for rural communities served by septic tanks, and a mid-range *per capita* export coefficient of 0.7 kg TP y^{-1} (Harper, 1992).

7.3 Results

The results suggest that there are probably about 1100 septic tanks in the Bassenthwaite catchment. The likely location of these is shown in Figure 7.1. TP losses from this source were estimated to be about 2,310 kg TP y^{-1}, ie about 14% of the total TP load to the lake in 1993 (**Figure 7.2**), and about 17% of the expected load after the STW upgrade. This constituted 34% of the total TP load from sewage related sources in 1993, before the Keswick STW upgrade, and 82% of that load once the upgrade had been completed (**Figure 7.3**).

7.4 Discussion

The Bassenthwaite catchment has a fairly large rural community, many of whom rely on septic tanks for the disposal of household waste. In the past, the likely TP load to the lake from septic tanks has been assumed to be small. However, the results of this study suggest that this may not be the case and that, after the Keswick STW upgrade in 1995, the TP load from this source may be as high as 17% of the total TP load to the lake and 82% of the TP load from sewage related sources.

Although it is difficult to say how accurately these calculations reflect the real situation, because little is known about the eventual fate of nutrients which enter septic tanks, these results are similar to those obtained for the catchment of Loch Leven where septic tanks are thought to account for 10% of the TP load to the loch (Frost, 1996).

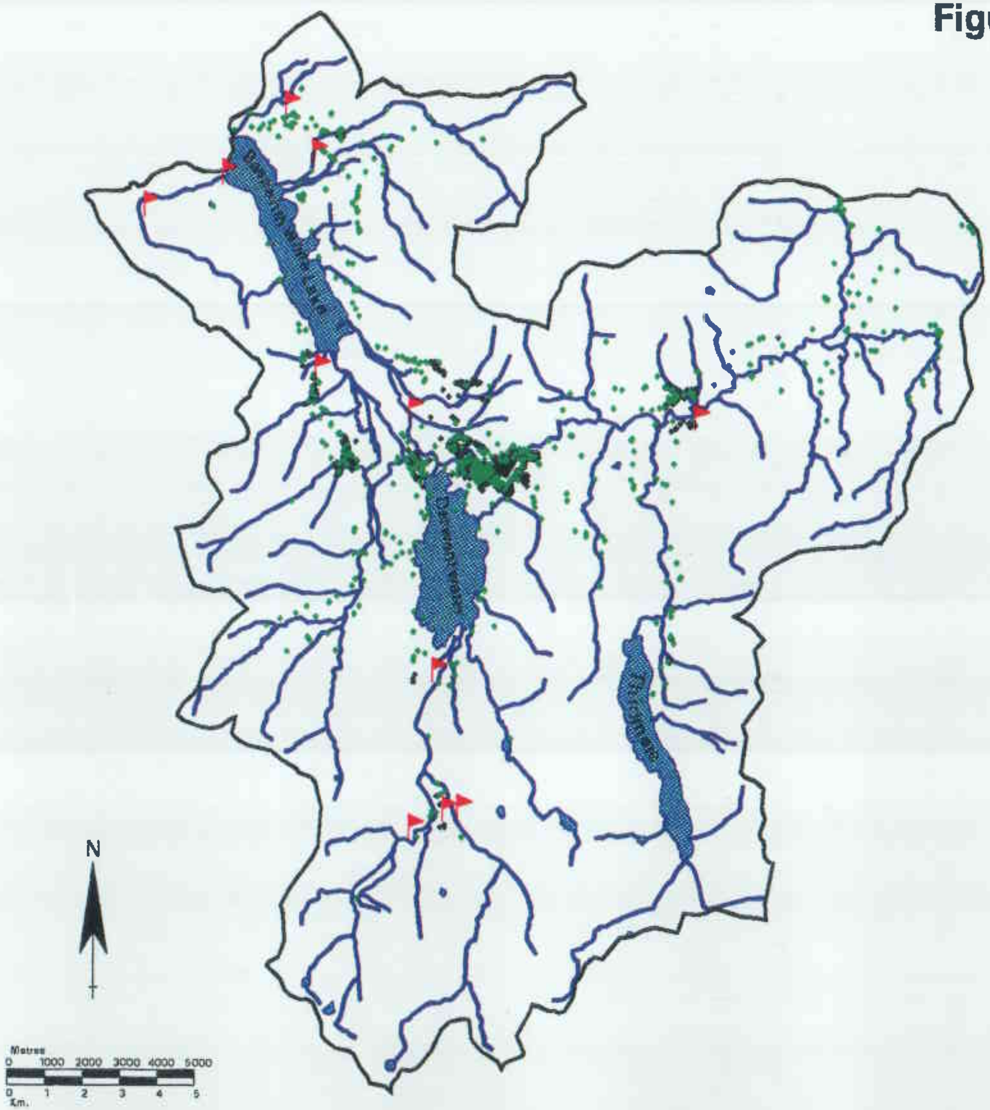


Figure 7.1 Bassenthwaite Lake and catchment showing location of premises served by septic tanks and those connected to the sewage treatment system.

Figure 7.2 Relative importance of TP losses from different sources within the catchment of Bassenthwaite Lake during 1993, including septic tanks.

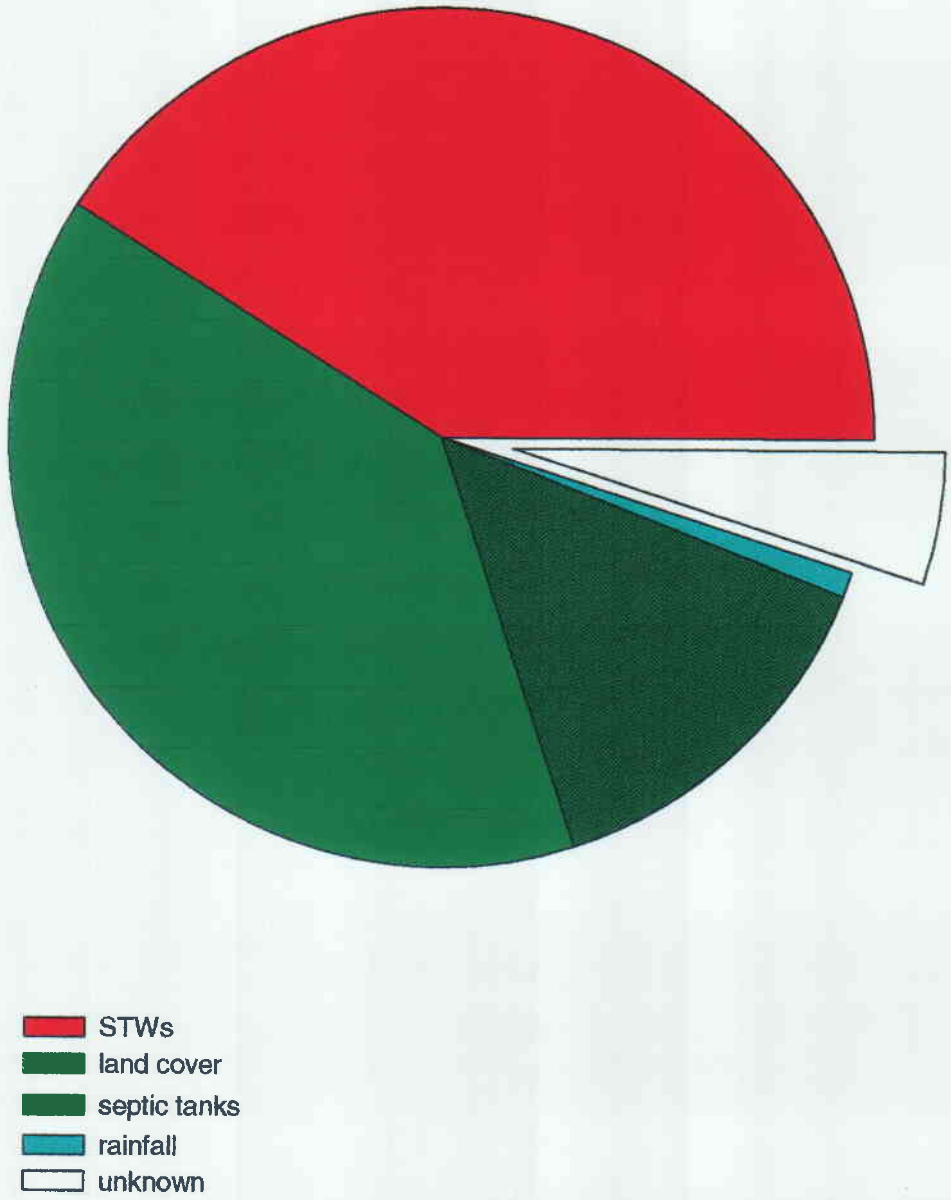


fig7_2.jnb

Figure 7.3 TP load from point sources (STWs) and diffuse sources (including septic tanks), before and after the STW upgrade.

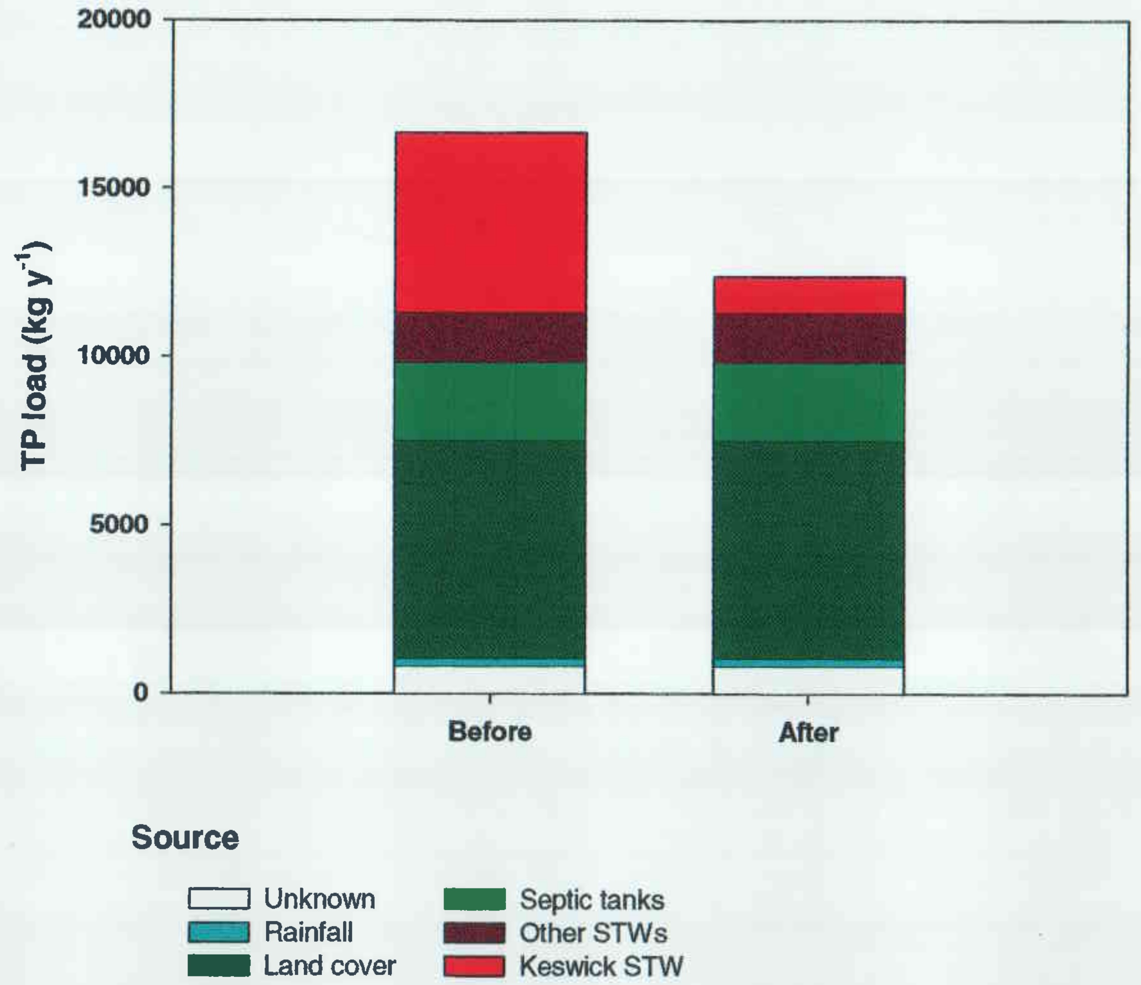


fig7_3b.jnb

8 Assessing the effects of changes in land cover on TP losses from the catchment

8.1 Introduction

Eutrophication problems in Bassenthwaite Lake have almost certainly been caused by an increase in TP load to the lake from its catchment in recent years. Higher discharges of TP-laden effluent from STWs, due to local population increases seem, largely, to blame. However, it is possible that changes in land cover within the catchment may also have made a significant contribution to the increased TP load to the lake. The increase in TP load likely to have been caused by such changes between 1972 and 1988 is assessed below.

8.2 Methods

Land cover survey data for 1972 and 1988 were provided by the LDNPA. Although it is difficult to detect changes in land cover between these years by visual comparison of the maps, the overlay capability of GIS allows us to highlight the areas of change while suppressing those areas that have remained under the same land cover (**Figure 8.1**). Associated changes in TP losses from these areas were estimated using the TP export coefficients given in **Table 6.1** and the methods described in **Section 6**.

8.3 Results

8.3.1 *Changes in land cover*

Changes in land cover between 1972 and 1988 are shown in **Figure 8.1**. Changes were recorded in only 1840 ha of the 34,741 ha catchment (**Table 8.1**). This amounted to only 5.3% of the total catchment area.

In general, most of the land cover changes were related to on-going forestry practices. Areas of cleared or new forest in 1972 had become mature forest by 1988, while many areas of established forest recorded in 1972 had been clear felled and, possibly, replanted by 1988. In addition, small areas of the catchment appeared to have changed from arable land to improved pasture.

Table 8.1 Areal changes in land cover between 1972 and 1988, and associated change in TP load from the catchment.

Land Use Category	Change in area (ha)	Change in TP load (kg y^{-1})
Urban/rural settlement (runoff only)	89	73.8
Upland Moor	-136	-13.6
Improved pasture	632	158.0
Coniferous forest	183	27.5
Cleared/new forest	4	0.8
Broadleaved forest	14	2.2
Mixed forest	-12	-1.9
Bogs & peat	0	0.0
Inland bare rock	33	3.3
Rough grazing	-727	-50.9
Arable	-78	-19.4
Other	-3	-0.3
		179.5

Some small increases in urban/rural settlement were also recorded in some areas. The most noticeable of these were the building of the Keswick by-pass and the development of a club house and golf course near Threlkeld (**Figure 8.1**). Other, smaller, changes included some new buildings, possibly housing developments, north-west of Applethwaite, in Bassenthwaite village and on the outskirts of Keswick.

8.3.2 *Effects of changes in land cover on TP losses from the catchment*

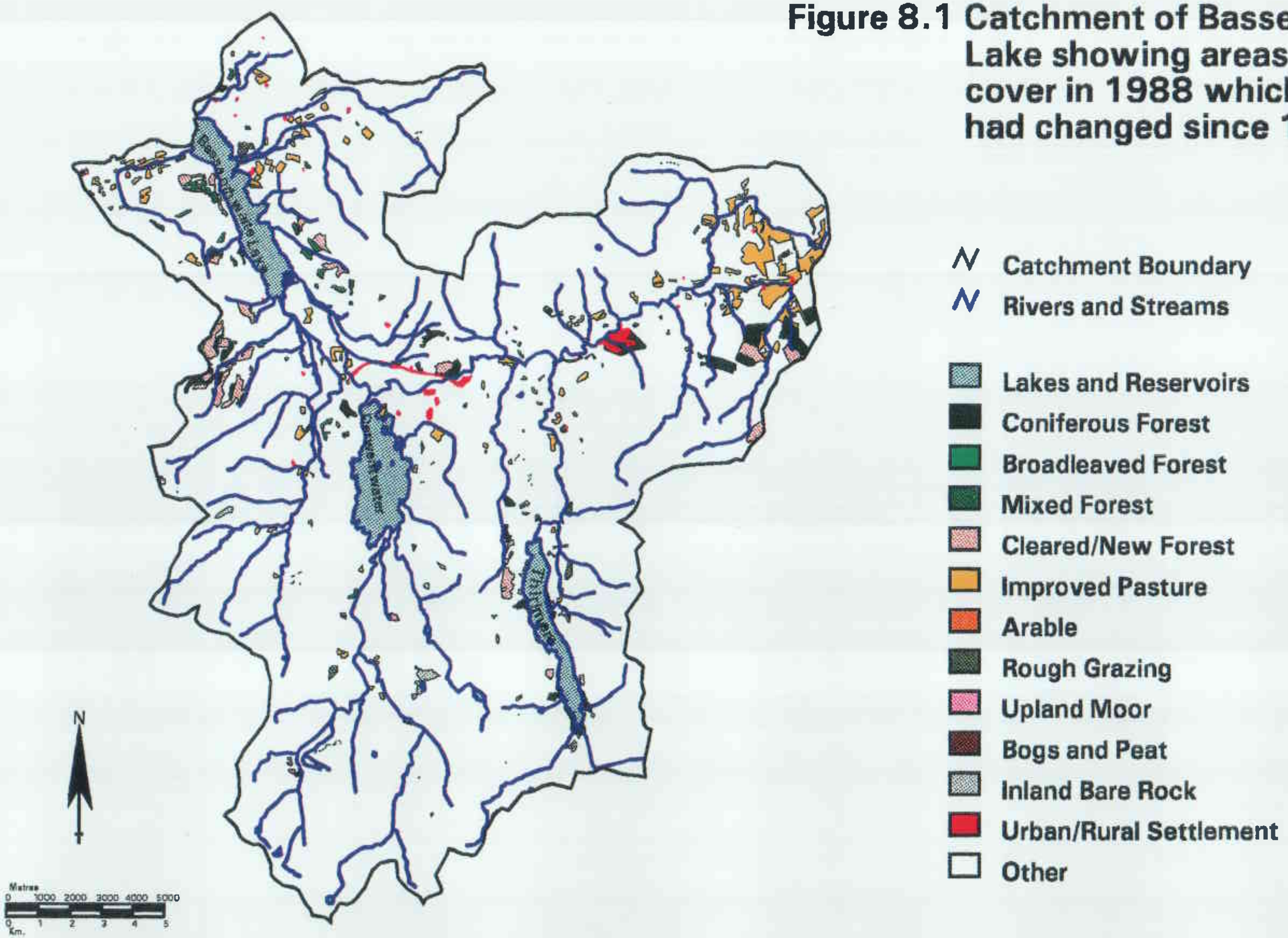
Table 8.1 shows the expected change in TP load to Bassenthwaite Lake associated with these changes in land cover between 1972 and 1988. The results suggest that this change in total

TP load amounts to an increase of only 180 kg TP yr^{-1} over this 16 year period. This represents increases of only 2.8% in the loading from land cover sources, and 1.1% in the total TP load to the lake.

8.4 Discussion

The results suggest that changes in land cover within the catchment are unlikely to have been responsible for any marked increase in nutrient load to the lake in the 16-year period between 1972 and 1988. Strict control over land use and development within the catchment is exercised by the LDNPA and other conservation bodies (LDNPA, 1993) and the results suggest that this has been successful in keeping changes in land cover, and related increases in nutrient load to the lake, to a very low level. Increases in TP laden discharges from STWs over this period are the more likely cause of increased TP loads to the lake and associated deteriorations in water quality.

Figure 8.1 Catchment of Bassenthwaite Lake showing areas of land cover in 1988 which had changed since 1972.



9 Introducing seasonality into the model

9.1 Introduction

The export coefficient approach, as it stands, predicts only the *annual* nutrient load to a lake from diffuse sources. In order to achieve the long term aim of using the output from the GIS as input to the dynamic lake model (Hilton *et al.*, 1993), it is necessary to introduce temporal variation into the nutrient loss predictions. The simplest way to do this is probably to derive a relationship between nutrient runoff and rainfall, *via* the effect of rainfall on stream flow. This chapter summarises work carried out by May *et al.* (1996) which goes some way towards achieving this by developing a model for the catchment which predicts stream flow from rainfall and soil characteristics. The method utilises readily available datasets, such as the national soils map and daily rainfall data.

9.2 Methods

The method used for predicting runoff from rainfall within the Bassenthwaite catchment is described in detail by May *et al.* (1996). In summary, the method allows the calculation of daily runoff values on the basis of incident rainfall, catchment wetness and soil hydraulic properties. Rainfall data for the period December 1992 to August 1993, were provided by EA, North West Region. Catchment wetness was derived from this. Soils information for the area, in combination with the Hydrology Of Soil Types (HOST) classification of Boorman *et al.* (1995), were also used in the runoff predictions.

9.3 Results

Ten soil types and fifteen different soil series were found within the catchment of Bassenthwaite Lake. **Table 9.1** gives the absolute and relative area of each soil type within the catchment, while **Figure 9.1** shows their geographical extent. In general, the soils of the catchment were composed of 3 main types. These were (1) well-drained loam with bare rocks and scree (38%), (2) shallow, acid upland peat (23%) and (3) fine loam (16%). The shallow acid upland peat occurred mostly on the uplands, while well-drained loam with bare rocks and scree was mostly found on the lower slopes and fine loam tended to cover the valley bottoms. Small areas of the remaining soil types, each amounting to less than 5% of the total catchment area, were scattered throughout the catchment. There was a strong correspondence between

Table 9.1 Areal extent of different soil types within the catchment of Bassenthwaite Lake.

Soil Type	Soil Description	Area (ha.)	Area (%)
1	Shallow, acid, upland peat	8,249	23
2	Well-drained loam, some bare rock	1,760	5
3	Reddish fine & coarse loam	20	0
4	Fine loam	5,720	16
5	Fine loam with peaty horizon	922	3
6	Stoneless fine silt & clay	658	2
7	Stoneless, clay, fine silt & loam	138	0
8	Thick, very acid peat soils	3,763	11
9	Gritty loam, very acid	610	2
10	Well-drained loam with bare rocks, crags & scree	12,945	38
		36,135	100

soil type and land cover. For example, 84% of shallow acid upland peat areas were covered by upland moor, while more than 65% of well-drained loam with bare rocks and scree and of fine loam were covered by improved pasture.

The results of the rainfall/runoff simulations for the Portinscale sub-catchment (which drains to sampling site 1a, see **Figure 3.1**) are shown in **Figure 9.2**. There is a marked correspondence between the predicted and measured values. This suggests that it is possible to predict temporal variation in stream flows from daily rainfall data and existing soils information for the catchment.

9.4 Discussion

The results show that fairly close interval temporal variation in runoff can be predicted from information about rainfall and soil type within the catchment. It should, therefore, be possible to extend this model to include the prediction of temporal variation in nutrient runoff. If so, this would allow the output from the catchment runoff model to be used as input to PROTECH, the dynamic lake model described in **Section 4**.

Figure 9.1 Catchment of Bassenthwaite Lake showing main soil types.

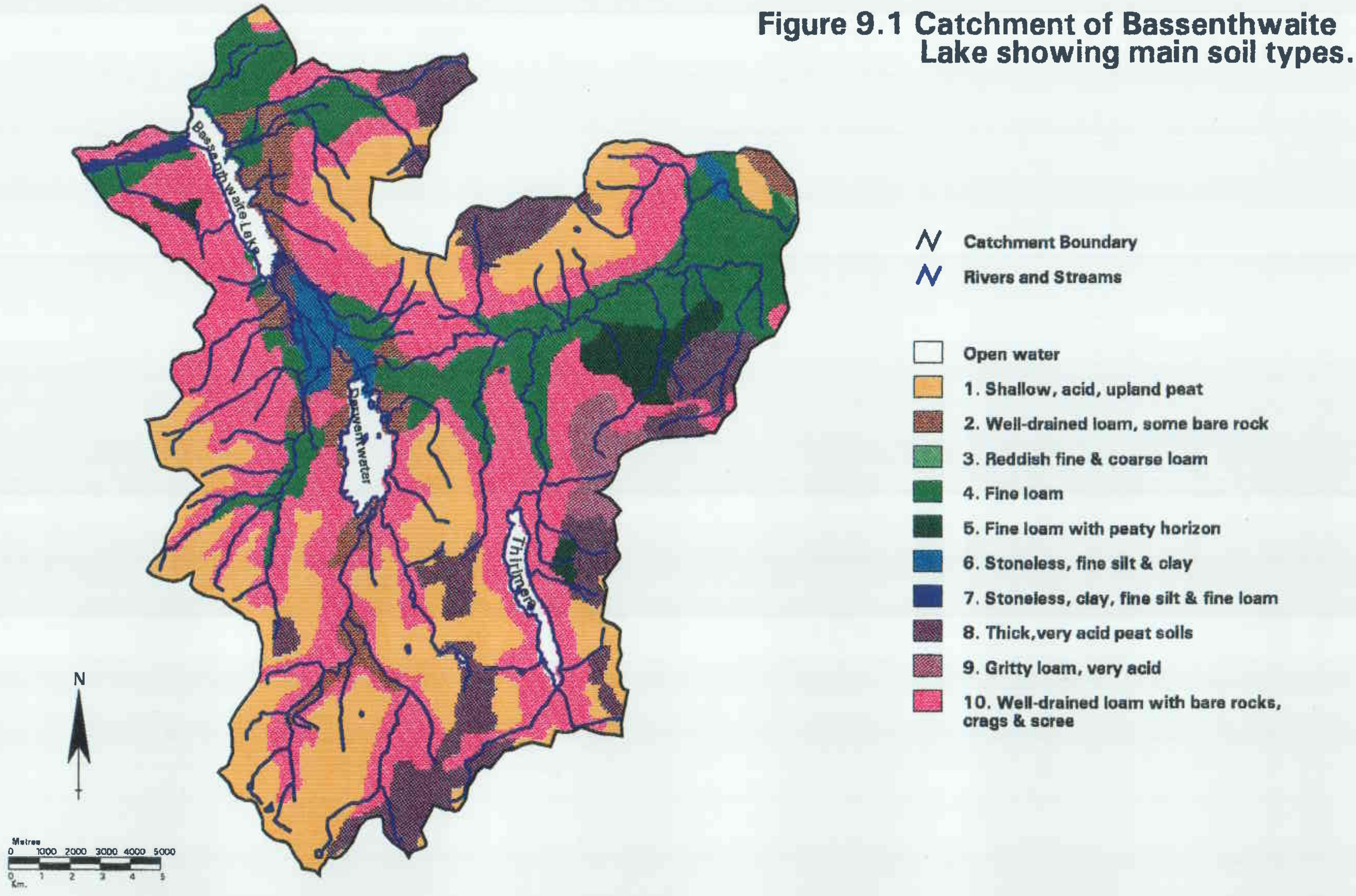
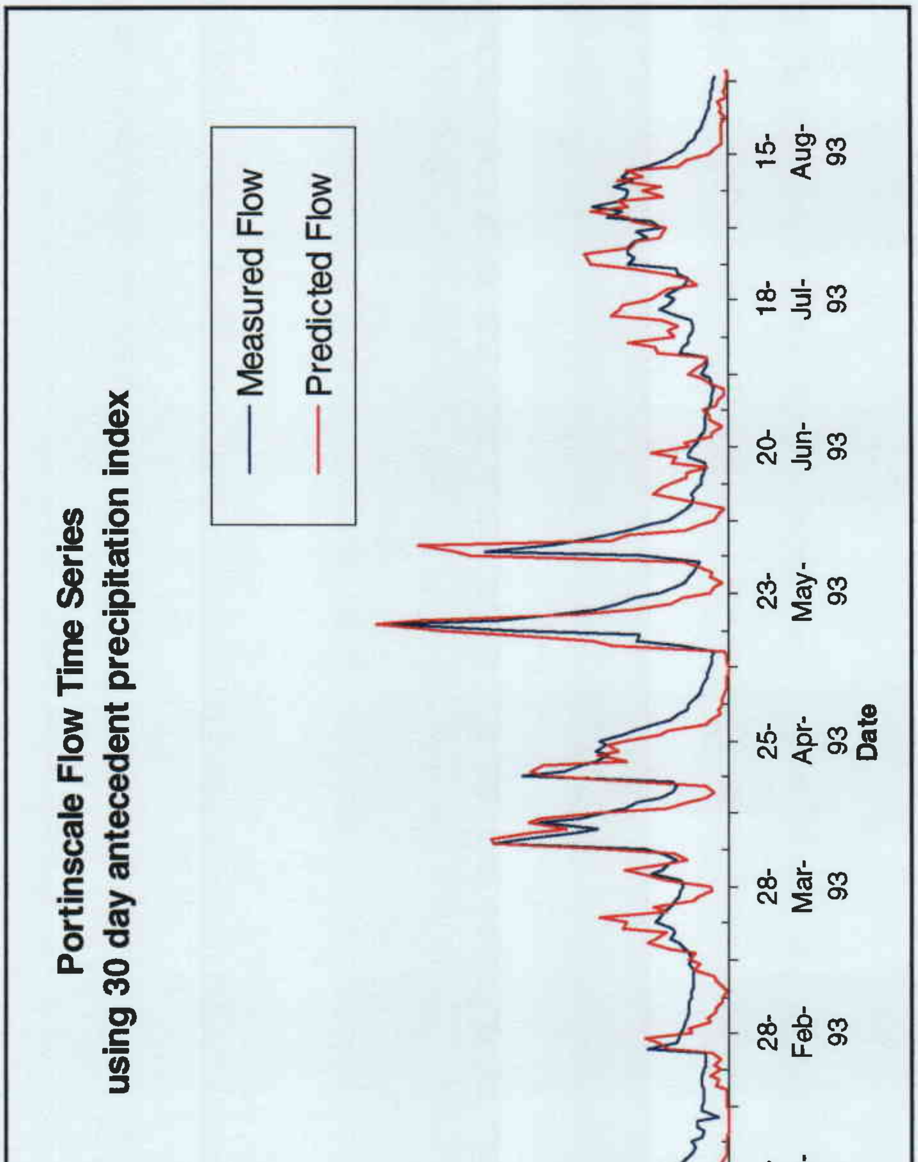


Figure 9.2 Predicted and measured flows for the River Derwent which drains the Portinscale catchment



10 General Discussion

Eutrophication, or nutrient enrichment, is a serious problem which affects many freshwater lakes and rivers in Britain. It is caused by increasing amounts of nutrients entering freshwater systems from their catchments, but is rarely recognised as a problem until it results in blue-green algal blooms. These are of great concern to water resource managers because they taint water supplies, clog filtration equipment and look unsightly, often resulting in increased water treatment costs and lost tourist revenues. Eutrophication may also affect the conservation status of a waterbody.

Improvements in water quality can only be achieved through a reduction in nutrient losses from the catchment. In order to do this it is, first, necessary to identify and then quantify the main sources of these nutrients. These fall into two main categories: point sources (such as effluent discharge pipes) and diffuse sources (such as farmland or forests). While it is relatively easy to assess nutrient losses from point sources, using simple end-of-pipe monitoring techniques, it is much more difficult to assess those arising from diffuse sources.

Some indication of the nutrient load from diffuse sources can be obtained by monitoring the streams draining the catchment. However, this method is expensive, time consuming, and gives little or no indication of where the nutrient load is coming from. An alternative approach is to predict nutrient loading using mathematical models and a range of catchment characteristics (e.g. river networks, drainage areas and land cover). Historically, this has involved the use of very labourious and time-consuming techniques to derive catchment information from paper-based maps. However, recent improvements in information technology have simplified the methodology by making these geographical datasets available in digital form. These data can now be analysed rapidly using specialist computer software, known as geographical information systems (GIS) to provide the information needed to run the nutrient runoff models. As a result, the catchment modelling method is now more cost-effective than the inflow monitoring technique and also has the major advantage that it can be used to compare a number of alternative catchment management strategies. This ability to evaluate "What if?" scenarios is of particular interest to water resource managers.

This project has demonstrated how a GIS-based nutrient runoff model can be used to assess the total phosphorus (TP) load to a lake from its catchment, using the example of Bassenthwaite Lake. This lake has a very high areal TP load (about 3 g $m^{-2} y^{-1}$) which is about 20 times higher than the OECD 'dangerous' limit for a lake of this size (OECD, 1982). Although this short retention time lake is able to sustain high TP loads without manifesting more than the occasional algal bloom, periodic deoxygenation of the deep still poses a threat to the survival of its rare vendace population (Hilton & McEvoy, 1993).

Nutrient inputs to Bassenthwaite Lake have increased since the mid- 1950s (George, 1992) due to many factors including increased population in the catchment, elevated use of phosphorus-based detergents and the general intensification of land use practices. However, no information on the nutrient load to the lake was available until the feeder streams were monitored in 1993 (Hilton *et al.*, 1993). Even then, there was little indication of where the nutrient load was coming from. The present study addressed this problem in relation to TP, as phosphorus had been identified as the limiting nutrient in this lake (Hilton *et al.*, 1993).

Annual TP losses from point sources were relatively easy to assess, as information about the size of each source was readily available. However, information on seasonal variation in TP output was available only for the large STW at Keswick. As the population in some areas of the catchment may double during holiday periods, much more detailed information on temporal fluctuations in outputs from these sources would be needed if the model were to be extended to include seasonal variation.

Losses from septic tanks were calculated using a *per capita* TP export coefficient obtained from the literature and an estimate of the number of septic tanks within the catchment. The latter was determined using a novel technique based on Ordnance Survey Point-Address data and sewerage connection data for the area. This technique is portable and could easily be used to assess TP losses from septic tanks for any catchment in Britain, but its validity depends on the accuracy of the export coefficient used. Very few studies have investigated the eventual fate of nutrients which enter septic tanks. However, this study suggests that they make an important contribution to the nutrient load of lakes and rivers and, as such, merit more detailed investigation than they have received so far.

Although annual TP losses from land cover sources were estimated using a GIS-based 'export coefficient' approach, the study showed that care must be taken in the choice of export coefficient used for this to give valid results. For example, the export coefficient taken from the literature for afforested areas significantly overestimated the measured TP losses from such areas in the Bassenthwaite catchment. At first, this suggested that the TP export coefficients determined for coniferous forests in Scotland could not be used on similar types of land cover in the Lake District. However, further investigation suggested that recent changes in forestry practice, aimed at reducing soil erosion and nutrient runoff, had probably reduced TP losses from afforested catchments since these earlier determinations (Harriman, 1978) were made . The present study suggested that these changes may have reduced TP losses from coniferous forests from 0.42 kg ha^{-1} y^{-1} to about 0.15 kg ha^{-1} y^{-1}, a reduction of about 64%.

The problem outlined above highlights the need for the degree of transferability of export coefficients between catchments to be investigated in more detail. Most published values have been determined for a particular catchment under local conditions of climate, underlying geology and soil type, degree of soil waterlogging, slope, local forestry and farming practices, *etc*. Many of these factors are known to affect TP loss rates (Harper, 1993). As a result, significant errors could occur when these values are applied to the same land cover type in other catchments with different topography and soil characteristics. It is essential, therefore, that dependence on catchment characteristics be addressed if a more robust and universally applicable approach is to be adopted. In the short term, however, the careful selection of export coefficients which have been determined for catchments with similar land cover, soil type, topography, climate, *etc*., seems to give results which are good enough to allow managers to identify the main causes of eutrophication within their catchments and target limited resources effectively. In the longer term, it would be better to understand the mechanisms which determine TP losses and use more complex models (such as those being developed by the IFE (Tipping, in press)) to predict TP load under different hydraulic conditions. This work could also be extended to include other nutrients, such as nitrate-N and silica, as these may also limit the production of certain phytoplankton species at certain times of year.

The export coefficient approach to predicting nutrient losses from diffuse sources results in a mean *annual* figure for nutrient runoff, only. While this is acceptable for some applications, for others it is necessary to introduce *temporal variation* into the predictions. This is something which is difficult to achieve using a simple GIS approach and requires more complex models to be linked to the GIS in such a way as to use output from the GIS as input to the models. As a first step in this process, May *et al.* (1996) derived a methodology for predicting temporal variation in stream flow from daily measurements of rainfall, using only readily available catchment scale parameters. This work could be extended to include the prediction of temporal variation in nutrient runoff, an approach which has been successful in addressing catchment management problems in the USA (He *et al.*, 1993; Mitchell et al., 1993; Srinivasan & Arnold, 1994; Tim & Jolly, 1994). However, the models used are not directly applicable to the different climate and soil types found in Britain, so further research would be needed to implement this methodology in the UK. Once successful, this would allow the GIS to be linked to a lake model such as PROTECH (Hilton *et al.*, 1993), resulting in a combined model which could be used to predict the effect of these loadings on the water chemistry and phytoplankton concentrations of the receiving waters. Such a link would allow water resource managers to evaluate different catchment management scenarios in a cost-effective manner.

This study illustrates the way in which a GIS system can be used to assess diffuse inputs of nutrients to freshwater systems from their catchments. The general methodology used can be readily transferred to other catchments, if similar datasets are available describing the catchment characteristics. Although the LDNPA land cover dataset used in the present study, covers only a limited geographical area, nutrient runoff can also be estimated for catchments outside this area through the use of a national dataset, such as the land cover dataset available from the Institute of Terrestrial Ecology. National datasets for soils, topography, river networks and meteorology are also readily available in digital form from a range of organisations.

11 Conclusions

(1) Phosphorus is the main nutrient limiting algal abundance in Bassenthwaite Lake.

(2) The main sources of TP from the catchment, following the upgrade of the Keswick STW, were land cover (52%), STWs (21%) and septic tanks (18%).

(3) GIS is a useful technique for estimating nutrient loads from diffuse sources.

(4) Further research is needed to introduce seasonality into the model so that it can be linked to a dynamic lake model, such as PROTECH.

12 Recommendations

The prediction of nutrient losses from point and diffuse sources within a catchment would benefit from the following:

- extending the range of nutrients considered to include OP, NO_3-N, and SiO_2, as these also affect algal growth
- assessing nutrient losses from septic tanks
- introducing temporal variation into the nutrient loss predictions
- linking to a dynamic lake model such as PROTECH

It is important, however, that any work carried out on the above contributes towards the original aim of the project which was to develop a generic model for use on any lake catchment.

13 Acknowledgements

We thank the following organisations who provided data for this study:

Environment Agency, North West Region
Institute of Hydrology
Institute of Freshwater Ecology
Institute of Terrestrial Ecology
Lake District National Parks Authority
North West Water Limited
Ordnance Survey
Soil Survey and Land Research Centre, Cranfield University

We are also grateful to Simon Courtney and Jane Robertson (NERC Computer Services), for their help in solving technical problems, to the Royal Mail Postcodes Service, Inverness, for their help in finding missing postcodes, and to Alan Fishwick and John Clayson, LDNPA, who originated the idea of using postcode data to locate septic tanks within the catchment.

14 References

AA (1990) *Hotels and Restaurants in Britain*. Automobile Association, Basingstoke.

Atkinson, K.M., Elliot, J.M., Heaney, S.I., Mills, C.A. & Talling, J.F. (1989). *Bassenthwaite Lake: a general assessment of environmental and biological features and their susceptibility to change*. Report to North West Water Authority, England, by the Freshwater Biological Association, 44 pp., 14 Tables, 23 Figures, 1 Appendix.

Bailey-Watts, A.E., Sargent, R., Kirika, A., & Smith, M. (1987) *Loch Leven Phosphorus loading*. Contract Report to Department of Agriculture and Fisheries, Nature Conservancy Council. Scottish Development Department and Tayside Regional Council.

Boorman, D.B., Hollis, J.M. & Lilly, A. (1995) *Hydrology of soils types: a hydrologically-based classification of the soils of the United Kingdom*. Institute of Hydrology, Report No. 126, Wallingford, UK.

Cranwell, P.A., Haworth, E.Y., Davies, P.S., Lawlor, A.J. & Lishman, J.P. (1995). *Bassenthwaite catchment studies phase 3b. Assessment of historical changes in Bassenthwaite Lake by analysis of a deep sediment profile*. Report to National Rivers Authority, North West Region, England, by Institute of Freshwater Ecology, 32 pp., 13 Figures, 7 Tables.

Casey, T.J., O'Connor, P.E. & Greene, R.G. (1981) A survey of phosphorus inputs to Lough Leane. *Irish Environmental Science* 1: 21-34.

Cooke, G.W. & Williams, R.J.B. (1973) Significance of man-made sources of phosphorus: fertilizers and farming. *Water Research* 7: 19-33.

Dillon, P.J. & Kirchner, W.B. (1975) The effects of geology and land use on the export of phosphorus from watersheds. *Water Research* 9: 135-148.

ESRI (1992) *Understanding GIS. The ARC/INFO Method*. Publ. Environmental Systems Research Institute Inc., Redlands, USA.

Frost, A. (1996) *Loch Leven and diffuse pollution*. In: Petchey, A. M., D'Arcy, B.J. & Frost, C.A. (eds.) Diffuse Pollution and Agriculture. Publ. The Scottish Agricultural College, Aberdeen, pp. 174-182.

George, D.G. (1992) *A general assessment of long-term changes in the larger lakes of the English Lake District*. Report to National Rivers Authority, 33pp.

Hancock, C.G. (1982) *Sources and utilisation of nutrients in the Loch of Strathbeg, Aberdeenshire*. PhD. Thesis, University of Aberdeen.

Harper, D.M. & Stewart, W.D.P. (1987) The effects of land use upon water chemistry, particularly nutrient enrichment, in shallow lowland lakes: comparative studies of three lochs in Scotland. *Hydrobiologia* 148: 211-229.

Harriman, R. (1978) Nutrient leaching from fertilised forest watersheds in Scotland. *J. Applied Ecology* 15: 933-942.

He, C.S., Riggs, J.F. and Kang, Y.T (1993) Integration of geographic information syatems and computer models to evaluate impacts of agricultural runoff on water quality. *Water Resources Bulletin* 29: 891-900.

Hilton, J. & McEvoy, J. (1993) *Bassenthwaite Catchment Studies - Phase 2: Terms of Reference to monitor the nutrient loading to Bassenthwaite Lake and assess the likely impact of phosphorus removal on lake productivity and water quality.* (Terms of Reference as negotiated with National Rivers Authority). IFE, Windermere.

Hilton, J., May, L. & Bailey-Watts, A.E. (1993) *Bassenthwaite Lake: an assessment of the effects of phosphorus reduction at the Keswick STW on the seasonal changes in nutrients and phytoplankton, using a dynamic model.* Report to the National Rivers Authority, North West Region by Institute of Freshwater Ecology, Edinburgh Laboratory.

IH (1978) *Low flow studies report. Section 1.* Institute of Hydrology, Wallingford.

Jones, J.G. (1972). Studies on freshwater micro-organisms: phosphatase activity in lakes of differing degrees of eutrophication. *J. Ecol.* 60: 777-791.

Lawlor, A.J. & Tipping, E.W. (1995) *Synoptic studies of nutrient leaching from soils of the catchment of Bassenthwaite Lake.* Report to the National Rivers Authority, North West Region by Institute of Freshwater Ecology, Windermere Laboratory, 16 pp., 4 figures.

Lelek, A. (1987). *The freshwater fishes of Europe.* Volume 9. Threatened fishes of Europe. AULA-Verlag, Wiesbaden.

Maitland, P. S. & Lyle, A. A. (1991) *Conservation of freshwater fish in the British Isles: the current status and biology of threatened species.* Aquatic Conservation: Marine and Freshwater Ecosystems 1: 25-54

May, L., Place, C.J. & George, D.G. (1995) *The Development of a GIS-based catchment model to assess the effects of changes in land use on water quality.* Report to National Rivers Authority, North West Region, by Institute of Freshwater Ecology, Edinburgh Laboratory, 21 pp., 7 Figures, 9 Tables, 2 Appendices.

May, L., Place, C.J. & George, D.G. (1996) *The effects of soil type on nutrient losses and runoff in the catchment of Bassenthwaite Lake.* Report to National Rivers Authority, North West Region, by Institute of Freshwater Ecology, Edinburgh Laboratory, 46 pp., 16 Figures, 4 Appendices.

Mitchell, J.K., Engel, B.A., Srinivasan, R. & wang, S.S.Y. (1993) Validation of AGNPS for small watersheds using an integrated AGNPS/GIS system. Water Resources Bulletin 29; 833-842.

Mubamba, R. (1989) *The ecology of coregonid fishes in the English Lake District*. Ph.D. Thesis, University of Wales.

OECD (1982) *Eutrophication of waters, monitoring assessment and control*. Organisation for Economic Cooperation and Development, Paris.

Pearsall, W.H. (1920) The development of vegetation in the English Lakes, considered in relation to the general evolution of glacial lakes and rock basins. *Proc. R. Soc.* (B) 92: 259-284.

Ramsbottom, A.E. (1976) *Depth charts of the Cumbrian Lakes*. Freshwater Biological Association Scientific Publication No. 33, 39 pp.

Rodda, J.C. & Jones, G.N. (1981) Preliminary estimates of loads carried by rivers to estuaries and coastal waters around Great Britain derived from the harmonized monitoring scheme. *J. Inst. Water Eng. Sci.* 37: 529-539.

Smith, I.R. (1974) The Structure and physical environment of Loch Leven, Scotland. *Proc. R.S.E. (B)* 74: 81-100.

Srinivasan, R. & Arnold, J.G. (1994) Integration of a basin scale water quality model with GIS. *Water Resources Bulletin* 30: 453-462.

SSEW (1983) *Legend for the 1:250,000 Soil Map of England and Wales (A brief explanation of the constituent soil associations)*. Lawes Agricultural Trust (Soil Survey of England and Wales), Rothamstead Experimental Station, Harpenden.

Tim, U.S. & Jolly, R. (1994). Evaluating agricultural non-point source pollution using integrated geographic information systems and hydrological water quality models. *Journal of Environmental Quality* 23: 25-35.

DISTRIBUTION SHEET

To be completed by all Project Leaders completing commissioned research project reports. Please bind a copy of this distribution sheet as the final page in all internal (IFE) copies of the report.

1	Title: An Assessment of the Nutrient Loadings from the Catchment to Bassenthwaite Lake Authors: May, L., Place, C.J., George, D.G. & McEvoy, J. Report ref: ED/T11067b7/1 Master copy held by: LM Report access code (assign a suitable code from list below): N		
2	DISTRIBUTION LIST [A)-H) standard, I) other]	No.copies	Date
A)	Contract customer: J McEvoy, Environment Agency	10	31/3/97
B)	Director - Professor A.D. Pickering	1	31/3/97
C)	Asst Director - Professor J. Hilton (title page and abstract only)	1	31/3/97
D)	River Laboratory Library	1	31/3/97
E)	Windermere Library	1	31/3/97
F)	Diana Morton (title page only + no.pages for adding to publication list)	1	31/3/97
G)	Project leader: D G George, Windermere	1	31/3/97
H)	Other (list below and indicate no.copies in RH column)		
1	L May	1	31/3/97
2	C J Place	1	31/3/97
3	J Clayson, Lake District National Parks Authority, Kendal	1	31/3/97
4	T R E Thompson, Soil Survey and Land Research Centre, Cranfield Univ.	1	31/3/97
5			
6			
7			
8			
9			
10			
	Total number of copies made	20	

REPORT ACCESS CODES

S **In strict confidence - restricted access** - Access to named customer(s) - (could be named restricted access individuals), IFE Directorate, Project Leader and all authors.

C **In confidence - restricted access** - Access to customer, IFE Directorate, Project Leader, all authors, and IFE staff with permission of Project Leader.

N **`Normal' access** - Access to customer and all IFE staff. Access to visitors and general public with permission of Project Leader.

G **General access** - General access to anyone as required.