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Monitoring the Trophic State of Reservoirs

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SUMMARY

The purpose of this study was to recommend a scheme suitable for the monitoring of the trophic status of reservoirs and lakes in the United Kingdom. After reviewing all options it is recommended that the simplest practical method would be the determination of total phosphorus and total nitrogen in 1 to 3 lake-side samples taken in the period January to March. Assessment of the trophic status can be based on the fixed boundary method for total P which was developed by OECD.

It is recommended that where record's are available chlorophyll measurements be used to confirm the classification. There should also be a further test survey of some 50 reservoirs to evaluate the usefulness of sedimentary pigments as an indicator of the trophic status of a water body.

OBJECTIVES

To establish requirements, methodology and a minimal data set for nutrient and algae status in water supply reservoirs in England which may be used as a protocol for future trend monitoring.

PROGRAMME OF WORK

1. Review literature and validate existing approaches.
2. Carry out desk study of methodology.
3. Optimise sampling strategy by cost effectiveness.
4. Conduct trial sampling analysis as and if required.
5. Liaise with water authorities in the selection of about 150 reservoirs, each of over 25 ha area suitable for study (subject to review of items 1-4).
6. Provide brief 6 monthly progress reports and multiple copies of an approved final report in manual form on the proposed methodology and reservoir classification.
7. Determine as part of Item 6 any need for additional research to pre-validate techniques.

BACKGROUND

For many years the quality of river waters in England and Wales has been classified and reported at about five yearly intervals using a standardised system. Changes with time are easily visualised allowing the effects of national policies to be assessed. More recently the DoE has felt that this approach could be usefully modified, with particular reference to eutrophication, and applied to lakes and reservoirs (Seventh Report of the royal Commission on Environmental Pollution, 1979). The feeling has been strengthened by the likelihood that phosphorus will become a class II compound in imminent EEC legislation. In 1984 the 4th. Biennial Report of the Standing Technical Advisory Committee on water quality alluded to the results of a survey of eutrophication in standing waters in the UK which they had carried out in response to the 7th report of the Royal Commission on Environmental Pollution. However, they concluded that their approach, using a questionnaire, could not be used as a basis for monitoring change in trophic status and should not be repeated.

In October 1985 a meeting of Water Authority representatives and other interested parties was convened by the Department to look at the feasibility of introducing a lake classification scheme into the 1985 River Quality Survey (RQS). For financial reasons a pragmatic compromise was reached to the effect that lakes on rivers for which a classification was already available would be included using the rivers classification. However, the meeting concluded that a high priority should be given to a research based study of eutrophication survey methodology with a view to producing a useable, low-cost survey and reporting procedure for use in the RQS report due in 1990. This contract is the resulting research study.

Trophic status - a definition

The term trophic status was originally introduced by Nauman (1919) to describe the clarity of waters with particular regard to the effect of algal turbidity. However, more recently the term has tended to be used to describe productivity. As the two functions are often related the intended definition of trophic status can often be unclear. Practically, lakes are generally split into five groups, depending on their productivity and/or their clarity:

oligotrophic - low productivity and extremely clear waters;

dystrophic - low productivity with brown coloured often acid water which reduces the clarity;

mesotrophic - intermediate levels of productivity and clarity;

eutrophic - high levels of production and very turbid water;

hypertrophic - productivity is so high that unsightly algal scums form, decaying and respiring algae can reduce the oxygen levels below those capable of sustaining fish and water clarity is similar to pea soup.

Over geological time lakes slowly reduce in the size due to sedimentation. This creates a natural progression from oligotrophic to eutrophic conditions. Hypertrophic conditions are generally but not always the result of man's activities. (A further subgroup of the eutrophic lakes are those which have experienced accelerated eutrophication due to man's activities. These are termed culturally eutrophic).

As eutrophication is so poorly defined, classification into groupings becomes subjective. However, it is relatively easy to assemble a list of the characteristics typically displayed by lakes at the trophic extremes (Table 1).

It is more difficult to classify lakes on a scale between these extremes but many schemes have been proposed based on the generally observed behaviour of the biological community as lakes move from oligotrophic to hypertrophic conditions. (Fig.1). Most classes of aquatic life have been suggested as indicator species, some examples are given in Table 2. There are several reasons why these classifications are not particularly useful in a national survey: i) they often require a high level of skill in species identification which is not commonly available; ii) many of the species changes are driven by changes in oxygen concentrations rather than directly by productivity increases. This would make it difficult to separate the effects of eutrophication from organic pollution; iii) the relationship with oxygen reduction results in low sensitivity to change at the oligotrophic/mesotrophic level (Wiederholm, 1984), i.e. early warning of change would not be identified; iv) the resulting classifications bear no quantitative relationship to concentrations of the usual causal, agencies (i.e. phosphorus and nitrogen) precluding their use in predictive models for testing management strategies (Lambou, et al., 1983).

Because of the difficulties caused by the subjective nature of the assignment of lakes to different categories, a great deal of effort has been expended on the development of more rigorous classifications based on the results of chemically and physically measurable parameters. These have the advantage that chemical expertise is more widely available and methods are more easily standardised than biological methods, however they too, eventually rely on a set of calibration lakes which are defined subjectively, although the use of international compilations (OECD, 1982) does produce a stable and comparable baseline.

A popular approach in the late 1970s was the use of Trophic Status Indices (e.g. Boland, 1976) where five to ten parameters were weighted and summed to give a single numerical value. For several reasons, but mainly the fact that highly correlated variables are used to obtain the index, these approaches have fallen into disuse more recently and have been replaced by ranking measurements of individual parameters directly related to the driving factors of increasing eutrophication e.g. chlorophyll, phosphorus, nitrogen, secci disc. The choice of determinands in the most rigorous study (OECD, 1982) is based on the concept that "accelerated eutrophication is caused by excessive nutrient load and trophic reaction of the affected bodies of water". The original choice of parameters is given in Table 3.

These parameters can be split into three basic types: a) directly measured parameters e.g. Total P concentration; b) load information requiring a knowledge of average concentrations in inflows and the flowrate; c) rate measurements e.g. primary production rates, oxygen depletion rates. Given the requirement of establishing a base line data set of trophic status at a minimum cost, load type information is inappropriate. It requires large amounts of information on nutrient concentrations in all the inflows to any waterbody and the respective volumes of water associated with each concentration. This is a costly exercise and is more appropriate in detailed local studies to isolate major sources of input prior to the costing of management options. The OECD (1982) report showed that in most cases inlake concentrations correlated well with loadings so that, for a national survey, there is no advantage in using loading data. A similar conclusion holds for the use of primary productivity rates obtained from water column samples versus inlake chlorophyll a concentration. Again, the former requires much more work and is correlated to the latter. However, it has been suggested (e.g. Guillizzani et al. 1982) that annual productivity can be estimated from the pigment content of a single sample of the surface sediments. This aspect will be discussed in more detail later.

Hypolimnetic oxygen depletion rates only require two measurements a year to obtain an estimate of the rate, one at the onset of stratification and one immediately prior to overturn. However, it is not applicable to shallow lakes which do not stratify and is difficult to interpret in lakes which do not mix completely every year. The OECD (1982) report suggested that more work was required to confirm the potential of this determinand. However, recent unpublished work by Dr Heaney at the FBA has shown that oxygen depletion in the hypolimnion of the South Basin of Windermere is related to the occurence of a specific alga, Oscillatoria bourrellyi. In years where major growth of this alga appear, oxygen is removed from the hypolymnion when the settling algal mass reaches bottom waters. In other years, when the same level of nutrient loading exists, but the climatic variables are different, Oscillatoria bourrellyi does not become abundant and oxygen reduction is minimal. Consequently, hypolimnetic oxygen reduction, although a consequence of eutrophication, is not a useful parameter for a periodic national survey because it is not linked directly and is irregular in its appearance.

From the list of possible methods we are left with direct measurement of secci disc depth (or water transparency), chlorophyll a concentration, inlake phosphorus concentration, inlake nitrogen concentration, and estimates of mean productivity from sediment pigment concentrations. A further possibility is the use of remote sensing to measure the equivalent of secci disc depth from orbiting satellites. Each of these methods will now be discussed in more detail.

Method Choice

Secci disc depth (SD depth)

This is the depth below the water surface at which a disc of standard size and marking just disappears from view. It is a function of water clarity and, in many lakes, correlates well (inversely) with equivalent chlorophyll a measurements e.g. summer minimum, annual mean, summer mean. However, background colour or turbidity can have a serious effect on the sensitivity of the measurement (Lind, 1986) and it is highly variable throughout the year requiring relatively large numbers of measurements for a reliable estimate of the mean annual, mean summer or summer minimum depth. Consequently this parameter could only be used if it were routinely monitored by the Water Authorities. Unfortunately, although it is a very rapid and easy test to carry out it must be measured where the water depth is greater than the secci disc depth, i.e. away from the waters edge. This requires the use of a boat and, because of Health and Safety regulations, two samplers. As a result measurement is expensive and is rarely carried out by Water authorities or companies.

In the last decade an alternative to measuring secci disc depth directly has been the use of reflectance properties sensed remotely from observing satellites. (Scarpace et al., 1979; McGarrigle and Murray, 1980; Raitala et al., 1984; McGarrigle and Reardon, 1986). SD depth correlates well with reflectance intensity in several wavelength bands of the multispectral scanner (Raitala et al., 1984) and satellite data collection is almost simultaneous for all lakes in the UK.

Data costs from three sensors on two satellites presently flying are given in Appendix 1. These are the only combinations which have a resolution approaching the requirements of the exercise. From Part a of Appendix 1 only about 15 pixels from the Landsat multispectral scanner (pixel size 80 x 80 m) would be useable to estimate the reflectance of a 25 ha lake after removing edge affected pixels which would be contaminated by land surface reflections. Both Spot (20 x 20 m pixel) and Landsat TM (30 x30 m pixel) would supply sufficient usable pixels. Spot data is slightly cheaper (£84K-£109K depending upon whether the data has already been archived in the UK or not, when a special acquisition program would be necessary) but its spectral resolution is not as good as the Landsat TM (@ £120K). It would be rather risky to assume that NRSC, Farnborough would acquire a complete archive data set for the whole of England and Wales so that it would probably require a special program. Costs of the two data sets are about the same. These costs, say £120K, are only for data acquisition and processing, for a single date. No inclusion has been made at this stage for collection of ground truth/calibration data, etc. As Scarpace et al. (1979) have recommended that a minimum of three sampling dates is necessary then remote sensing would cost at least £360K.

Chlorophyll a concentration

The OECD (1982) report suggests that any one of the annual mean, the summer mean or the summer maximum can be used as an indicator of trophic status. However, chlorophyll a concentrations are highly variable throughout the year. For example, in a single year in Esthwaite Water values can vary by two orders of magnitude from 1 to 100 µg/l (Talling et al., 1986). Even when winter minima are excluded, and means are calculated for the 'summer' period from April to September the range can still be as wide. With such high variability a relatively large number of samples would be required to obtain a mean with a significant level of reliability. Statistical analysis of data from Esthwaite Water, which can be considered a worst case, show that the relative standard deviation (RSD = SD/mean) about the annual mean logarithmically transformed data from weekly samples is about 100%. The standard error of the mean is given by $SD/\sqrt{n}$, where SD^2 is the true variance and n is the number of samples taken. Hence the standard deviation of the mean would be 50% for four samples, 33% for 9 samples, 25% for 16 samples and 20% for 25 samples. The latter would be equivalent to weekly samples through the summer (April-September inclusive). Weekly sampling = 20%, fortnightly = 29%, and monthly = 41%. This assumes that variations are random but the annual change in chlorophyll follows a regular pattern, and if samples are taken at regular intervals throughout the summer, then the s.e. of the mean will be hard to calculate but lower than these estimates. The example of Esthwaite is a particularly severe case as it has a late spring clear water phase, increasing the variability compared to many other lakes.

As a consequence chlorophyll a can only be used if measurements are made routinely on the majority of water bodies of interest. In a survey of Water Authorities carried out as part of this contract (see later) chlorophyll analysis frequency varied from never to weekly depending on the perceived nuisance level of eutrophication in any region. Hence the use of chlorophyll a, as the sole indicator of trophic status, without considerable government money and pressure on the Water Authorities to increase their sampling, would give a biased indication of the extent of eutrophication. However, wherever this information is available it should be collected as part of the baseline survey to corroborate other procedures.

Phosphorus

Increasing concentrations of phosphorus are usually regarded as the main cause of cultural eutrophication. This was confirmed by the OECD (1982) who showed that even where nitrogen was apparently the limiting nutrient, phosphorus levels had been artificially elevated and reduction of phosphorus inputs to a level where phosphorus was limiting, was a more useful management option than nitrogen removal to ameliorate the effects of eutrophication. Several forms of phosphorus can be measured but the two most appropriate parameters are soluble reactive phosphorus (SRP) and total phosphorus (TP).

SRP has the same level of variability throughout a year as chlorophyll a and would be subject to the same limitations so that its usefulness in a baseline survey would be limited. Total phosphorus on the other hand maintains a relatively constant concentration throughout the year (RSD 25% on untransformed data). Using the same approach outlined in the chlorophyll a section the standard error of the annual mean (untransformed) can be estimated as a proportion of the mean for different numbers of samples. A single sample gives a standard error of 25%, two samples 17.7%, three samples 14.4% and four samples 12.5%. In other words the error associated with an estimate of the annual mean total phosphorus concentration from a single sample is less than the errors on the estimate of the annual mean chlorophyll a concentration obtained using weekly sampling throughout the year (N.B. all standard errors quoted for chlorophyll earlier are on log transformed data). There seems little point in taking more than three samples, as cost is a major factor in this exercise, and even a single sample (particularly taken between Jan-March where concentrations are very close to the annual mean, Fig. 2) would be acceptable. Appendix 2 shows that samples can be taken from the edge of the water body and still give a good estimate of the mean concentration reducing costs further. (This work was carried out during the summer when heterogeneity is likely to be at a maximum so that these are worst case data and the conclusions are equally valid for winter sampling.

Unfortunately very few Water Authority laboratories measure TP as its temporal invariance gives it little value as an operational management aid. It would put quite a heavy financial burden onto the Water Authorities if they were forced to introduce an extra method for a few samples a year, particularly when analyses must be carried out manually because of inhomogeneity in the sample (i.e. large samples need to be analysed as the inhomogeneous nature of particulate material makes results from micro-analysis very variable). However, TP is very stable and, once subsampled into a reaction vessel, changes in the form of phosphorus are irrelevant as the analytical treatment returns them all to orthophosphate. Hence samples for TP can be taken at one site and processed at a distant laboratory, where TP analysis is carried out routinely, without storage changes occurring. The same cannot be said for SRP where even filtered samples loose phosphorus due to irreversible absorption onto container walls (Heron, 1962). Because of its lack of temporal variability and its chemical stability Total phosphorus is an excellent parameter for monitoring long-term changes in trophic status.

Nitrogen

Several studies have concluded that Total (or Kjeldahl) nitrogen is a good indicator of trophic status (OECD, 1982; Labour et al., 1983). It is highly correlated with both TP and chlorophyll a. When reported in conjunction with TP it can be used to indicate whether a water body is nitrogen or phosphorus limited. Arguments relating to the sampling and analysis of TP are also valid for TN, except that samples must be treated with acid to pH 2 prior to storage to prevent loss of ammonia. A similar sampling strategy to that for total phosphorus would be adequate.

Sedimentary Pigments

Algae, when they die, settle to the lake bed. On the way a large proportion of the cells are degraded and, in oligotrophic lakes, only small proportion of the pigments (chlorophyll and carotenoids) reach the bottom, where, because of the high oxygen content in the water, degradation continues leaving very low concentrations in the sediments. However, as eutrophication increases, the increased rain of cells results in more pigment reaching the sediment surface, where, because of the onset of anaerobic conditions, degradation is much reduced.

In a series of publications it has been established that the concentration of pigments in lake sediments is related in a qualitative way to the trophic status of a lake (a good review is given by Swain (1985)). Adams et al. (1978) and Guilizzani et al. (1982, 1982) developed these ideas further and gave qualitative relationships for Italian lakes. On the basis of this work Murray and O'Byrne-Ring suggested the use of sediment pigments for ranking Irish lakes in order of trophic status.

Although increasing trophic state tends to increase the preservation of pigments, it is only a relatively slight effect compared to the increase in pigment input so that the relationship between productivity and pigment concentration is approximately linear (Guilizzani et al., 1982) allowing early warning of change to be observed. In theory a single sample from the deepest point should suffice to rank a lake, however a recent study of annual variability in sedimentary pigment concentrations (Hilton et al., submitted for publication) has shown that at least two samples are required and that total carotenoids are a better estimator than chlorophyll degredation products. A study of the effect is given in Appendix 3. The disadvantage of this method is that it requires samples from points away from the shore i.e. two men are obligatory, but it is a useful comparative method when chlorophyll a values are not available or when the cost of obtaining them would be prohibitive.

Presentation of results

Once again, we come up against the problem of the original subjective definition of trophic status. The difficulties can be seen in Figures 3 (a-e). Here each site in the OECD (1982) study was subjectively defined as ultra oligotrophic, oligotrophic, mesotrophic, eutrophic or hypertrophic using the normal qualitative criteria and a frequency distribution was plotted for each category for several important chemical measures of trophic status. The root of the problem is the large overlap between groupings which is worst for total nitrogen where the oligotrophic and mesotrophic groupings almost lie on top of each other. This is realistically reasonable for total N as most fresh waters contain relatively high concentrations of nitrogen so that the relationship with trophic status only becomes important at high trophic status i.e. high demand for nitrogen). The OECD (1982) suggested two methods of quantitatively defining trophic status based on this data. One method has fixed boundaries and the second has open (stochastic) boundaries.

The ranges for the fixed boundary method (Table 4) are obtained from the intersections of the different distributions. This has the advantage that it is easy to apply by non-specialists and a site can only be classified into one group, but there is a good chance that a site classified as, say, mesotrophic using this method could equally well be either eutrophic or oligotrophic by another method. The latter problem is so bad in the case of total nitrogen that it becomes impossible to obtain realistic boundaries to separate oligotrophic and mesotrophic ranges.

The open boundary system differs by using the principle of opting out, i.e. a site is excluded from a category if the parameter of interest is more than two standard deviations (log transformed data) away from the mean of each range (Table 5). This makes it much more compatible with the qualitative system while still maintaining quantitative ranges. However, it does mean that a site can be classified into more than one category which is not particularly useful in a trend monitoring survey.

Because of the dilemma created by the choice of either of these methods, i.e. closed ranges classify uniquely but possibly incorrectly; open ranges classify correctly but not uniquely, the OECD (1982) suggest that classification should never be carried out using a single variable. As many variables as possible should be used to crosscheck each assignment.

Ranges, either open or closed, have not been defined for sedimentary pigment concentrations. However, Guilizzani et al., (1982) have presented regressions of chlorophyll degradation products (CDP), carotenoids and total pigment concentrations against primary production and Vollenweider and Kerekus (1980) have published a relationship between productivity and phosphorus concentrations. Range limits can be estimated by back calculation from the phosphorus boundary values given by OECD (1982). Values are listed in Table 6 (NB the units used by Guilizzani et al., (1982) are 10 times the units recommended by Swain (1985). The latter units will be used in this work).

The size of the survey

An important factor in estimating the costs of any survey is the number of water bodies which must be included. Initial published estimates (Smith & Lyle, 1979) suggested that inclusion of lakes smaller than 25 ha (= 0.25 km^{-2}) would make the survey too large and costly. By sampling random maps and extrapolating to the whole of the UK Smith & Lyle (1979) suggested that 274 water bodies in England and Wales would be greater than 25 ha of which approximately 50% would be reservoirs. A better estimate of the numbers involved was attempted from a questionnaire to the Water Authorities (Appendix 4). Unfortunately replies were only received from 7 out of 10 but they indicated 132 water bodies greater than 25 ha of which 67% were water supply reservoirs.

As a final attempt to count the likely numbers of water bodies, 1/50 000 scale maps were searched manually and all lakes greater than 25 ha were noted, along with their name, grid reference, approximate area and altitude. 381 lakes were found (Fig. 4) of which 179 (47%) were indicated as reservoirs by their name. Combination of the WA survey and the map survey suggests that an equal number of lakes without the epithet "reservoir" are also used for potable water supply. Hence a best estimate would imply that 358 (70%) of all the lakes greater than 25 ha are used for potable supply.

Conclusions and recommendations

Secci disc depth is not a viable option as very few water authorities measure this property on lakes, while the use of remote sensing is quite expensive. Chlorophyll a measurements are a good indicator of trophic status but require relatively large numbers of samples to get a reliable estimate of either the annual mean or maximum. Water authorities generally only acquire this information in reservoirs and lakes where eutrophication is considered to be a problem. Reliance on chlorophyll a would result in a biased survey which grossly over estimated the importance of eutrophication. However, because of the OECD's (1982) recommendation to use as many estimates of trophic status as possible to corroborate classifications, chlorophyll a data should be located and combined with the results of a more extensive survey wherever possible.

Although sedimentary pigment content has been suggested for use as an indicator of trophic status it has not been tested to the same extent as other methods. We recommend that a low level of investment be made in studies to reduce the costs of collection and that in the year following the national survey a subsample of reservoirs (at least 50) are cored and analysed for sedimentary pigments. Their ranking could then be compared with the original survey and the method's usefulness as an indicator assessed for possible inclusion in future surveys.

Total phosphorus should be used as the prime basis of a national survey of trophic status. Total nitrogen should be analysed on all samples and used to corroborate classifications at the eutrophic/hypertrophic end of the scale. Because these parameters are not commonly analysed by all water authorities, samples should be collected and analysed by an outside agency which is equipped to do such work. This is made easier by the fact that no more than three samples collected between Jan and March are required from each site. Classification of trophic status should be reported using the fixed boundary OECD (1982) method for TP but open boundary classifications for TP, TN and annual mean and maxima Chlorophyll a. (where available) should be recorded to qualify the basic ranking. Soluble reactive phosphorus and nitrate should be analysed on each sample and plotted against TP and TN to give an indication of the limiting nutrient in each lake.

The original contract suggested that a survey should aim to cover 150 of the water bodies > 25. This was based on Smith and Lyles (1979) original estimates of the number of reservoirs in this size range. However, better estimates suggest that 250 out of the 358 standing water bodies in England and Wales, greater than 25 ha are likely to be reservoirs. Of the remainder many, e.g. lake district lakes, Norfolk Broads, are the basis of a large tourist industry. Hence, in the first instance, any survey should aim to assess all 358 lakes in England and Wales.

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Table 1. Qualitative characteristics of oligotrophic and eutrophic lakes taken from Welch (1980) and Mason (1981).

	Oligotrophic	Eutrophic
Depth	deep	shallow
hypolimnion vol: epilimnion vol.	>1	<1
depletion of hypolimnetic oxygen	no	yes
plant nutrient flux	low	high
primary productivity	low	high
rooted macrophytes	few	abundant (low in hypertrophic)
planktonic algal density	low	high
algal species diversity	high	low
frequency of planktonic blooms	rare	common
dominant algal group	chlorophyceae	cyanophyceae
animal production	low	high
fish	salmonids and coregonids	coarse fish

Table 2. Examples of semi-quantitative biological methods of trophic status assessment.

algal indicator species	Rawson (1956)
Araphidinae/centrales ratio in lake sediments	Stockner (1972)
Chlorocoeales/Desmideae ratio in waters	Nygaard (1949)
Zooplankton assemblages	Pejler (1983)
Chironomid assemblages	Saether (1975, 1980)
Oligochaete indicator communities	Milbrink (1978, 1983)
Fish species	Leopold et al. (1986)

Table 3

CONDENSED MEASUREMENT DATA USED FOR DATA ELABORATION
IN THE OECD PROGRAMME FOR MEASURING EUTROPHICATION OF INLAND WATERS
(Alpine, Nordic, Shallow Lakes and Reservoirs Projects)

Name of Lake: Year:

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1. Nutrient Load and Output

Units: tons/year

Variables:

total-P
PO_4-P
total-N
$(NH_4-N)+(NO_3-N)+(NO_2-N)$

2. Nutrient Concentrations

Units: mg/m^3

Variables:	Reporting units for each variable:
total-P	– spring overturn peak values of mixed layer
PO_4-P	– mean spring overturn concentration of total lake
tota-N	
$(NO_3-N)+(NO_2-N)$	– mean annual concentration of total lake;
NH_4-N	– mean concentration of euphotic zone, winter
SiO_2	– mean concentration of euphotic zone, spring
	– mean concentration of euphotic zone, summer
	– mean concentration of euphotic zone, autumn
	– mean concentration of euphotic zone, year

3. Planktonic Primary Production

Variables:	Units:
annual production	$g\ C/m^2/year$
minimal daily production	$g\ C/m^2/day$
maximum daily production	$g\ C/m^2/day$
average daily production, winter	$g\ C/m^2/day$
average daily production, spring	$g\ C/m^2/day$
average daily production, summer	$g\ C/m^2/day$
average daily production, autumn	$g\ C/m^2/day$
highest yearly maximum on depth profiles	$g\ C/m^3/day$
lowest yearly maximum on depth profiles	$g\ C/m^3/day$

4. Depth of Euphotic Zone

Units:

Method of calculation:

- from production profiles
- from photometric measurements
- from Secchi disc readings

Reporting Units:

- maximum value
- minimum value
- mean value

5. Phytoplankton and Chlorophyll a of the Euphotic Zone

Depth of euphotic zone is given in metres.

Concentration and standing mass

Variables:	Units: Concentration	Standing mass
– chlorophyll *a*	mg/m^3	mg/m^2
– algal volume	mg/m^3	mg/m^2

Reporting units for each variable:

- annual mean concentration and standing mass
- annual maximum concentration and standing mass
- mean winter concentration and standing mass
- mean spring concentration and standing mass
- mean summer concentration and standing mass
- mean autumn concentration and standing mass

6. Secchi Depth

Reporting units (in metres).

- annual mean
- mean winter
- mean spring
- mean summer
- mean autumn
- annual maximum
- annual minimum

7. Hypolimnetic Oxygen Depletion — Units: $g\ O_2/m^2$, $g\ O_2/m^3$

Reporting units:

– Difference between onset and end of summer stratification	$g\ O_2/m^2$
(unit volume of hypolimnion)	$g\ O_2/m^3$
– Average montly depletion rate	$g\ O_2/m^2$/month
(unit volume of hypolimnion)	$g\ O_2/m^3$/month

8. Physical and Hydrological Characteristics of Lake Catchment Area

Variable:	Units:
– catchment area excluding lake	km^2
– lake surface area	km^2
– volume of lake	m^3
– yearly water input	m^3
– yearly water output	m^3
– area of hypolimnion	m^2
– volume of hypolimnion	m^3
– maximum depth	m

Table 4. Proposed Boundary Values for Trophic Categories

(fixed boundary system)

Trophic Category	[P]	[chl]	[max] [chl]	[See]	[min] [Sec]
	mg/m^3			m	
Ultra-oligotrophic	$\leqslant 4.0$	$\leqslant 1.0$	$\leqslant 2.5$	$\geqslant 12.0$	$\geqslant 6.0$
Oligotrophic	$\leqslant 10.0$	$\leqslant 2.5$	$\leqslant 8.0$	$\geqslant 6.0$	$\geqslant 3.0$
Mesotrophic	10–35	2.5 – 8	8 – 25	6 – 3	3 – 1.5
Eutrophic	35 – 100	8 – 25	25 – 75	3 – 1.5	1.5 – 0.7
Hypertrophic	$\geqslant 100$	$\geqslant 25$	$\geqslant 75$	$\leqslant 1.5$	$\leqslant 0.7$

Table 5

PRELIMINARY CLASSIFICATION OF TROPHIC STATE
IN THE OECD EUTROPHICATION PROGRAMME

The geometric mean (based on log 10 transformation) was calculated after removing values < or > 2 SD obtained (where applicable) in the first calculation

Variable (Annual Mean Values)		Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Total		8.0	26.7	84.4	
Phosphorus	$\bar{x} \pm 1$ SD	4.85 – 13.3	14.5 – 49	48 – 189	
mg/m^3	$\bar{x} \pm 2$ SD	2.9 – 22.1	7.9 – 90.8	16.8 – 424	
	Range	3.0 – 17.7	10.9 – 95.6	16.2 – 386	750 – 1200
	n	21	19 (21)	71 (72)	2
Total	$\bar{x}$	661	753	1875	
Nitrogen	$\bar{x} \pm 1$ SD	371 – 1180	485 – 1170	861 – 4081	
mg/m^3	$\bar{x} \pm 2$ SD	208 – 2103	313 – 1816	395 – 8913	
	Range	307 – 1630	361 – 1387	393 – 6100	
	n	11	8	37 (38)	
Chlorophyll *a*	$\bar{x}$	1.7	4.7	14.3	
mg/m^3	$\bar{x} \pm 1$ SD	.8 – 3.4	3. – 7.4	6.7 – 31	
	$\bar{x} \pm 2$ SD	.4 – 7.1	1.9 – 11.6	3.1 – 66	
	Range	.3 – 4.5	3. – 11	2.7 – 78	100 – 150
	n	22	16 (17)	70 (72)	2
Chlorophyll *a*	$\bar{x}$	4.2	16.1	42.6	
Peak Value	$\bar{x} \pm 1$ SD	2.6 – 7.6	8.9 – 29	16.9 – 107	
mg/m^3	$\bar{x} \pm 2$ SD	1.5 – 13	4.9 – 52.5	6.7 – 270	
	Range	1.3 – 10.6	4.9 – 49.5	9.5 – 275	
	n	16	12	46	
Secchi	$\bar{x}$	9.9	4.2	2.45	
Depth (m)	$\bar{x} \pm 1$ SD	5.9 – 16.5	2.4 – 7.4	1.5 – 4.0	
	$\bar{x} \pm 2$ SD	3.6 – 27.5	1.4 – 13	.9 – 6.7	
	Range	5.4 – 28.3	1.5 – 8.1	.8 – 7.0	0.4 – 0.5
	n	13	20	70 (72)	

$\bar{x}$ = geometric mean
SD = standard deviation
( ) = value in bracket refers to the number of variables (n) employed in the first calculation.

Table 6. Absorbance units/g. org. matter*

	ultradigotrophic
Chlorophyll deg$\underline{h}$ products	$\leqslant$2.5
Carotenoids	$\leqslant$1.6
Total pigments	$\leqslant$2.6

* as defined by Swain (1985).

oligotrophic	mesotrophic	eutrophic	hypertrophic
≤6.4	6.4–12.8	12.8–21.7	>21.7
≤4.0	4.0–12.0	12.0–24.3	>24.3
≤10.3	10.3–28.2	28.2–51.3	>51.3

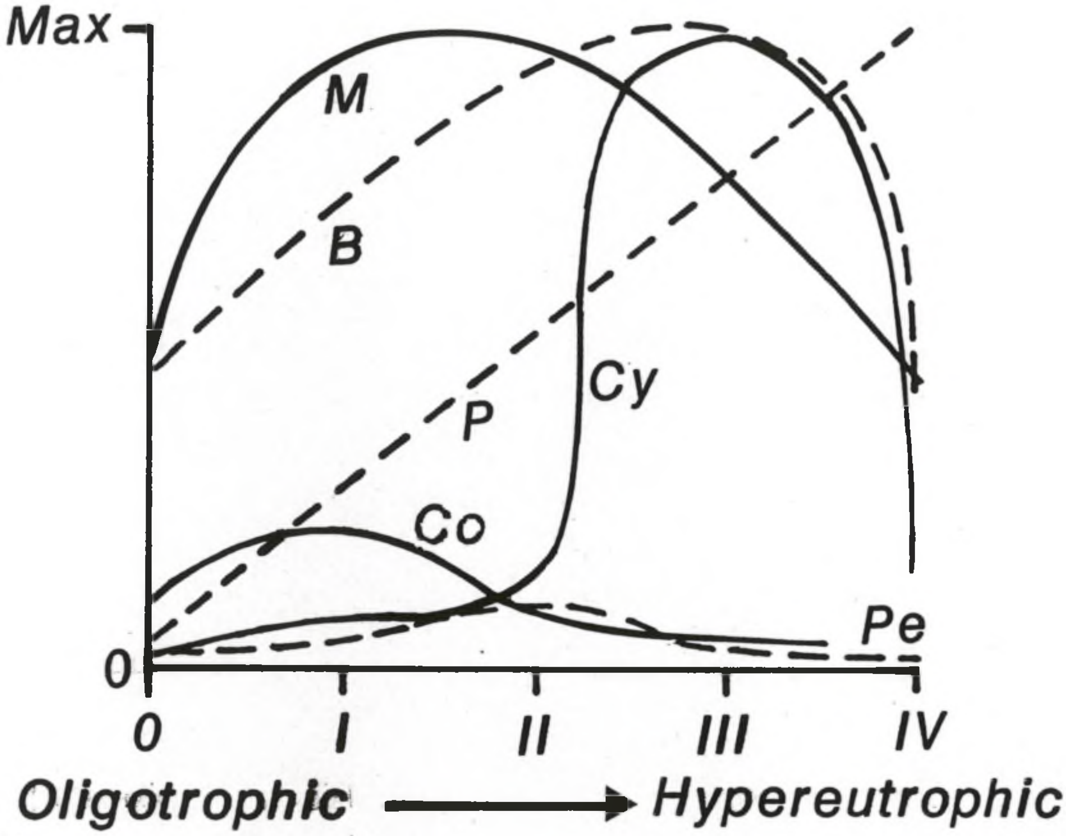


Fig. 1. Trends in eutrophicating lakes. B = density of benthos, Co = yield of whitefish (coregonids), Cy = yield of cyprinid fish, M = submerged macrophytes, P = phosphorus content of water, density of plankton and turbidity, Pe = yield of percid fish, O-IV = stages of eutrophication (from Mason, 1981).

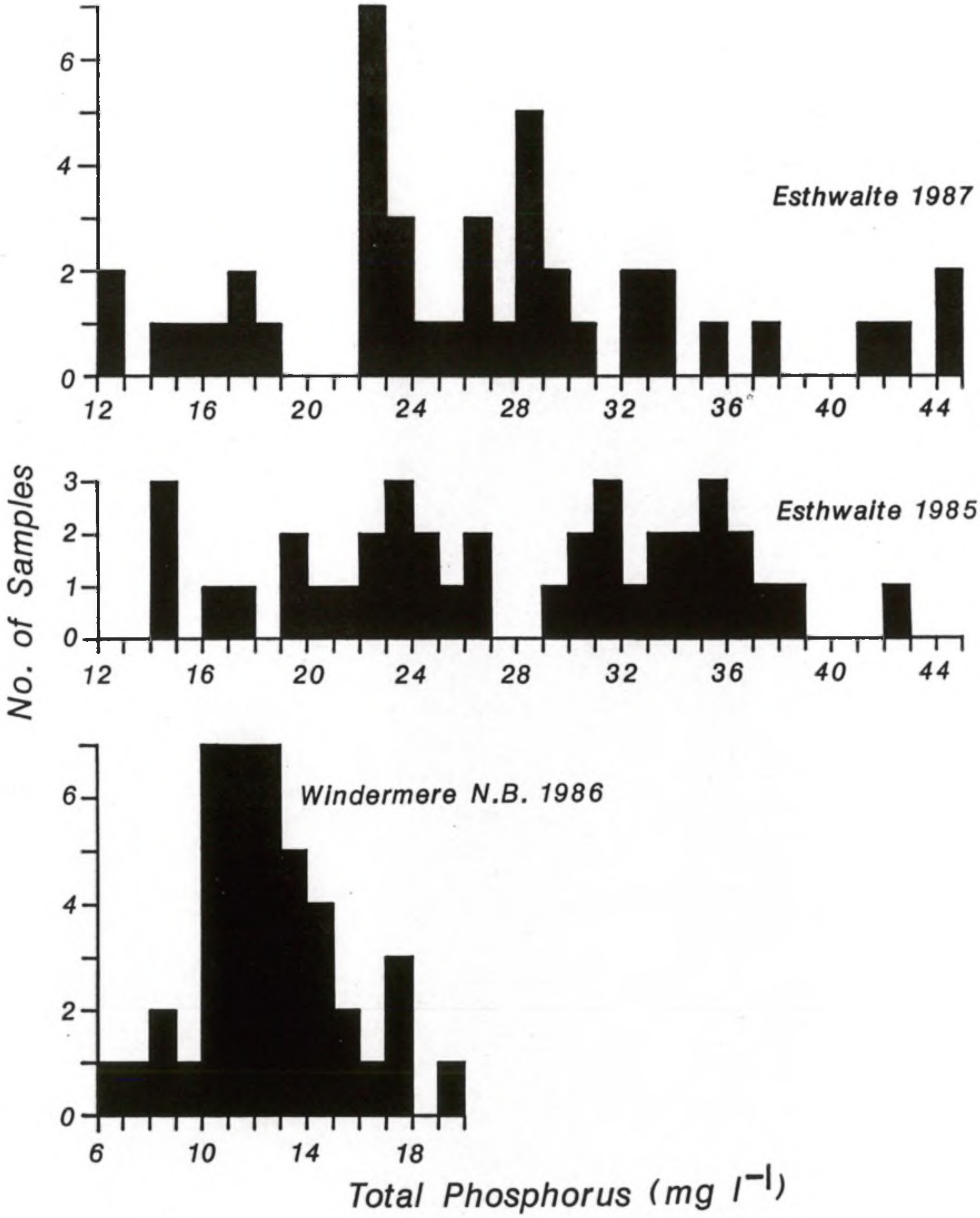


Figure. 2. Frequency distributions of Total phosphorus. Annual mean concentrations: Est 1987 = 26.7; Est 1985 = 27.6: Wind 1986 = 12.3

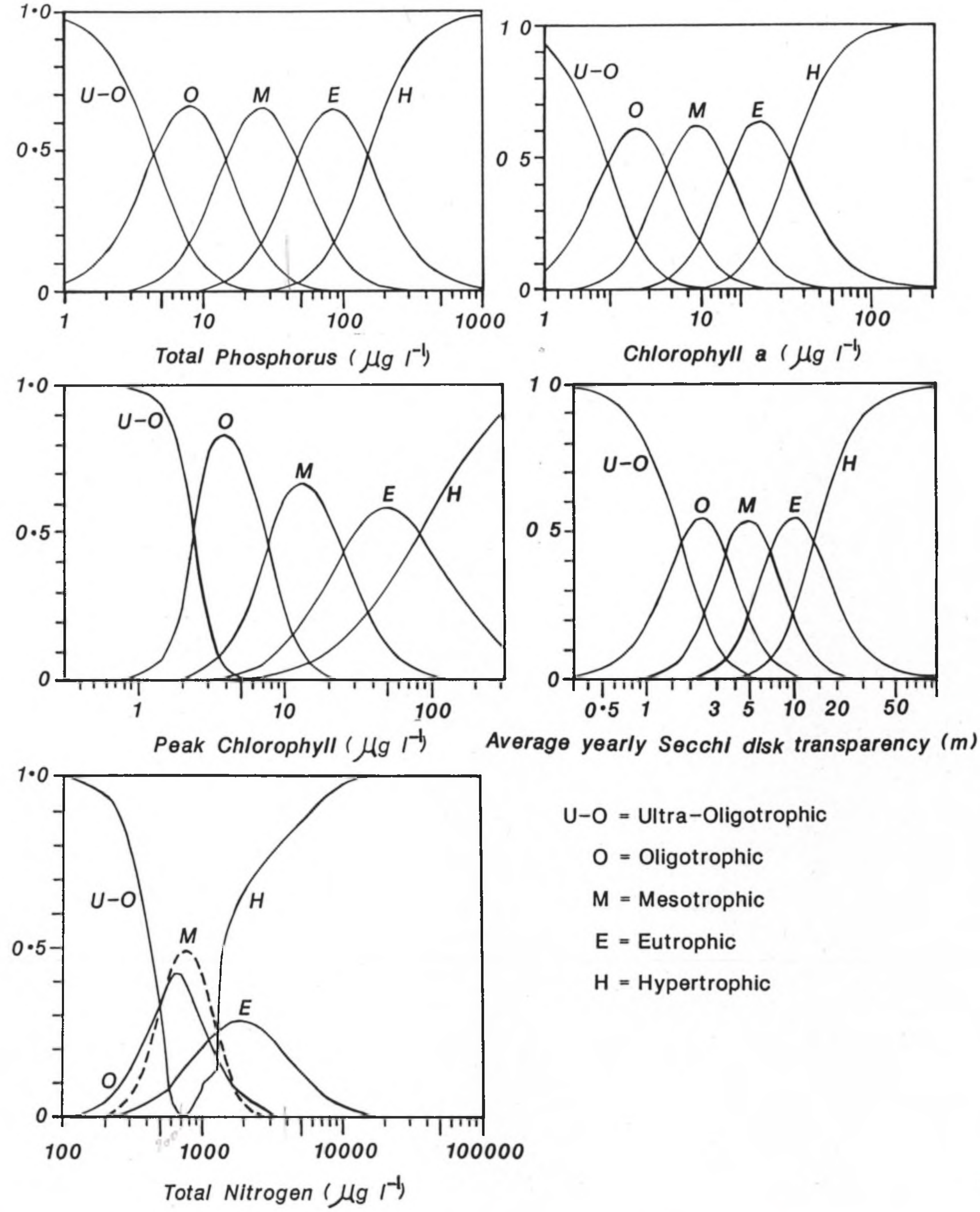


Figure 3. Probability distributions for trophic categories for several ecologically important variables.

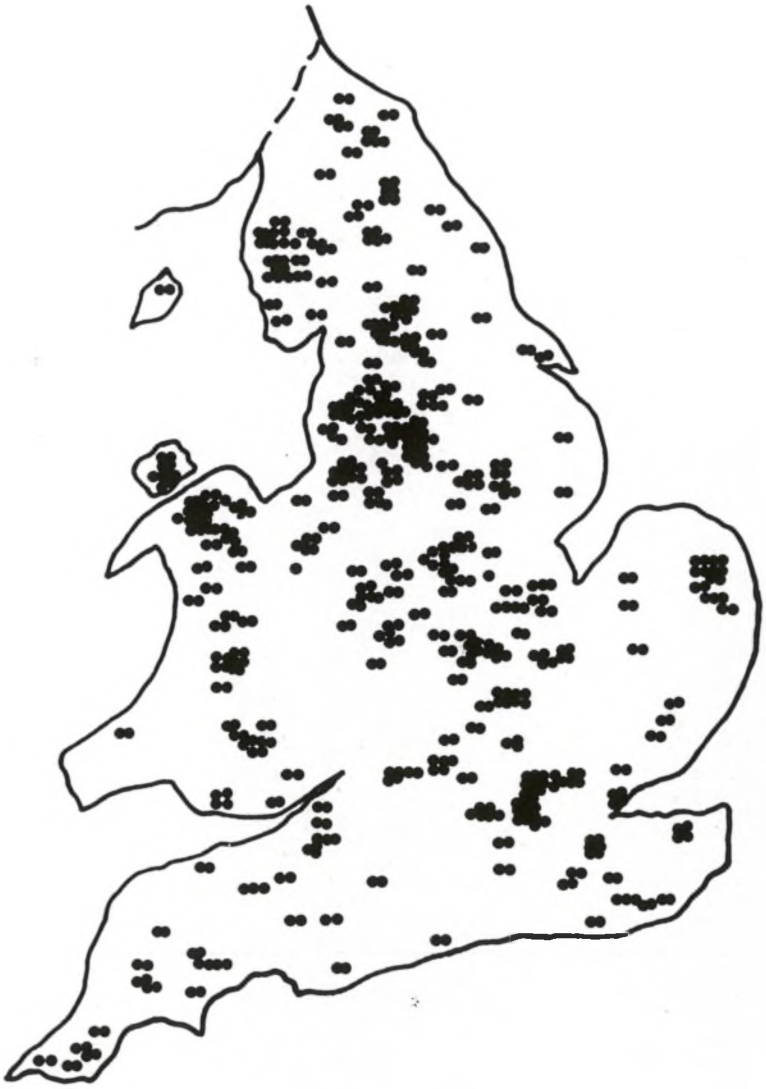


Fig. 4. The distribution of water bodies greater than 25 ha in area located from 1:50 000 OS Maps

Appendix 1.

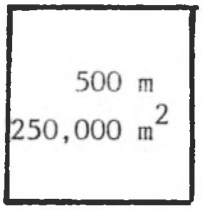
Remote sensing data requirements and costs

a) The number of pixels available for estimating reflectance intensity in lakes of 25 ha.

Assume lakes approximate to either a square or circular shape. Then:

25 ha area

500 m



r = 282 m

d = 564 m

perimeter 2000 m 1772 m

If we discard pixels immediately adjacent to or cutting the perimeter, as reflectance from these will be contaminated by land reflectance which is much more intense, then the area occupied by this discard is given by:

satellite	Spot	Landsat	Landsat
sensor	3 band HRV xS	Multispectral Scanner	7 band Thematic mapper
pixel area	20 x 20 m	80 x 80 m	30 x 30 m
abbreviation	(S)	(MSS)	(TM)

Assuming the worst case exists where all edge pixels have minimal overlap of the perimeter then:

Square

	S	MSS	TM
area of overlap (m^2)	40,000	160,000	60,000
prop^n of total area (%)	16	64	24
number of pixels averaged in remaining area	525	14	211

Circle

	S	MSS	TM
area of overlap (m^2)	35,440	141,760	53,160
prop^n of total area (%)	14	57	21
number of pixels averaged in remaining area	536	17	218

/over

b) calculation of costs for a single overflight

Satellite	Spot	Landsat	Landsat
sensor	3 band HRV XS	MSS	MSS
cost/scene (ex vat)			
radiometric & geometric correction	a) £1000		
(a) + geographic alignment	b) 13,000 Francs £1,300	£574	£3254
scene size	60 x 60 km	185 x 185 km	185 x 185 km
no. of scenes to cover England and Wales	42	16	16
data cost (ex vat)	a) £42,000 b) £54,600	£10,562	£59,874

assuming an equivalent cost for data processing

total cost per single	£109K	£11.2K	£120K

costs of Spot data may be reduced (£84K) if the data is already archived but this can never be guaranteed.

Appendix 2

Sampling strategies for water quality monitoring in lakes

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Abstract

Five different water sampling techniques have been compared in a series of lakes. In deep lakes, no significant differences were observed between mean summer nutrient concentrations measured in (i) a tube sample integrating over the photic zone taken from the deepest point; (ii) a surface dip sample taken at the deepest point; (iii) a surface dip sample taken by wading into the water's edge; (iv) a dip sample taken slightly further off shore by suspending a bottle below a buoy thrown out about 30 m from the shore; and (v) a sample taken along a short transect out from the shore using a model boat to transport the sample bottle. In shallower lakes the integrating tube sampler gave significantly higher estimates of mean concentrations than other methods due to the increase in volume of the unmixed hypolimnion which reduced the depth of the well mixed epilimnion to less than the tube length. For national survey purposes samples taken from the edge of the lake are the most cost effective.

Introduction

It is common practice in lake water quality monitoring programmes to represent each lake by a single sample. This is often collected by boat from an open water site and with health and safety aspects in mind, a two man crew. Hence sampling is very expensive due to the cost of a second person and the length of time taken to get a boat out to open water. As sample collection costs are a major factor in the total cost of a monitoring programme, any increases in efficiency would be worthwhile. To this end we report here a comparison of several sampling techniques and assess their effectiveness with respect to both relative costs and comparability of summer mean values for different chemical determinands.

Methods

Five sites in the English Lake District, Esthwaite Water, Blelham Tarn, Grasmere, Windermere North Basin and Windermere South Basin, were chosen for comparisons for the following reasons: (a) they already formed part of a routine monitoring network so that analytical results could be interpreted in the light of considerable background knowledge: (b) four of the five sites contained a point source of nutrients in the form of a sewage works inflow creating culturally eutrophic conditions which were felt to be likely to show greater spatial variability compared to oligotrophic systems; (c) two of the sites, Esthwaite Water and Windermere South had previously been shown to produce spatial inhomogeneities under certain conditions (Heaney, 1976; George, 1981; George and Heaney, 1978). The lakes range in size (Ramsbottom, 1976) from Blelham (0.102 km^2) through Grasmere (0.644 km^2), Esthwaite (1.004 km^2), Windermere South (6.178 km^2) to Windermere North (8.046 km^2). Sampling positions are shown in Figure 1.

Five sampling methods were tested, although not all methods were used on all lakes. Long-term data for all the test sites had been obtained using a 5 or 7 m length of 19 mm diameter polythene tubing, weighted at the lower end, which was lowered into the water at the deepest point of the lake until the upper end was just above the water surface (Lund, 1949). The lower end was then pulled to the surface using a thin cord so as to enclose a volume of water representative of the top 5 m of water in Esthwaite, Blelham and Grasmere and the top 7 m of both basins of Windermere (hitherto referred to as tube samples). At the same location in each lake a surface water sample was obtained by plunging an open 800 ml polythene sample bottle just below the water surface (surface dip samples). The other three sampling techniques were tested by a single operator working from the lake shore. The simplest method required the sampler to wade into the water to about knee depth and plunge the 800 ml polythene sample bottle beneath the water surface as far away from his body as possible (wade sample). In a more sophisticated alternative to obtain samples from slightly further offshore the sampler threw out a weighted sample bottle tied about 0.3 m below a small buoy while retaining one end of a rope to which the assembly was attached (throw sample). A specially constructed cap, with one short length and one long length of rigid plastic tube protruding through a normal cap into the bottle, was screwed onto the bottle prior to sampling to stop any contamination of the contents as the container was retrieved. Finally, a small (1 m long, 0.35 m wide), battery driven, remotely-controlled boat, constructed in-house so as to enable one man to transport it to remote locations on a back pack was used to collect an "integrated" surface sample (boat sample). The boat was steered over a fixed transect up to a hundred metres long out from the shore towards the deepest point while pumping water in short bursts throughout the run into a 5 litre, polythene sample bottle mounted on board. One further sample type was taken from the edge of Blelham Tarn by dipping a polythene bottle into the water in a bed of reeds to see if results were biased by the phosphorus recycling supposed to occur there (Wetzel, 1975).

Samples were taken on ten occasions from Esthwaite, Blelham and the two Windermere sites and eleven occasions from Grasmere during the period March to October 1987, i.e. the period of summer stratification, with a minimum period of one week between samples. Analysis of the samples for soluble reactive silica, nitrate, ammonia, soluble reactive phosphorus and total phosphorus was carried out immediately on return to the laboratory using standard methods (SiO_2 : Strickland and Parsons, 1968; NH_3 : Weatherburn, 1967; these two methods modified for use on a Pye Unicam discrete analyser; NO_3 : Hilton and Rigg, 1983; PO_4, total P : Mackereth et al., 1978).

The five methods were compared statistically by two-way analysis of variance with sample date as the blocking factor. Plots of residuals suggested that transformation of the data gave no improvements compared to untransformed values.

Results and Discussion

Results are summarised in Table 1. There are only three occasions where significant differences were observed between the means of dip, wade, throw and boat methods in all lakes. Ammonia values in Windermere South Basin and phosphate concentrations in Blelham included several below the limit of detection. These are recorded as zero creating a distribution which could not be transformed to normal. The remaining significant difference in Total P concentrations in Esthwaite Water could reasonably be expected by chance since significance was tested at the 5% (1 in 20) level.

When all the methods, including tube samples, are compared some interesting patterns are observed. For Windermere North and South Basins, excluding the comparisons of ammonia data which have been discussed earlier, only one determinand, total P in North Basin, shows significant differences at the 5% level and can reasonably be expected by chance. Total P in Grasmere also indicates significant differences at the 5% level. However it is caused by a very high concentration in each method on a single occasion, resulting from an unusual practice carried out in Grasmere, namely, the injection of sewage effluent into the hypolimnion during the summer. This increases the nutrient load enormously (Reynolds, Lund, in press) and releases large pulses of nutrients during the erosion of the hypolimnion prior to complete overturn.

Results from Blelham Tarn show significant differences between tube samples and the other methods for several determinands, with the tube mean greater than the mean derived from other methods. Although results from Esthwaite Water only show a significant difference between methods for total P. Again the tube mean for all determinands is consistently greater than the mean derived from other methods. This trend is not observed at the other three sites. A temporal plot of the concentration of ammonia in the tube and surface dip samples, as a percentage of the mean concentration of wade, throw and boat samples recorded on the same graph as an estimate of the upper surface of the hypolimnion and the oxycline (conc. $O_2 < 0.1$ µM) depth is given in Fig. 2. Both lakes exhibit well developed stratification with complete anoxia approaching to within 7 m and 5 m of the lake surface in Esthwaite and Blelham respectively. The plots show that the differences between techniques in the two lakes are coincident with the maximum excursion of anoxia and are therefore likely to be caused by the tube sample entering either the anoxic hypolimnion or the poorly mixed region immediately above it. No biased values were obtained for Grasmere as the sampling events did not coincide with the period when the oxycline approached (i.e. 6 m) the lower boundary of the tube sample. The North and South Basins of Windermere are much deeper and so the oxycline never approaches the sampling region (Talling et al., 1986).

There were some indications among the data that during spring/early summer, deep water samples in some lakes contained higher concentrations of nutrients, particularly phosphate, than samples taken from the edge of the lake. This may result from the activities of benthic algae and bacteria (Jones, 1980, Moss, 1968) in the littoral metabolising nutrients, but data from this time period are too scarce to cause significant differences in estimates of the means.

Different sampling techniques have been developed to address different problems encountered while sampling in the natural environment. Tube samplers were introduced (Lund, 1949) to obtain representative estimates of lake algal numbers for population change studies. Heaney (1976) gave a graphic example of the problem which occurs when motile algae are present. On one of his sampling days large numbers of Ceratium hirundinella were located at 3.5 m ± 0.20 m. Cell numbers were a factor of ten greater in this compact region compared to the rest of the water column and the use of a simple surface dip would have grossly underestimated the population. However one consequence is that at certain times of the year, particularly in lakes of about 10-30 m depth, the tube will exceed the depth of the well-mixed epilimnion and enter at least the metalimnion, if not the hypolimnion. In this region many chemical concentrations change rapidly from bulk concentrations in the epilimnion so that biased estimates of epilimnetic concentrations may result, although in reality these nutrients may be available for algal growth.

At the other extreme horizontal variations can be significant. Heaney (1976) and George and Heaney (1978) showed this to be the case in many lakes, particularly when motile algae following diurnal migration patterns are transported by "conveyor belt" water movements so as to concentrate at either the upwind or downwind end of the lake. These variations are considerably lower than observed in the vertical plane (2-5x compared to 10-100x respectively) but random sampling over a series of transects is a reasonably method of allowing for these effects (Heaney, 1976). The model boat sampler is a low cost method of achieving this. However, difficulties in seeing and directing the small boat at a distance limit the maximum working distance to about 100 m from the operator, and this only in calm conditions. Hence, except on small lakes, it is of limited value in obtaining horizontally representative samples.

Samples taken by wading into the edge of a lake are probably the cheapest method of sampling. "Throw" samples were taken to avoid contamination by possible resuspension of sediments by wave action close to shore (George, 1981). Although no differences were observed between the two methods, any simple tool which can extend the distance of the sampling point from the shore could be an advantage. A stick with a retaining clip for the sample bottle is probably a reasonable compromise. In Blelham Tarn an extra sample set was taken from the centre of a small reed bed. Contrary to expectations chemical concentrations did not differ from samples taken away from the reed beds.

We must conclude from this work that there is no such thing as a single sample truly representative of a whole lake, except possibly during well mixed periods of the winter period that are free from ice-cover. In any other situation the sampling method must be matched to the required information. An integrating tube sample is excellent for its designed purpose of obtaining a good estimate of the total algal population, but concentrations of nutrients measured in the same sample will be higher than for most of the epilimnion at certain times of the year in shallow lakes. Whether a tube sample, a surface dip or a sample integrated over a variable depth related to the photic zone at the time of sampling is the best type of sample to take when relating algal growth to nutrient availability is beyond the scope of this paper. Conversely when an estimate of the total amount of any material is required for a mass balance within a lake neither a tube sample or a surface dip is adequate. Samples must be taken at discrete depths through the water column, the resulting concentrations multiplied by appropriate volumes and integrated for the whole lake. For a simple survey requiring a temporal mean concentration of a determinand in some part of the water column there is no advantage in using either a tube or central surface dip. As long as sites close to point sources of pollutants are avoided, edge samples are quite adequate and are the most cost-effective way of surveying.

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Table 1 Means, standard deviations (in brackets) and significant differences between means for untransformed nutrient analyses of samples obtained by a range of different methods.

	Tube	Dip	Wade	Throw	Boat	Reeds	SE of differences of mean	Differences between all methods	Differences between all methods except tube
South Basin, Windermere									
[1] SiO_2	0.64(0.53)	0.65(0.58)	0.73(0.58)	0.71(0.57)	0.73(0.59)		0.04	NS	NS
[2] NO_3	472.6 (213.8)	487.5 (212.6)	478.8 (225.7)	475.9 (225.4)	473.8 (241.9)		8.14	NS	NS
[2] NH_3	10.6 (16.4)	18.4 (27.1)	16.2 (14.8)	8.8 (11.6)	16.6 (17.4)		2.2	** [a]	** [a]
[3] PO_4	5.7 (6.7)	10.0 (10.4)	6.2 (7.3)	5.3 (7.1)	6.2 (7.9)		1.0	NS	NS
[3] Total P	24.4 (4.1)	30.1 (10.1)	28.2 (6.4)	22.7 (5.0)	23.7 (5.0)		2.6	NS	NS
North Basin, Windermere									
[1] SiO_2	0.85(0.55)	0.82(0.55)	0.85(0.57)	0.85(0.60)	0.85(0.61)		0.03	NS	NS
[2] NO_3	453.9 (135.4)	453.7 (143.8)	448.7 (152.9)	448.9 (168.2)	447.2 (163.9)		11.4	NS	NS
[2] NH_3	6.7 (13.79)	10.50 (13.91)	14.7 (16.2)	12.4 (13.7)	13.6 (14.4)		1.6	** [a]	NS
[3] PO_4	1.78 (2.6)	2.78 (4.76)	2.06 (1.99)	2.19 (2.67)	2.23 (2.87)		0.84	NS	NS
[3] Total P	13.1 (2.6)	19.2 (8.3)	24.4 (14.9)	15.5 (2.9)	14.4 (3.5)		3.6	*	NS
Grasmere									
[1] SiO_2	1.06(0.60)	1.07(0.60)	1.08(0.61)				0.01	NS	NS
[2] NO_3	367.0 (174.3)	359.5 (184.0)	343.8 (180.1)				11.3	NS	NS
[2] NH_3	42.6 (64.9)	41.9 (61.9)	40.8 (57.8)				2.8	NS	NS
[3] PO_4	2.76(3.85)	2.88(3.28)	2.46(2.60)				0.45	NS	NS
[3] Total P	24.0 (9.1)	20.7 (7.2)	20.8 (6.4)				1.4	* [b]	NS
Esthwaite									
[1] SiO_2	0.78(0.75)	0.71(0.73)	0.73(0.74)	0.78(0.72)	0.77(0.78)		0.09	NS	NS
[2] NO_3	460.3 (326.3)	413.4 (321.2)	411.1 (315.0)	430.5 (296.2)	399.6 (320.1)		19.0	NS	NS
[2] NH_3	42.3 (42.3)	36.3 (36.2)	37.3 (33.1)	36.3 (31.8)	38.1 (38.6)		4.13	NS	NS
[3] PO_4	1.23(0.91)	1.03(0.81)	0.95(0.60)	0.86(0.62)	0.95(0.63)		0.19	NS	NS
[3] Total P	28.0 (4.2)	24.2 (5.6)	25.0 (6.1)	27.2 (8.3)	25.2 (7.2)		1.5	*	*
Blelham									
[1] SiO_2	1.00(0.73)	0.98(0.82)	0.98(0.80)	0.98(0.80)	0.98(0.8[illegible])	0.88(0.76)	0.02	**	NS
[2] NO_3	543.7 (350.7)	507.1 (350.3)	507.5 (348.2)	505.8 (348.8)	509.3 (348.8)	453.8 (336.5)	6.82	NS	NS
[2] NH_3	47.0 (34.6)	31.8 (18.5)	31.8 (17.2)	31.1 (15.6)	29.5 (17.8)	31.0 (15.7)	6.37	*	NS
[3] PO_4	1.09 (0.52)	0.76(0.57)	0.44(0.58)	0.57(0.63)	0.45(0.59)	0.57(0.73)	0.12	*** [a]	* [a]
[3] Total P	28.3 (5.4)	24.0 (6.7)	25.3 (8.5)	24.3 (6.1)	24.6 (6.4)	24.0 (6.2)	1.8	NS	NS

[1] $mg\,l^{-1}$ as Si: [2] $\mu g\,l^{-1}$ as N: [3] $\mu g\,l^{-1}$ as P.
*** significant differences at 0.1% level
** significant differences at 1% level
* significant differences at 5% level

[a] many zeros in data set
[b] one large outlier in each data set

Figure 1. Sampling positions in the five lakes. A: tube and surface samples; B: edge, throw and boat samples; C: edge sample only. Bathymetric data from Ramsbottom (1976); a) Windermere North Basin, max depth 65 m; b) Windermere South Basin, max depth 45 m; c) Esthwaite Water, max depth 15.5 m; d) Blelham Tarn, max depth, 13.5 m; e) Esthwaite Water, max depth 21.5 m

Figure 2. Concentrations of ammonia in tube (dotted) and surface dip (solid line) samples as a percentage of the mean of edge, throw and boat samples on the same date. a: minimum upward extension of the hypolimnion obtained from temperature data; b: zero oxygen depth.

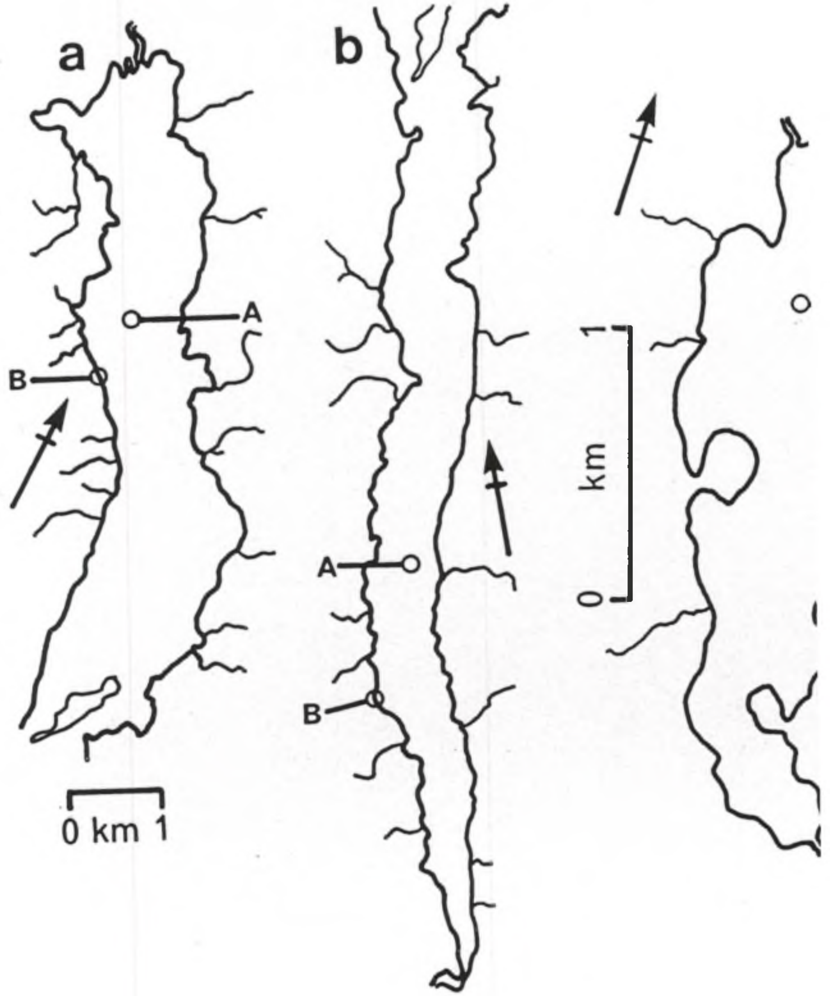

a
b
A
B
A
B
0 km 1
0 km 1

Fig. 1

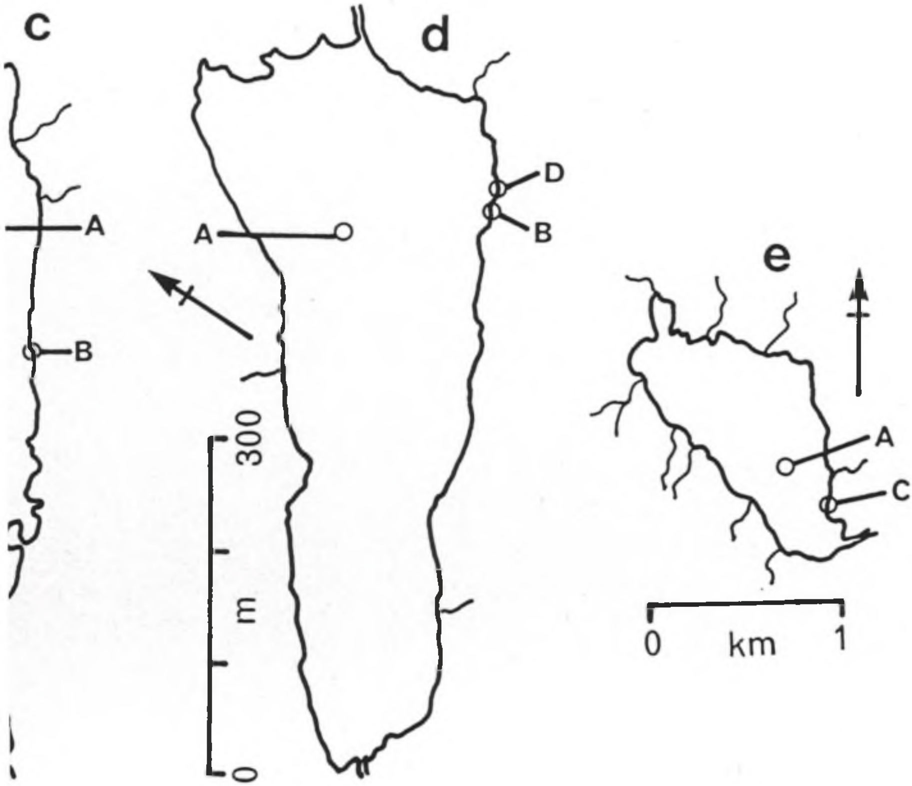
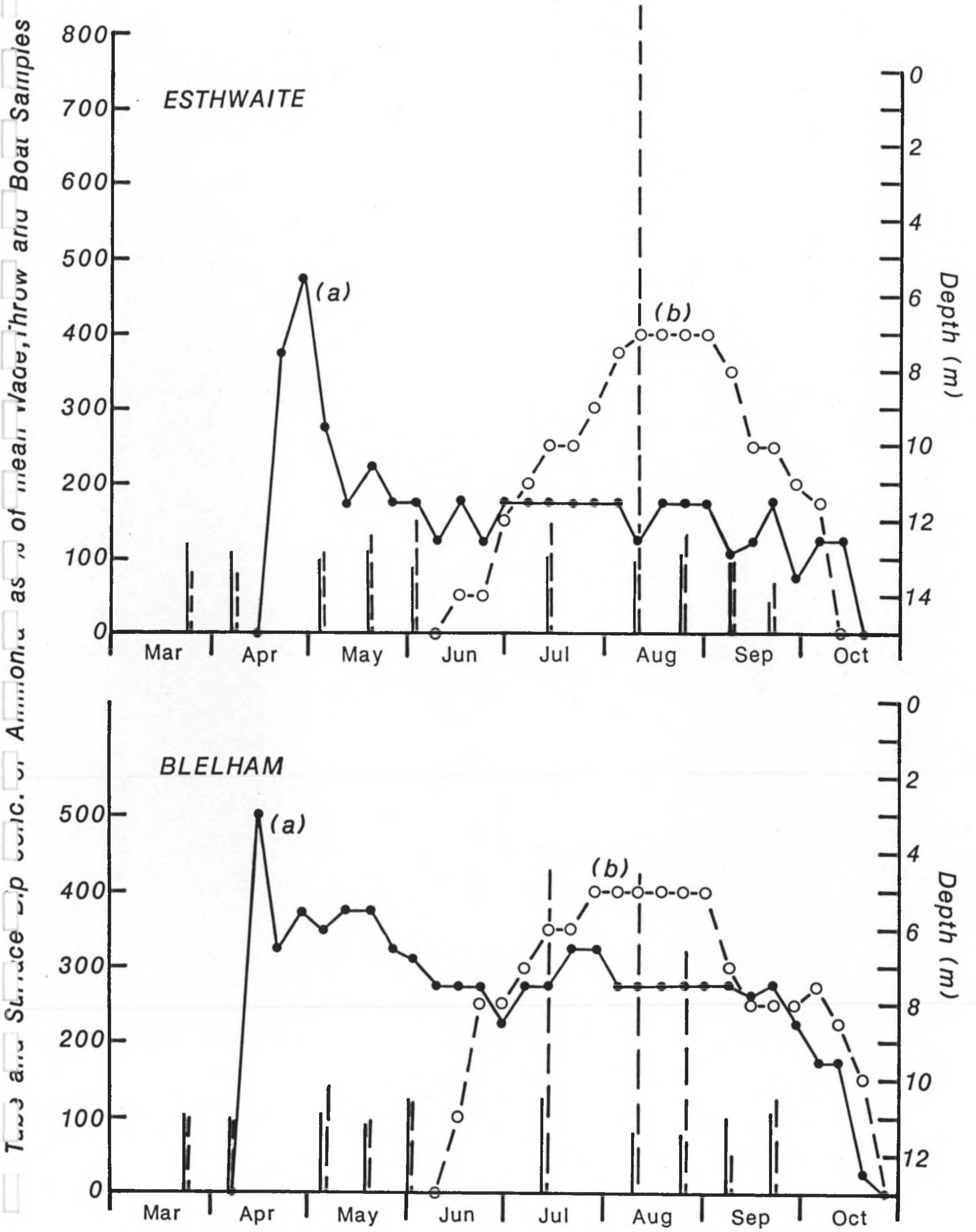


Fig 2



ESTHWAITE
BLELHAM
(a)
(b)
Depth (m)
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
0
100
200
300
400
500
600
700
800
2
4
6
8
10
12
14

Appendix 3

Annual variability in sedimentary pigment concentrations and its implications for trophic status assessment.

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Abstract.

Pigment concentrations in surface sediments in two lakes were analysed on ten occasions over a year. Statistical analysis showed that mean concentrations varied throughout the year. Hence, sediment pigment concentrations are likely to be unreliable if based on a single sample and the advantages of several alternative sampling strategies are discussed. Total Carotenoids and the ratio degredation products/total carotenoids are shown to be the best determinands for ranking in order of trophic status or for estimating mean annual algal productivity.

Introduction

Over the past two or three decades since Vallentyne's (1955) pioneering work sedimentary pigment concentrations have become accepted pales indicators of productivity changes within a given lake (Swain, 1985). More recent work (eg Gorham et al. (1974); Guilizzoni et al. (1982, 1983) has suggested that the concentration of these determinands in surface sediments can be used to obtain a good estimate of the mean annual rate of algal productivity from the analysis of a single sediment sample compared to the extensive monitoring programme required to obtain the same information from water column measurements. This would make it a very cost effective means of ranking lakes in order of their trophic status for national surveys (Murray and O'Byrne-Ring, 1980). In these studies there has been an implicit assumption that the concentration of pigments in surface sediments does not vary throughout the year so that samples taken at any time of the year can be considered to be representative. However, it is well known that the rate of sedimentation varies throughout the year (Pennington, 1974) and there are local observations of large changes in algal cell numbers on the sediment surface over very short periods of time (Gorham, 1958). In this study we present pigment data from the surface sediments of two lakes over a period of a year and discuss the implications of the data for the assessment of trophic status and mean annual algal productivity from sedimentary pigments.

Methods

10 sets of sediment samples were taken at slightly more than monthly intervals from two lakes in the English Lake District over the period May 1987 to April 1988. At both sites 5 replicates were generally taken within a few metres of each other at each of a shallow site and at the deepest point using Jenkin corer (Ohnstad and Jones, 1982). Esthwaite water (Hilton et al., 1986;

Jones et al., 1979) is a highly eutrophic (mean total P = 30 mg 1^{-1}), relatively shallow (max depth = 15.5 m), monomictic lake whose hypolimnion is anaerobic for most of the stratified period. Apart from the top few millimetres, the bottom muds remain anoxic all year round. Devoke Water is an oligotrophic (mean total P = 5 mg 1^{-1}), slightly acid (pH = 6.3) lake. It has a surface area of about 34 ha, maximum depth 14 m and mean depth 4 m. However, it is very exposed in its organic catchment so that it stratifies for only short periods of time (George, Hewitt unpublished results). Shallow samples were taken just to the north of the boathouse in approximately 1.5 of water in Esthwaite and midway between the perimeter and the island in 4 m of water on Devoke.

The top centimetre of each core was collected on the sampling day and immediately frozen until required for analysis. Samples were allowed to thaw out slowly for 24 hours in the dark prior to analysis. Total Chlorophyll degredation products (TDP), % native chlorophyll and total carotenoids (TC) were determined according to Swain (1985). Pheophytinization was carried out according to standard texts (American Public Health Assoc., 1975). Total carbon was measured directly on the dried sediment using a Carlo Erbon 1106 CHN analyser and converted to organic matter by multiplying by 2 (Mackereth, 1966). Estimates of the analytical variability were made after analysing 8 replicates from the same horizontal wet sediment sample.

One way analysis of variance against time was carried out on untransformed data for the whole data set for each pigment analysis type. Total variances and residual variances for each determinand at each site were obtained directly from this analysis. Residuals were evenly spread except for the ratio degredation products (DP)/Total carotenoids (TC) which was corrected by means of a log transformation. The efficiency of determining trophic status was assessed as follows. Plots of log variance against log mean (Elliott, 1979) were used to obtain appropriate normalising transformations: DP untransformed; TDP log; TC cube root; TDP/TC and DP/TC, 1/square root. For each date and each analytical representation the mean (S_p) of the variance estimates for data sets from the deepest point in both lakes was calculated. A total variance was estimated by treating the two sets of data as a single set. The variance due to trophic status differences (S_m) was obtained by subtracting the mean individual variance from the total variance. The separation efficiency of determinands was ranked by the size of S_m/S_p.

Results and discussion

Mean concentrations and 95% confidence limits on the mean for each primary determinand on each sampling date are given in figure 1. Deep sites in both lakes show a peak in May/June, presumably due to the demise of the spring diatom bloom, and again in September/October at the end of the summer when algal populations crash. Shallow sites have less in common between the two lakes but they peak in August/September. This could be the result of macrophyte growth or benthic algal development. An alternative explanation is that during quiescent summer conditions the shallow areas are more effective sediment collectors (Reynolds, 1984) than deep areas but increased wave action brought about by autumn and winter gales resuspends much of this material which is transported to deeper water and in the process is exposed to more degredation in the oxic water.

We have little conclusive evidence to decide the relative importance of these effects but some deductions are possible. Except for a short period is May/June, the percentage of native chlorophyll in shallow sites was twice that at deeper sites in both the lakes (Fig. 1). This is contrary to the normal expectations of Swain (1985). At the shallow Devoke site macrophytes were present which were impossible to remove completely from sediment samples prior to analysis. In Esthwaite Water samples were taken about 10-15 m away from a reed bed so that macrophyte contributions could be significant but the water was only about 1.5 m deep so that benthic algae could also make a sizeable contribution to the undegraded chlorophyll. Total carotenoids in Devoke show a similar pattern to percent native chlorophyll with concentrations at the shallow site either greater than or equal to those at the deeper site, corroborating the influence of macrophytes at the shallow site, as aquatic macrophytes contain more carotenoids, compared to chlorophyll, than algae (Gorham and Sanger, 1975). Conversely, the higher concentrations of carotenoids in the deeper sediments from Esthwaite, in agreement with Swain's (1985) generalisations, implicate either benthic algae of more efficient trapping as the source of excess native chlorophyll at the shallow site.

The results of a one-way analysis of variance, with time as the dependent variable, are given in Table 1. On all tests on data from Devoke, except three, plots of residual versus mean concentration on each date showed some evidence of a wedged shape. However, on the majority of occasions this was due to the effects of a large variance on a single sampling date and, hence, did not constitute grounds for transforming the data. A log transformation of the ratio DP/TC was carried out as significant order was found in the residuals from the analysis of data at all sites. % Native chlorophyll, TDP, TC, Native Chlorophyll, DP and TDP/TC show significant differences between means obtained on different dates over the vast majority of combinations of determinand and site. Only the ratio DP/TC showed any convincing evidence of independence from changes with time. (NB. Although these data show that most pigment concentrations in the surface centimetre of lake sediments vary significantly throughout the year, we have no evidence that these are other than surface effects and we find it reasonable to continue to assume that pigments in sediments buried below this active region will be invarient with time and be indicative of paleoenvironmental conditions.)

The evidence presented here suggest that it would be very expensive to attempt to rank a number oflakes in terms of either their trophic status using the statistically most satisfactory sampling strategy of replicate samples from each lake at several different times of the year. Costs would be comparable with those of estimating the mean algal biomass directly from the water column, making the use of sediments pointless. However the total variance of each determinand at each site can be subdivided to show the relative contribution from the three main sources of error, i.e. temporal, spatial and analytical variability, (Table 2) and more cost effective strategies explored. Analytical errors contribute very little to the total variability so that there is no advantage in carrying out replicate analyses on each sample. Statistically, the second best sampling strategy, after multiple replicates on multiple dates, would be single samples from each lake (usually the deepest point) at several times throughout the year. This would still require almost as much boat time, and hence cost, as multiple reps at multiple dates. However, as these replicates contain both spatial and temporal variability 2 replicates would reduce the standard error of the mean (SE = mean/N (number of samples)) by 30% and 3 by 42%, both fairly substantial reductions. The cheapest sampling strategy available to us to reduce the errors on the estimation of a mean value makes use of the fact that, in 80% of all determinations at all sites, spatial variability is greater than temporal variability (Table 2). Hence replicate sampling at each site on a single occasion would significantly reduce the SE of the mean. In this case, as these replicates only include the spatial component, 2 or 3 replicates would reduce the SE by at least 15 or 21% respectively. Greater numbers of replicates would have limited return.

Although there is general agreement that pigment diversity is not a useful indicator of trophic status (Murray and O'Byrne-Ring, 1980; Sanger and Gorham, 1970), there have been many suggestions as to the most appropriate and sensitive indicators. Using some of the more recent examples: Flannery et al. (1982) obtained only a poor correlation between TDP and trophic status whereas Gorham et al. (1974) and Adams et al. (1978) found a reasonable relationship between TDP and algal standing crop and a good straightline relationship between TC and algal standing crop while Guilizzoni et al. (1983) obtained power series relationships between TDP and TDP + TC and productivity. Murray and O'Byrne-Ring (1980) suggested that the ratio TDP/TC was a good indicator of trophic status whereas Guilizzoni et al. (1983) suggested that it was not. The data obtained in this study allow us to make some objective assessments of the best indicators of trophic status. Esthwaite Water is eutrophic and develops anoxia in the hypolimnion very early after the onset of stratification creating an environment of low oxygen, low light and high input of pigments. Devoke on the other hand is very exposed and does not stratify for any significant periods. It is oligotrophic and can be considered to be well separated, in trophic status, from Esthwaite. In order to assess which determinand gave the widest separation between the means of samples from the deepest point, compared to the variability due to spatial and temporal variance, a statistic described earlier was calculated and, for each date, the determinands were ranked in order of increasing size (Table 3). The determinand most commonly used to define trophic status, i.e. TDP, consistently performed worst along with DP. This may be due to the distinct plateau in plots of TDP or productivity which occurs at high levels of algal productivity (Gorham et al., 1974). TC concentrations consistently produced good separation between the two lakes and, given the good linear correlation with productivity observed by Gorham et al.

(1974), would appear to be a useful determinand which deserves more widespread use. The two ratios TDP/TC and DP/TC were almost as effective as TC but were not quite as consistent, occasionally producing the worst ranking. When combined with the lack of temporal variability in DP/TC, this ratio is a good means of ranking lakes in terms of trophic status with the lowest cost strategy, i.e. single occasion with spatial replicates.

The majority of correlations between productivity or trophic status and sedimentary pigments have used total degredation products, i.e. the absorbance of the crude acetone extract, rather than degredation products, i.e. the absorbance of the acidified extract. Acidification degrades any chlorophyll to pheophytin (one of the degredation products commonly found in sediments) with an extinction coefficient about 40% lower than chlorophyll and similar to the extinction coefficient of other sedimentary pigments derived from chlorophyll. If DP were used more widely, although this work suggests that other determinands are better for trophic status assessment, then it is likely that many of the apparent anomalies in the sedimentary pigment literature would disappear. It is obvious from the literature that the proportion of undegraded chlorophyll varies widely from sample to sample as evidenced by the reported effect of light on measured TDP concentrations and the correlation between TDP and productivity. For example Fox (1944) found no loss of absorbance on exposure of sediments to light whereas Fogg and Belcher (1961) observed a loss of extracted colour from wet sediments which had been allowed to stand in air. Similarly although many workers (e.g. Gorham et al. (1974), Guilizzoni et al. (1982)) have found a good correlation between trophic status measures and TDP, Flannery et al. (1982) found a much poorer correlation. The latter group were working in very shallow lakes where large benthic algal populations would be likely to develop and distant estimates of TDP when no account was taken of "native chlorophyll". In our work the variance decreased by 73% and 66% at the deepest points in Esthwaite and Devoke respectively on changing from TDP to DP, and the coefficient of variation reduced by 7% (to 22%) and 12% (to 48%) respectively. The minor extra effort involved in the determination of DP rather than TDP would appear to be well worth while simply from the point of reducing the variance at a single site but its more widespread use would probably increase the comparability of data between sites and make generalisations much more meaningful.

Acknowledgements.

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Table 1. One way analysis of variance with time for different pigment determination.

	Esthwaite		Devoke	
	Shallow	Deep	Shallow	Deep
% Native Chlorophyll	*	***	NS[b]	*
Total degredation products (TDP)	***	**	***	***[b]
Total carotenoids (TC)	**	NS	***[b]	**[a]
Native Chlorophyll	***	***	***[a]	**[b]
Degredation products (DP)	**	*	***	***(b)
TDP/TC	NS	*	***	***[b]
DP/TC	NS[a]	NS[b]	*[b]	NS[a]
$\log_e$ (DP/TC)	NS	NS	NS	**

o a) residuals wedged

b) residuals wedged but due to the effects of a single date

* significant differences between mean values on different dates at the 5% level

** significant differences between mean values on different dates at the 1% level

*** significant differences between mean values on different dates at the 0.1% level

Table 2. The proportion of the total variance, as a percentage, attributable to various sources of error: A = analytical; S = spatial/sampling; T = temporal.

	Esthwaite						Devoke					
	Shallow			Deep			Shallow			Deep		
	A	S	T	A	S	T	A	S	T	A	S	T
% NC	2	69	29	4	35	61	1	99	0	4	72	24
TDP	1	55	44	1	63	36	1	34	65	2	50	48
TC	1	67	32	1	86	13	4	37	59	8	56	36
NC	0	58	42	0	35	65	0	53	47	0	66	34
DP	0	70	30	0	80	20	0	40	60	0	41	59
TDP/TC	0	99	1	2	58	40	0	67	33	0	77	23
DP/TC	0	94	6	5	95	0	0	73	27	0	79	21

Table 3. The number of occasions a statistic, describing the separation on individual sampling days of the mean value of each determinand in Esthwaite and Devoke compared to the spatial and temporal variability, achieves the ranking defined below.

	Rank				
	1	2	3	4	5
TDP	1	1	0	2	6
TC	4	2	4	0	0
DP	1	1	0	5	3
TDP/TC	3	2	3	1	1
DP/TC	1	4	3	2	0

Figures 1. Temporal changes in pigment concentrations in the surface centimetre of sediments. Error bars indicate 95% confidence limits about the mean.

a) Percent native chlorophyll in Esthwaite Water: d = deepsite, s = shallow site.

b) Percent native chlorophyll in Devoke Water: d = deepsite, s = shallow site.

c) Total Carotenoids in Esthwaite Water: d = deep site, s = shallow site.

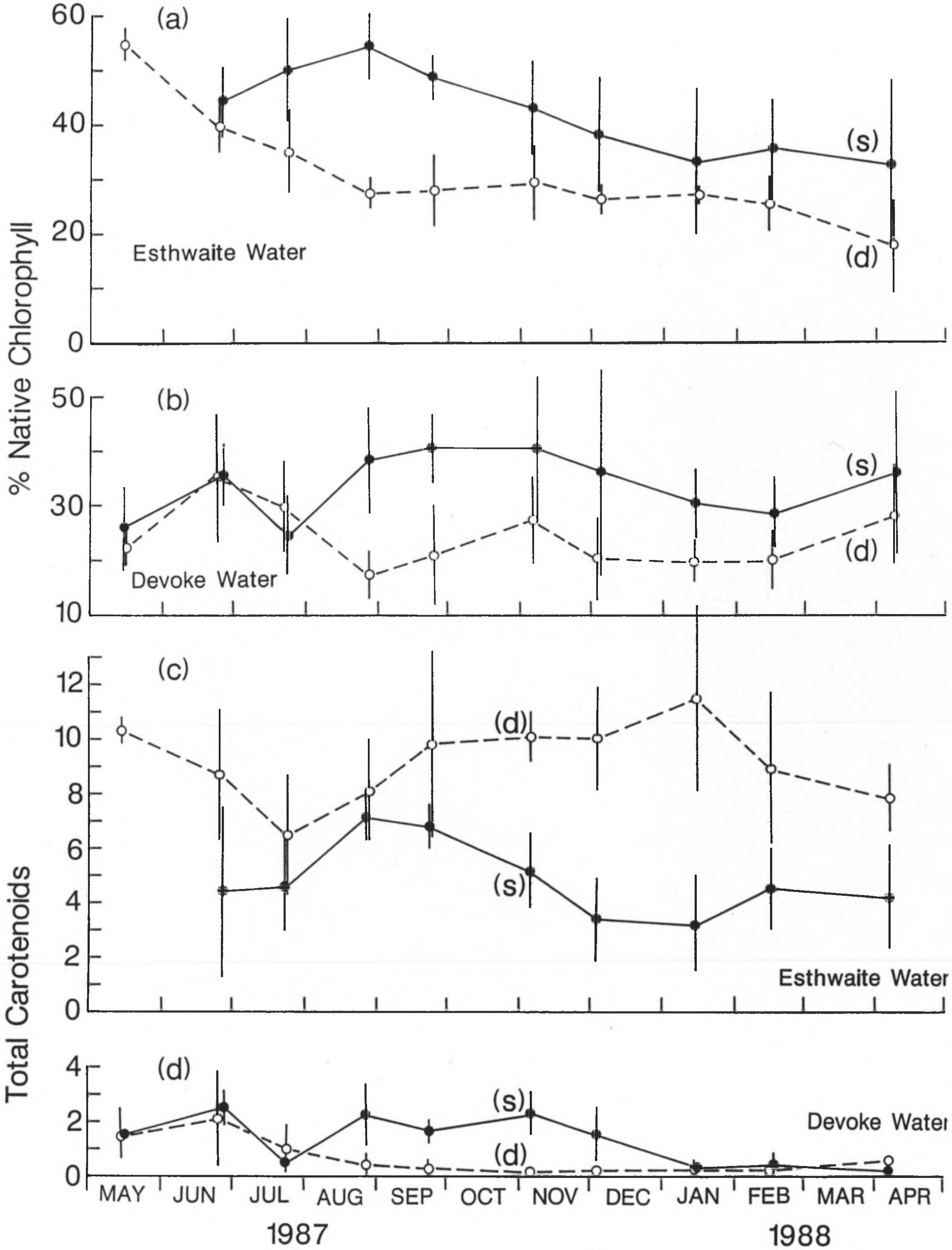
d) Total Carotenoids in Devoke Water: d = deep site, s = shallow site.

e) Total degredation products (TDP) and degredation products (DP) at the deep site.

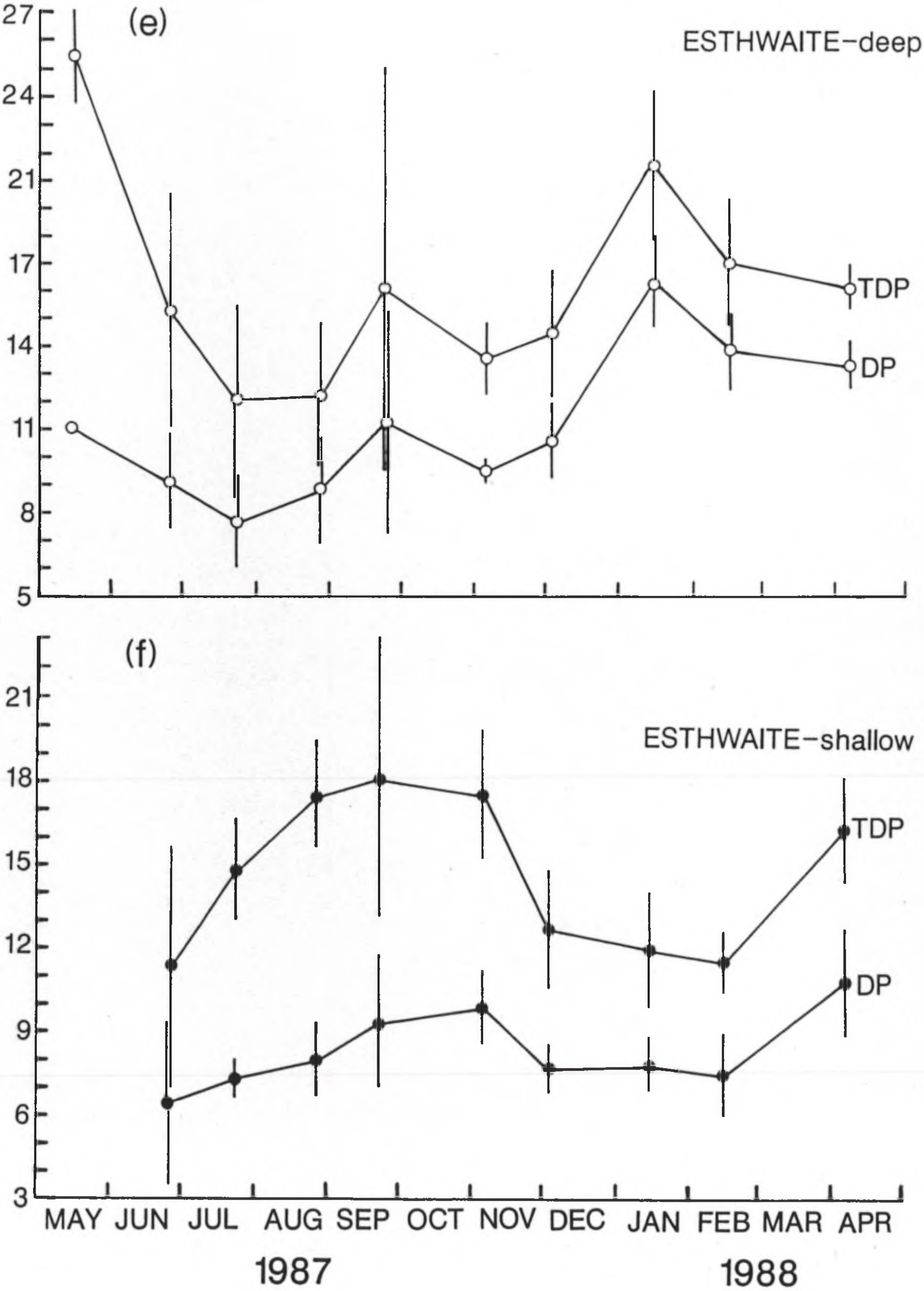
f) Total degredation (TDP) and degredation products (DP) at the shallow site in Esthwaite Water.

g) Total degredation (TDP) and degredation products (DP) at the deep site in Devoke Water.

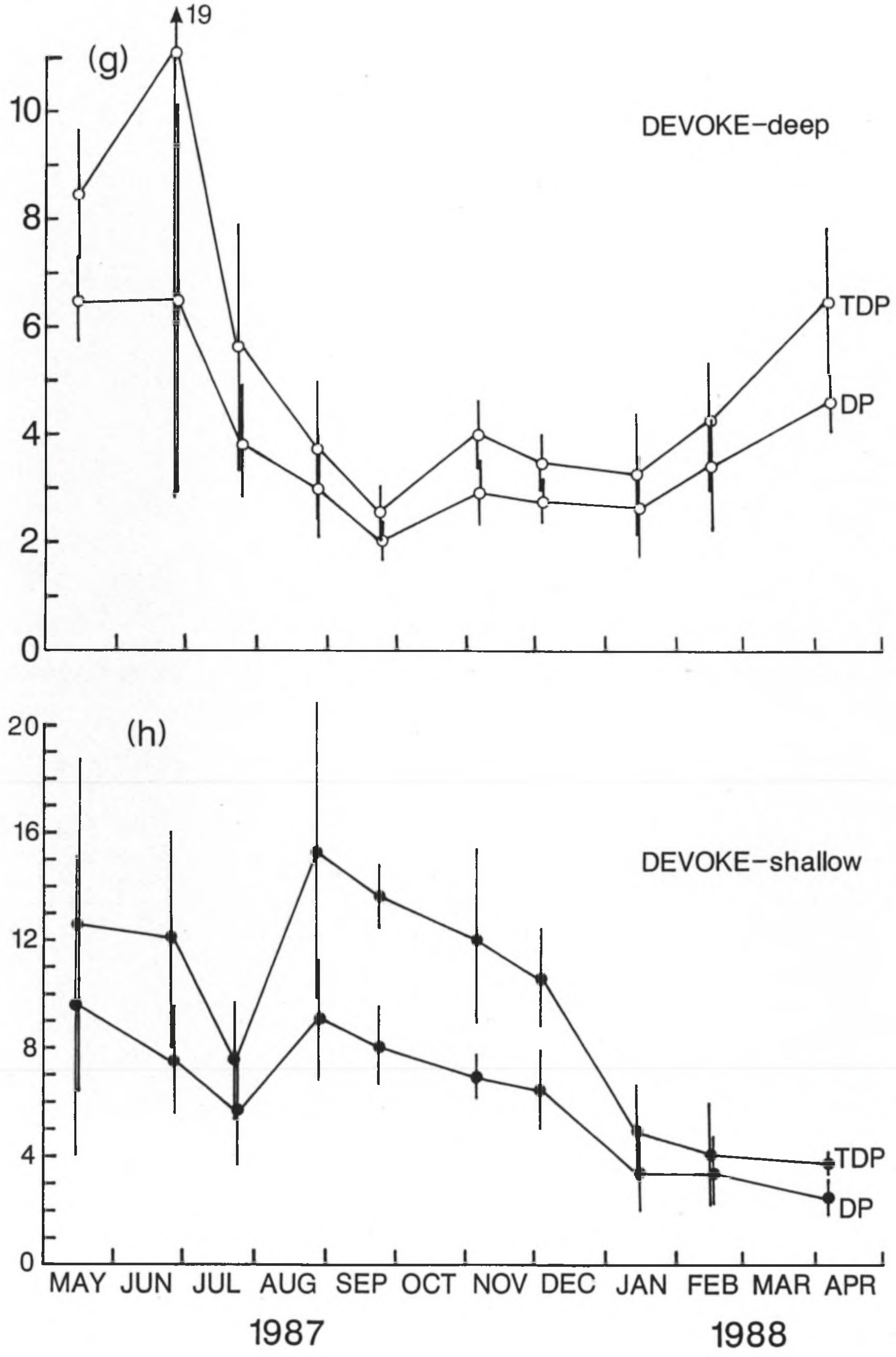
h) Total degredation (TDP) and degredation products (DP) at the shallow site in Devoke Water.



% Native Chlorophyll
(a)
Esthwaite Water
(s)
(d)
(b)
Devoke Water
(s)
(d)
Total Carotenoids
(c)
(d)
(s)
Esthwaite Water
(d)
(s)
(d)
Devoke Water
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
1987
1988



(e)
ESTHWAITE–deep
27
24
21
17
14
11
8
5
TDP
DP
(f)
ESTHWAITE–shallow
21
18
15
12
9
6
3
TDP
DP
MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR
1987
1988



19
(g)
10
8
6
4
2
0
DEVOKE–deep
TDP
DP
20
(h)
16
12
8
4
0
DEVOKE–shallow
TDP
DP
MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR
1987
1988

Appendix 4

Lakes greater than 50 ha located from 1:50 000 scale OS maps. Numbers refer to approximate areas in hectares. Total numbers of lakes per water authority:

Anglian	47
Northumbrian	23
Northwest	62
Southern	17
Severn Trent	49
Southwest	14
Thames	50
Welsh	63
Wessex	12
Yorkshire	45
	382

ANGLIAN

HARDLEY MARSHES	25
NAMELESS	50
NAMELESS	50
FILBY BROAD	50
TALLINGTON LAKE	50
RANWORTH BROAD	25
NAMELESS	25
NAMELESS	25
NAMELESS	25
AMPTON WATER	50
RAVENSTHORPE RESERVOIR	50
HICKLING BROAD	100
HAMMINGFIELD RESERVOIR	400
ROCKLAN BROAD	25
NAMELESS	25
ALTON WATER	150
RUTLAND WATER	1200
COVENHAM RESERVOIR	100
HORSEY MERE	25
DAVENTRY RESERVOUIR	25
EYEBROOK RESERVOIR	200
OULTON BROAD	75
NAMELESS	25
GRAFHAM WATER	600
HOVETON GREAT BROAD	25
WILLEN LAKE	50
ARDLEIGH RESERVOIR	50
HOLLOWELL RESERVOIR	50
ORMESBY BROAD	50
BLATHERWYCKE LAKE	25
NAMELESS	25
NAMELESS	25
PITSFORD RESERVOIR	350
ABBERTON RESERVOIR	400
STEWARTBY LAKE	100
WROXHAM BROAD	25
NAMELESS	25
NAMELESS	50
WILSTONE RESERVOIR	25
FOXCOTE RESERVOIR	25
BARTON BROAD	50
NAMELESS	25
NAMELESS	25
NAMELESS	50
FRITTON DECOY	50
ROLLESBY BROAD	50
SYWELL RESERVOIR	25

NORTHUMBRIAN

GREENLEE LOUGH	50
SMIDDY SHAW RESERVOIR	25
BALDERHEAD RESERVOIR	100
KIELDER RESERVOIR	1000
TUNSTALL RESERVOIR	25
SWEETHOPE LOUGHS	50
HURY RESERVOIR	50
HALLINGTON RESERVOIR	100
DERWENT RESERVOIR	400
GRASSHOLME RESERVOIR	50
BROOMLEE LOUGH	25
BAKETHIN RESERVOIR	75
COLT CRAG RESERVOIR	50
SELSET RESERVOIR	100
NAMELESS	25
CATCLEUGH RESERVOIR	100
HURWORTH BURN RESERVOIR	25
BLACKTON RESERVOIR	25
TINDALE TARN	25
WASKERLEY RESERVOIR	25
BURNHOPE RESERVOIR	50
COW GREEN RESERVOIR	300
FONTBURN RESERVOIR	50

NORTHWEST

CRUMMOCK WATER	200
LOWESWATER	75
DERWENT WATER	600
DEVOKE WATER	25
ASHWORTH MOOR RESERVOIR	25
BLACKSTONE EDGE RESERVOIR	25
RIVINGTON RESERVOIR	100
RYDAL WATER	25
TORSIDE RESERVOIR	75
NAMELESS	25
BASSENTHWAITE LAKE	500
NAMELESS	50
ESTHWAITE WATER	100
WET SLEDDALE RESERVOIR	25
BELMONT RESERVOIR	50
ENNERDALE WATER	300
WAST WATER	200
FERNILEE RESERVOIR	25
SCOTMANS FLASH	25
NAMELESS	25
THIRLMERE	300
CLOWBRIDGE RESERVOIR	25
STOCKS RESERVOIR	100
HOLLINGWORTH LAKE	50
GREENBOOTH RESERVOIR	25
ELTON RESERVOIR	25
BOTTOM FLASH	25
BUTTERMERE	100
AUDENSHAW RESERVOIR	25
NAMELESS	75
ULLSWATER	900
CONISTON WATER	400
YARROW RESERVOIR	25
ERRWOOD RESERVOIR	25
AUDENSHAW RESERVOIR	25
TABLEY MERE	25
WAYOH RESERVOIR	50
OGDEN RESERVOIR	25
GRASSMERE	50
NAMELESS	25
BOSLEY RESERVOIR	25
DOVESTONE RESERVOIR	25
WATERGROVE RESERVOIR	25
THE FLASH	75
VALEHOUSE RESERVOIR	25
COMBER MERE	50
AUDENSHAW RESERVOIR	25
TATTON MERE	25
TALKIN TARN	25
TURTON & ENTWISTLE RESERVOIR	50
BUDWORTH MERE	25
ROSTHERN MERE	50
NAMELESS	25
NAMELESS	25
HAWESWATER RESERVOIR	400
WOODHEAD RESERVOIR	75
SEATHWAITE TARN	25
DELPH RESERVOIR.	25
HEATON PARK RESERVOIR	25
KILLINGTON RESERVOIR	75
WINDERMERE	1400
ANGLEZARKE RESERVOIR	75

SOUTHERN

DARWELL RESERVOIR	70
HIGHAM MARSHES	25
BEWL LAKE	400
NAMELESS	50
ARDINGLY RESERVOIR	100
ARDINGLY RESERVOIR	100
POWDERMILL RESERVOIR	25
HIGHAM MARSHES	25
SOWLEY POND	250
NAMELESS	50
BOUGH BEECH RESERVOIR	150
NAMELESS	50
WEIR WOOD RESERVOIR	150
WESTBERE MARSHES	50
WESTBERE MARSHES	25
ARLINGTON RESERVOIR	50
HIGHAM MARSHES	50

SEVERN TRENT

	ha
BELVIDE RESERVOIR	75
THE POOL	25
FOREMARK RESERVOIR	100
COOMBE POOL	25
CHASE WATER	75
DERWENT RESERVOIR	100
THE GREAT POOL	25
THE POOL	25
CROPSTON RESERVOIR	50
NAMELESS	25
RUDYARD RESERVOIR	100
CLUMBER LAKE	25
SHUSTOKE RESERVOIR	25
AQUALATE MERE	75
COLE MERE	25
NAMELESS	100
NAMELESS	25
BLITHFIELD RESERVOIR	300
LLYN CLYWEDOG	300
SWITHLAND RESERVOIR	100
THE MERE	50
TITTESWORTH RESERVOIR	100
CHELMARSH RESERVOIR	50
NAMELESS	25
GREAT LAKE	50
UPPER BITTELL RESERVOIR	25
BLACKBROOK RESERVOIR	25
STANFORD RESERVOIR	75
LADYBOWER RESERVOIR	200
NAMELESS	25
NAMELESS	25
NAMELESS	25
THORESBY LAKE	25
DRAYCOTE WATER	325
HOWDEN RESERVOIR	75
NAMELESS	25
NAMELESS	25
GREAT POOL	25
KNIPTON RESERVOIR	25
NAMELESS	25
BARTLEY RESERVOIR	50
EDGBASTON RESERVOIR	25
NAMELESS	25
THORNTON RESERVOIR	25
NAMELESS	50
STAUNTON HAROLD RESERVOIR	75
LLYN EFYRNWY	400
NASEBY RESERVOIR	25
NAMELESS	25

SOUTHWEST

FERNWORTHY RESERVOIR	25
ARGAL RESERVOIR	25
DRIFT RESERVOIR	25
KENNICK RESERVOIR	25
STITHIANS RESERVOIR	150
MELDON RESERVOIR	25
SLAPTON LEY	100
WISTLANDPOUND RESERVOIR	25
BURRATOR RESERVOIR	100
UPPER TAMAR LAKE	25
THE LOE/CARMINOWE CREEK	50
CROWDY RESERVOIR	50
SIBLYBACK LAKE	50
COLLIFORD LAKE	400

THAMES

NAMELESS	25
STOCKER'S LAKE	25
NAMELESS	50
KING GEORGE VI RESERVOIR	150
NAMELESS	25
LOCKWOOD RESERVOIR	25
NAMELESS	25
KING GEORGE'S RESERVOIR	250
NAMELESS	25
THE LAKE	25
NAMELESS	25
NAMELESS	25
NAMELESS	100
NAMELESS	50
NAMELESS	50
QUEEN ELIZABETH II RESERVOI	150
NAMELESS	25
NAMELESS	50
FLEET POND	25
VIRGINIA WATER	50
NAMELESS	25
WRAYSBURY RESERVOIR	200
NAMELESS	25
NAMELESS	50
BESSBOROUGH RESERVOIR	25
NAMELESS	25
BODDINGTON RESERVOIR	25
THORPE PARK	100
STAINES RESERVOIR	100
NAMELESS	25
BRENT RESERVOIR	50
NAMELESS	25
FARMOOR RESERVOIR	150
THE QUEEN MOTHER RESERVOIR	200
NAMELESS	25
BANBURY RESERVOIR	25
NAMELESS	50
QUEEN MARY RESERVOIR	250
NAMELESS	25
STAINES RESERVOIR	50
ALDENHAM RESERVOIR	25
WILLIAM GIRLING RESERVOIR	150
ISLAND BARN RESERVOIR	50
FRENSHAM GREAT POND	25
NAMELESS	25
NAMELESS	25
NAMELESS	25
GREBE LAKE	25
HILFIELD PARK RESERVOIR	25

WELSH

NEUADD RESERVOIR	25
LLYN CWMYSTRADLLYN	25
LLYN COWLYD RESERVOIR	100
ALWEN RESERVOIR	150
LLYN GYNON	25
LLYN GEIRIONYDD	25
PENYGARREG RESERVOIR	50
LLYN CELYN	300
PONTSTICILL RESERVOIR	150
OGSTON RESERVOIR	50
LLYN BRENIG	400
LLYN CONWY	50
CABAN-COCH RESERVOIR	125
LLYN DINAS	25
LLYN NANTLLE UCHAF	50
LLANDEGFEDD RESERVOIR	200
CARREG-DDU RESERVOIR	100
NANT-Y-MOCH RESERVOIR	300
LLYN PENRHYN	25
LLYN-Y-GADAIR	25
LLYN GWYNANT	50
USK RESERVOIR	150
LLANISHEN RESERVOIR	25
PENTWYN RESERVOIR	50
LLYN BODLYN	25
LLYN CRAFNANT RESERVOIR	25
LLYS-Y-FRAN RESERVOIR	100
LLYN BRIANNE RESERVOIR	300
LLYN EIGIAU RESERVOIR	50
LLYN TEIFI	25
LLYN ALWEN	25
EGLWYS NUNYDD RESERVOIR	100
LLYN CWELLYN	100
LLYN ALED	50
LLYNNAU MYMBYR	25
LLYN LLYWENAN	50
LLYN TEGID	500
YSTRADFELLTE RESERVOIR	25
LLYN PADARN	125
LLYN ALAW	300
TANYGRISIAN RESERVOIR	50
CRAIG GOCH RESERVOIR	100
LLANGORSE LAKE	150
LLYN OGWEN	25
GLASLYN	25
KENFIG POOL	25
ALED ISAF RESERVOIR	25
HANMER MERE	25
LLYN TRAWSFYNDD	500
LLYN CORON	25
CLAERWEN RESERVOIR	300
LLYN PERIS	75
LLWYN-ON RESERVOIR	75
BROAD WATER	100
LLYN TRAFFWLL	25
LLYN ARENIG FAWR	25
LLYN MAELOG	25
CEFNI RESERVOIR	100
CRAY RESERVOIR	50
TAL-Y-LLYN LAKE	50
LLYN LLYDAW	50
TALYBONT RESERVOIR	150

WESSEX

THE ROYAL PORTBURY DOCK	25
CHEDDAR RESERVOIR	100
NAMELESS	25
DURLEIGH RESERVOIR	25
EAST/WEST FLEET	500
CHARD RESERVOIR	25
WIMBLEBALL LAKE	250
CLATWORTHY RESERVOIR	100
SUTTON BINGHAM RESERVOIR	100
[FONTHILL LAKE]	25
CHEW VALLEY LAKE	500
BLAGDON LAKE	200

YORKSHIRE

UNDERBANK RESERVOIR	50
WITHENS CLOUGH RESERVOIR	25
DAMFLASK RESERVOIR	50
GREAT LAKE	25
WHITE HOLME RESERVOIR	50
LOWER BARDEN RESERVOIR	25
BAITINGS RESERVOIR	25
ARDSLEY RESERVOIR	21
LEIGHTON RESERVOIR	25
ECCUP RESREVOIR	75
WARLEY MOOR RESERVOIR	25
NAMELESS	50
HORNSEA MERE	200
MORE HALL RESERVOIR	25
ANGRAM RESERVOIR	50
THRUSCROSS RESERVOIR	50
NAMELESS	25
REDMIRES RESERVOIR	25
SCAR HOUSE RESERVOIR	75
SCAMMONDEN WATER	50
NAMELESS	25
SCALING RESERVOIR	25
NAMELESS	25
SWINSTY RESERVOIR	75
AGDEN RESERVOIR	25
SEMER WATER	25
BROOMHEAD RESERVOIR	50
NAMELESS	25
FEWSTON RESERVOIR	50
LANGSETT RESERVOIR	50
GRIMWITH RESERVOIR	150
BLACKMOORFOOT RESERVOIR	25
MALHAM TARN	75
WARLAND RESERVOIR	25
DALE DIKE RESERVOIR	25
WINSCAR RESERVOIR	50
LINDLEY WOOD RESERVOIR	50
WIDDOP RESERVOIR	25
UPPER BARDEN RESERVOIR	25
WINTERSETT RESERVOIR	50
INGBIRCHWORTH RESERVOIR	25
ROUNDHILL RESERVOIR	25
SOUTHFIELD RESERVOIR	25
GOUTHWAITE RESREVOIR	200

Appendix 5

1) Name of Water Authority? ....

2) Name of water body? .... Map ref...............

In multiple-choice questions please circle appropriate answer(s).

3) Is the water body: Natural : Man made : Standing water : Riverine

If man-made is it: Purpose built reservoir : Dammed river

Flooded gravel working : Flooded peat digging : Other (specify) ....

4) Major use: Industrial water supply Potable water supply

Coarse fishery Game fishery Fish farm Water sports

Aesthetic SSI Amenity Other (specify): ....

5) Physical characteristics:

Is the bathymetry known: Yes/No

Is flow data (inlet or outlet) available: Yes/No

Is the retention time available: annual mean : winter mean : summer mean : no

Does the lake stratify:

unknown : continuously : most of summer : short periods : seldom/never

6) Chemical data:

	Frequency		Frequency
Major ions	....	Algae	....
Trophic state	....	Zooplankton	....
Non-specific determinands	....	Invertebrates	....
Other (please specify)	....	Fish	....

8) Contact:-

Name ....

Address ....

.... Tel ....

Please return to:- Dr J. Hilton, Freshwater Biological Association
The Ferry House, Ambleside, Cumbria, LA22 OLP

NOTES

3) Most British lakes have had some modification by man. Use 'Natural' to include minor modifications and 'Man made' when man has actually created the hole.

Riverine should be used to describe a lake into and out of which a reasonably sized river flows, i.e. the lake is a simple widening of the river bed. Lakes into which several small streams flow and collect before flowing out of a single outlet should be called a standing water.

4) 'Major Use' refers to the use which takes priority in water quality decisions. If two or more uses have equal first status, circle more than one.

5) continuously = meromictic; most of summer = monomictic; short period = polymictic.

6 & 7) For 'frequency' use either W, M, Q, A, O or N as an abbreviations for Weekly, Monthly, Quarterly, annual, Occasional, None. Use the smallest time scale which includes your sampling frequency, e.g. one sample every two months would require the answer 'Q'.

6) Major ions includes all or some of: Ca, Mg, Na, K, Cl, Alkalinity, Sulphate.

Trophic status includes some or all of: NH3, NO2, NO3, PO4, total P, total N, organic P, N, chlorophyll a.

Non specific determinands includes some or all of: pH, conductivity, turbidity, suspended solids, secci disc, colour, dissolved oxygen, BOD.

7) Algae includes counts or speciation. Pigment analyses should be treated as a measure of trophic (see 6).

No distinction should be made between quantitative, semi-quantitative, and qualitative data for section 7.

8) A contact name is only required if it is different for different lakes in a Water Authority. As a default I will assume that the respondent (or named delegate) is the contact for all enquiries.

AUTHORITY ANGLIAN

No. LAKES 31

TYPE

	1st USE	2nd USE
POTABLE WATER	11	-
COARSE FISHERY	16	5
GAME FISHERY	1	-
SSSI	-	-
NONE	1	-
AMENITY	1	H
WATERSPORTS	-	-
BIRD WATCHING	-	-
DUCK SHOOT	-	-
AESTHETIC	-	-
CLAY DIGGING	1	-
CANAL FEEDER	-	-
RIVER REGULATION	-	-
COMPENSATION	-	-
INDUSTRIAL WATER	1	-
FLOOD STORAGE	-	-
FISH FARM	-	-
SSI	-	-
RSPB RESERVE	-	-

	KNOWN	UNKNOWN
BATHIMETRY	10	21
FLOW	13	18
STRATIFICATION BEHAVIOUR	21	10
ARTIFICIAL MIXING	3	

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never
MAJOR IONS (one or more of Ca,Mg,Na,k,Alkalinity,SO_4)	6	1	15	-	-	-	9
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	-	-	-	-	-	-	-
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	6	1	15	-	-	-	9
ALGAE (counts or speciation)	7	-	14	-	-	1	8
ZOOPLANKTON	6	-	6	-	-	7	-
INVERTEBRATES	-	-	-	-	-	-	-
FISH	-	-	-	-	-	-	-

AUTHORITY NORTHUMBRIAN

No. LAKES 14

TYPE	1st USE	2nd USE
POTABLE WATER	10	-
COARSE FISHERY	-	-
GAME FISHERY	1	-
SSSI		
NONE		
AMENITY		
WATERSPORTS		
BIRD WATCHING		
DUCK SHOOT		
AESTHETIC	3	-
CLAY DIGGING		
CANAL FEEDER		
RIVER REGULATION		
COMPENSATION		
INDUSTRIAL WATER		
FLOOD STORAGE		
FISH FARM		
SSI		
RSPB RESERVE		

	KNOWN	UNKNOWN
BATHIMETRY	8	6
FLOW	10	4
STRATIFICATION BEHAVIOUR	10	4
ARTIFICIAL MIXING	-	-

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never	D
MAJOR IONS (one or more of Ca,Mg,Na,k,Alkalinity,SO_4)	3	-	2	-	3	-	6	-
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	2	-	2	3	3	-	4	-
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	2	-	3	-	3	-	4	1
ALGAE (counts or speciation)	-	-	-	1	-	1	12	-
ZOOPLANKTON	-	-	-	-	-	1	13	-
INVERTEBRATES	-	-	-	-	-	1	13	-
FISH	-	-	-	-	-	-	14	-

AUTHORITY SOUTHERN

No. LAKES 16

TYPE

	1st USE	2nd USE
POTABLE WATER	8	-
COARSE FISHERY	4	2
GAME FISHERY	-	6
SSSI		
NONE		
AMENITY		
WATERSPORTS	1	2
BIRD WATCHING	1	-
DUCK SHOOT	1	-
AESTHETIC		
CLAY DIGGING		
CANAL FEEDER		
RIVER REGULATION		
COMPENSATION		
INDUSTRIAL WATER		
FLOOD STORAGE		
FISH FARM	1	-
SSI	2	-
RSPB RESERVE		

	KNOWN	UNKNOWN
BATHIMETRY	5	11
FLOW	5	11
STRATIFICATION BEHAVIOUR	5	11
ARTIFICIAL MIXING	1	-

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never
MAJOR IONS (one or more of Ca,Mg,Na,k,Alkalinity,SO_4)	-	-	-	-	-	9	7
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	-	-	-	-	-	8	8
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	-	-	-	-	-	4	12
ALGAE (counts or speciation)	-	-	-	-	-	3	13
ZOOPLANKTON	-	-	-	-	-	-	16
INVERTEBRATES	-	-	-	-	-	-	16
FISH	-	-	-	-	-	10	2

AUTHORITY South West Water

No. LAKES 10

TYPE

	1st USE	2nd USE
POTABLE WATER	10	-
COARSE FISHERY	-	-
GAME FISHERY	-	-
SSSI	-	-
NONE	-	-
AMENITY	-	-
WATERSPORTS	-	-
BIRD WATCHING	-	-
DUCK SHOOT	-	-
AESTHETIC	-	-
CLAY DIGGING	-	-
CANAL FEEDER	-	-
RIVER REGULATION	-	1
COMPENSATION	-	-
INDUSTRIAL WATER	-	-
FLOOD STORAGE	-	-
FISH FARM	-	1
SSI	-	-
RSPB RESERVE	-	-

	KNOWN	UNKNOWN
BATHIMETRY	10	-
FLOW	10	-
STRATIFICATION BEHAVIOUR	7	3
ARTIFICIAL MIXING	3	-

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never
MAJOR IONS (one or more of CA,Mg,Na,k,Alkalinity,SO_4)	-	-	10	-	-	-	-
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	-	-	10	-	-	-	-
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	-	-	10	-	-	-	-
ALGAE (counts or speciation)	-	-	10	-	-	-	-
ZOOPLANKTON	-	-	1	-	-	-	9
INVERTEBRATES	-	-	-	-	-	-	10
FISH	-	-	-	-	-	8	2

AUTHORITY THAMES

No. LAKES 14

TYPE		1st USE	2nd USE
	POTABLE WATER	14	-
	COARSE FISHERY		
	GAME FISHERY		
	SSSI		
	NONE		
	AMENITY		
	WATERSPORTS		
	BIRD WATCHING		
	DUCK SHOOT		
	AESTHETIC		
	CLAY DIGGING		
	CANAL FEEDER		
	RIVER REGULATION		
	COMPENSATION		
	INDUSTRIAL WATER		
	FLOOD STORAGE		
	FISH FARM		
	SSI		
	RSPB RESERVE		

	KNOWN	UNKNOWN
BATHIMETRY	14	
FLOW	14	
STRATIFICATION BEHAVIOUR	10	4
ARTIFICIAL MIXING	5	

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never
MAJOR IONS (one or more of Ca,Mg,Na,k,Alkalinity,SO_4)	14	-	-	-	-	-	-
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	14	-	-	-	-	-	-
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	7	-	-	-	-	2	5
ALGAE (counts or speciation)	14	-	-	-	-	-	-
ZOOPLANKTON	7	-	-	-	-	1	6
INVERTEBRATES	-	-	-	-	-	-	14
FISH	-	-	-	-	-	1	13

AUTHORITY WESSEY

No. LAKES 7

TYPE

	1st USE	2nd USE
POTABLE WATER	6	1
COARSE FISHERY	-	-
GAME FISHERY	-	-
SSSI	-	-
NONE	-	-
AMENITY	-	-
WATERSPORTS	1	-
BIRD WATCHING	-	-
DUCK SHOOT	-	-
AESTHETIC	-	-
CLAY DIGGING	-	-
CANAL FEEDER	-	-
RIVER REGULATION	-	-
COMPENSATION	-	-
INDUSTRIAL WATER	-	-
FLOOD STORAGE	-	-
FISH FARM	-	-
SSI	-	-
RSPB RESERVE	-	-

	KNOWN	UNKNOWN
BATHIMETRY	7	
FLOW	7	
STRATIFICATION BEHAVIOUR	7	
ARTIFICIAL MIXING	3	

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never
MAJOR IONS (one or more of Ca,Mg,Na,k,Alkalinity,SO_4)	3	-	4	-	-	-	-
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	6	-	1	-	-	-	-
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	7	-	-	-	-	-	-
ALGAE (counts or speciation)	3	-	4	-	-	-	-
ZOOPLANKTON	3	-	1	-	1	-	2
INVERTEBRATES	-	-	-	-	1	1	5
FISH	-	-	-	-	4	3	-

AUTHORITY YORKSHIRE

No. LAKES 30

TYPE

	1st USE	2nd USE
POTABLE WATER	18	-
COARSE FISHERY	-	1
GAME FISHERY	-	5
SSSI	3	2
NONE	-	-
AMENITY	-	6
WATERSPORTS	-	3
BIRD WATCHING	-	-
DUCK SHOOT	-	-
AESTHETIC	-	-
CLAY DIGGING	-	-
CANAL FEEDER	2	-
RIVER REGULATION	1	-
COMPENSATION	5	-
INDUSTRIAL WATER	-	-
FLOOD STORAGE	1	-
FISH FARM	-	-
SSI	-	9
RSPB RESERVE	-	1

	KNOWN	UNKNOWN
BATHIMETRY	26	4
FLOW	25	5
STRATIFICATION BEHAVIOUR	19	11
ARTIFICIAL MIXING	-	-

	w'kly	2 w'kly	m'thly	q'trly	y'rly	occas.	never
MAJOR IONS (one or more of Ca,Mg,Na,k,Alkalinity,SO_4)	-	-	2	2	-	22	4
TROPHIC STATUS (one or more of NH_3,NO_2,NO_3,PO_4,Total N, organic P,N,chlorophylla)	-	-	2	3	-	22	4
NON SPECIFIC IONS (one or more of pH,cond,turbidity, susp.solids,secci disc, colour,DO,BOD)	20	-	2	3	-	1	4
ALGAE (counts or speciation)	1	-	-	1	-	1	27
ZOOPLANKTON	-	-	-	-	-	-	30
INVERTEBRATES	-	-	-	-	-	-	30
FISH	-	-	-	-	4	3	23