Institute of Freshwater Ecology

Eutrophication Case Studies: Phase II, an assessment based on desk analysis of catchments and summer limnological reconnaissances

Volume I. An analysis of the whole spectrum of waters studied

Principal Investigators:

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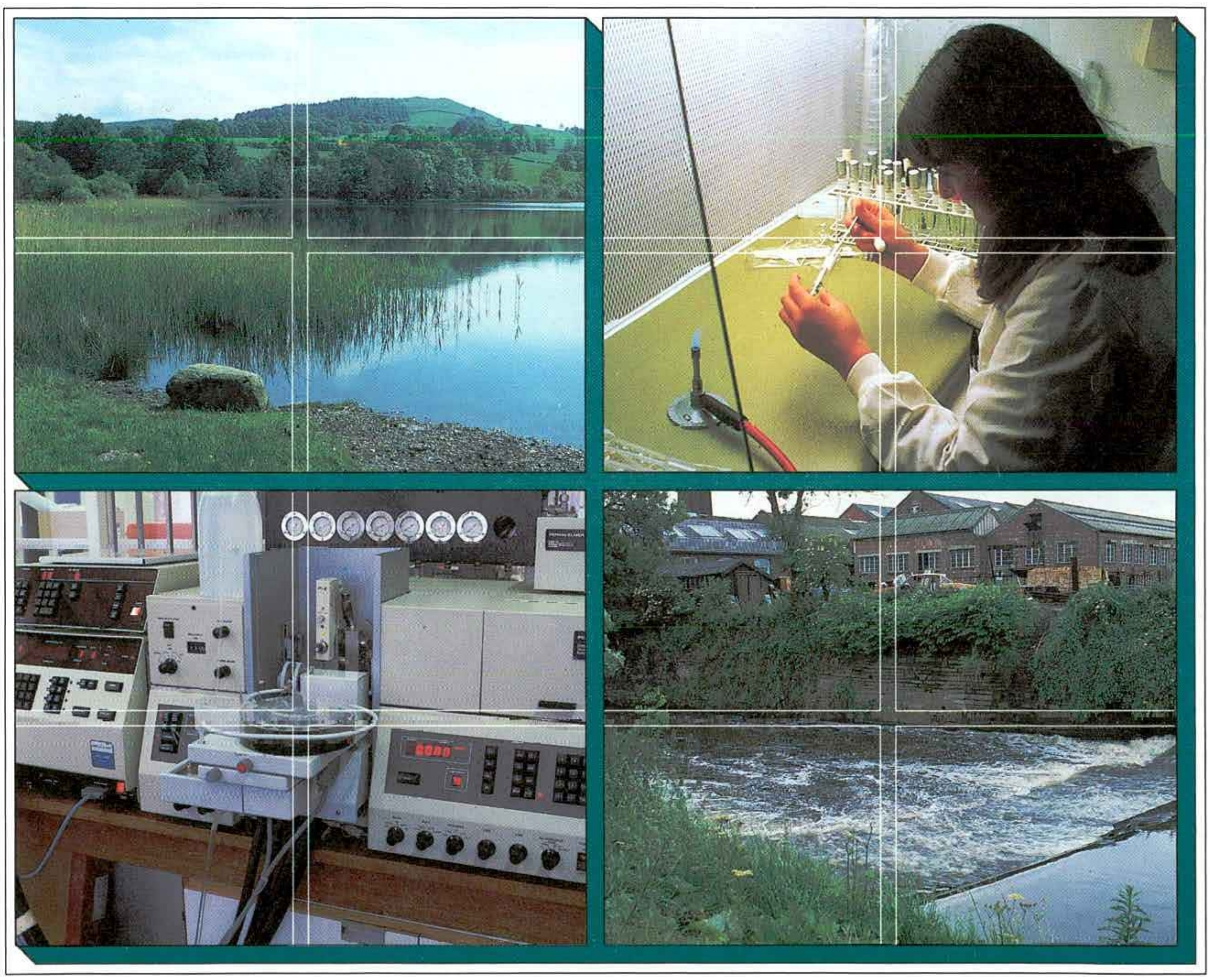
Final report to the Nature Conservancy Council for Scotland (March 1992)



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Summary

The trophic status (measured by the summer phosphorus content) of a broad spectrum sample of 26 Scottish lochs (Volume I), generally correlates well ($r^2 = 0.71$) with annual mean, lake-wide, flushing-corrected P levels predicted from:

(i) land use and human occupancy of the catchments, combined with appropriate (published) P export coefficients for estimating loadings from e.g. arable land, forest areas, rural communities, and fish farms.

(ii) information on rainfall over the catchments, for flushing rate calculations.

The measured and predicted values do not correspond so well for every loch sampled. Various reasons for this are discussed (Volume II).

In arriving at these conclusions, the project has generated an extensive body of new limnological information for Scotland. It examined a range of waters varying in orders of magnitude in terms of biological, chemical (water and sediments) and physical features.

The various issues, analyses and interpretations covered in this eutrophication study, are presented with reference to the following relationship:

pressures x sensitivity factors = responses

Pressures concern the (predicted) burdens of P. Sensitivity factors include loch size (especially the mean depth) and flushing rate. The responses of major interest here are nutrient levels and the abundances and species composition of the phytoplankton, although patterns of rotifer species occurrence which relate to summer P concentrations have also been found.

The majority of the waters examined are at least tending towards the eutrophic state, although indications of 'chemical eutrophy' are not always accompanied

by signs of 'biological eutrophy'.

The study assesses to what extent the P retaining capacity of lochs lying in the catchment of others, protect the downstream waters.

Few, strong relationships have been found so far, between measures of sediment P content, and predicted P loads, but further analyses of the data are still needed.

The individual physical characteristics of a waterbody influence strongly the relationship between summer phytoplankton biomass and predicted annual P burden.

The study shows that the desk approach can provide a credible assessment of loch trophic status, and give meaningful clues to the likely levels of nutrients and plankton, and to the general balance between the planktonic flora and the communities of rooted/attached plants. As such, it should attract much interest from planners, developers, conservationists and fishery managers and the like.

Much work is still needed to improve on the estimates of nutrient losses from different types of land. Seasonal variation in pressures, sensitivity factors and responses also needs to be more adequately assessed.

Other issues requiring new work are listed, and these range from further analyses of the existing data and material, to extra field studies, and from mathematical modelling to basic biological taxonomy.

1. INTRODUCTION

1.1 Aims

This eutrophication study was initiated in April 1991. It followed the completion of the first phase of work which reviewed the reports on previous case studies funded by the Nature Conservancy/Nature Conservancy Council over the last 25 years (Bailey-Watts and May 1991). The aims of the present work are as follows:

- to assess in broad terms, through analysis of map information on e.g. land use, topography and rainfall, the phosphorus loadings (as a major indication of eutrophication pressures on *ca* 30 lochs; this group of waters was chosen by NCCS as representative of Scottish waters already exhibiting signs of accelerated enrichment, or considered to be imminently threatened by such enrichment.

- to adjudge the general sensitivity of each waterbody to the perceived pressures, by examining factors which determine the extent to which enhanced supplies of nutrients are likely to be manifested in, for example, accumulations of troublesome plants, and planktonic algae in particular; sensitivity factors which can also be drawn from maps include the catchment-to-loch area ratio and flushing rate, while at least one field reconnaissance is necessary for data on water clarity, thermal and chemical stratification of the water column, and an indication of the availability of nutrients such as silica (SiO_2), as well as nitrogen (N) and phosphorus (P).

- to examine, by means of a single reconnaissance and analysis of water and sediments, features indicating the net effect of pressures and sensitivity, ie the responses of the waters.

- to test the usefulness of this approach by comparing the annual mean, lake-wide P levels calculated from the loadings predicted by the desk analyses, to an index of actual P content - and a single summer value is used for this purpose.

The results are reported in two ways. Volume I looks at the relationships between the various factors over the whole spectrum of waters; this is with the view to furthering knowledge of the extent and consequences of eutrophication in Scotland. By contrast, Volume II is a series of limnological profiles of each loch. These provide more details about eutrophication and P in particular, and, where appropriate, make recommendations on future research, monitoring and management as far as nutrient enrichment is concerned.

1.2 Background and rationale

The earlier review (Bailey-Watts and May 1991) highlighted 3 main issues that have influenced the planning and execution of the present phase: (i) the overall importance of eutrophication in freshwater ecology*, (ii) the individuality of lake systems, and (iii) the complexity of freshwater communities in regard to temporal changes and the multifactorial structure of the environment controlling these changes.

1.2.1 *Eutrophication as a major factor in limnology*

Quantitative understanding of the causes of eutrophication, and its effects on the dynamics of freshwater ecosystems, is vital for the improved management of these systems for conserving species and communities, for improving the quality of water destined for potable supply and irrigation, for sustaining commercial fisheries, and for accommodating a variety of recreational activities. The work is also fundamental to planners' requirements for effective assessments and predictions of the impacts of town and country development on the freshwater networks; this recognises that standing waters in particular, are major depositories of wind- and

*This point is also stressed by Harper (1992) in his fine book that appeared during the latter stages of the preparation of this report.

water-borne substances derived from the land. Phase II reflects this thinking by considering lochs as an integral part of a broader unit - the freshwater catchment.

1.2.2 *The individuality of lake systems*

The individual structure and functioning of a lake system is emphasised by the earlier review. This led to major differences in the scope of, and approaches adopted by, the major case studies (of the Bosherston Lakes, Esthwaite Water, Loch Eye, Loch Leven, Malham Tarn and the Norfolk Broadland). Indeed, there were few determinands common to all of these studies: for example, actual P loading figures were not universally available. As a result, an original intention to examine spectra of values for such determinands was thwarted(!). The conclusion of major relevance to the planning of work on further catchments, was that a uniform approach should be adopted - and this was adopted in Phase II.

1.2.3 *Temporal and structural complexity of freshwater ecosystems*

The long-term studies reviewed in Phase I revealed the highly complex nature of the aquatic biota, and the multi-factorial structure of the environment controlling, and in part controlled by, temporal and spatial variation in these organisms. Two considerations stemming from these findings were incorporated in the preparations for Phase II. The first concerns the fluctuations, over various timescales, in a wide range of physical, chemical and biological factors which are important in explaining their causal interrelationships. Indeed, the identifying of this complex temporal 'behaviour' of aquatic ecosystems is what illustrates the value of the long-term sampling schedules which characterise the major case studies. Plainly, however, to cover an envisaged 30 sites, an alternative strategy for each site was needed, and this reflects what is likely to be a continuing requirement. Many custodians of the freshwater environment, including planners, have neither the time, nor funds to support more long-term studies - however necessary such investigations still are. Phase II thus tailored its approach to rapid assessments, by combining desk studies with single field surveys of each catchment.

1.2.4 *The main approach - pressures, sensitivity and responses*

The 'new' approach tested during Phase II makes considerable use of the data and the experience of the previous work. Three areas are of importance in this connection:

- the basic framework: investigating pressures on the system, the factors determining the sensitivity of the (standing) water to those pressures, and some of the responses of the system, ie the combined impact of the pressures and the sensitivity factors.

- the choice of factors for assessing pressures, sensitivities and responses, ie the key determinands (summarised below).

- the assessment of eutrophication *per se*, ie the likely rates of loss of nutrients from land under different uses, such as forestry, and cereal production, and other activities likely to cause eutrophication, e.g. fish-farming and sewage effluent disposal; the best information on nutrient export coefficients, ie losses in e.g. kg ha^{-1} yr^{-1}, stem from the long term studies.

Information on factors determining the eutrophication *pressures* was drawn largely from maps although NCCS staff were consulted on details about the catchments. The maps were analysed with the view to estimating the areas of catchments and lochs, and approximate indices of the annual runoff of water and P. A general guide to P loadings was then obtained by assigning the appropriate export coefficient to (i) areas of land under a particular use, and (ii) sewage treatment works and fish farms, according to, respectively, the numbers of people served, and the annual weights of fish produced.

Maps were also evaluated with the view to estimating the factors important in determining the *sensitivity* of the lochs to the nutrients they receive. These include (i) catchment-to-loch area ratios, (ii) the ratio of the annual runoff volume to loch volume (for calculating mean annual flushing rate, ρ, in loch volumes), and (iii) the areal water loading, q_s (in m y^{-1}), which is the annual throughput of water (in m^3) divided by loch surface area, A_l (in m^2); from this an index of the retention coefficient of P (R_p) can be obtained. Chemical factors influencing the sensitivity of waters, include soil and geological features, but these have not been examined. However, an index of total ionicity in feeder stream and loch waters has been obtained by measuring the electrical conductivity. pH has been measured as a further descriptor of the general chemical environment.

Other sensitivity factors include features of the standing water bodies themselves. Flushing (ρ) is again of paramount importance, along with bathymetry and the tendency to stratify; these affect (i) the degree of wind-induced vertical mixing, and thus the light climate of planktonic organisms, and (ii) the fluxes and vertical distribution of chemical and biological materials. Indeed, the outcome of the interaction between depth features, stratification patterns and ρ, is possibly the major determinant of the response of any system to its nutrient income. For example, conceptual models of nutrient dynamics, and changes in phytoplankton abundance and species composition, have been markedly improved by incorporating information on ρ into the database on Loch Leven (Bailey-Watts, Kirika, May and Jones 1990). As this is a broad, shallow and essentially unstratified system, it might be expected to be especially sensitive to changes in flushing in any event. However, deep waters which stratify in summer can be considered as becoming shallow as far as a number of features important for phytoplankton growth are concerned. It is thus conceivable that these summer populations, when largely entrained within the upper, epilimnetic zone, are especially susceptible to increased flushing in wet summers. This is because while the volumes of runoff are, as year-round, derived from the large catchments normally associated with large-volume waters, only the surface waters and the algae therein are washed out; in this otherwise favourable, shallow, lit zone, algae have to either grow or aggregate rapidly to build up significant concentrations (biomass).

Within a waterbody, ρ is also of paramount importance in controlling the time periods over which a number of developments are likely to take place - 'unhindered' that is, until the flushing regime alters. Included here are the accumulations of nutrients released from sediments, and the build-up of phytoplankton cells, that can proceed during periods of low flushing, but which are curtailed during spells of high flushing and the washing out of these nutrients and cells. Indeed, the changing conditions as regards flushing are likely to have a sorting effect on phytoplankton - with slow-growing species being able to become prominent only during periods of low flushing. In addition, ρ is an important consideration when impacts of different sources of nutrients are being assessed. It plainly controls the rates of transport, ie loadings, of materials in runoff, while it only affects the concentrations of runoff-independent inputs from e.g. STWs, over-wintering wildfowl, and fish cages.

The amounts of dissolved, coloured material and particulate matter also affect the underwater light climate, and how much primary production will result per unit of nutrient supply. In the most productive waters, much of the particulate matter consists of the algae themselves (Bindloss 1976).

While in-loch nutrient levels can be classified as sensitivity factors, it is convenient to consider them under 'responses' (see below). However, SiO_2 could be treated as a special case, as its availability will determine very much the quality of the plant response to the enrichment with the 'classic' nutrients, ie N and P. Plainly, the diatom contribution to phytoplankton and benthic algal productivity is affected by SiO_2 availability (Bailey-Watts 1976a, b), but so are the performances of Chrysophyceae (McGrory and Leadbeater 1981) and numerous higher plants (Lewin and Reimann 1969; Simpson and Volcani 1981).

The *'responses'* aspect of the work focuses primarily on nutrient and biological features of the open water column - although many of the determinations were also carried out on water sampled from the outflow of each loch. However, sediment cores down to *ca* 10 cm, and the water immediately overlying these deposits, were also collected, primarily for P analysis.

The summer was chosen for the fieldwork, because it is a key time for obtaining information likely to provide clues to the functioning of a other than the actual moment of sampling. In this connection, vertical profiles of physical and chemical features - and, not least, the bottom water temperatures - give clues to the duration of the stratification.
Summer-time sampling is also important, as the potential for a water to exhibit major accumulations of planktonic and/or attached algae, or growths of rooted hydrophytes, is likely to be greatest at this time of the year.

Plainly, the data obtained from the surface waters are of the 'snapshot' type, although some assumptions about conditions relating to periods outside the sampling time can be made. For example, knowledge of the likely rates of increase of an alga that is recorded, facilitates some assessment of the time that must have been required for that species to achieve the population density estimated. Also, much of the information gained from the sediments is probably representative of a considerable timescale. While phytoplankton population densities can change 2- or 3-fold in a week, the total concentrations of P in surface sediments, for example, are not likely to change significantly over a year; what is more, data collected, though not reported here, on the vertical distribution of nutrients in the bottom deposits, can give clues to eutrophication trends over decades (Moss 1980, Haworth 1984).

1.3 General features of the sites studied

Approximately 60 aquatic SSSIs were proposed by NCCS for consideration in the current programme. This list was reduced, in consultation with NCCS, to 30; the main criteria for choosing this number were (i) that neither funds nor time (within a single summer) would probably allow greater coverage, but (ii) that something approximating to 30 sites was necessary to build up a database of a statistically acceptable size, and one which would also be considered a reasonable 'sample' of Scottish catchments. As a result, a good deal of valuable information can be gained on not only the assessment and management of eutrophication and the specific problems at each site (Volume II), but also the interrelationships between spectra of values for a range of physical, chemical and biological factors (Volume I); the latter is likely to prove especially significant in furthering our understanding of the issues nation-wide.

In the event, 31 catchments were considered, 26 of which were visited between mid-June and late August 1991. The 31 included 30 chosen by NCCS, plus the Loch of Cliff (Shetland), which was sampled during August, along with 4 other Shetland lochs, i.e. Spiggie, Brow, Tingwall and Asta. The 5 waters missed out (though in terms of a field reconnaissance, not desk analysis), were Duddingston (Edinburgh), Castle Loch (Lochmaben), Cran and Flemington (both near Nairn) and Carlingwark (Castle Douglas). Also, at the Mill Loch (Lochmaben) sampling was limited to duplicate dip samples from open water, for nutrient and phytoplankton analysis. All 31 waters - comprising 46 basins - are listed in **Appendix I** with the dates of sampling and their locations are shown in **Figure 1**.

Geographical coverage spans nearly 6 degrees of latitude, from Carlingwark at 54°56'N and Branxholme Easter (elsewhere in this report referred to as Branxholme) at 55°24'N in the south of the country, to the Loch of Cliff at 60°47'N on Unst, Shetland (**Figure 2**). Along with the Loch of Cliff, 2 of the other 4 Shetland waters studied, Spiggie and Brow, lie between 1 and 2 m a.s.l., while Lindean and Branxholme are in the Selkirkshire hills at 268 and 262 m a.s.l respectively (**Figure 3**). The average annual rainfall over the sites ranges from *ca* 670 mm over the South East, near-coast sites Coldingham (Berwickshire), Kilconquhar (Fife) and Duddingston, to 2600 mm at Shiel in the north-west. Catchments range from comparatively pristine landscapes in the north-west, albeit affected now by forestry operations, to urban areas e.g. Duddingston, Mill and Kilconquhar.

The waterbodies themselves exhibit order-of-magnitude ranges in the following physical features: mean depth ($\bar{z}$) from < 1.0 m to 40 m (**Figure 4**), maximum depth (z_{max}) from *ca* 1.0 m to 128 m (Figure 5), surface area (A_l) from 6 ha to 1959 ha (Figure 6), and volume (V_l) from 13 x 10^4 m^3 to 79 x 10^7 m^3 (Figure 7).

Superimposed on these spectra of physical attributes, are considerable ranges in the summer water chemistry as exemplified by the minimum and maximum values of pH (Figure 8) - 6.0 (e.g. Veyatie) and 10.3 (Brow) - and of conductivity (Figure 9) - *ca* 40 µS cm^{-1} (Shiel) and 595 µS cm^{-1} (Spiggie).

2. INVESTIGATIVE METHODS

2.1 Desk studies

2.1.1 Map analysis of the catchments

1:25 000 scale maps giving information on topography, rainfall, potential evaporation and land-use have been examined to assess the pressures and some of the sensitivity factors identified above. The exercise was aided by a questionnaire which was sent to NCCS regional staff for their assessment of land-use features and urbanisation. An example of what can be done with a full set of information, using preliminary Geographical Information Systems (GIS) techniques is presented in Appendix II; however, only a few catchments are documented to the extent necessary for such a display, but work along these lines is continuing. For present purposes, an approach that is compatible with a number of previous studies carried out by this laboratory has been adopted (eg Maitland, Smith, Jones, East, Morris and Lyle 1981). Major patterns of land use have been assessed on the basis of the distribution of altitude in the drainage areas, and four altitude classes have been identified; these correspond as follows to different types of potential land use - although latitudinal and longitudinal variations occur within Scotland:

(i) ≤ 15 m a.s.l.; this is considered to be on flood plains and therefore susceptible to marine influences; non-arable.

(ii) 15-183 m a.s.l.; this is the main agricultural zone and where arable farming and forestry is likely to be concentrated.

(iii) > 183 - 610 m a.s.l.; in this band the land is rarely ploughed, though afforestation and rough grazing can be extensive.

(iv) > 610 m a.s.l.; the 610 m contour (*ca* 2000') is taken to be the upper limit of tree growth.

Table 1. Phosphorus losses (in kg ha^{-1} yr^{-1} unless otherwise stated) from various types of land.

Land Use	P losses	Reference source
heathland and woodland:		
in N. America and Switzerland	0.05 - 0.15 TP	1,2,10,12,24,31
woodland-dominated catchment:		
Loch of the Lowes, Scotland	0.15 - 0.18 SRP	13,14
non-arable land:		
Southern England	0.07 TP	7,8
low intensity agriculture:		
N. America and Switzerland	0.10 - 0.40 TP	10,31
improved grassland:		
N. America	0.10 - 0.50 TP	10, 31
Scotland	0.25 TP	17
N. Ireland (Lough Neagh)	0.41 TP, 0.17 SRP	18, 30
intensive agriculture:		
N. America and Switzerland	0.20 - 0.60 TP	10, 12, 25, 26, 31
Scotland	2.0 TP	17
" (Loch Leven)	0.28 SRP	4, 6
N. Ireland (Lough Neagh)	0.22 SRP	11
Coniferous forest fertilised within 3 years:		
S.E. Scotland	2.0 TP	20
mid-Scotland (Loch Ard)	2.2 TP	16
general agricultural catchments:		
Loch Leven (S.E. Scotland)	0.41 - 1.67 TP	4, 6
	0.12 - 0.16 SRP	4, 6
Loch Eye (N.E. Scotland)	0.18 - 0.22 TP	5
	0.10 - 0.12 SRP	5
	0.04 PP	5
Lough Neagh (N Ireland)	0.14 - 0.22 SRP	11, 19, 27
Balgavies Loch (mid-Scotland)	0.11 - 0.27 SRP	15
mixed arable and urban sub-catchment:		
Loch Leven (S.E. Scotland)	1.10 TP	6
arable land:		
S.E. England	0.60 TP	21
Southern England	0.25 TP	7, 8
Netherlands	0.25 SRP	29
urban areas:		
Loch Leven sub-catchment	0.83 TP	6
North America	0.50 - 5.0 TP	10
mid-Scotland (Forfar Loch)	2.8 - 9.0 TP	15
STWs - Loch Leven catchment	1.77 - 2.42 TP g per person d^{-1}	6
Loch Neagh catchment	0.65 - 0.88 per person yr^{-1}	3
general	0.50 TP (human waste)	9, 15
	0.70 TP (detergents)	9, 15
rural areas (septic tanks)		
N. America	0.3 - 1.8 kg P per person yr^{-1}	22, 23 24
over-wintering wildfowl:		
England	200 mg $bird^{-1}d^{-1}$	7, 8
Loch of Strathbeg, Scotland	239 - 330 mg $bird^{-1}d^{-1}$	13
cage-farmed trout :) *cage-reared salmon:*) *smolts:*)	10-30 kg TP $tonne^{-1}$ fish produced	18, 28

References

1. Ahl 1975; 2. Ahl and Odun in Ahl 1975; 3. Alexander and Stevens 1976; 4. Bailey-Watts and Kirika 1987; 5. Bailey-Watts and Kirika 1991a; 6. Bailey-Watts, Sargent, Kirika and Smith 1987; 7. Cooke 1976; 8. Cooke and Williams 1973; 9. Deevey and Harkness 1973; 10. Dillon and Kirchner 1974; 11. Foy, Smith, Stevens and Stewart 1982; 12. Gachter and Furrer 1972; 13. Hancock 1982; 14. Harper 1986; 15. Harper and Stewart 1987; 16. Harriman 1978; 17. Holden 1975; 18. IoA, IFE and ITE 1990; 19. Jordan and Smith 1985; 20. Malcolm and Cuttle 1983; 21. Owens 1970; 22. Porter, Lauer, Messinger and Bouldin 1975; 23. Reckhow, Beaulac and Simpson 1980; 24. Reckhow and Simpson 1980; 25. Sawyer 1947; 26. Shannon and Brezonik 1972; 27. Smith 1977; 28. Solbé 1987; 29. Steenwoorden and Oosterom 1979; 30. Stevens and Stewart 1981; 31. Vollenweider 1968.

The information from this classification is compared with data on numbers of people, and the extents of forest, improved grassland, arable crops etc., to improve the assessment of land-use. These data are then used in conjunction with the nutrient export coefficients discussed next, to gauge the total phosphorus burden and the relative importance of the different sources of this nutrient to each waterbody.

2.1.2 *Assessment of the extent and relative importance of different nutrient sources*

The strategy adopted for this whole study draws heavily on the experiences gained from the long-term eutrophication programmes. Limnological knowledge accrued, over the last 20-25 years in particular, has defined what are now considered to be the key determinands for assessing freshwater systems. However, the nutrient export coefficients obtained from the major, intensive studies, perhaps comprise the most crucial data for estimating nutrient burdens in the absence of further schedules of long-term, short-time interval sampling. **Table 1** lists a number of coefficients relating to different types of land-use practices, to treated sewage discharges and cage-fish farms. It also includes information on the outputs of nutrients from septic tank systems, although there are no UK figures for this. Small sewage handling units of this type prevail in many rural areas in Scotland, including a number of the catchments studied here. In Northern Ireland, septic tank effluent generally drains direct to water courses, while in Eire, soil-soak systems predominate (Patrick 1988); curiously, administrative factors, not differential soil conditions, are the cause of this dichotomy.

There are likely to be large error bands surrounding the values estimated by the studies reviewed in the Table (Stevens and Stewart 1981). What is more, loadings of diffuse, runoff-derived material will vary with different annual rainfall regimes between the localities, not least due to the effect on the transport of particulate P (see Jordan and Smith 1985; Bailey-Watts and Kirika, 1987). Nevertheless, there is a fair consistency in the findings from generally similar catchments. It thus seems reasonable for the purposes

TABLE 2

of the present study, to assign the following TP loss rates to the various land types:

- 0.07 kg ha^{-1} y^{-1} to the high ground, devoid of agricultural development
- 0.10 kg ha^{-1} y^{-1} to the areas of low intensity, non-arable farming, to woodland, and to rough grazing land; for coniferous forest, values of 2.0 kg ha^{-1} y^{-1} over 3 years, or 0.4 kg ha^{-1} y^{-1}, are appropriate for plantations ≤ 15 years old, while 0.2 kg ha^{-1} y^{-1} is assigned to older plantations.
- 0.25 kg ha^{-1} y^{-1} for land put over to arable agriculture
- 0.40 kg ha^{-1} y^{-1} for improved grassland.

Indoor rearing of animals has been ignored for present purposes. Where recordable numbers of people are resident, a *per capita* figure of 1.0 kg TP y^{-1} appears to be appropriate for rural communities on septic tanks, while an export coefficient of 0.75 kg TP y^{-1} is probably the more appropriate figure for sewer-served populations.

Where numerous geese over-winter, the likely yearly inputs are 250 mg $bird^{-1}$ or 0.04 kg y^{-1} assuming a residence period of 5 months. Finally, a figure of 20 kg TP t^{-1} of fish produced is used where salmon smolts or rainbow trout are reared in cages suspended in a loch, or in bankside tanks.

2.1.3 *Estimation of flushing rates*

In the present study, the attention to flushing has been limited to estimating the annual average value for each catchment. Thus, while seasonal differences in this factor are of major importance (Bailey-Watts, Kirika, May and Jones 1990; Bailey-Watts and Kirika 1991b; Bailey-Watts, May and Kirika, 1991), the analysis of the weekly rainfall records to assess these is outwith the scope of this study. Equally, for present purposes, each annual value refers to an entire loch, regardless of whether this consists of more than 1 basin.

The rates have been calculated from information derived from a variety of sources, but especially from the bathymetric data produced by Murray and Pullar (1910) who surveyed 25 of the sites studied here. However, while their information on lake morphometry (e.g. surface areas, depths and volumes) remains invaluable, checks on their figures for catchment areas, against our planimetry of current maps, revealed some considerable differences. We attribute these to the availability of the more recent and detailed maps and better planimetric instrumentation. There has been a change due to water transfer into the Loch Insh catchment. Additional sources of information that were consulted, include, for example, Bailey-Watts, Lyle, Kirika and Wise (1987) for Coldingham Loch, Hancock (1982) on Strathbeg, and unpublished reports by Bailey-Watts (1973) on Branxholme Easter, and by Maitland (1980) on Lindean. The method of catchment runoff calculation was that described by the Institute of Hydrology (1980). Average rainfall and evaporation-corrected values are derived from the relevant Meteorological Office maps (period 1941-70). The product of the resulting annual net precipitation and the areas of the catchment and loch (evaporation from the loch surface being taken as 1.2 times that from land is the total runoff. When this is divided by the loch volume, an annual flushing rate (ρ) is obtained. The reciprocal of ρ is the theoretical retention time - in units of years, although it is often expressed in days.

2.1.4 Estimation of the phosphorus retention coefficients

It is important to gauge how much of the P entering a system is retained, as this fraction may be recycled from the sediments ('internal loading'), to cause eutrophication problems even when the rate of input of P from the catchment is reduced - see section 4.6. The P retention coefficients (*R*) have been calculated according to the empirical model of Kirchner and Dillon (1975). This model was based on observations on 17 Canadian lakes varying considerably in physical and chemical features. Certainly, data based on extensive, close-time interval sampling and P loading estimations at Loch Leven in 1985, fitted this model very closely (Bailey-Watts, Sargent, Kirika and Smith 1987). It is now known, however (Bailey-Watts, May and Kirika 1991), that the wet summer in the year of sampling was very significant in this respect, because recycling of P from the sediment was minimal. Had it been a dry summer, net gains of P by the water column due to recycling from the deposits, would have resulted in an export of P (*via* the outflow) much higher than predicted by the model. As a consequence, R would have been much lower than predicted. Indeed, any marked lack of fit to the Kirchner and Dillon equation is often indicative of significant sediment release.

The central term of the model is q_s, the 'areal water loading', in units of m y^{-1}; this is the volume of water entering a lake, V_{in} (m^3 y^{-1}) divided by the surface area of the lake, A_l (in units of m^2). The model then predicts R from q_s according to:

$$R = 0.426e^{(-0.271q_s)} + 0.574e^{(-0.00949q_s)}$$

2.1.5 Estimation of the tendency to stratify

As already suggested, the influence of flushing rate on phytoplankton populations may be considerable under (summer) stratified conditions. At the same time as establishing whether a waterbody stratifies, by the temperature profiling work (see **section 2.2.3** below), an estimate of the likelihood of stratification was examined using the following relationship suggested by Hanna (1990), between thermocline depth (z_t in metres) and loch area (A_l in km^2) in temperate lakes:

$$\log z_t = 0.185 \log A_l + 0.842 \quad (r = 0.91)$$

The calculated z_t was compared to the mean depth (z) and maximum depth (z_{max}) of each loch, which could then be allocated to one of three categories, as follows:

(i) if $z_T > z_{max}$, the loch is assumed never to stratify

(ii) if $z_{max} > z_t > z$, the loch may occasionally stratify but probably only in deep basins

(iii) if $z_T < z$, the loch should exhibit marked stratification which will strongly affect the hydrodynamic functioning of the site and the effective flushing rate for that period.

2.1.6 Water circulation and mixing

Important, but not within the practical scope of this study, are water circulation and mixing patterns within the lochs. For example, where an isolated basin exists, this is noted, since it affects the validity of the calculated mean annual flushing rate.

2.2 Fieldwork

2.2.1 *Catchment assessments*

Field assessment of catchment characteristics was limited mainly to noting the general features of the terrain leading up to the edge of the lochs. However, this facilitated checks on the suitability of sampling locations - previously chosen from maps. Areas of forest-felling, for example, were avoided, in aiming to collect sediment material most representative of a particular basin.

2.2.2 *Sampling and recording at the inflows*

It was not possible to visit all of the approximately 220 feeder waters featured on the maps referred to in **section 2.1.1**. At one extreme, Loch Shiel has 111, although at the other, Lindean and Kilconquhar, for example, have no well-defined inflows. Thus, a total of 80 waters considered significant in terms of (i) the proportions of the total loch catchments that they drain, and/or (ii) 'hot spots' of nutrient pollution, were sampled. This number included all inflows for most of the lochs fed by ≤ 3 streams, and a selection of these where > 3 waters enter, e.g. 11 of the 22 draining into Loch Veyatie, 10 of the 43 feeding Loch Eck, and 8 of the 13 passing into St Mary's Loch.

These waters were sampled a few metres above their confluences with the lochs primarily for information on nutrients. However, a Corning 'Check Mate' field probe system was used to measure the following:

- dissolved oxygen content, to check whether any streams were organically polluted to the extent of severe oxygen depletion at their mouths.
- electrical conductivity, as an indicator of overall ionicity.
- pH as a basic descriptor of the acid-base status.
- water temperature, for comparison with the values obtained in the open waters.

In the event, no waters appeared to be severely polluted, and there were no features of major relevance to this study as regards conductivity, pH and temperature.

In common with all of the water collection during this study, the following procedures were observed: duplicate samples were taken; polyethylene bottles that had been acid-washed and repeatedly rinsed in hot tapwater were used throughout, and just prior to taking the samples, these were rinsed in the stream or loch water; samples were also kept as cool as possible, and in the dark until further processing. In the case of the feeder stream samples, ½-litre bottles were immersed in the water with their open ends facing upstream.

Filtering, sub-sampling etc. was often done at the loch side. Unfiltered aliquots of water were stored for the analysis of total phosphorus (TP) and turbidity measurement, while subsamples filtered under vacuum through Whatman GF/C discs were saved for the determinations of total soluble P (TSP), soluble reactive P (SRP), nitrate ($NO_3.N$), dissolved silica (SiO_2) and dissolved colour. [Additional subsamples have been treated for major ion and metal analysis, but the results of these aspects are not reported here].

2.2.3 *Sampling and recording in open water*

a. *surface water collections*: Open water sampling was limited to a single site at or near the deepest point, in each basin; at sites < 2.5 m deep, 3- to 4-litre volumes of water were collected by plunging wide-mouthed aspirators under the surface. At sites greater than 2.5 m in depth, a 2-m length of 6-cm diameter, 'Marley' drain pipe was lowered vertically into the water, until its upper end was just under the surface; a tight fitting rubber bung was then pushed into this end, and the whole tube was raised until the lower end was just below the water surface and could be closed by hand. The 2-m column of water was then lifted out of the loch and transferred to a plastic bucket.

Extra phytoplankton material was collected (for taxonomic studies) by towing a 28-µm mesh, silk net through the water for a few minutes (the time depending on the general abundance of plankton). Quantitative samples of rotifer and micro-Crustacean plankton were collected by means of vertical hauls with respectively, 28-µm and 118-µm mesh tow nets, over measured depths e.g. from 3.5 m or 5.0 m to the surface. In shallow waters, where vertical net-tows were not possible, water was collected in plastic aspirators as above, and measured volumes poured through the nets to concentrate the animals.

Onshore, subsamples were taken for nutrient determination and the colour and turbidity measurements as described in **section 2.2.2**. Additional sub-samples were saved for chlorophyll *a* analysis and for phytoplankton species composition and abundance work.

Two 50-ml aliquots of water were taken from each basin for phytoplankton analysis; each of these was fixed with *ca* 0.25 ml Lugol's Iodine (a saturated solution of iodine in a saturated aqueous solution of potassium iodide). Half-litre samples kept for rotifer analysis were fixed immediately with 0.5 g procaine-hydrochloride (see May 1985), and then, after 24 hours, with formalin to a final strength of 4%. The concentrates of micro-Crustacean zooplankton were fixed immediately with formalin to give a final strength of *ca* 4%. [N.B. The Crustacea samples have not yet been analysed].

b. *vertical profiling*: the main points of focus of this aspect of the work, which was also carried out at or near the deepest point in each basin, were the distributions of temperature with depth, and associated vertical patterns of oxygen concentration - each giving a measure of mixing depth. With the 'Windermere Profiler' instrument which was used in most of the lochs, pH and conductivity levels were also recorded simultaneously. Water clarity was assessed by Secchi disc transparency. All data recorded with the 'Profiler' were stored in a Husky 'Hunter' logger connected to the surface unit of the system. At the end of each day, this information, along with records of other field observations that were entered into the 'memo' facility in the logger, was printed out on a portable, Kodak 'Dionix' ink-jet printer.

For the field trip covering the 5 Shetland lochs (Spiggie, Brow, Tingwall, Asta and Cliff) and the northernmost loch on the Scottish mainland (St John's) surface water and sediment-overlying water temperatures, dissolved oxygen contents, conductivities and pH values were measured with the 'Check Mate' probes; the results indicated that only one of the Shetland basins (Tingwall South - maximum depth 16.5 m), was stratified to any marked extent.

c. *bottom water and sediment studies*: Sediment cores were collected from a single site in each of a total of 29 basins. In an attempt to obtain information most representative of each waterbody, the echo-sounder was used to find as flat an area of sediment as possible, rather than a deep 'pot'. At each site, 6 cores were collected with a Jenkin Surface Mud sampler. Water overlying the 2 cores with the most level surfaces, was siphoned off for later analysis, and the muds were extruded. The top centimetre and each 2-cm slice down to 9 cm depth from each core were stored separately in polythene bags. These bags were immediately sealed by knotting, in an attempt to minimise oxygenation of the material and chemical changes in e.g. the phosphate adsorption status; however, we are well aware that such changes probably did take place - although to what extent is not known - but it was impossible during this campaign to use the otherwise ideal, 'glove-box' techniques and process the muds under an atmosphere of e.g. nitrogen. The only subsample of mud removed from each slice during the extrusion stage was 0.1 - 0.2 cm^3 for diatom analysis, but the results of this aspect of the work are not reported here.

The 'Check Mate' instrument was used to measure the temperature, dissolved oxygen content, conductivity and pH of the water taken from within 10 cm of the sediment surface. Subsamples of this water were also filtered in the field, through Whatman GF/C discs for analysis of TSP, SRP and SiO_2.

[Surface material from another core was kept for rotifer resting egg hatching experiments (see May 1987), and the uppermost 5 cm of a 4th core was transferred to a plastic Freeman jar and fixed with formalin for later analysis of the macro-invertebrate assemblages. However, these aspects are not reported here].

2.2.4 *Sampling and recording at the outflows*

The work done at the outflows was the same as that carried out for the surface, open waters (section 2.2.3a), except that (i) dip, rather than 2-m tube samples were taken for chemistry, phytoplankton and rotifers, and (ii) no micro-Crustacea samples were taken, nor any other collections involving net hauls.

2.3 Laboratory analyses

2.3.1 *Chemistry*

a inflows, open waters and outflow waters: nitrate, phosphorus fractions, dissolved silica, colour and turbidity were all determined by absorption spectroscopy using the following methods.

Nitrate was analysed by this laboratory's modification of the cadmium reduction method (APHA 1976). The procedure is a combination of two methods, modified as a batch process (as opposed to either a reduction column or an automated method). Nitrate reduction to nitrite was achieved using copper-cadmium in ammonium chloride solution; the nitrite was then determined by addition of hydrochloric-acidified sulphanilamide solution, followed by N-(1-Naphthyl)-ethylenediamine dihydrochloride (N.E.D.). The optical density of the resulting solution at 543 nm was measured in a Philips PU 8670 spectrophotometer and converted to concentrations determined from a calibration against various dilutions of a standard solution containing 500 μg NO_3.N. Samples analysed by this method need to be within a pH range of 5 to 9. None of our samples had a pH of < 5 units, and all of those originally > 9 (Checkmate field reading) and freeze stored (at -4°C in screw-top polypropylene tubes) were found to be < 9 pH (~ 7) due to absorption of CO_2 and loss of NH_3. For soluble reactive P (SRP) - the fraction of P most immediately available for algal growth - the spectrophotometric method described by Murphy and Riley (1962) was used; while it was suspected that some of the concentrations of SRP would be around a few microgrammes per litre, no prior concentration of the phosphate (in e.g. hexanol) was done. Instead, the aliquots and proportions of molybdate reagent were modified, and 4-cm path length cuvettes were used, to obtain absorbance readings such that differences *ca* 3 μg P l^{-1} could be considered significant. Soluble reactive silica (SiO_2), which is an important nutrient for diatoms and many chrysophycean algae - was determined using the method of Mullin and Riley (1955) and adopting the procedures outlined in Golterman, Clymo and Olmstad (1978); the limit of detection is 50 μg SiO_2 l^{-1}. Determinations of the levels of total P (TP) and the total soluble fraction (TSP) was also carried out, in triplicate, on each sample. TP concentrations constitute a useful index of trophic status, while a measure of TSP provides information on the levels of soluble un-reactive P (SURP or dissolved 'organic' P) from:

$$SURP = TSP - SRP$$

Similarly, the difference between TP and TSP gives the concentration of particulate P (PP).

b sediment interstitial waters: TSP, SRP and SiO_2 were determined on the sediment pore waters from each of the depth slices, by the spectrophotometric methods already outlined for loch and inflow waters. Pore water was obtained by firstly centrifuging the wet sediment and decanting the supernatant, and secondly, vacuum-filtering the supernatant through Whatman GF/C pads.

c sediments per se: the immediate focus is on the total P content of the sediments. This was determined as for TP in the waters, but on a known weight of wet sediment (*ca* 0.2 g) from each core slice. This was later diluted with distilled water to 50 ml; this was mixed by means of a magnetic stirrer, and while the mixing was in progress, a 1-ml aliquot was withdrawn and transferred to a reagent tube.

At various stages of handling the sediments, the weights and volumes of material originally obtained, and those of the various subsamples taken for total sediment and pore water analyses, were recorded. The wet and dry weights of the material remaining after that needed for the nutrient analyses had been removed, were also measured. Thus, all concentrations of P, for example, can be expressed on a dry weight, wet weight or volume basis. The intention is to determine the ash and organic contents of the sediments, so that the nutrient levels can be expressed as a function of these parameters as well.

2.3.2 *Biology - open water and outflow plankton*

a *Algae*: an index of total phytoplankton biomass was obtained by measuring the concentration of chlorophyll *a*. The algae from known volumes of water (eg 100 ml where the crops were dense, and 400-500 ml where sparser populations prevailed), were concentrated by filtration onto Whatman GF/C discs which were then steeped in 90% methanol overnight at *ca* 4°C. The resulting extracts were centrifuge-cleared, before transferring to a spectrophotometer cuvette. Optical densities of the extracts were then read in a Cecil 303, grating spectrophotometer, against solvent standards at 665 nm and, for turbidity correction, 750 nm. The equation derived by Talling and Driver (1963) was used to convert the readings to concentrations of chlorophyll *a*. Note that as no correction was made for pheophytin *a* - a breakdown product of chlorophyll *a* with a peak absorbance very near 665 nm - the values obtained are likely to overestimate the actual amounts of 'healthy' chlorophyll present.

The population densities of a number of the most prominent species of phytoplankton were estimated by counting. The algae in the 50-ml iodised samples were first concentrated 10-fold by centrifugation. A Lund nanoplankton counting chamber was then filled with the (well-mixed) concentrate. A number of algal types differing considerably in both size and general abundance were assessed by examining the assemblages at a range of magnifications from 40x to 600x on a Vickers Photoplan microscope (see Bailey-Watts 1978). At the lower power (ie using a x4 objective in combination with x10 eyepieces), the whole chamber was scanned with the view to enumerating the relatively large species, although much smaller forms can often be discerned if the crop is generally sparse. Since the volume of the chamber used throughout this study is 0.45 ml, the effective volume of water scanned is 4.5 ml, because the algae were concentrated 10-fold. This means that organisms as rare as *ca* 2 per 10 ml can be recorded. At progressively higher magnifications, the attention is on progressively smaller species. Thus, at the highest power adopted here (x50 objective - x10 eyepiece combination) nanoplankton (≤ 15 μm) and even picoplanktonic forms (ca 2 μm) can be assessed, but on the basis of random quadrats (defined by a square incorporated into an eyepiece graticule), rather than whole chamber coverage. In order to estimate the population of at least the most numerous species in the sample, with 95% confidence limits of *ca* ± 20%, approximately 100 specimens of that alga were counted. Usually, but not universally, small organisms are considerably more abundant than large forms in phytoplankton assemblages, and in the present arrays, populations exceeding 10^6 ml^{-1} have been occasionally estimated.

Even though the study was confined to 'summer' sampling, an enormous variety of 'species' has been recorded; many of the forms have proved difficult to identify, however - not least, because they were rare and very few individuals were seen. For present purposes, therefore, the focus has been more on the composition of the crops in terms of the different morphological types present [e.g. large *vs* small forms (see e.g. Bailey-Watts 1986), heavy diatoms *vs* buoyant blue-green algae, and motile forms (flagellates) *vs* non-motile types], and exploring the distribution of algae differentiated on this basis, in relation to lake type and water quantity (see also Reynolds 1984; 1990).

b Rotifera: samples for rotifer analysis were concentrated by sedimentation in glass measuring cylinders for 24 h and siphoning off the overlying water.

Each concentrated sample was then placed in a microscope sedimentation chamber and allowed to settle. The bottom of the chamber was scanned with a Wild M40 inverted microscope at x 100 magnification. Where possible, all of the rotifers in each chamber were identified and counted.

Where identifications were uncertain, specimens collected by 23 µm-mesh net tow were examined more closely under a Vickers M15c binocular microscope at magnifications of up to x 400. Even then, some animals could be identified only to genus level and a few remained unidentified. Rotifers are notoriously difficult to identify, especially when dealing with preserved material. This is because many of the diagnostic features of soft-bodied forms are often lost or distorted by the preservation process. Further identification of these animals (especially *Polyarthra* spp., *Asplanchna* spp., *Synchaeta* spp. etc.) would have required very detailed analyses of the material collected, including size measurements and scanning electron microscopy of the mouthparts (trophi) (Koste & Shiel 1989, Sonoamuang 1992). This would have been very time-consuming and could not have been carried out within the time limits imposed on this project. Nevertheless, of almost 12,500 animals examined in this survey, less than 1% could not be identified to genus level, at least. Rotifer identifications were carried out according to the nomenclature of Koste (1978).

3. RESULTS AND DISCUSSION I: THE PRESSURES - FACTORS DETERMINING THE LIKELY EXTENT OF NUTRIENT ENRICHMENT

3.1 The nature of the catchments

3.1.1 Size, use and human occupancy

The area of catchment, usage, and level of human occupancy are the 3 major factors determining the potential external loadings of nutrients to a standing waterbody. The catchments included in this study ranged over 3000-fold (**Figure 10**), from the 32 ha draining into Coldingham to the 82 x 10^3 ha associated with Loch Insh (Inverness-shire). Even excluding these extremes, the areas associated with Branxholme (41 ha), Lindean (54 ha) and Duddingston (98 ha) contrast considerably with the north western sites Shiel (23 x 10^3 ha), Veyatie (12 x 10^3 ha), and Eck (10 x 10^3 ha), and St Mary's in the Borders (11 x 10^3 ha). On this basis, the external burdens of nutrients can be expected to increase through the series, from Coldingham Loch to Loch Insh. However, this would only be the case if both land use and the level of human occupancy were uniform, and if areal loss rates of materials were the same throughout the country.

Altitude distribution gives a first indication of the likely variation between catchments as regards land use and the density of people. From **Table 2** the following catchments can be considered to have high eutrophication potential because all, or a great majority of, the drained land lies below 183 m: Coldingham, Kilconquhar, Linlithgow, Rescobie, Strathbeg, Mill, Spiggie, Brow, Tingwall, St John's, Cliff, Castle, Cran and Flemington. These would contrast with the other areas, a considerable proportion of which lie at higher levels; of particular note are the following, in that > 40% of their catchments are situated above 183 m: Davan, Eck, Shiel, Clunie, Butterstone, Lowes, Craiglush, Veyatie and Insh.

Table 2. Catchment areas and the percentages of land (ie exc. standing waters) within four altitude bands (m.a.s.l.)

Catchment	ha	< 15 m	15-<183 m	183-610 m	> 610 m
Coldingham	33	0	100	0	0
Lindean	54	0	0	100	0
Branxholme	41	0	0	100	0
St Mary's	10638	0	0	90	10
Kilconquhar	109	0	100	0	0
Linlithgow	476	0	100	0	0
Balgavies	2360	0	89	11	0
Rescobie	2015	0	93	7	0
Marlee	7318	0	47	49	0
Clunie	5732	0	38	59	0
Butterstone	2149	0	37	56	0
Lowes	1386	0	37	60	0
Craiglush	973	0	26	74	0
Strathbeg	5297	20	80	0	0
Davan	3472	0	21	78	1
Eck	9890	0	27	71	2
Shiel	22961	4	35	54	7
Mill	172	0	99	0	0
Spiggie	1418	17	81	2	0
Brow	392	21	77	2	0
Asta	455	10	79	0	0
Tingwall	267	10	90	0	0
St John's	437	0	100	0	0
Veyatie	11610	0	34	61	1
Insh	81952	0	0	77	22
Cliff	2930	6	90	2	0
Duddingston	98	0	85	15	0
Castle	689	0	96	0	0
Carlingwark	1183	0	54	46	0
Cran	822	26	74	0	0
Flemington	851	0	100	0	0

A somewhat similar split between the sites is obtained when those in which the majority of the land is put over to agriculture and/or improved grassland, are compared with those in which rough grazing is important (**Table 3**). Included in the first group are Kilconquhar, Balgavies, Mill and Castle (with > 60% of their areas covered by agriculture and/or improved grass), while in the second, are Clunie, Butterstone, Craiglush, Shiel, Veyatie and Insh (> 40% rough grazing).

Table 3. Catchment areas and the approximate percentages of land under forest, arable agriculture, rough grazing and improved pasture (ie excluding open water and land dominated by buildings)

Catch. no.	ha	% forest	% arable	% rough	% improved
Coldingham	33	5	29	24	45
Lindean	54	6	0	93	0
Branxholme	41	4	40	56	0
St Mary's	10638	8	2	87	0
Kilconquhar	109	24	76	0	0
Linlithgow	476	1	40	0	10
Balgavies	2360	8	80	4	6
Rescobie	2015	11	67	10	12
Marlee	7318	19	25	42	8
Clunie	5732	22	15	52	4
Butterstone	2149	42	8	41	3
Lowes	1386	48	6	39	3
Craiglush	973	49	1	48	0
Strathbeg	5689	4	26	8	37
Davan	3472	12	35	35	18
Eck	9890	37	23	30	10
Shiel	22960	20	1	75	4
Mill	172	2	29	7	55
Spiggie	1418	0	2	89	9
Brow	392	0	28	51	21
Asta	455	0	27	49	23
Tingwall	267	0	2	68	30
St John's	437	0	33	33	33
Veyatie	11610	1	9	85	0
Insh	81952	2	1	97	0
Cliff	2930	0	10	87	0
Duddingston	98	0	0	50	25
Castle	689	7	31	0	58
Carlingwark	1183	1	20	30	48
Cran	822	50	25	0	25
Flemington	851	30	40	0	30

The calculations have not yet taken account of the possible impacts of people or overwintering wildfowl on the potential export of nutrients from the catchments. Yet, there are a few sites in which these are likely to be significant (Table 4).

Table 4. Catchments in which the numbers of people and/or overwintering geese are likely to contribute significantly to the overall nutrient burdens to the receiving waters.

'People catchments' (> 0.25 people/ha)	'Geese catchments' (> 1 bird ha^{-1})
Coldingham (0.60)	Balgavies (1.70)
Kilconquhar (0.27)	Strathbeg (4.13)
Linlithgow (16.83)*	Davan (6.34)
Mill (1.74)	Castle (10.16)
Duddingston (4.10)	
Castle (1.39)	
Carlingwark (1.64)	
Flemington (0.28)	

*this high value assumes that a large urban area is included in the catchment; some high concentrations of P in the feeder streams suggest that waste from it reaches the loch.

These lists include the following waters which have already been adjudged high in terms of likely eutrophication pressures - on the basis of both altitude and landuse: Coldingham, Kilconquhar, Linlithgow, Mill, Castle, Flemington and Strathbeg. What is more, the Castle Loch at Lochmaben (which in past years was an important Vendace site - Maitland and Lyle 1990) ranks high in both lists in **Table 4**.

3.1.2 *The potential losses of phosphorus, and the relative importance of different external sources*

The total inputs of P to each of the waters can now be estimated by assigning to the areas of each landuse or altitude class, the P export coefficients discussed in **section 2.1.2**. The ranking of the catchments is then as shown in **Figure 11** which also highlights the similarity between the two sets of results. The relative positions of some of the waters in these arrays differs considerably, however, from those suggested on the basis of the altitude and landuse percentage figures. This is because the actual areas of the catchments have now been accounted for. Thus, Veyatie and Insh, which are good examples of catchments that consist of relatively pristine landscapes, are nevertheless likely to export considerable amounts of material by virtue of the large areas involved.

Naturally, the systems identified in **Table 4** with significant numbers of people and/or overwintering wildfowl, move up through the rankings when the P export potential of treated sewage, of septic tank waste and of the roosting birds is included; compare thus, their values in **Figure 12** with those in **Figure 11**.

The values plotted in **Figure 12** incorporate data on yet another nutrient-enriching activity - fish-farming. Only 4 lochs in this series are affected, and 3 of these are associated with catchments that so far have been viewed as relatively nutrient-poor, i.e. Butterstone (5.1 t rainbow trout y^{-1}), Shiel (80 t salmon smolts) and Veyatie (possibly 5.0 t salmon smolts); contrastingly the Loch of Cliff (producing a total of *ca* 46 t salmon smolts y^{-1} but only *ca* 10 t in a floating cage) has been considered a relatively rich system on the basis of its altitude distribution.

The relative importance of the various sources of P to the estimated total burdens to each loch is shown in **Table 5**. Plainly each system is individual, but the following general features are evident:

Table 5. The percentage contributions of forestry land, rural and urban communities, arable agriculture, rough grazing and improved pasture land, to the total phosphorus loading predicted from land use, and the numbers of people, wildfowl and caged fish in 31 catchments.

catchment	% forestry	% rural (septic tanks)	% urban (sewage works)	% agric-culture	% rough	% improved
Coldingham	<1	28	0	21	7	43
Lindean	25	0	0	0	75	0
Branxholme	33	0	0	44	22	0
St Mary's	17	10	0	5	67	0
Kilconquhar	1	86	0	8	5	0
Linlithgow	<1	8	0	2	0	74
Balgavies	2	36	0	43	1	3
Rescobie	4	44	0	39	2	11
Marlee	15	20	0	29	13	14
Clunie	19	17	0	19	18	14
Butterstone	34	12	0	9	13	6
Lowes	54	8	0	9	15	6
Craiglush	71	5	0	1	22	0
Strathbeg	1	31	0	11	1	26
Davan	9	7	0	17	5	14
Eck	36	4	0	29	11	20
Shiel	22	13	0	3	23	5
Mill	3	26	0	17	1	53
Spiggie	0	69	0	1	19	11
Brow	0	52	0	19	9	21
Asta	0	20	0	27	14	3
Tingwall	0	26	0	2	20	52
St John's	0	28	0	25	7	40
Veyatie	2	11	0	22	56	0
Insh	7	15	17	<1	60	0
Cliff	0	19	0	17	41	0
Duddingston	0	0	0	0	23	77
Castle	3	14	0	9	0	27
Carlingwark	1	18	65	3	1	12
Cran	37	17	0	15	1	30
Flemington	12	46	0	19	0	23

(i) there are 7 catchments in which a single landuse type contributes more than two-thirds of the predicted total input of P: Duddingston and Linlithgow for improved grassland; Lindean and St Mary's with rough grazing (although values of 56% and 60% are obtained for Veyatie and Insh respectively); Craiglush with forestry; Kilconquhar and Spiggie with the rural communities;

(ii) while 6 lochs - Linlithgow, Mill, Duddingston, Carlingwark, Cran and Flemington are situated in heavily urbanised catchments, it appears that treated sewage passes only into Carlingwark, and here, this source of nutrients could supply some 65% of the total P load. The only other system where STW effluent is likely to contribute a significant proportion of the total P load, is Insh, for which a value of 17% has been estimated.

(iii) agriculture, excluding improved grassland contributes various percentages to the total loads, ie from < 5% in e.g. Lindean and Shiel, to > 40% in Branxholme and Balgavies.

(iv) the corresponding highest percentages for improved grassland are 77 at Duddingston, and 74 at Linlithgow.

(v) for the 4 catchments with over-wintering geese densities of > 1 ha^{-1} (see **Table 4**), the birds appear to contribute significantly to the total annual P loadings, ie Davan with 48%, Castle with 23%, Strathbeg with 30% and Balgavies with approximately 15%.

(vi) the predicted amounts of P exported from fish farms in Lochs Cliff, Butterstone and Shiel are also significant, ie 23%, 25% and 33% respectively, of the estimated total loads. The tanks associated with the main inflow to the only other loch in this series where fish are farmed - Loch Veyatie - would seem to contribute < 10% of the likely P exported from its large catchment; however, the value of 5 t for the annual fish production attributed to the farm at Veyatie, is a guess.

(vii) if the whole set of catchments is considered as one unit, diffuse sources of P far outweigh the inputs from point-sources - and especially so if rural community export in septic tank discharges is considered a non-point source; as noted under (ii), only in Carlingwark is it likely that the point-source component exceeds the diffuse loading.

3.1.3 *The nitrogen situation: contrasts with phosphorus*

This report is not paying as much attention to N as it is to P, because for much of the year in the vast majority of temperate waters, P is likely to be the major plant growth-limiting nutrient (see eg. Bailey-Watts, Kirika and Howell 1988). However, N can be important in this respect in summer (Bailey-

Watts 1988; Bailey-Watts 1990, 1992); indeed, the prominence of atmospheric N-fixing cyanobacteria may well be due to reduced availability of nitrate at this time (see also Horne and Commins 1987).

In general, the specific areal losses of N from land, are often more than 10 times those of P, and where intensive agriculture features, 100 times or more (Harper and Stewart, 1987; Holden 1975; Foy, Smith and Stevens 1982; authors' unpublished data). The N-to-P loading ratios for many waters are thus greater than the ratio of the plant growth requirements for these nutrients (Bailey-Watts 1988 gives cell N and cell P data for diatom plankton as an example). After secondary treatment, sewage effluent is likely to contain only 3 times as much N as P, however (e.g. Deevey and Harkness 1973).

3.2 The transfer of nutrients from catchments to lochs

3.2.1 *Rainfall regimes and runoff*

Average annual rainfall over these catchments is lowest at *ca* 700 mm near the south-east coast, ie Duddingston, Kilconquhar and Coldingham, and near the north-east coast, ie Cran and Flemington. Highest values are 1600 mm at St Mary's (Borders Region), and 1950 mm at Veyatie, and 2600 mm at Eck and Shiel (all in the north-west of the country). On the basis of the data for the 29 catchments included here, there appears to be very little correspondence between rainfall and altitude, and there are no obvious trends in rainfall or in altitude, either along, or across the country.

On the basis of a log-log linear regression, some 95% of the variation in the estimated evaporation-corrected volume of water running off a catchment, is associated with variation in catchment area, whereas only 51% of this variation is associated with the variation in rainfall *per se* (ie annual amounts in mm); thus, the influence of size of catchment on runoff volume (the latter being a measure of the water available for transporting materials from the catchment), is much greater than the influence of the rain regime.

As a result, if eutrophication *per se* was measured purely in terms of the amounts of runoff water (= the annual flushing volume), the lochs receiving greatest burdens of nutrients would be: Shiel (51 x 10^7 m^3) > Insh (27 x 10^7 m^3) > Eck (22 x 10^7 m^3) > Veyatie (18 x 10^7 m^3) and St Mary's (10 x 10^7 m^3). At the other end of the spectrum, the following are likely to export the lower amounts of material as they have the smallest runoff volumes: Coldingham (8 x 10^4 m^3) < Lindean (21 x 10^4 m^3) < Branxholme and Duddingston (25 x 10^4 m^3 each) < Kilconquhar (26 x 10^4 m^3).

3.2.2 *Rainfall-dependent and rainfall-independent exports of nutrients from catchments*

Ignoring for present purposes the dry-deposited, aeolian inputs of nutrients directly into standing waters, only wildfowl faeces of the various types of nutrient source considered so far, require no runoff water for their transport from the catchment. Fish cages can be viewed in a similar light, with the continual 'rain' of faeces and waste feed into the water column. Sources from agricultural areas, forests, soakaway and septic tank discharges, all enter the surface water network strongly influenced by rainfall-runoff. Contrastingly, point sources of nutrients which, in the present study appear to be comprised solely of the effluents from sewage treatment works (STWs), enter lochs in a manner more-or-less independent of seasonal runoff patterns.

It is important to distinguish between the various nutrient inputs on this basis. Above all, the runoff-controlled inputs will exhibit erratic patterns of delivery in keeping with varied weather regimes, while the supplies from STWs will show relatively stable, if cyclical, loading patterns (Bailey-Watts and Kirika 1987; Bailey-Watts, Sargent, Kirika and Smith 1987; Bailey-Watts 1990, 1992). This contrast alone would lead to different responses by a loch, even if the total annual loading and the 'cocktail' of nutrients remained unchanged. As it happens, the different sources tend to contrast also in terms of the N to P ratio, the mix of other chemical constituents, and the volumes and concentrations (Bailey-Watts 1990, 1992).

Table 6a. Total phosphorus levels ($\mu g\ P^{-1}$) in all of the inflows sampled during summer 1991

CO tp	BX tp	My tp	LL tp	BV tp	RE tp	MR tp	CU tp	BU tp	LW tp	CG tp	SB tp
5.7	9.5	6.8	272.7	70.0	38.6	21.0	21.9	21.4	12.4	13.8	363.4
		10.9	263.6	84.3	415.2	39.0	42.4		8.6	9.0	8.8
		9.1	80.5		53.3	1181.0			166.7		48.0
		8.2			151.4	31.9					
		3.6				112.4					
		7.7									
		9.1									
		10.0									

DV tp	EK tp	SH tp	SP tp	BR tp	AS tp	TW tp	SJ tp	Vy tp	IN tp
21.9	8.1	135.4	36.6	12.8	11.9	12.8	56.0	17.7	15.5
8.6	6.2	93.6	20.4	10.5		137.3		7.5	6.1
18.1	10.5	9.0	172.4					9.3	18.5
	58.6	24.7	12.4					9.3	
	8.1	6.2						8.4	
	8.1	9.5						9.3	
	10.5	4.8						7.9	
	6.2	7.6						5.6	
	5.7	4.8						8.4	
	10.0	8.6						7.5	
		4.8						7.0	
		9.0							

Table 6b. Total soluble phosphorus levels (μg P l^{-1}) in all of the inflows sampled in summer 1991.

CO tsp	BX tsp	MY tsp	LL tsp	BV tsp	RE tsp	MR tsp	CU tsp	BU tsp	LW tsp	CG tsp	SB tsp
4.5	4.0	4.5	253.2	63.8	25.5	13.7	14.7	10.9	8.5	7.1	127.5
		6.4	114.1	16.5	333.8	24.6	21.7		7.1	6.1	50.8
		5.5	66.4		30.3	867.6			97.9		19.2
		5.9			109.7	29.3					
		2.3				87.0					
		4.5									
		6.4									
		6.8									

DV tsp	EK tsp	SH tsp	SP tsp	BR tsp	AS tsp	TS tsp	SJ tsp	VY tsp	In tsp
13.8	5.7	109.4	9.4	6.7	5.8	10.3	38.8	12.4	11.9
5.8	5.7	88.5	16.9	6.7		120.3		5.2	5.2
5.3	10.0	7.1	137.7					7.1	17.0
	69.0	16.2	8.0					5.2	
	5.7	4.8						5.7	
	7.6	7.6						5.2	
	8.1	3.8						4.8	
	3.8	5.2						4.8	
	4.8	3.3						5.7	
	7.6	5.7						5.1	
		3.3						4.3	
		6.2							

Table 6c. Soluble reactive phosphorus levels (µg P^{-1}) in all of the inflows sampled in summer 1991.

CO srp	BX srp	MY srp	LL srp	BV srp	RE srp	MR srp	CU srp	BU srp	LW srp	CG srp	SB srp
2.5	3.7	0.0	192.8	53.1	12.2	3.0	8.7	3.5	3.0	3.9	82.2
		2.6	102.7	3.5	209.9	13.9	17.0		2.6	3.5	33.1
		0.0	52.4		19.6	765.6			58.4	9.5	
		2.2			92.8	18.7					
		2.2				68.4					
		1.3									
		1.7									
		2.6									

DV srp	EK srp	SH srp	SP srp	BR srp	AS srp	TW srp	SJ srp	VY srp	IN srp
7.0	4.5	85.4	3.7	4.1	3.3	6.6	36.0	5.8	4.1
4.1	4.5	70.7	11.6	4.1		103.7		6.7	2.0
5.0	8.5	5.4	118.6					7.2	5.2
	63.1	9.4	5.8					4.0	
	3.6	3.1						3.6	
	4.9	4.9						3.6	
	5.8	2.7						4.0	
	4.0	3.6						3.6	
	4.0	3.1						4.0	
	7.2	3.1						5.8	
		2.7						3.6	
		3.6							

On the basis of the information on catchment areas, P loss coefficients and estimated P loads discussed above, the majority of the waters covered by this study are likely to be dominated by diffuse inputs of nutrients.

3.2.3 *Summer nutrient levels in the inflows*

In general, the number of feeder streams increases with size of catchment. Hence, the large number entering Shiel, Eck and Veyatie; however, water from the largest catchment - that of Loch Insh - reaches the loch at relatively few points, and primarily *via* the Spey River, although also through an extensive, marshy area. At the other end of the scale, a number of small systems appear to have no well-defined feeder channels e.g. Branxholme Easter, Lindean and Kilconquhar.

Table 6 shows that, of the 22 sets of feeder streams, very few were at this time more or less pure, ie with 'universally' ≤ 10 TP µg l^{-1}. The only 2 systems where concentrations of 10 µg TP l^{-1} or less 'prevail', ie Coldingham and Branxholme - with only one inflow each, anyway. However, only 1 stream out of the 8 sampled at St Mary's exhibited a higher figure, (and this was only marginally higher than 10 µg l^{-1}); Asta and Brow are similar to St Mary's in this respect. At least one inflow to each of the other relatively 'pristine' sites gave considerably higher values, ie 17 µg l^{-1} at Veyatie, 22 at Davan, 59 at Eck, 25, 94 and 135 at Shiel, 137 at Tingwall and 167 at Lowes. A third group of catchments comprises the remaining 11 sites. All of these appear to be universally rich in P, but especially Linlithgow, Rescobie, Strathbeg, Spiggie, Tingwall and Marlee: Tingwall with values of > 100 µg l^{-1}, and Marlee with a value of > 1 mg l^{-1} are of particular interest. Corresponding analyses of soluble P show that, in all cases, this fraction contributes the major proportion (*ca* 70%) of the total amounts of P; what is more, at least 60% of this is soluble reactive P (SRP). Certain farm effluents constituting agricultural point-sources of P, could explain the high values, but in some situations, e.g. Linlithgow and Rescobie and the other lochs on the Lunan system, sewage effluent of various types is a possible additional cause.

Table 7. Nitrate-N concentrations (μg N l^{-1}) in all of the inflows sampled during summer 1991.

CO NO_3	BE NO_3	MY NO_3	LL NO_3	BV NO_3	RE NO_3	MR NO_3	CU NO_3	BU NO_3	LW NO_3	CG NO_3	SB NO_3
9800	736	173	1320	3080	741	852	289	89	917	194	29
		10	491	227	3820	4707	2915		811	44	220
		63	914		4068	157			2643		245
		10			1438	2902					
		394				750					
		162									
		88									
		19									

DV NO_3	EK NO_3	SH NO_3	SP NO_3	BR NO_3	As NO_3	TW NO_3	SJ NO_3	VY NO_3	IN NO_3
470	137	34	6	17	4	13	42	7	69
126	10	50	144	11		129		11	103
8	37	14	138					13	
	226	8	72					18	
	84	14						13	
	49	12						3	
	10	12						2	
	141	11						6	
	77	19						3	
	72	21						8	
		11						15	
		33							

Human influence in the form of waste from hotels, caravan parks etc. may also explain the 'hot-spots' around Loch Eck, for example. Otherwise, values of *ca* 50 μg TP l^{-1} are similar to the mean concentrations measured over the year in the major inflows draining agricultural land surrounding Loch Leven (e.g. 1-3 m^3 s^{-1} annual mean flows), and equivalent figures of 100-300 μg l^{-1} correspond to small farm ditches and drainage channels (< 0.01 m^3 s^{-1} annual mean discharge) in that catchment (Bailey-Watts and Kirika 1987).

Nitrate concentrations (**Table 7**) were often very different between streams flowing into the same loch; the two streams entering Clunie, for example, gave values of 0.29 and 2.9 mg N l^{-1}. Nevertheless, Shiel and Veyatie exhibit low values more or less all round the catchment (generally < 20 μg N l^{-1}), while St Mary's has higher concentrations of up to 400 μg l^{-1}. These contrast considerably with the more intensively developed catchments of Linlithgow (0.49 - 1.3 mg N l^{-1}), Rescobie (0.74 to 4.1 mg l^{-1}) and Marlee (0.16 to 4.7 mg l^{-1}). The overall range of N concentrations is some 1500-fold, from *ca* 7 μg N l^{-1} in Asta, Spiggie and Veyatie to 9.8 mg l^{-1} in the small, piped inflow to Coldingham Loch.

4. RESULTS AND DISCUSSION II: THE SENSITIVITY FACTORS DETERMINING THE IMPACT OF NUTRIENT INPUTS ON LOCH WATER QUALITY

So far, the pressures by way of general nutrient burdens have been considered separately from the waters receiving them. This section examines certain relationships between the lochs and their catchments as well as features of the lochs themselves; it is these factors which determine the impacts of the nutrient supplies. Plainly, a large number of physical and chemical factors are involved, and the relative importance of any one factor varies between waterbodies, and also temporally (eg seasonally), within a system. Here, lochs with features enhancing the conversion of nutrients to aquatic plants are contrasted with the systems that appear not to possess these features.

4.1 The relationships between predicted phosphorus loading and loch morphology

The combination of the size of the lochs and the amounts of phosphorus entering them, indicates how pressured the waters are. **Figure 13** uses data on surface area, mean depth and volume as indices of size, and the P loadings predicted from landuse and the numbers of people in rural and urban communities, of overwintering geese, and of caged fish.

The lines superimposed on these plots show that most of the waters lie within 100-fold bands in terms of P load on these size parameters, ie 0.001 t - 0.1 t ha^{-1}, 0.01 t - 1.0 t m^{-1}, and 0.01 t - 1.0 t 10^{-6} m^3. From Bailey-Watts, Sargent, Kirika and Smith (1987), the corresponding values for Loch Leven are 0.015 t ha^{-1}, 5.4 t m^{-1} and 0.42 t 10^{-6} m^3. On this basis, Loch Insh - which gives the highest load-to-area ratio (Figure 13a) - is under considerably greater pressure than Leven; other waters with a larger load-to-area ratio than 0.015, include Balgavies, Carlingwark, Cran, Davan, Strathbeg, Clunie and Marlee (which are the 2 lowest lochs in the lower Lunan series). By contrast, Branxholme, Duddingston, Lindean, Coldingham, Tingwall, Lowes, St Mary's and St John's are the least pressured on this basis.

Only one of these waters, however, compares with Loch Leven, in terms of the tonnages of P per metre mean depth; this is Strathbeg (**Figure 13b**) - another broad shallow system, although one in which rural communities and wildfowl are the main sources of P, rather than urban communities and, in 1987, industry as at Leven (see Bailey-Watts, May and Kirika, 1991). While this result is not surprising, because the eutrophication of the Strathbeg system is reasonably well-documented, it adds credibility to the strategy adopted for the present study.

Moving away from the extreme value for t P m^{-1}, the next most pressured systems on this basis, are Davan and Insh followed by a similar list of waters to those considered most burdened on the basis of the values for t P ha^{-1}. Again too, the waters judged as being under least pressure in terms of t P m^{-1}, ie Branxholme, Lindean, Coldingham, St Mary's and Tingwall, also featured in this category in terms of t P ha^{-1}, although St John's moves up the series with a value of *ca* 0.1 t m^{-1}. The dispersion of the points in **Figure 13c** differs from those in **Figures 13a** and **13b**, although e.g. Strathbeg, Insh, Balgavies, Carlingwark and Linlithgow again appear at the upper end of the scale. Values for these, plus e.g. Kilconquhar, Brow and the Lochmaben waters, are similar to, or exceed that for Loch Leven; this is 0.42 t P 10^{-6} m^3, which would produce a theoretical lake-wide, annual mean P concentration of 420 $\mu g\ l^{-1}$ - *not corrected for flushing rate* (see below).

A further assessment of trophic status can be made by calculating, from the data in **Figure 13a**, the specific areal loadings of P (ie units of g m^{-2}) and relating these to mean depth (**Figure 14**) according to the models of Vollenweider (1968), and OECD (1982). Certainly, the intensive studies at Loch Leven (Bailey-Watts and Kirika 1987; Bailey-Watts, Sargent, Kirika and Smith 1987) produced results on inflow and in-lake P concentrations, and on the loading and the P retention coefficient, which fitted very closely to these models. On the basis of **Figure 14** (on which the Leven value would come just to the right of the point for Rescobie ('Re')), none of the Scottish waters would be classed as oligotrophic. Indeed, apart from St Mary's Loch, Loch Shiel, the two small, high altitude Selkirkshire lochs, and possibly

Tingwall, this set appears to be receiving quite unacceptable, even 'dangerous' loadings of P. Many of them would rank with the most 'notorious' of Europe's waters, prior to the P reduction programmes carried out on them (Sas 1989). However, for reasons outlined below, it is unlikely that, in spite of increased loadings, deep waters would exhibit *'pro rata'* increases in phytoplankton biomass; hence our positioning of the 'eutrophic' and 'oligotrophic' labels on **Figure 14**.

The impact of a given loading of nutrients depends to a considerable extent on the general morphology of the loch basin. Thus, a deep waterbody of small surface area would respond in a very different way to a broad, shallow expanse of water. Not least, mixing and thus the light climate of photosynthetic organisms would be different, as would the availability of lit substrates for colonisation by hydrophytes and attached algae. Ideally, the area-depth and volume-depth curves should be assessed for this purpose, but time does not allow this to be done at present. Instead, the relationships between factors that determine the nature of these curves ie A_1, z and V_1 are examined. From **Figure 15** the potential contrasts in the types of plant community that are likely to capitalise on the nutrient supplies, can be identified. Each of the plots serves to distinguish between 4 major forms of basin. These are:

- from the plot of A_1 on z (**Figure 15a**):

(i) large, shallow waters of which Strathbeg is the most striking example

(ii) relatively large, deep lochs eg Shiel, Eck, St Mary's and Veyatie

(iii) relatively small, but deep waters, of which Mill is the only 'outlier'

(iv) relatively small, shallow systems such as Branxholme and Lindean.

- from the plot of V_1 on A_1 (**Figure 15b**), Mill Loch is identified as the relatively largest volume-smallest area water, and Strathbeg is prominent as the smallest volume-largest area system. However, this graph is characterised primarily by the axis passing from the points for the group of small volume-small area waters (Branxholme, Duddingston, Coldingham, Lindean, Asta and Brow), to those corresponding to the waters that are large in terms of both volume and area, ie Shiel, Eck, St Mary's and Veyatie.

- from V_1 plotted on z (**Figure 15c**), a relationship which is similar to that between V_1 and A_1 emerges. However, it differs from the plot in **Figure 15b**, in the position of some of the waters lying on the (limited) axis passing from top left to bottom right of the graph; this highlights a contrast between e.g. Mill and Strathbeg, in that the former is much the deeper, and the latter much the broader expanse of water.

By virtue of its large area and extreme shallowness, Strathbeg is likely to support an important community of attached plants. The balance between rooted hydrophytes and associated epiphytic algae on the one hand, and unattached ie planktonic, algae, on the other, will vary with season, and with degree of sediment resuspension. Under prolonged periods of calm weather, relatively dense stands of motile and/or buoyant, phytoplankton per unit of nutrient supply can be expected. Contrastingly, in rougher weather (heavier) diatoms may predominate as long as (i) silica is available (see below, and (ii) the sediments are not of the flocculent type that would be easily re-suspended and occlude light to the point of advantage to emergent macrophytes, or other hydrophytes that grow up to, or near, the water surface.

Relatively large waters (in terms of volume/area) which are of moderate depth e.g. 3-5 m can be expected to exhibit a relatively efficient conversion of nutrients to phytoplankton year-round; included here would be Coldingham, Balgavies, Rescobie, Butterstone, Cliff and Spiggie. Plant production is also likely to be high - given suitable nutrient resources - in somewhat deeper waters in summer if they stratify; here the potential examples are Craiglush, Tingwall, Mill, Lowes, Marlee and Clunie.

Contrasting with all of the above types of basin, are the sites that resemble most closely the 'classic' type of Scottish loch, ie. the large, deep waters e.g. Shiel, Eck, St Mary's and Veyatie. Except during prolonged periods of calm weather when shallow stable epilimnia may develop, these are unlikely to be highly productive as regards photosynthetic plants - even if nutrient burdens are high.

4.2 Flushing rate

Another point about the early Vollenweider models is that they did not take account of water renewal (or flushing rate, ρ). If this is not incorporated into the analysis, quite misleading conclusions will be drawn. Consider for example, the potential, lake-wide, annual mean P concentrations that would result if the predicted P loads were distributed in just a volume of water equivalent to each loch (**Figure 16**). Even taking into account likely losses due to sedimentation, these values are plainly nonsense. It is for this reason that Vollenweider and others developed new models which incorporated flushing rate, and the findings from the present study are considered below in the light of these.

There are reasons why the importance of ρ cannot be over-emphasised, and Bailey-Watts, Kirika, May and Jones (1990) discuss a number of aspects of the ecology of freshwater phytoplankton influenced by ρ. It determines not only the loadings from many of the diffuse sources of nutrients, but also the time available for phytoplankton to capitalise on these resources and produce more cells. In this way, seasonal variation in ρ within a waterbody, and differences in the general regime between waters, are likely to have strong influences on sequences of phytoplankton; only the relatively rapid-growing species can establish themselves (in the absence of other losses incurred through sinking and/or grazing) under high flushing conditions; otherwise, only rooted, or other attached plants can flourish. Regardless of whether an environment has the potential to favour, and indeed exhibit, high plankton *productivity* (see eg Brook and Woodward 1956), through being, for example, moderately shallow and well-fed with nutrients, this potential will not be realised as high biomass, if the water is rushing through the system such that heavy losses by washout are incurred.

Good examples of waters that receive large amounts of P, but are also rapidly flushed, are Insh, Strathbeg and Carlingwark with estimated P loads of 9.1, 3.2 and 1.9 t respectively and annual ρ values of 21.4, 14.5 and 11.7 loch volumes respectively (**Figure 17**). However, if the results on long-term variation in ρ at Loch Leven are applicable to other Scottish waters, there is a 5% chance of flushing rates varying from -60% to +60% of the 'average' values. Then, if the values plotted in **Figure 17** are accepted as averages, the theoretical retention time of a system such as Strathbeg, could vary from 10 to 40 days; plainly, the responses of phytoplankton would differ as a result.

A further obvious, but often neglected point about ρ, is that it defines the volume of 'new' water entering a system in say, a year. By introducing it into considerations about the likely in-lake P levels that would result from the estimated loadings, a quite different array of values to those presented in **Figure 16** is obtained. As the correction is $^1/_\rho$, the point in **Figure 18*a*** for Davan, for example, corresponds to a P concentration less than one-twentieth of that plotted in **Figure 16**, while that for Coldingham Loch is some 3 times greater than the corresponding value in **Figure 16**. Nevertheless, many waters still register predicted values of > 100 µg P l^{-1}, and should therefore be considered eutrophic. But, by comparing the values in **Figure 18a**, with the OECD boundary system of lake classification, few waters fall within the hypertrophic category - see inset **Figure 18a**.

Figure 18b shows how the lochs can be categorised when the predicted annual P loads are related to the product of mean depth and flushing rate (or z divided by $^1/_\rho$) following Vollenweider (1975). This exercise emphasises that the flushing volume (V_f) of a system rather than the loch volume *per se* should be examined when assessing the likely impacts of (applications for) fish farm installations, or for any catchment development likely to increase nutrient burdens to a waterbody. The two parameters are plotted in **Figure 19**, while **Table 8** highlights the contrasts in the V_f values of pairs of lochs of similar V_l, and identifies another water whose V_l is similar to these V_f values. The common message from these considerations is that the siting of say, a fish farm on a waterbody with a V_f of x is likely to cause less serious eutrophication problems, than its siting in a waterbody with a V_l of x.

Table 8. Comparisons and contrasts between selected lochs on the basis of their physical volumes (V_l) and the flushing volumes (V_f) ie the product of V_l and ρ; all values in units of 10^4 m^3.

Pair of waters of similar V_l	V_l	V_f	Another water with V_l similar to V_f
Coldingham	25	10	Duddingston (11)
Lindean	24	24	-
Branxholme	13	57	-
Brow	14	302	Spiggie (314)
Craiglush	139	612	Lowes (630)
Strathbeg	151	2190	Rescobie (2014)
Lowes	630	1008	Insh (1285)
Marlee	550	3740	Veyatie (3007)

Similarly, while Loch Insh (V_l, 1285 x 10^4 m^3) is some $^1/_{60}$ the size of Loch Shiel (V_l, 79 x 10^7 m^3), the annually renewed volume of water in the Insh system (27 x 10^7 m^3) is some 50% of that in the slow-flushed larger loch (55 x 10^7 m^3).

Plots of ρ on z, and on V_l (**Figure 20**) contrast the systems in which attached plants are likely to dominate primary photosynthetic biomass, with those in which the planktonic flora is more favoured.

4.3 Likely seasonal patterns of input to nutrients from the different sources

The sampling strategy adopted for this study cannot assess seasonal variation in nutrient inputs. However, it is important to appreciate that temporal patterns in the delivery of N and P will vary according to source. In this way alone, the different sources will impact differently on the receiving waterbodies.

The dependence on ρ is a useful basis on which to distinguish external sources, in this connection - and Bailey-Watts and May (1992) demonstrate the contrasting patterns of loadings and concentrations that result, according to nutrient source. As examples, flushing-dependent (runoff-related) inputs from rough grazing will vary with rainfall patterns, while the various schedules of fertiliser application to different arable crops, forest areas and improved grassland, will also affect the loading seasonality. Contrastingly, the STW-derived inputs will vary according to day-of-the-week but, setting aside the influence of stormwater overflows, they will not be so closely linked to rainfall. Nevertheless, influxes of tourists in summer and/or winter in some of the areas included in this study, will also affect the patterns of nutrient export from urban and rural sources. Still different loading regimes will be associated with overwintering wildfowl, and with fish farms.

4.4 Stratification

If a thermally stable column of water develops with well-defined epilimnion, thermocline and hypolimnion, algal growth is likely to be enhanced even in deep, oligotrophic systems; also, certain motile and buoyant phytoplankton forms are probably advantaged over say, 'heavy' diatoms. Under such conditions however, this otherwise favourable, surface epilimnetic zone, is the most affected by flushing; the throughput of water can be thought of as being more 'focused' on this upper layer at this time. By the same token, the hypolimnion is characterised by a longer residence period than at other times of the year when the water column is mixed throughout its depth. Then, material raining down into the deeper zone, or released from the sediments at its base, can accumulate (see next section).

Of the 36 basins in which temperature profiles were recorded, 13 appeared to be more or less isothermal over the whole column, 7 exhibited a slight and/or general decrease in temperature with depth, while the remaining 16 showed clear thermal layering of the water (**Table 9**). **Figure 21** illustrates some of the striking profiles obtained. The grouping of the lochs in terms of the field data on stratification, compared reasonably with the situation suggested by Hanna's (1990) equation discussed in **section 2.1.5**, and the relationships between predicted thermocline depth (z_t) and the z and z_{max} values for the basins.

Table 9. Waters grouped on the basis of the extent of thermal stratification - summer 1991

Isothermal waters	Waters exhibiting ± 'classic' 3-layer structure:
Coldingham	Balgavies east
Lindean	" west
Branxholme	Rescobie east
Kilconquhar	Marlee east
Rescobie west	" west
Strathbeg east	Clunie
" west	Butterstone
Spiggie	Lowes
St John's	Craiglush
Veyatie east	Eck north (2 major discontinuities)
Veyatie central	" south
Cliff central	Shiel north
	" south
Waters exhibiting a general decrease in temperature with depth, but no sharp discontinuities:	Tingwall north*
	Veyatie west
	Insh east
	Cliff arm*
	Cliff entrance to arm*
St Mary's	
Linlithgow	
Davan	
Brow	
Asta	
Tingwall south	
Insh West	

*assumed from differences between surface and bottom temperatures, but no profiles taken

4.5 Phosphorus retention and the potential for release of phosphorus from the sediments

Phosphorus retention values (R_p - shown in **Figure 22**), derived from the areal water loading (q_s, **section 2.1.4**), ranged from just under 0.1 (Loch Insh) to over 0.9 (Kilconquhar and Coldingham); in other words, the study includes waters in which the amounts of P they retain each year approximates to between 10% and 90% of the annual loadings received. The indications are, however, that many of the waters are likely to retain between 40% and 50% of what they receive, and only the very highly flushed waters retain such smaller proportions, and only very low-flushed systems retain much larger proportions. Note in **Figure 22**, however, that some shallow lochs e.g. Coldingham, Kilconquhar and St John's feature at the upper end of the R_p spectrum - because they are also low-flushed.

Where a standing water lies within the catchment of another loch, it can be considered as ameliorating the potential effects of catchment eutrophication, by 'absorbing' a certain amount of the P otherwise destined for the lower loch. In this regard, a proportion of the losses of P from the Balgavies catchment does not reach that loch because Rescobie intervenes; similarly, Tingwall retains some of the P heading for Asta. However, the Lunan series of lochs provide a marvellous example of a cascade of waters - 5 in all, starting with Craiglush and ending with Marlee (**Appendix II**). A preliminary investigation of the cumulative effects of the series on the P loading to Marlee loch (Winkler 1991), distinguishes between the 'immediate' catchment of each loch, and the portion of the catchment draining them *via* the preceding water(s). It can be calculated that, if there were no gains in land catchment area from loch to loch, virtually none of the P coming into Craiglush (R_p 0.47) would reach Marlee. As it is, the land area does increase *via* Lowes, Butterstone, and Clunie, and P is lost from these areas; thus, while still only a small *fraction* of P entering Craiglush is likely to reach Marlee, the loading to Marlee is considerable. The loadings discussed earlier for each loch are corrected for the P-retaining capacity of standing waters in their catchments and the effects of doing this are discussed in the accounts of each of the waterbodies in Volume II.

In most waters, the amounts of P measured are not solely derived from recent inputs from the catchment. The water columns of both shallow lakes (e.g. Loch Leven - Bailey-Watts, Kirika, May and Jones 1990), and deep systems (Mortimer 1942) can gain P at rates far in excess of those explainable by external sources, and this is due to release of P - primarily in the form of phosphate or soluble reactive P (SRP) - from sediments. There are a number of release mechanisms; wind-induced mixing of deposits and P-rich interstitial water can take place in shallow waters (Drake and Heaney 1987), while redox-controlled desorption of phosphate ions from iron and manganese hydroxides, for example, occurs especially in deep, deoxygenated waters (Mortimer 1941, 1942, 1971). However, evidence from a column circulation experiment at Coldingham Loch (Bailey-Watts, Wise and Kirika 1987) and the long-term surveillance of Loch Leven, suggests that shallow, warm sediments may release P, even though the water to within a few millimetres of the sediment surface is reasonably well-oxygenated. Thus, sites in which P release could be important, include not only the thermally well-stratified waters which exhibited near, or virtual anoxia near the sediments, but also a number of shallow lochs that were isothermal, but warm. In shallow, productive systems too, photosynthesis-induced increases in pH can also lead to enhanced P mobility. The total list is as follows:

a: thermally-stratified columns, near anoxia at depth

Balgavies (both basins)	Butterstone
Rescobie (east)	Lowes
Marlee (both basins)	Craiglush
Clunie	

b: more or less isothermal, but warm columns

Kilconquhar (17.4°C)	Brow (17.6°C)
Rescobie (west basin 17.4°C)	Asta (17.1°C)
Strathbeg (west basin 18.8°C)	Cliff (all 3 basins - 18.0°C, 17.2°C, 17.8°C)

Notable exclusions from these lists are the well-stratified waters, in which bottom water temperatures are low and dissolved oxygen levels are at least 60% saturation:

St Mary's (7.9°C @ 44 m)
Eck - north basin (8.3°C @ 42 m)
- south basin (11.9°C @ 21 m)
Shiel - north basin (6.5°C @ 100 m)
- south basin (11.8°C @ 31 m)
Veyatie - west basin (9.0°C @ 10 m)
Insh - east basin (9.4°C @ 22 m)

The bottom water temperatures vary inversely with loch depth, but none of these lochs is a classic, dimictic water, in which the bottom water remains at *ca* 4°C in summer. This is because either the water masses are so enormous that heat cannot be lost rapidly enough for temperatures to fall as low as this (as in the case of Shiel - Smith, Lyle and Rosie 1981), or the basins are sufficiently shallow to remain more-or-less well mixed until 'summer' temperatures prevail and the associated higher density-intergrades bring about more permanent stratification (Hutchinson 1957).

4.6 Light penetration, water colour and turbidity

The present study has not categorised the waters on the basis of colour or turbidity, but these can affect the extent to which nutrients are taken up by e.g. phytoplankton, in 2 ways. One effect is on the penetration of light, and thus, the climate for photosynthesis. In many of the lochs, the depth at which light in the photosynthetically active radiation band (400-700 nm) is reduced to 1% of the surface values, is 5 m to 12 m. The main exception is Rèscobie in which a very dense crop of a picoplanktonic cyanobacterium was present; this, rather than the intrinsically clear water itself, was the major light-attenuating factor - a situation well-documented for Loch Leven (Bindloss 1974, 1976) where 'self-shading' of phytoplankton (see Talling 1960) used to exert an important control on the biomass maxima (Bailey-Watts 1988). Dissolved yellow (humic) substances also absorb light (Kirk 1983), but there are no exceptionally peaty waters in this study.

The second effect on phytoplankton production potential, also concerns humic content. It may affect primary production by sequestering phosphate and thereby rendering it less immediately available to algae (Jones, Salonen and de Haan 1988).

4.7 Conductivity and pH

The spread of conductivity and pH values has already been noted (**Figures 8** and 9). Within both of these arrays, the dilute, deep systems plainly contrast with rich, shallow, and especially near-coast waters; indeed, the 2 rankings are generally similar, such that variation in pH is associated with 60% of the variation in (log) conductivity (**Figure 23**).

Far from pondering on simply the potential effects of enhanced nutrient enrichment, the main concern with many of these waters is the existing high levels of eutrophication pressure. Indeed, the prevailing concentrations of nutrients (see below) and associated plant biomass, presumably contribute to the higher conductivity and pH values recorded. Nevertheless, given favourable physical conditions (e.g. long residence time, clear water, and suitably shallow mixing depth), the addition of nutrients to even the lowest conductivity systems is likely to result in increased algal and/or hydrophyte productivity and, usually, biomass as well (Bailey-Watts, Kirika and Howell, 1988).

4.8 Silica concentrations

Plainly, the more plentiful the dissolved silica, the greater the likelihood of diatoms as well as other algae, capitalising on the (enhanced) supplies of other nutrients - although again physical conditions will determine the actual extent to which biological uptake of this nutrient takes place. Thus, from **Table 10** diatoms would be expected to be more prominent in e.g. Linlithgow, Balgavies, Rescobie and most of the lochs on the River Lunan system, than in e.g. Veyatie.

Table 10. Silica levels (mg SiO_2l^{-1}) in all of the inflows sampled during summer 1991.

CO SiO_2	BE SiO_2	MY SiO_2	LL SiO_2	BV SiO_2	RE SiO_2	MR SiO_2	CU SiO_2	BU SiO_2	LW SiO_2	CG SiO_2	SB SiO_2
7.1	5.8	2.8	10.7	11.0	7.7	1.8	4.0	0.87	4.5	3.3	15.2
		2.5	10.1	7.3	7.9	8.4	11.9		9.7	5.3	15.6
		1.5	9.5			11.5			8.1		16.1
		3.1				8.8					
		5.3				12.8					
		3.5									
		2.7									
		3.0									

DV SiO_2	EK SiO_2	SH SiO_2	SP SiO_2	BR SiO_2	AS SiO_2	TW SiO_2	SJ SiO_2	VY SiO_2	IN SiO_2
13.1	2.3	3.5	0.5	5.5	0.3	3.1	4.8	1.2	3.8
10.2	1.7	4.3	13.6	8.8		6.9		2.1	9.7
9.4	0.9	3.0	11.0					2.8	4.6
	2.0	4.5	8.1					1.3	
	1.9	4.1						1.4	
	1.6	1.2						1.2	
	1.2	1.7						1.4	
	2.4	1.8						0.8	
	2.4	1.7						1.3	
	3.2	1.7						2.0	
		1.7						1.2	
		3.5							

5. RESULTS AND DISCUSSION III: THE RESPONSES - THE COMBINED EFFECTS OF PRESSURES AND SENSITIVITIES AS INDICATED BY WATER QUALITY IN SUMMER 1991

5.1 Nutrient status of the open and outflow waters

A number of features can be established from the results on the nutrient content of open waters (including the water immediately above the sediments) and of the corresponding outflows:

- relative trophic status
- clues to horizontal mixing and/or changes taking place within the loch basin
- indications of whether P is being released from the sediments.

Further comparisons with the data on the feeder streams can give information on the degree of net losses of nutrients to, or from the sediments.

The range of open water TP levels measured in summer, are shown in **Figure 24.** This suggests that Kilconquhar is by far the richest water, although with values exceeding 50 μg P l^{-1}, Mill, Rescobie, Balgavies and Strathbeg are still eutrophic. At the other end of the range are Eck, Shiel (north basin), St Mary's (north basin) and Veyatie with levels of < 10 μg l^{-1}.

One of the most exciting findings of this study - because it supports a 'hunch' that the strategy adopted in this work would be appropriate - is embodied in **Figure 25a.** This shows a tolerably good relationship over the whole spectrum of waters studied, between the desk-predicted annual P loading expressed as a flushing-corrected P concentration, and the single measure of actual P level, ie the summer concentration. Indeed, a log-log linear regression analysis shows that 70.1% of the variation in one variable is associated with the variation in the other variable (ie the coefficient of variation, r^2, is 0.709, where n = 26). However, the value for Kilconquhar ('Kq') is highlighted as having a large standard residual value and a large influence on the regression. The lower panel of **Figure 25a** plots the data excluding Kq; more exploratory analysis is necessary, but the indications are that by discounting, in addition to Kq, the data for Branxholme ('Be') and Mill ('Ml'), an even stronger relationship between the 2 variables would result. An immediate conclusion to draw from these results, is that the desk analysis is an appropriate method for categorising waters over a broad spectrum of trophic status.

It is important to stress, however, that the similarity between the predicted and measured values for any system is coincidental. Even if the P loadings and the annual mean, lake-wide, flushing-corrected concentrations derived from them were 'right', there are numerous reasons why they need not equal the P levels measured in summer. First, P levels fluctuate seasonally - albeit less so in large oligotrophic waters than small eutrophic systems; the predicted values could then either exceed, or fall below the measured value. A second reason for the discrepancy between predicted and measured values, concerns the line shown in **Figure 25** for y (log measured summer P concentration) = x (log annual mean lake-wide P level predicted from the desk-estimated loadings) - and this concerns the varying proportions of the P entering a basin that are lost to the sediments. In this case, the desk-predicted loadings and concentrations would be expected to exceed any measured values - and indeed, **Figure 25a** shows this is so with most of the present summer values. Losses to the sediments is a factor accounted for by the model of Dillon and Rigler (1974) - to which incidentally Loch Leven measurements fitted extremely closely. This model predicts the mean annual in-lake P concentration ($[TP]_l$ in $\mu g\ l^{-1}$), from the P retention coefficient (R), the P loading (L, in $mg\ m^{-2}\ y^{-1}$), lake mean depth (z, in m) and the flushing rate (ρ in lake volumes y^{-1}), as follows:

$$[TP]_l = \frac{L(I - R)}{z \times p}$$

When the values predicted for L, R and ρ, together with information collated for z, are related in this way, and the P concentrations measured in the Scottish lochs in summer $[TP]_s$ are regressed on the predicted $[TP]_l$ figures, the following equation is obtained:

$$\log [TP]_s = 0.756 \, [TP]_l + 0.483$$

$$(n = 26, r^2 = 0.49).$$

Thus only 49% of the variation in one variable is associated with the variation in the other - although again, the 'aberrant' results for Branxholme have a large standard error, while the Kilconquhar figures have a large influence on the equation.

Figure 25b shows the graphs from this analysis; note that the y = x line now passes through the main group of points.

A third area relevant to the differences between predicted and measured P levels relates to the fact that the summer P concentration in particular may well be higher than the annual average concentration, (i) if algae constitute the major component of the P and/or (ii) if P is released from the sediments. Finally, low P concentrations in a loch may under-represent the water column *per se*, as they ignore rooted plants and periphytic algae; indeed, the water of the 'weedy' Linlithgow Loch - an intrinsically quite rich waterbody, was extremely clear, with the highest recorded Secchi disc reading of this study, i.e. 5.6 m (**Figure 26**).

Table 11 shows that there are only slight horizontal differences in TP in the surface waters, although this does not necessarily mean that the P comprises the same proportions of dissolved and particulate fractions throughout a waterbody. However, there are a large number of lochs where SRP levels in the bottom water are significantly higher than those found at the surface, but still moderate i.e. < 8 µg SRP l^{-1} as in e.g. Clunie, Butterstone, and the north basins of Eck and Shiel. In others, the near-sediment concentrations are high by any standards, as in e.g. Linlithgow, Balgavies, Davan, Brow and Asta.

Table 11. Surface open-water (op), outflow (ou) and sediment-overlying (ov) concentrations of total phosphorus (TP) and the total soluble (TSP) and soluble reactive (SRP) fractions, recorded in 1 loch basins during summer 1991.* denotes no data. N = north basin, S = south basin, E = East basin, W = West basin, C = Central basin and A = 'Arm'

Basin	op TP	op TSP	op SRP	ou TP	ou TSP	ou SRP	ov SRP
Coldingham	49.5	28.1	4.5	31.0	28.1	4.5	4.8
Lindean	13.8	8.5	2.5	13.3	8.5	2.1	4.3
Branxholme	15.7	7.1	1.7	25.7	8.5	2.1	2.5
St Mary's N	8.2	3.6	1.3	7.7	4.1	0.4	2.0
St Mary's S	12.3	5.5	0.9	7.7	4.1	0.4	*
Kilconquhar	1252.3	1163.6	1133.2	1263.6	1097.7	1088.4	1151.8
Linlithgow E	26.8	19.5	3.4	23.6	18.2	3.4	28.4
Linlithgow W	38.6	27.7	8.5	*	*	*	*
Balgavies E	57.1	45.0	24.0	64.3	55.3	36.6	71.0
Balgavies W	61.9	30.3	14.8	*	*	*	*
Rescobie E	79.5	14.2	4.4	63.8	11.8	3.0	5.7
Rescobie W	85.2	12.8	3.0	*	*	*	*
Marlee E	26.2	10.4	3.0	19.0	10.4	2.6	7.8
Marlee W	19.5	8.5	2.6	*	*	*	*
Clunie	11.4	8.0	2.6	15.7	8.5	2.6	7.2
Butterstone	23.8	10.4	3.0	21.9	9.5	3.0	6.3
Lowes	15.7	10.9	3.5	19.0	11.8	3.5	22.2
Craiglush	11.4	6.1	2.2	15.2	8.5	3.0	3.7
Strathbeg E	61.1	16.0	3.7	63.4	13.4	2.9	*
Strathbeg W	57.8	13.8	2.9	*	*	*	*
Davan	32.8	23.2	11.6	32.3	20.5	8.7	50.7
Eck N	8.1	4.3	1.8	6.7	3.3	1.8	4.3
Eck S	6.2	3.8	*	*	*	*	*
Shiel N	7.1	3.3	1.8	6.7	3.3	2.2	6.3
Shiel S	12.4	3.3	2.2	*	*	*	*
Mill	92.4	13.4	3.3	*	*	*	*
Spiggie	22.8	8.9	2.5	19.5	8.0	2.9	2.7
Brow	26.6	7.1	4.1	29.0	8.0	4.1	11.8
Asta	16.2	6.2	3.7	10.5	5.8	3.3	10.6
Tingwall N	17.6	9.8	3.3	11.4	5.3	2.1	6.8
Tingwall S	10.9	5.3	2.5	11.4	5.3	2.1	3.5
St John's	16.6	8.5	2.9	20.4	9.8	3.3	3.3
Veyatie E	10.3	7.1	4.5	7.9	6.2	4.0	3.6
Veyatie C	9.3	6.2	2.7	*	*	*	*
Veyatie W	8.4	5.7	3.1	*	*	*	3.3
Veyatie A	4.7	4.3	2.2	*	*	*	2.0
Insh E	14.6	3.5	3.2	13.1	8.8	2.9	*
Insh W	13.3	9.9	3.0	*	*	*	*
Cliff C	16.2	9.8	2.1	*	*	*	2.3
Cliff E	39.9	16.5	4.5	*	*	*	3.7
Cliff A							

All of the sediments of these waters must be suspected of releasing phosphate, and most of them exhibited near-anoxic conditions at depth (cf. **section 4.6**). However, Linlithgow and Davan are major exceptions, while the results from Eck and Shiel may well reflect the greater utilisation of SRP by algae in the surface waters, rather than any vigorous desorption of phosphate from the bottom deposits.

A comparison between these in-lake P concentrations, with the values obtained at the inflows (where these feeder streams exist), suggests that the water columns of Coldingham, Davan, Brow and Asta may gain extra P from their sediments, while there is a marked net flux of P from the water columns of Linlithgow and St John's (due to rooted hydrophytes and epiphytic algae?), and from those of Balgavies, Marlee, Clunie, Strathbeg and Tingwall (to the sediments?). In the absence of more detailed information on the sub-catchments associated with each of the inflows sampled, the remaining waters show no evidence of marked flux of P to, or from, the sediments (ie St Mary's, Rescobie, Butterstone, Craiglush, Eck, Shiel, Spiggie, Veyatie and Insh).

Table 12 shows that the outflows and open waters of the following lochs are reasonably similar in nitrate content: Lindean, Branxholme, Linlithgow, Balgavies, Butterstone, Eck, Shiel, Brow, Tingwall, St John's and Veyatie. Contrastingly, the open water levels exceed the outflow concentrations in the following systems: Coldingham, Kilconquhar, Marlee, Clunie, Lowes, Craiglush, Strathbeg, Davan and Asta. Only in 4 of the waters are the outflow concentrations significantly higher than the open water values ie St Mary's, Rescobie, Spiggie and Insh. A preliminary assessment of these results suggests few consistent associations between the relationship of open and outflow nitrate levels, but over a total range of 3-2115 $\mu g\ N\ l^{-1}$ in the open waters, the lower values tend to correspond to the very shallow lochs (**Figure 27**). This is in keeping with observations on the shallow Loch Leven, where summer nitrate minima can be explained by the high rates of bacterial de-nitrification at the (warm) sediment surface (Bailey-Watts, Kirika, May and Jones 1990).

The higher the nitrate concentrations in open water - even in summer, when in many temperate waters the nitrate minimum occurs - the lesser the likelihood of N-fixing cyanobacteria being prominent. However, this does not mean that the species that often fix atmospheric N under conditions

Table 12. Nitrate concentrations (μg N/l) in the surface open water (op), the outflow (ou) and the sediment-overlying water (ov) of 41 loch basins sampled in summer 1991. *denotes no data. North, South, East, West and Central basins are denoted by N, S, E, W and C respectively while side arms are indicated by A.

basin	op	ou	ov
Coldingham	71	37	74
Lindean	19	18	21
Branxholme	24	22	21
St Mary's N	162	200	167
St Mary's S	198	*	*
Kilconquhar	10	70	10
Linlithgow E	31	315	289
Linlithgow W	341	*	*
Balgavies E	187	188	241
Balgavies W	190	*	*
Rescobie E	33	94	55
Rescobie W	30	*	*
Marlee E	2115	1629	2062
Marlee W	2000	*	*
Clunie	687	294	884
Butterstone	95	96	90
Lowes	143	72	146
Craiglush	88	10	162
Strathbeg E	8	4	*
Strathbeg W	8	*	*
Davan	132	112	133
Eck N	147	162	192
Eck S	156	*	195
Shiel N	39	42	92
Shiel S	43	*	89
Mill	168	*	*
Spiggie	3	33	6
Brow	9	8	7
Asta	14	5	6
Tingwall N	6	4	9
Tingwall S	5	*	75
St John's	8	9	7
Veyatie E	18	20	18
Veyatie C	18	*	*
Veyatie W	22	*	42
Veyatie A	35	*	32
Insh E	79	92	*
Insh W	*	*	*
Cliff C	2	*	6
Cliff E	16	*	18
Cliff A	9	*	11

of low NO_3.N are any less likely to appear; their success then depends more on physical conditions and the situation as regards grazing zooplankton (Bailey-Watts 1986).

5.2 Phosphorus levels in the sediments

5.2.1 *Sediment interstitial water*

Pore water SRP concentrations averaged over the uppermost 5 cm of the sediments ranged from *ca* 4 $\mu g\ l^{-1}$ to 300 $\mu g\ l^{-1}$. The richest sites on this basis include those with the largest catchments ie Insh, Shiel and St Mary's, but also Lowes, Linlithgow and Coldingham (**Figure 28a**) - an enormously disparate group of waters in terms of many of the physical and chemical characteristics discussed so far. The lowest concentrations were also recorded in a mixed set of systems including the high-pH Asta and Brow and the low-pH western arm of Loch Veyatie. There would thus appear to be little correspondence between this ranking, and the general order based on any other single determinand - even degree of anoxia, or warmth of bottom waters (see **Section 4.6**).

However, if just 3 of the systems are excluded from the analysis, there is a reasonable correspondence between interstitial SRP and the predicted P loads to the lochs expressed as t P y^{-1} (**Figure 28b**). The 3 main outliers are Coldingham, Branxholme and Lindean; why this is so has not yet been investigated. Curiously, there is little semblance of a relationship such as shown in **Figure 28b**, where the loading is expressed either as g P m^{-2}, or as the P retention coefficient-corrected values for loading or specific areal loading. Why this is so also requires further investigation.

Numerous studies have shown that the amounts of P dissolved in the pore waters represent but a minor fraction of the total P in the sediment (Bostrom, Jansson and Forsberg 1982; see also Bailey-Watts 1990 for previous information on the Loch of Cliff, Bailey-Watts, May and Kirika 1991 on Loch Leven, and Bailey-Watts and Kirika 1991a on Loch Eye). It is probable therefore that if sediment P reflects eutrophication pressures at all strongly, it will more likely do so in the total P content, and this is examined in the following section.

5.2.2 *Particulate matter*

The ordering of the basins in terms of the total P in the top 5 cm of the sediments (**Figure 29a**) suggests that the deposits in Lowes and at the confluence of the arm with the main basin of the Loch of Cliff (Unst, Shetland) are the richest in P. The latter record is of note, in that effluent from a bankside fish farm used to be piped out to this point (Bailey-Watts 1990). Contrastingly, the value for Lowes is larger than those obtained from the 3 waters below it in the Lunan series. What is more, apart from Lowes, the sediment content increases down that system, i.e. Craiglush < Butterstone < Clunie < Marlee. This suggests that any supposed cumulative retention of P down the cascade (see **section 4.6**) is offset by the pressures from the immediate catchments of each water.

The sediments in which P comprises > 0.3% on a dry-weight basis include - in addition to the lowest 3 Lunan lochs - Linlithgow, Balgavies, Spiggie and Insh, and all of these have been classified as representing the richer end of the spectra of various other trophic pressure indicators. Nevertheless, as with the results on pore water P levels, waters of quite different character can be grouped closely together on the basis of % P per unit dry weight; compare for example the relative positions here with those based on e.g. predicted P loading (**Figures 18** and **25**) of Davan and Kilconquhar, Branxholme and Brow, and Tingwall and Rescobie. Also, while on the basis of predicted annual mean and measured summer P concentrations in the water column, St. John's comes more-or-less in the middle of the range, its sediments appear to be the poorest in P. Many of these values, however, lie within the range 0.1 to 0.2% P of dry-weight, which is commonly found for eutrophic muds (see e.g. survey by Bostrom, Jansson and Forsberg 1982), but sites in Loch Leven gave values ranging from 0.1% to 0.4% (Bailey-Watts, May and Kirika, 1991).

The conclusion drawn from this aspect of the work is that while conceptually, the P content of the muds would be expected to reflect external P loads, neither the predicted load expressed as t P y^{-1} or g P m^{-2} nor the products of these values and the calculated P retention coefficients show any consistent relationship with surface sediment P content. **Figure 29b** illustrates this with the figures for t P y^{-1}.

5.3 Phytoplankton abundance and species composition

5.3.1 Chlorophyll a concentrations

Phytoplankton biomass varied over 2 orders of magnitude - from a few microgrammes chlorophyll *a* per litre in Asta, Lindean, Shiel, St Mary's, Eck, and Insh, to 145 µg l^{-1} in Mill. The distribution of values is considerably skewed, so the concentrations are plotted on a logarithmic scale in **Figure 30**. With the vast majority of the basins supporting less than 10 µg l^{-1} in summer, the set of waters as a whole would appear to be of little concern. Nevertheless, these values represent the outcome of the combined results of phytoplankton biomass production and losses due to e.g. grazing and sedimentation. Of interest is the relative similarity in algal levels in waters of markedly different mean depths e.g. the shallow Kilconquhar and St John's on the one hand, and Insh and Eck on the other. One way of viewing this is that higher plants may be stemming phytoplankton production in e.g. St John's, and zooplankton grazing is depressing algal levels in e.g. Kilconquhar; as a result, these intrinsically rich waters appear oligotrophic. Another view might be that 'classically' nutrient-poor, deep environments like Shiel and Eck, are showing signs of eutrophication by producing - under summer, stratified conditions - crops comparable to those in the richer, shallow lochs.

Although the overall levels of algae are low, there is a good relationship between the log-transformed values and water clarity measured as Secchi Disc transparency (**Figure 31**). This suggests that in general, much of the variation in water clarity is associated with algal biomass, and not dissolved coloured material or detrital particles.

These summer pigment levels do not relate in a consistent way to mean depth, but three groups of waters can be discerned (**Figure 32**). Group I consists of Mill and Rescobie comprising the major outliers with chlorophyll concentrations of *ca* 145 and 80 µg l^{-1} respectively. The second group consists of 7 waters of which 5 are between 1 m and 2 m mean depth, and therefore potentially very 'weedy' - at least in summer. The third group, which is comprised of the other 17 lochs, describes a fairly strong chlorophyll-loch depth relationship.

Algal biomass is related somewhat similarly to the mixed depth (or epilimnion depth - **Figure 33**) as to mean depth. Unfortunately, no temperature profiles were taken at Mill Loch but the prominent cyanobacterial bloom (see below) corresponded to very hot calm weather - indeed, a surface value of 19.4°C was recorded. So, not only was the column likely to have been very sharply stratified but the mixed depth (z_{epi}) was also probably very shallow. It is thus quite reasonable to expect that the point for Mill Loch would have lain as indicated in **Figure 33** ie corresponding to a z_{epi} value of *ca* 0.5 m. It would then have extended the reasonably consistent chlorophyll-z_{epi} relationship described by the systems referred to as group III in **Figure 33**. As with the biomass-mean depth plot, Rescobie remains an outlier, suggesting a very efficient build-up of algal biomass. In relative terms, Coldingham Loch and the eastern and central basins of Veyatie can be considered similarly efficient. The shallow waters referred to as group II in **Figure 32**, occupy a relatively similar area of **Figure 33**, but are 'joined' by Clunie, Craiglush and Insh. Under summer stratified conditions, epilimnetic populations of algae are likely to incur enormous losses by washout. Hence, the predominance of benthic *Oscillatorias* and diatoms in Insh (Watson 1991).

The overall relationship between summer algal biomass and the predicted P load is poor (**Figure 34**). However, the foregoing considerations allow reasonably confident statements to be made as to why a particular water occupies the position shown. For present purposes, let the major factors determining the position of the systems within the area to the right of the line drawn on this Figure be assessed. On the basis of the summer chlorophyll values, each of these waters appears to be low in algae per unit of P load - relative to the remaining 6 waters, ie Branxholme, Lindean, Coldingham, Brow, Rescobie and Mill:

a. a group of lochs in which algal biomass is likely to be limited by low P levels - ie dilution of the P load, whatever this burden may be; examples are the large lochs Shiel, Eck and St Mary's.

b. a group in which, whatever the P load or [P] achieved, the physics of the systems mediate against achievement of high phytoplankton biomass; examples are firstly, the deep waters including Shiel, Eck, St Mary's and Tingwall, secondly, the very shallow systems such as St John's and Kilconquhar, and thirdly, the highly flushed waters such as Insh, Davan, Strathbeg, Butterstone, Asta and Balgavies - all of which have ρ values of $\geq$ 8 loch volumes y^{-1} (compared to the value of 1.8 for Loch Leven).

c. a group of waters in which the physics are again important, but this time by way of small mean depth which enhances the success of rooted hydrophytes and attached algae, and offers these communities a competitive edge over the phytoplankton; examples are St John's, Linlithgow and Strathbeg.

Plainly where a waterbody is listed in more than one of the categories above, the cumulative effect of low nutrient levels and shallowness, and possibly high flushing too, is likely to be evident; Davan would appear to be the best example of such a situation.

5.3.2 Qualitative features of the phytoplankton and associations with the loch environment

The total number of species recorded exceeds 100, even in this set of seasonally restricted samples. This may reflect the generally low biomass levels, and of note in this connection are too contrasting situations, i.e.

(i) the more or less pure stand of *ca* 12 x 10^3 colonies ml^{-1} *Microcystis aeruginosa* Kütz *emend.* Elenkin, corresponding to 145 µg chlorophyll *a* l^{-1} in Mill Loch, and (ii) the dense crops of 0.45 and 1.2 x 10^6 cells ml^{-1} of a less-commonly recorded *Synechococcus* (near *S. plankticus* Drews, Prauser and Uhlmann 1968) in the Rescobie basins where values of 76 and 81 µg chlorophyll *a* were recorded. The actual number of species is not known, however, because many of the types have not yet been assigned with any confidence to the 'species' level. Indeed, in the case of the majority of the many nanoplanktonic algae including chrysoflagellates no greater than 5 µm, and all of the picoplankters (≤ 2 µm - see Sieburth, Smetacek and Lenz 1978), the question of identity focuses on whether an organism is, for example, a chlorophyte, a cyanophyte or chrysophyte. A number of these small organisms are not likely to be noticed by a less experienced observer, yet these algae and cyanobacteria (see Carr and Whitton 1982) can be very numerous. Starting with the picoplankton, the following paragraphs attempt to associate the differing phytoplankton assemblages with characteristics of the various loch environments. In addition to overall trophic status (as indicated in **Figure 18**), mean and mixed depths (**Figures 20 and 24**), flushing rate (**Figure 20**), the levels of nitrate and SRP related as shown in **Figure 35** are taken into account; this is because the ratio of N to P can be an important determinant of algal quality.

The *Synechococcus* that was abundant in Rescobie was also present (though at densities of only 10^3 - 10^4 ml^{-1}) in the more highly flushed Balgavies into which Rescobie water eventually flows. This cyanobacterium, which can be classed as 'picoplankton' even though the cell length exceeds 2.0 µm (see e.g. Bailey-Watts and Komarek 1991), is thus associated with the relatively highly-enriched waters, of 'ideal' mean depth, and ones which, in any case, stratify to produce a warm shallow layer. Partly as a result of the growth of the *Synechococcus*, nitrate-N and phosphate-P levels are low in summer, although a favourable weight ratio of *ca* 10N:1P is maintained. 'True' picoplankters ie ≤ 2 µm in all dimensions, were present in prodigious numbers in a wide range of waters. These include what may well be single cells of the colonial cyanobacterium *Aphanothece clathrata* W. *et* G.S. West (see below). Population densities tended to increase with general richness ie from *ca* 10^3 ml^{-1} in

Lindean and Branxholme to > 10^6 ml^{-1} in Strathbeg and Brow. However, 10^3 to 10^4 ml^{-1} were estimated in the samples from the 'oligotrophic' Eck and Shiel, and from Davan which is a potentially rich system but one in which high flushing mediates against major planktonic algal biomass accumulation. In this respect, Davan resembles Loch Dee in Galloway (Bailey-Watts and Kirika 1991b).

Aphanothece clathrata as somewhat larger aggregations/loose colonies but still mostly < 40 µm, was observed in almost all of the waters, but the higher densities were recorded in Strathbeg (2.2 x 10^6 ml^{-1}), Rescobie (0.1 x 10^6 ml^{-1}) and Balgavies (25 x 10^3 ml^{-1}). Notably however, the chemically and morphometrically oligotrophic Tingwall gave values of ca 2 x 10^3 colonies ml^{-1}. Tingwall was also special in being the only loch in which abundant *Rhabdoderma lineare* Schmidle and Lauterborn was noted, ie 40 x 10^3 ml. This organism is similar to *Aphanothece* in the delicate, loosely structured, mucilaginous 'colonies', but differs in that the cells are relatively long and narrow, ie 4 or 5 µm by *ca* 1 µm, while those of *Aphanothece* are generally 1-2 µm and spherical (except during cell division). A second colonial cyanobacterium which was also recorded in any major abundance in only 1 loch is *Merismopedia* Meyen; it was found in Strathbeg where the estimated population density was *ca* 25 x 10^3 ml^{-1}. This shallow loch is perhaps not surprising as a *Merismopedia* site in that the plate-forming colonies are likely to be suited to a surface-sediment existence as much as to the water column itself.

The only remaining colonial cyanobacterial of major note in the present study (ie excluding the bloom-forming *Microcystis* in Mill Loch itemised above) is *Gomphosphaeria* Kütz. It is somewhat similar to *Microcystis* except that (i) there are strands of dense mucilage which radiate from the centre of the colonies, (ii) cells divide longitudinally, not cross-wise, and are especially prominent at the outer edges of the colony and (iii) the colonies rarely exceed say, 60 µm in breadth, whereas *Microcystis* aggregations can reach millimetres. The species recorded is near *G. naegeliana* (Ung.) Elenk. but the taxonomy of it and similar-looking algae is under review (Komarek and

Hindak 1988). One of its features is that the colonies often fragment in Lugol's Iodine; thus, as a colony may contain many thousands of cells, it is not surprising that it has been recorded as single cells in many of the waters here, ie *ca* 10^3 ml^{-1} in Marlee, Clunie and Tingwall, *ca* 10^4 Butterstone and Lowes, and 45 x 10^3 in Spiggie. Nevertheless, it plainly formed a minor background to the *Microcystis* in Mill Loch, (*ca* 50 colonies ml^{-1}) and was important also in Cliff (40 ml^{-1}) and Spiggie (*ca* 700 ml^{-1}).

Filamentous cyanobacteria of note in this study, include *Aphanizomenon* and a range of straight or more-or-less curved, as well as coiled, species of *Anabaena*. The *Aphanizomenon* (almost certainly *A. flos-aquae* Ralfs ex. Born. *et* Flah.) was recorded in only 1 water - Kilconquhar. This is notable in that Kilconquhar has been grouped with Coldingham on the basis of the combination of shallowness and low flushing, and prior to mixer installation in the Berwickshire Loch, it produced substantial blooms of this alga (Bailey-Watts 1987). What is more, while the NO_3-N to SRP weight ratio in summer in Coldingham Loch is now around 10:1-20:1, it used to be *ca* 0.2:1 due to massive release of phosphate from the sediments, and associated (? microbial) denitrification. In this respect it then resembled the current condition of Kilconquhar where the summer N-to-P ratio is very much in favour of P ie 0.004:1 (**Figure** 35), although as argued in the limnological profile on this loch (**Volume** II) sediment release is probably not the main cause of the high P levels in Kilconquhar. Under such a regime it is not surprising that the incidence of N-fixing cells ('heterocysts' - see Fay, Stewart, Walsby and Fogg 1968) in the *Aphanizomenon* was high, i.e. *ca* 30% of the filaments bore at least one heterocyst.

There is however, another feature of the situation at Kilconquhar which raises an issue of considerable importance in the general interpretation of algae-environment associations - and this is grazing by zooplankton. A number of authors have noted that in many temperate waters, large algae (such as bloom-forming cyanobacteria) are relatively more abundant in summer than winter, and, by the same token, small algae are the more prominent at the beginning and end of the year. Plainly, physical factors such as the development of a stable water column in summer are involved, and indeed, the *Microcystis* bloom in Mill Loch and the larger *Aphanothece* colonies elsewhere, are reflections of this. However, the additional influence of grazing zooplankton should not be overlooked. Certainly, the explanation of a number of long-term and seasonal changes in the phytoplankton of Loch Leven is improved when fluctuations in the abundance of e.g. *Daphnia* are taken into account (Bailey-Watts 1978, 1982; Bailey-Watts and Kirika 1981; Bailey-Watts 1986). Similarly, the situation at Kilconquhar is more explicable, bearing in mind that it was the only water visited in which many large filter-feeding Cladocera were observed. These are known to be very efficient grazers - on, primarily, small algae (e.g. Gliwicz 1980). Time has not yet permitted analysis of the crustacean zooplankton samples collected during this study, but the intention is to look at this aspect. The final point to be made regarding the Kilconquhar results, is that the large-bodied (ie 2-3 mm) *Daphnia* observed there, indicate low predation by fish - a 'top down' effect on the structure of the pelagic system (Northcote 1988). This fits with anecdotal accounts of 'no fish in this loch'.

Other than in Mill and Kilconquhar Lochs, there were no massive blooms of large cyanobacteria. Nevertheless, *Anabaena flos-aquae* (Lyngb.) Breb., was numerous enough to be noticed with the unaided eye in Eck, Spiggie and St John's (10-20 colonies ml^{-1}), Brow (*ca* 50 ml^{-1}) as well as Coldingham (*ca* 100 ml^{-1}) - the latter being sampled in mid-June when the temperature was still only 11°C. The record for Eck indicates that not only are blue-green algae by no means the preserve of rich shallow waters, but that a classic 'eutrophic' genus such as *Anabaena*, can appear in an ostensibly oligotrophic, large, deep loch - other physical factors permitting. This suggests that these lochs are not as bereft of nutrients as might be generally thought. In this connection, it is important to note the presence of *Anabaena(s)* albeit at densities of $< 10\ ml^{-1}$, in the relatively oligotrophic Branxholme, Veyatie, Lowes and Craiglush, as well as those waters which are thought of as more eutrophic eg Butterstone.

The other group of cyanobacteria of note in this sample of waters, includes the narrow (*ca* 1-3 μm) *Oscillatoria* species of e.g. of the *O. limnetica* Lemm., *O. planctonica* Wolosz., and *O. redekei* Van Goor types (also under taxonomic review - Meffert 1988), and the morphologically similar *Pseudanabaena* (likewise being re-classified - Anagnostidis and Komarek 1988). These are non-heterocystous, and are more-or-less confined to the richer shallow lochs, ie Strathbeg (6 x 10^3 of *O. limnetica* and of *Pseudanabaena*), Brow (300 *Pseudanabaena* ml^{-1}) and Asta (60 *Pseudanabaena* ml^{-1}) which were, at the time of sampling, nevertheless, relatively low in inorganic N and P content.

Diatoms were prominent in rather few waters, but this is not surprising, since these algae are more commonly associated with spring and autumn; their main incidences are as follows:

- *Asterionella formosa* Hass. (> 100 cells ml^{-1}): St Mary's (both basins) and Veyatie (east, central and west basins); these records are important in showing an association between an alga indicative of mild eutrophication, and (i) the first-mentioned loch in the catchment of which forestry has increased and the Megget reservoir was constructed over recent years, and (ii) the latter loch on the main inflow of which a fish farm is situated.

- unicellular centric diatoms (> 100 ml^{-1}): Rescobie (east), Marlee (both basins), Strathbeg, Veyatie (the western arm) and Cliff. The inclusion of Veyatie in this group is puzzling in that this arm is so unlike the other waters; however, the species of diatom is different - ie *Cyclotella comensis* Grunow as opposed to forms of *C. comta* (Ehrenb.) Kutz. and *Stephanodiscus hantzschii* Grunow (see Bailey-Watts 1988).

This list of 'diatom waters' does not correspond very well to the group identified on the basis of inflow SiO_2 levels (**section 4.9**), but that view refers to the relative likelihood of diatoms being prominent over the year as a whole - not just the summer. Indeed, the general lack of diatoms in the present samples probably reflects the overall thermally stable columns than any marked unavailability of silica - since many of the lochs contained ≥ 1 mg SiO_2 l^{-1} (**Figure 36**).

Green algae were recorded in all of the waters, but in the context of eutrophication the abundances of Chlorococcales are of greatest significance. These include a diverse assemblage of unicellular types (both non-motile and flagellate forms), colonial species in which a mucilage investment is prominent, and coenobial forms. They were generally most abundant in the waters that have been ranked the richest on the basis of predicted loadings etc. ie Balgavies, Rescobie and Strathbeg. However, they contributed moderate proportions of the populations found in Cliff, Tingwall and Spiggie, as well as those in the 'oligotrophic' sites Eck, Shiel and Branxholme.

The remaining species of algae that were recorded, fall into one of two major groups - the cryptoflagellates and the chrysoflagellates. These were represented in every loch but, at present, there seems to be no clear association between their abundance and any major features of these loch environments. For example, the summer numbers of *Rhodomonas* and *Cryptomonas* (Cryptophyceae) were by far the highest in the west basin of Rescobie (*ca* 22 x 10^3 ml^{-1}), while populations of between 2 x 10^3 ml^{-1} and 4 10^3 ml^{-1} were recorded in 3 very contrasting waters - Rescobie east, the arm of Cliff, and Davan.

This preliminary examination of the phytoplankton in general and the last comments regarding crypto-flagellates in particular, highlight the need for further analysis, and one which looks at a number of physical and chemical features of the loch at one and the same time.

5.4 Rotifer composition with reference to special indicators of trophic status

5.4.1 *Species composition and abundance*

Almost 50 species of rotifer could be distinguished in the samples collected. Of these, 24 were identified to species level, 12 to genus (**Table 13**) and the remainder were classified as unidentified.

Total rotifer densities ranged from relatively low values in Kilconquhar (2 ind l^{-1}) and St Mary's (64 ind. l^{-1}) to fairly high values in Cliff (2136 ind. l^{-1}) and Brow (2174 ind. l^{-1}) (**Figure 37**). It is misleading to draw too many conclusions from these data alone, as the values are based on a single visit to each site. Rotifer population densities can change very rapidly because of their high reproductive rates and short lifespans, so it should be borne in mind that a repeat visit just a week later could have given very different results in terms of absolute numbers. However, in relative terms, the abundant populations would still have been abundant, while the low numbers would still have been low. Bearing this in mind, the data suggest that higher rotifer densities occurred in smaller, shallower lakes with low water transparency (Secchi disk) rather than larger, deeper, clearwater lakes (**Figures 38-40**). They also tended to be more abundant in warmer waters (**Figure 41**).

The only species which was found at almost every site was *Keratella cochlearis*. This was absent only from Kilconquhar and Linlithgow. Other commonly occurring species included *Keratella quadrata* (12 sites), *Polyarthra dolichoptera* and *Kellicottia longispina* (11 sites), *Synchaeta ?kitina* (9 sites) and *Polyarthra vulgaris* (8 sites). The remaining species were found at a very small number of sites (< 6).

Rotifer abundance varied greatly from species to species, the highest densities being recorded for *Keratella cochlearis* (2108 ind. l^{-1}) in Brow, *Polyarthra vulgaris/dolichoptera* (1128 ind. l^{-1}) and *Trichocerca pusilla* (792 ind. l^{-1}) in the arm of Cliff, and *Trichocerca similis* (466 ind. l^{-1}) in Butterstone. Most other rotifers were present in very low numbers often less than 100 ind. l^{-1}, and frequently less than 10 ind. l^{-1}.

The occurrence of *Ascomorpha ovalis* (8 ind. l^{-1}) in Asta is of particular interest because this species feeds almost exclusively on the dinoflagellate *Ceratium* which was also found in abundance at this site. Similarly, *Gastropus stylifer*, which feeds predominantly on dinoflagellates, was usually found in association with *Ceratium*. The relative abundance of *Polyarthra* *vulgaris/dolichoptera* (112 ind. l^{-1}) in the arm of Cliff is also worthy of note because *Polyarthra* generally feed on small flagellates, especially *Cryptomonas* and *Rhodomonas*, and large numbers of these flagellates were found at this site.

5.4.2 *Rotifers as environmental indicators*

Perhaps the more important feature of these rotifer samples is species composition. Most rotifer species produce resting eggs which are resistant to desiccation and are easily dispersed by a variety of agents, such as the wind and migratory birds. So, their presence or absence at different locations within a small geographical area, such as Scotland, probably reflects their environmental preferences. Many species are very sensitive to environmental conditions and can only establish a population where conditions are favourable. Because of this, it has been suggested that many species may have value as environmental indicators (Thumark 1945; Berzins 1949; Lillieroth 1950; Järnefelt 1952; Pejler 1957, 1965, 1983; Radwan 1976, 1984; Gannon and Stemberger 1978; Berzins and Pejler 1989; Pontin and Langley 1992).

Many people have suggested that rotifers may be good indicators of the trophic status of waterbodies (e.g. Gannon and Stemberger 1978; Berzins and Pejler 1989). Of the 23 species identified during this survey, 19 are considered to be potential indicators of lake trophy and 15 have been assigned a trophic ranking number, based on their occurrence in Swedish lakes, by Berzins and Pejler (1981) (**Table 13**).

The presence or absence of each of these latter 15 species in each of the survey lochs is shown in **Table 14**. The rotifers are ordered according to their trophic ranking number (Pejler 1989), while the lochs themselves are ranked according to measured open-water, total phosphorus levels. Even with this incomplete data set, there was a tendency for 'oligotrophic' species to be more common in lochs with low total P values, such as Shiel, Eck and St Mary's, while 'eutrophic' species were more often found in lochs with much

Table 13. Species list of rotifers found during the survey of Scottish lochs. Those considered to be indicators of the trophic status are indicated with an asterisk (*) and those which have been given a trophic ranking number by Pejler (1989) are indicated with a (+).

Brachionidae

+ * *Brachionus angularis*

+ * *Keratella cochlearis*

+ * *Keratella quadrata*

+ * *Kellicottia longispina*

Anuraeopsis sp.

Lecanidae

+ * *Lecane lunaris*

Lecane ?opias

Lecane spp.

Trichocercidae

Trichocerca similis

Trichocerca ?inermis

* *Trichocerca pusilla*

Trichocerca sp.

Gastropidae

+ * *Ascomorpha ovalis*

+ * *Ascomorpha ecaudis*

Ascomorpha sp.

+ * *Gastropus stylifer*

Asplanchnidae

Asplanchna spp.

Synchaetidae

Synchaeta ?kitina

Synchaeta ?oblonga

* *Synchaeta* spp.

* *Ploesoma hudsoni*

+ * *Polyarthra vulgaris*

+ * *Polyarthra dolichoptera*

+ * *Polyarthra euryptera*

Polyarthra spp.

Testudinellidae

+ * *Pompholyx sulcata*

+ * *Filinia longiseta*

Conochilidae

+ * *Conochilus unicornis*

Conochilus sp.

Collothecidae

* *Collotheca* sp.

genera *Polyarthra, Asplanchna, Synchaeta, etc.* In addition, some key indicator species may have been overlooked by sampling each site only once, as many rotifer species are seasonal in occurrence. An attempt was made to improve this situation by collecting samples from the lake bottom so that 'out-of-season' species lying dormant in the sediments could be added to the species list for each loch (May 1986). However, insufficient time was available for these samples to be examined in detail.

Table 14. Rotifer indicators of trophic status in relation to measured open water P concentrations of the 25 lochs visited.

Cn - *Conochilus unicornis*
Ae - *Ascomorpha ecaudis*
Gs - *Gastropus stylifer*
Kl - *Kellicottia longispina*
Ao - *Ascomorpha ovalis*
Ed - *Euchlanis dilatata*
Ps - *Pompholyx sulcata*
Ba - *Brachionus angularis*
Kq - *Keratella quadrata*
Fl - *Filinia longiseta*
Pv - *Polyarthra vulgaris*
Pd - *Polyarthra dolichoptera*
Kc - *Keratella cochlearis*
Pe - *Polyarthra euryptera*
Ll - *Lecane lunaris*

Loch	Open water P conc. ($\mu g l^{-1}$)	Rotifers - Trophic indicator species														
		Oligotrophic ——————> Eutrophic														
		Cn	Ae	Gs	Kl	Ao	Pv	Pd	Kc	Pe	Ll	Ed	Ps	Ba	Kq	Fl
Shiel (N)	7.1			+	+			+	+							
Eck (N)	8.1				+		+		+							
St Mary's (N)	8.2				+		+		+							
Veyatie (C)	9.3				+			+	+							
Clunie	11.4				+			+	+		+					
Craiglush	11.4				+				+		+					
Lindean	13.8	+		+	+				+						+	
Branxholme Easter	15.7	+		+	+		+		+						+	
Lowes	15.7	+			+				+			+			+	+
Asta	16.2			+		+	+		+							
St John's	16.6				+		+	+	+						+	
Tingwall (N)	17.6		+	+			+	+	+	+						
Spiggie	22.8							+	+							
Butterstone	23.8						+	+	+		+	+				
Marlee (E)	26.2				+				+							
Brow	26.6							+	+							+
Davan	32.8							+	+						+	
Linlithgow (W)	38.6			+				+		+					+	
Cliff (A)	39.9				+											
Coldingham	49.5								+						+	
Balgavies (E)	57.1						+	+	+				+	+	+	+
Strathbeg (E)	61.1														+	+
Rescobie (E)	79.5								+				+	+	+	+
Mill	92.4								+						+	+
Kilconquhar	1252.3															

6. RESULTS AND DISCUSSION IV: OVERVIEW

The aim of this section is to draw together the findings of the study in two ways. The major characteristics and special features of each of the waterbodies examined - site 'profiles' - are presented in **Volume II**. The other part of the overview is presented below and looks at the set of catchments as a 'sample', perhaps representative of the Scottish loch environment as a whole, and the eutrophic waters in particular.

The study illustrates well the enormous variety of waters to be found in Scotland. The range in size and chemical character is considerable, even if, for example, the smallest and largest systems, the most acid and the most alkaline, and the most and least enriched are ignored. Stratification patterns differ from loch to loch according to local weather and the specific dimensions of the basins, but the lack of 'classic' hypolimnia with bottom temperature of around 4°C, undoubtedly reflects the highly variable, oceanic climate of Scotland. What is more, Scotland has good examples of small, i.e. shallow and low-volume systems, which are also low-flushed. The tendency is to associate low flushing solely with large waters in Temperate regions. The prominence of a picoplankton in this set of waters is notable. However, in contrast to the physical and chemical features highlighted so far as being of particular importance in Scotland, the presence of these minute algae is not likely to prove so special. The more probable explanation is that these smaller elements are generally overlooked.

Turning to eutrophication issues, very varied mixtures of nutrient sources have been identified. Superimposed on the range of systems described, these inputs have - not surprisingly - produced a variety of chemical and biological responses. Nevertheless, diffuse sources of nutrients outweigh point sources by far, even setting aside the large, reasonably 'wild', catchments, such as that of Insh - the drainage area of which is approximately the same as all of the other catchments put together. Indeed, the predominance of non-point inputs of nutrients to the surface water network, suggests that considerations about the assessment, control and prevention of eutrophication should now focus more on diffuse enrichment, e.g. from rural developments.

Because the study concerns eutrophication, the selection of lochs is biased towards nutrient-enriched systems. It is not surprising, therefore, that at least some of the (predicted) phosphorus loadings are very high. That many of these certainly exceed the values measured at Loch Leven, i.e. 0.015 t per ha of surface, 5.4 t per metre mean depth, and 0.42 t per 10^6 m^3 volume, is perhaps disturbing. However, when the study waters are examined in terms of the relationship between specific areal loading of P (ie g m^{-2}) and the product of mean depth and flushing rate, a different perspective is gained. Then, oligotrophic, mesotrophic and eutrophic lochs are broadly identified as follows:

	oligotrophic	mesotrophic	eutrophic
increasing P status ↓	Branxholme Lindean Insh Veyatie St Mary's Shiel Eck Tingwall	Cliff Clunie Asta Marlee Duddingston Coldingham Butterstone Lowes St John's Spiggie	Craiglush Balgavies Castle Brow Mill Davan Linlithgow Rescobie Strathbeg Carlingwark Kilconquhar

Only *ca* 3 of these waters would be judged more eutrophic than Leven - Kilconquhar, Strathbeg and Carlingwark. These, and a number of other 'chemically eutrophic' systems need not always be seen as seriously affected, however, unless they also appear to be 'biologically eutrophic' i.e. with blooms of algae, or overgrowths over other plants. Chapter 7 suggests that the present data should be analysed further, in relation to other criteria, and other models for ranking waters in terms of trophic status.

The project as whole highlights the importance of the generally wet weather in Scotland in ameliorating, through its effects on flushing rates, the biological results of nutrient enrichment. The situation would be quite different if continental rather than oceanic weather regimes prevailed. Even if total annual rainfall remained unchanged, prolonged hot, dry summers would effect many more instances of dense (cyanobacterial) blooms. Still, the Scottish environment exhibits numerous chemical signs of eutrophy, such as hypolimnetic de-oxygenation, and evidence of phosphorus release from sediments. Also, while real 'hot-spots' in the way of thick aggregations of algae are few in this series of waters, P-rich feeder streams are not rare, and waters in which dense macrophytic growths and attached algae (as opposed to phytoplankton) predominate, are common. As emphasised again below, the albeit sparse populations of 'eutrophic' algae in such waters as Eck and Veyatie, should be carefully noted, and the condition of these and many other waters, monitored.

7. EVALUATION OF THE STRATEGY ADOPTED FOR ASSESSING FRESHWATER CATCHMENTS, AND SOME VIEWS ON MONITORING EUTROPHICATION TRENDS IN LOCHS

The results suggest that the general programme of catchment analysis combined with limnological reconnaissance is appropriate. Plainly, some very valuable information has been gained, and this has enhanced our quantitative understanding of the factors determining some of the responses of lake systems to eutrophication pressures. This particular study has also been instructive in covering such an enormous variety of catchments. Especially encouraging are (i) the correspondence found between predicted loadings of P and the summer measure of nutrient status, and (ii) the information that has facilitated reasonably sensible interpretations of the varied responses of phytoplankton between the different systems. However, improvements to the approach are necessary, and some suggested modifications are outlined later, and include immediate requirements for assessing and monitoring sites. There are other issues that the work has identified as worthy of further attention, and these include:

(i) multivariate analysis of the data - much of the progress so far being based on bivariate analysis.

(ii) formulation of models that may describe better the 'Scottish' situation with regard to relationship between e.g. stratification patterns and lake form, and P loadings and in-lake P levels; at present, only existing models have been used.

(iii) development of models taking account of the cumulative P retention capacity of standing waters on the same river system; the Craiglush to Marlee chain would provide a very good system on which to base further work of this type.

(iv) incorporation of seasonal loading patterns into the 'pressures - sensitivity - responses' theme; in common with much of the eutrophication literature world-wide, the present study has limited the analyses to annual mean values for e.g. P loadings.

(v) basic biological studies on picoplankton.

(vi) the extent and occurrence of sediment P release in certain shallow waters which, while stratifying only intermittently, have warm bottom deposits in summer.

(vii) the use of rotifer assemblages as trophic indicators.

(viii) further analysis of sediment data.

(ix) further analysis of chemical and biological material already collected, and interpretation alongside the existing database; major opportunities exist for 'mapping' the distribution of planktonic micro-Crustacea, and the stratigraphy of diatom frustules, heavy metals and radionuclides in the sediments.

(x) examination of schemes additional to those covered by this report, for ranking waters in terms of trophic status ('oligotrophic', 'mesotrophic' etc); there is a need to highlight even further the difference between models focusing on chemical eutrophy and those concerned with biological eutrophy (Bailey-Watts 1990b).

As to improving the present strategy for assessing nutrient loadings, (but still focusing primarily on desk analysis rather than detailed field work), more up-to-date censuses of land use and population numbers are needed. Maps are soon outdated in these respects, and even local authorities have difficulty in maintaining records on housing, for example. While still not advocating intensive sampling programmes, a winter-time collection of water from main inflows and the outflow of each waterbody would enhance the work; chemical and biological analyses would then indicate the standing stock of nutrients, for example, at the start of the year, and the over-wintering plankton populations.

Other work needed to improve the assessments of nutrient loadings, concerns intensive studies on losses from land areas limited to a single, well-defined use. Data on P and N loss coefficients for specific forage crops and vegetables are needed. More information is also required, on the impact of rural communities - through the behaviour of septic tank effluents on soakaway systems in different soils - on the nutrient status of surface waters. In this connection, 'hot spots' of high N and/or P concentrations in the inflows already obtained, would be worth investigating further.

Although primarily a reflection of time availability, there are a number of omissions from the current analysis on the factors controlling the sensitivity of a waterbody to its nutrient burden. Firstly, more detailed exploration of lake bathymetry ie lake 'form' would facilitate more quantitative predictions about the balance between hydrophytes and other rooted/attached plant communities on the one hand, and the planktonic flora on the other. Secondly, there is considerably more to be obtained from the existing data set, if a number of features could be considered basin by basin, rather than on just a loch basis. Important here, are physical parameters e.g. ρ, z and z_{max}, and values such as P retention coefficients derived from them, as well as nutrient loadings.

For monitoring the condition of the present sample of waters, and indeed of any new sites, a summer sampling reconnaissance of the type described in this report, combined with a wintertime visit, would be very valuable. Certainly, attempts should be made to measure oxygen levels in the hypolimnia of stratifying waters once per year. Of course, the more intense the sampling (in time and space), the greater the amount of information obtained. However, experience of the present programme and a number of previous studies carried out by this laboratory, suggests that duplicate samples for chemical and biological analysis, taken from 1 open water site, a major inflow and the outflow at *ca* 6-weekly intervals would usually be adequate. Adjustments would need to be made according to loch; large, deep systems tend to change more slowly than smaller shallow systems, due to the differing susceptibility to changing weather patterns.

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Appendix I. Letter codes, the names of the lochs, and the sampling dates ('*' denotes sediment sampling as well as water collections)

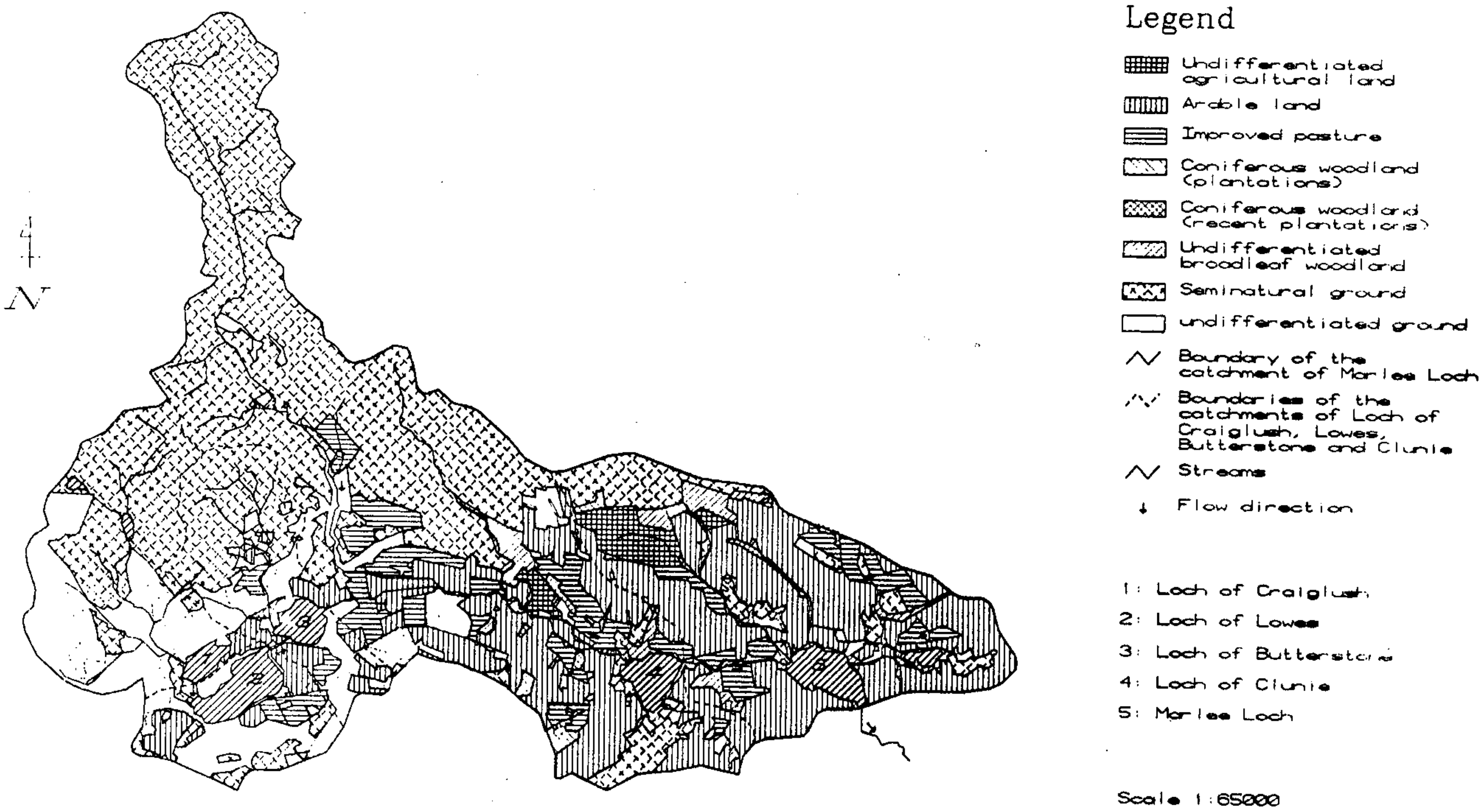
Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

APPENDIX II

An example of a GIS-based, digitised catchment

Redrawn with annotations from Ordnance Survey 1:25 000 Map Sheets numbers NO 05/15, NO 04/14, and 1:50 000 Map Sheet No 53

Landuse within the catchment of the Marlee Loch



Source:- Derived from 1988 1:24000 Aerial Photographs and O.S. 1:50000 and 1:25000 maps

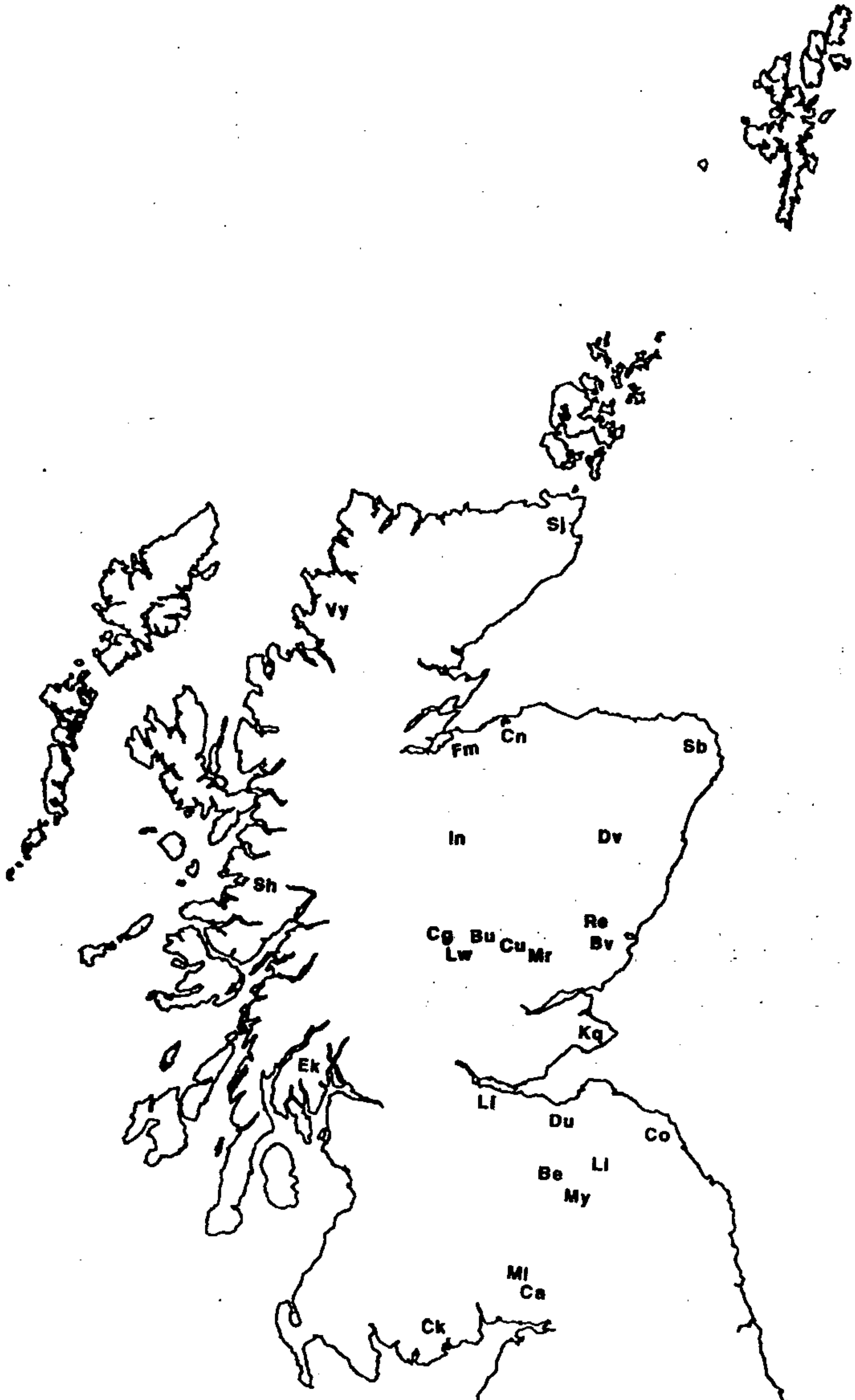
Compiled:- by Gabriele Winkler on ARC/INFO, August 1991

Figure Legends

Each legend includes a table of the 2- and 3-letter codes and the full names of the catchments, and the date(s) on which they were sampled. * indicates the waters from which sediment samples were also taken. Some co-ordinates are so similar that the code labels overlap, making them difficult to read; this Table thus indicates by means of vertical bars, the sites for which similar values were measured.

Figure 1a. The locations of the lochs sampled on the Scottish mainland

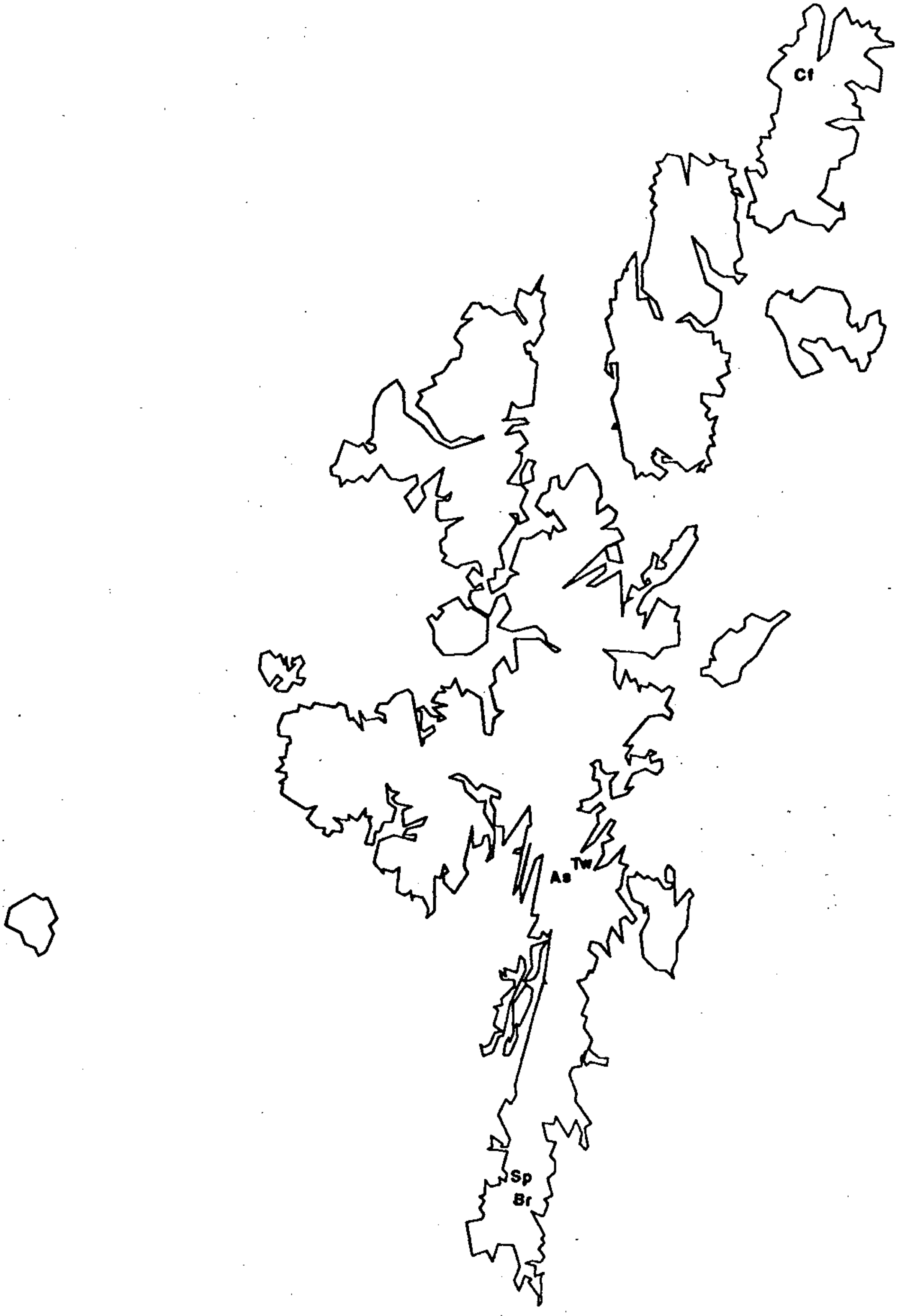
Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	



Sj
Vy
Cn
Fm
Sb
In
Dv
Sh
Re
Cg
Bu
Cu
Mr
Lw
Bv
Kq
Ek
Ll
Du
Co
Ll
Be
My
Ml
Ca
Ck

Figure 1b. The locations of the lochs sampled on the Shetland Isles

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled



Cf
As
Tw
Sp
Br

Figure 2.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Lochs ranked according to latitude – degrees North

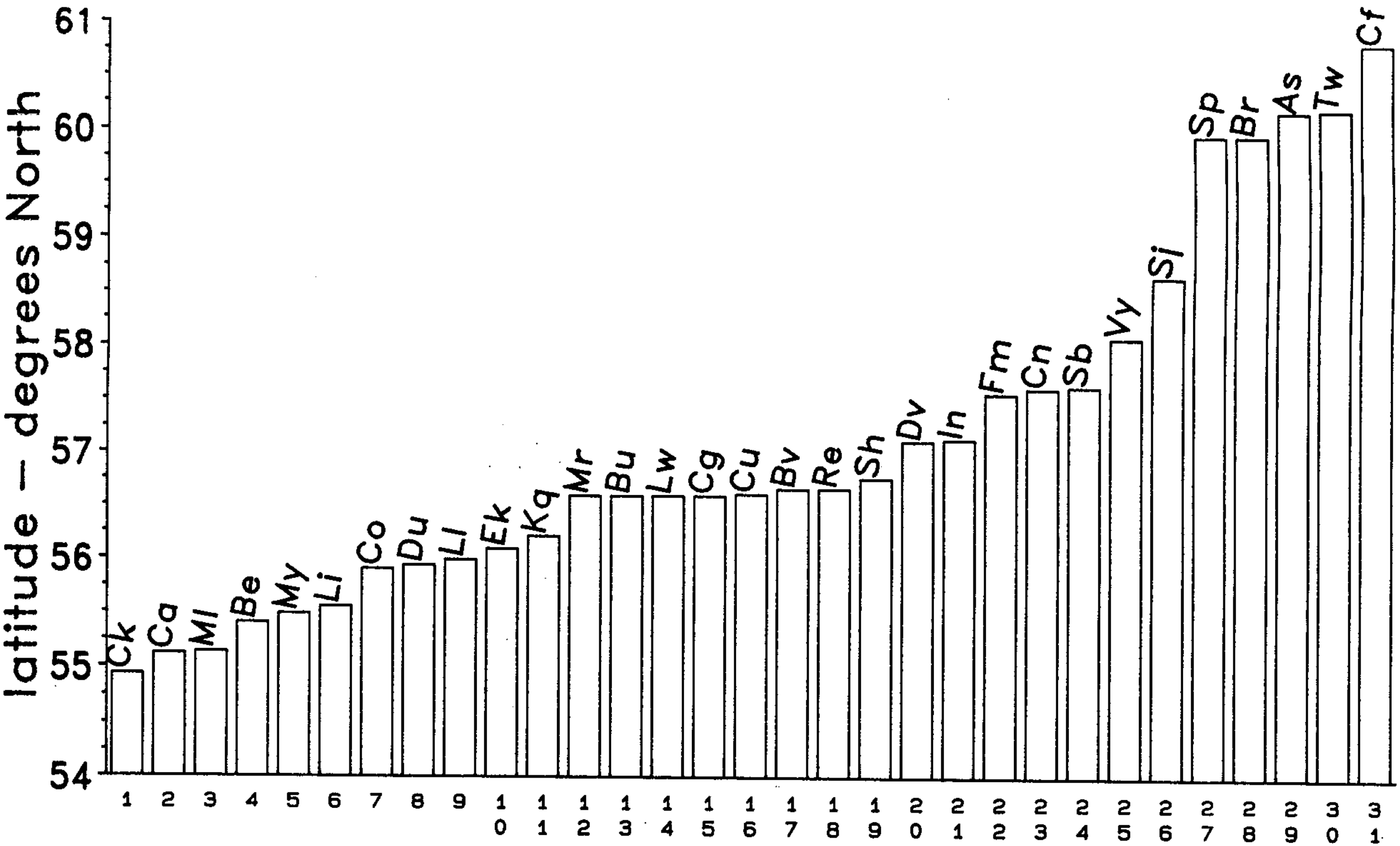


Figure 3.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Lochs ranked according to altitude – m a.s.l.

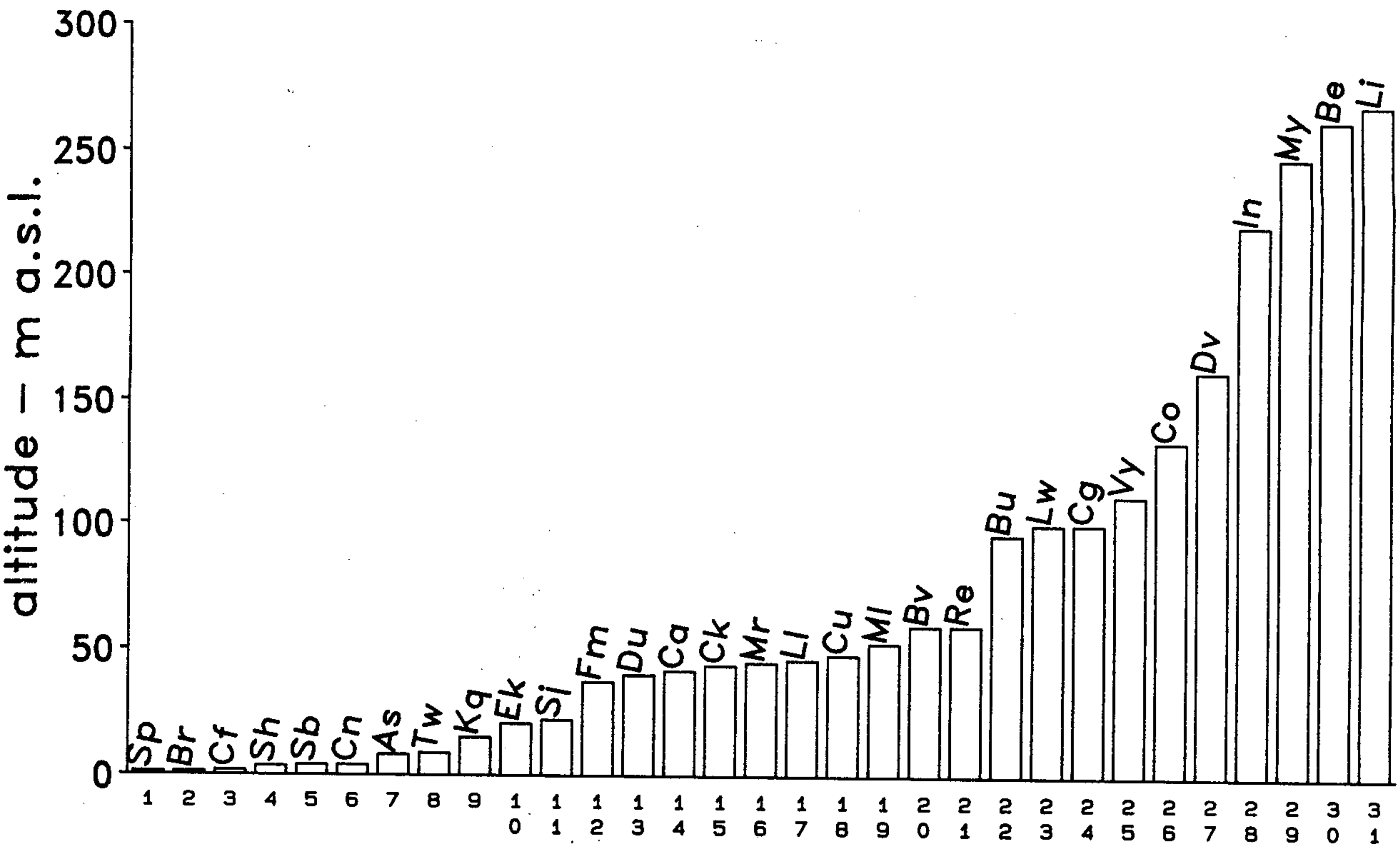


Figure 4.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

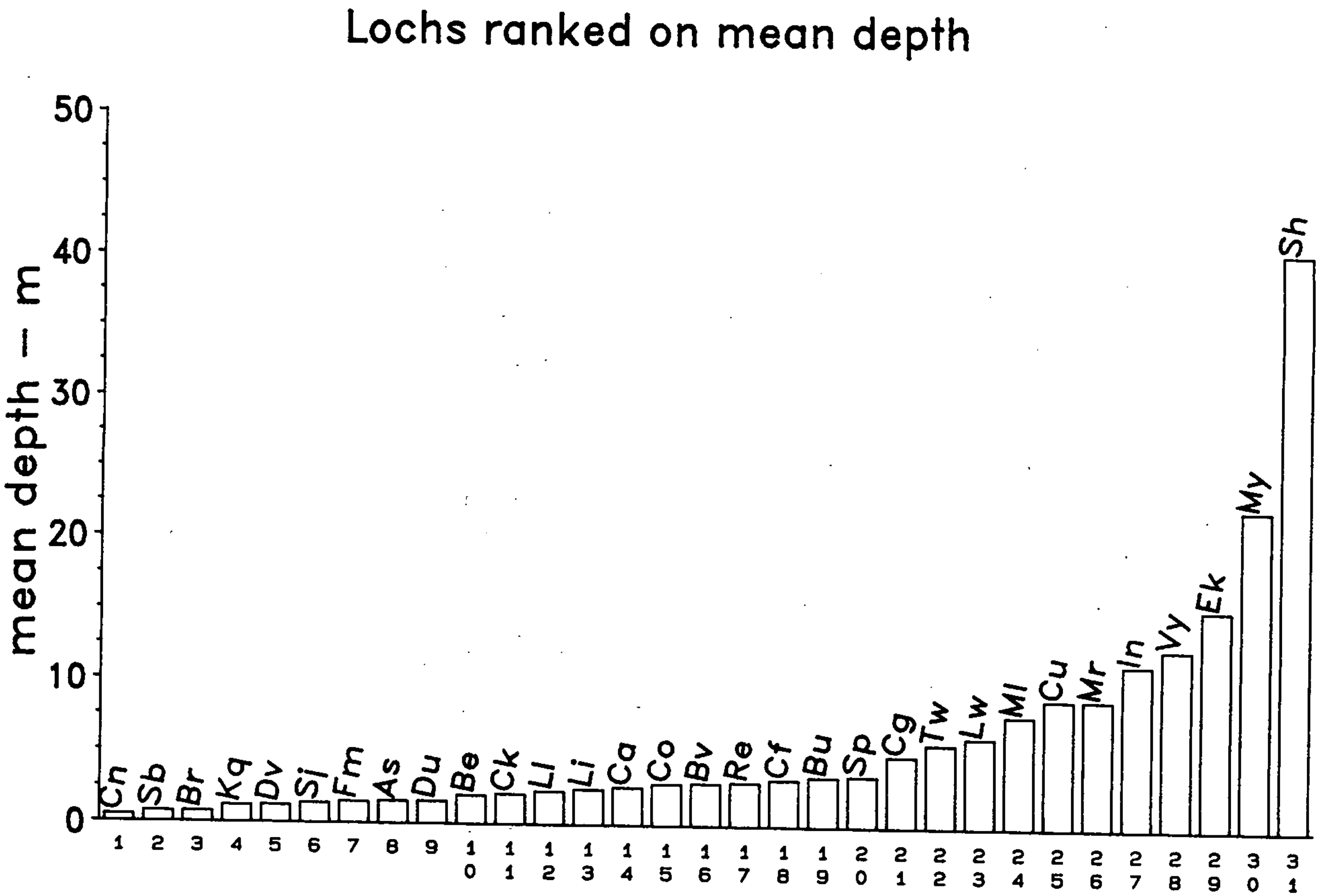

Lochs ranked on mean depth
mean depth – m
0
10
20
30
40
50
Cn
Sb
Br
Kq
Dv
Si
Fm
As
Du
Be
Ck
Ll
Li
Ca
Co
Bv
Re
Cf
Bu
Sp
Cg
Tw
Lw
Ml
Cu
Mr
In
Vy
Ek
My
Sh
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

Figure 5.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

Lochs ranked on maximum depth

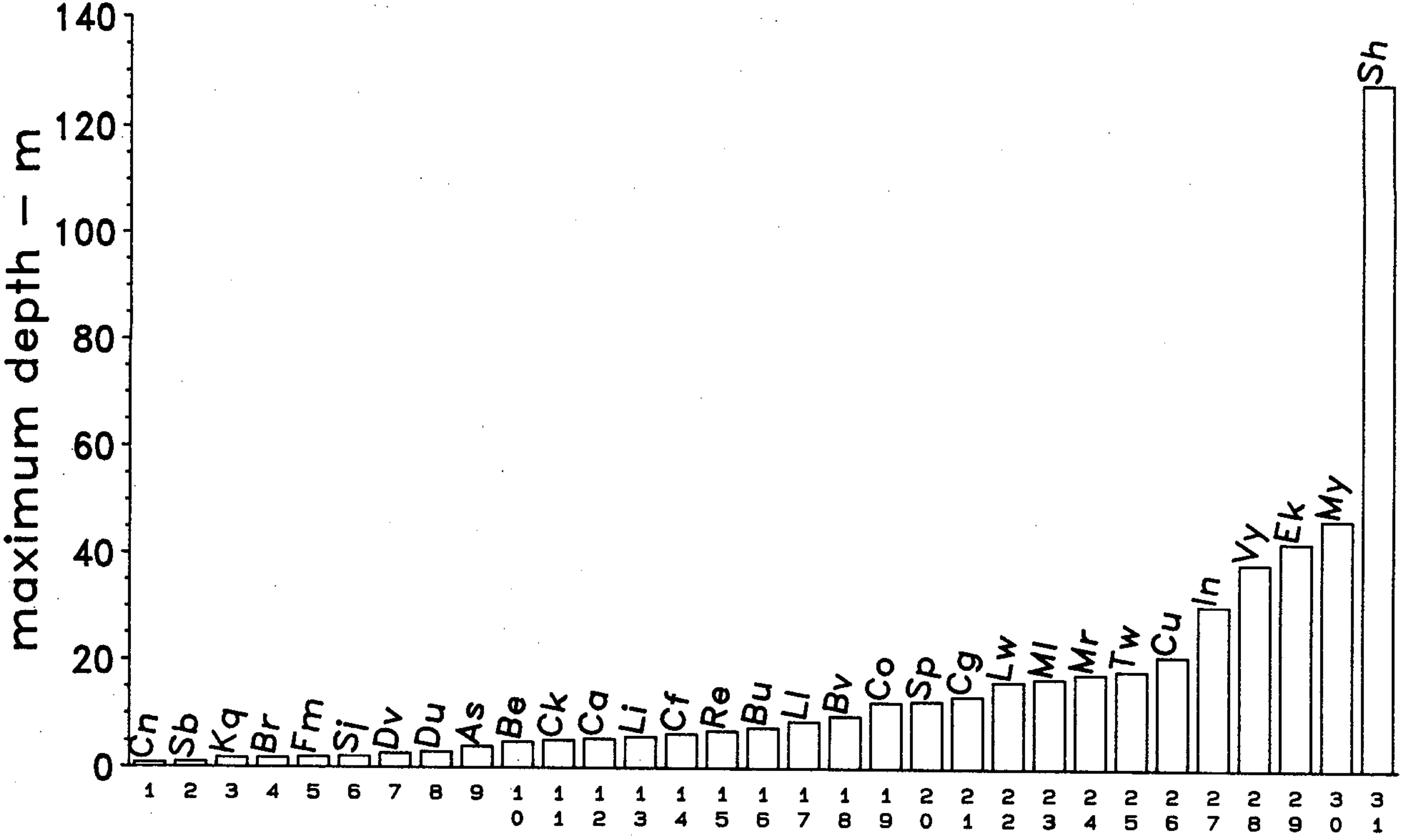


Figure 6.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

Lochs ranked on surface area (exc. Shiel @ 1960 ha)

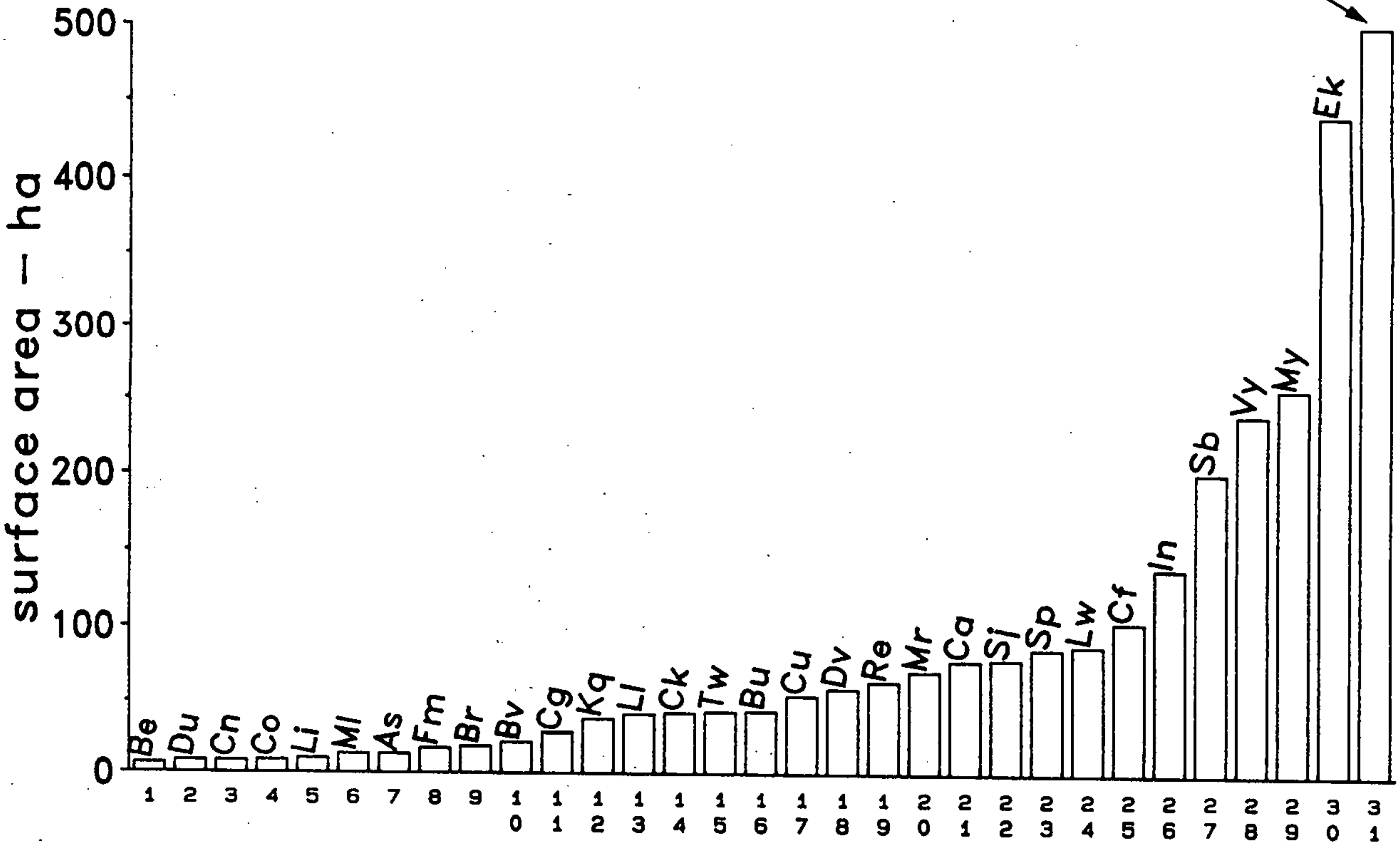
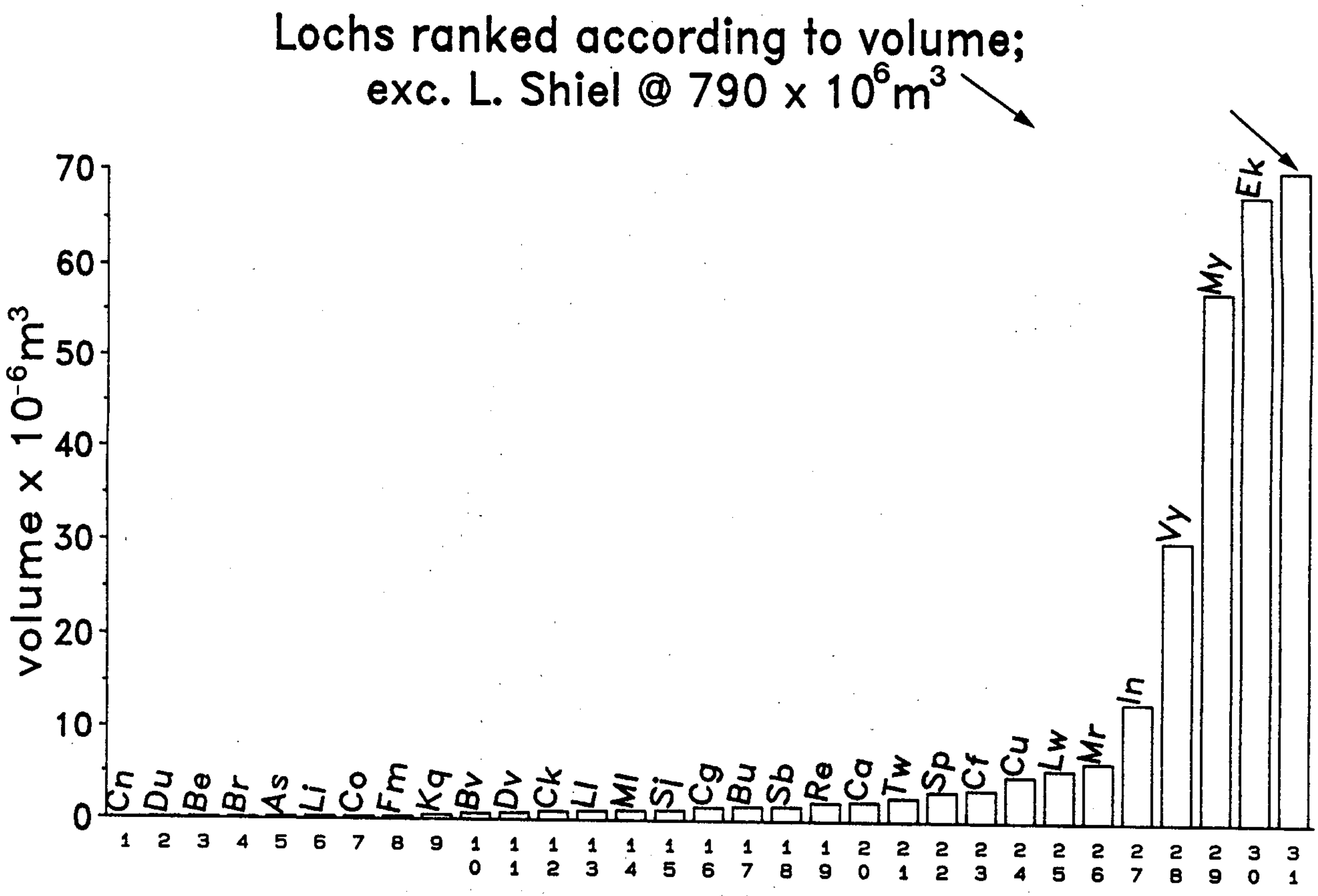


Figure 7.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled



Lochs ranked according to volume;
exc. L. Shiel @ 790 x 10^6 m^3
volume x 10^-6 m^3
0
10
20
30
40
50
60
70
Cn
Du
Be
Br
As
Li
Co
Fm
Kq
Bv
Dv
Ck
Ll
Ml
Sl
Cg
Bu
Sb
Re
Ca
Tw
Sp
Cf
Cu
Lw
Mr
In
Vy
My
Ek
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

Figure 8.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine-	Insh (east)	18 July *
Inw-	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled

Loch basins ranked according to open water pH measured in summer 1991

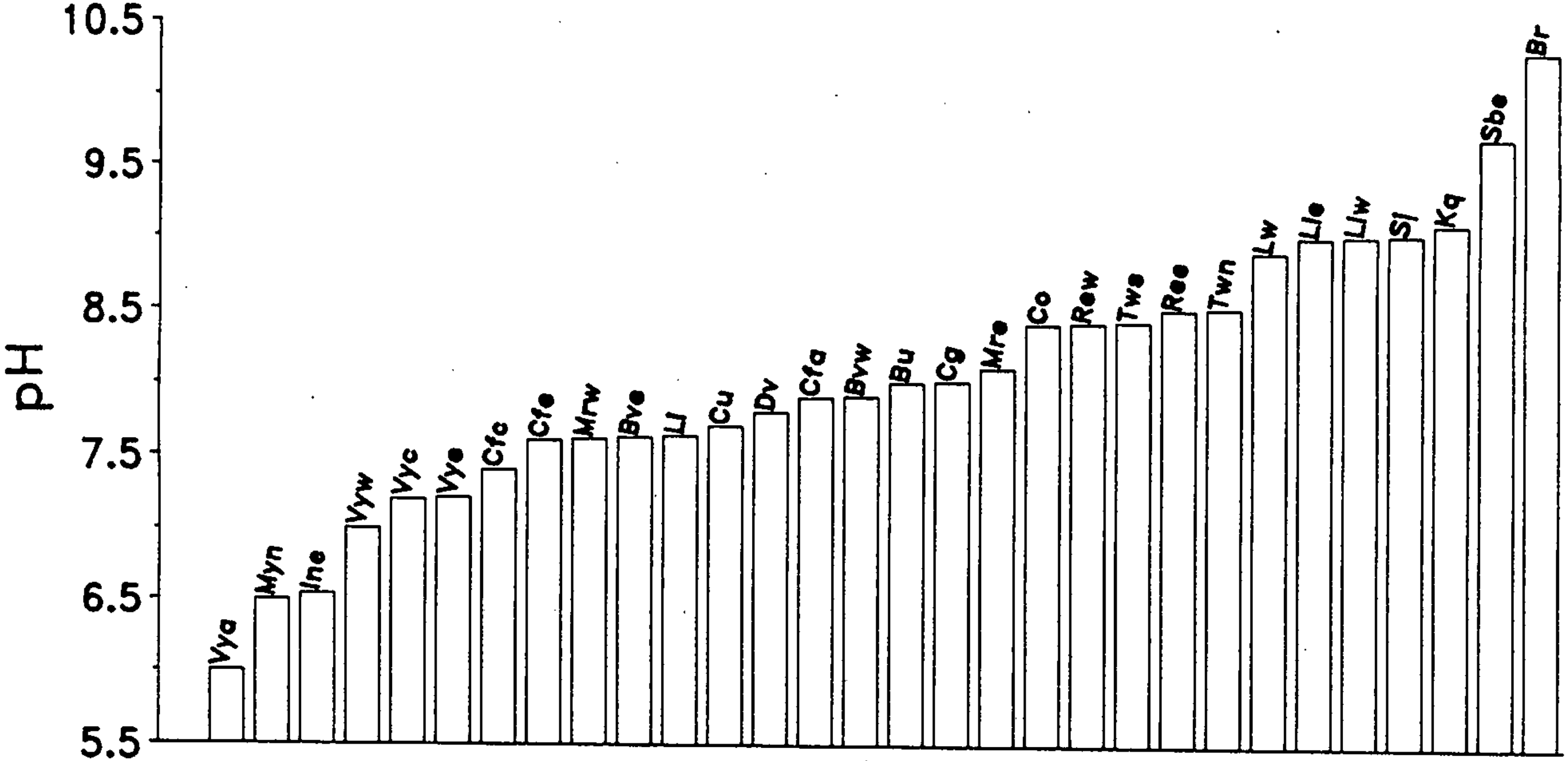


Figure 9.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine-	Insh (east)	18 July *
Inw-	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled

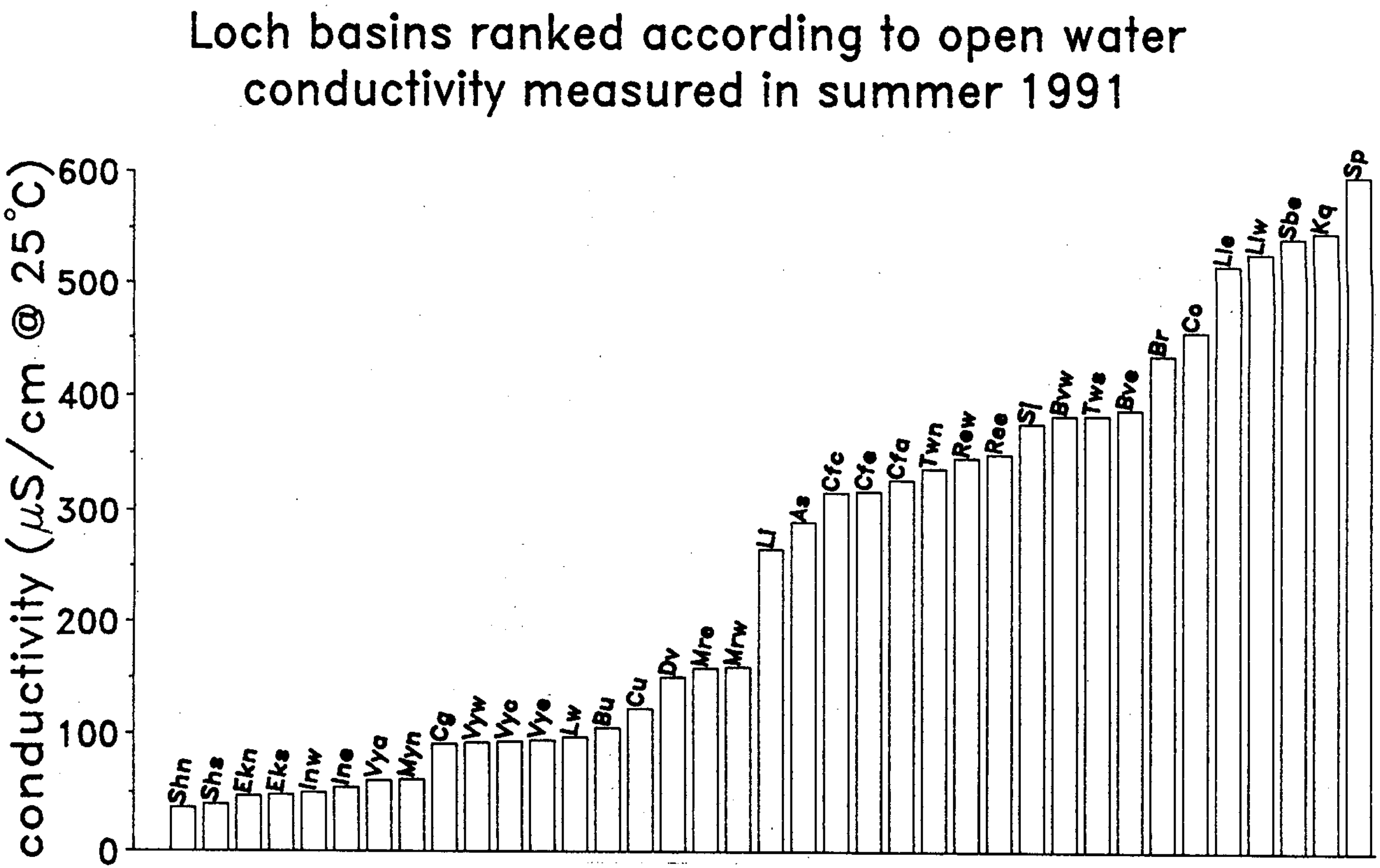

Loch basins ranked according to open water conductivity measured in summer 1991
conductivity (µS/cm @ 25°C)
0
100
200
300
400
500
600
Shn
Shs
Ekn
Eks
Inw
Ine
Vya
Myn
Ca
Vyw
Vyc
Vye
Lw
Bu
Cu
Dv
Mre
Mrw
Ll
As
Cfc
Cfe
Cfa
Twn
Rew
Ree
Sl
Bvw
Tws
Bve
Br
Co
Lle
Llw
Sbe
Kq
Sp

Figure 10.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

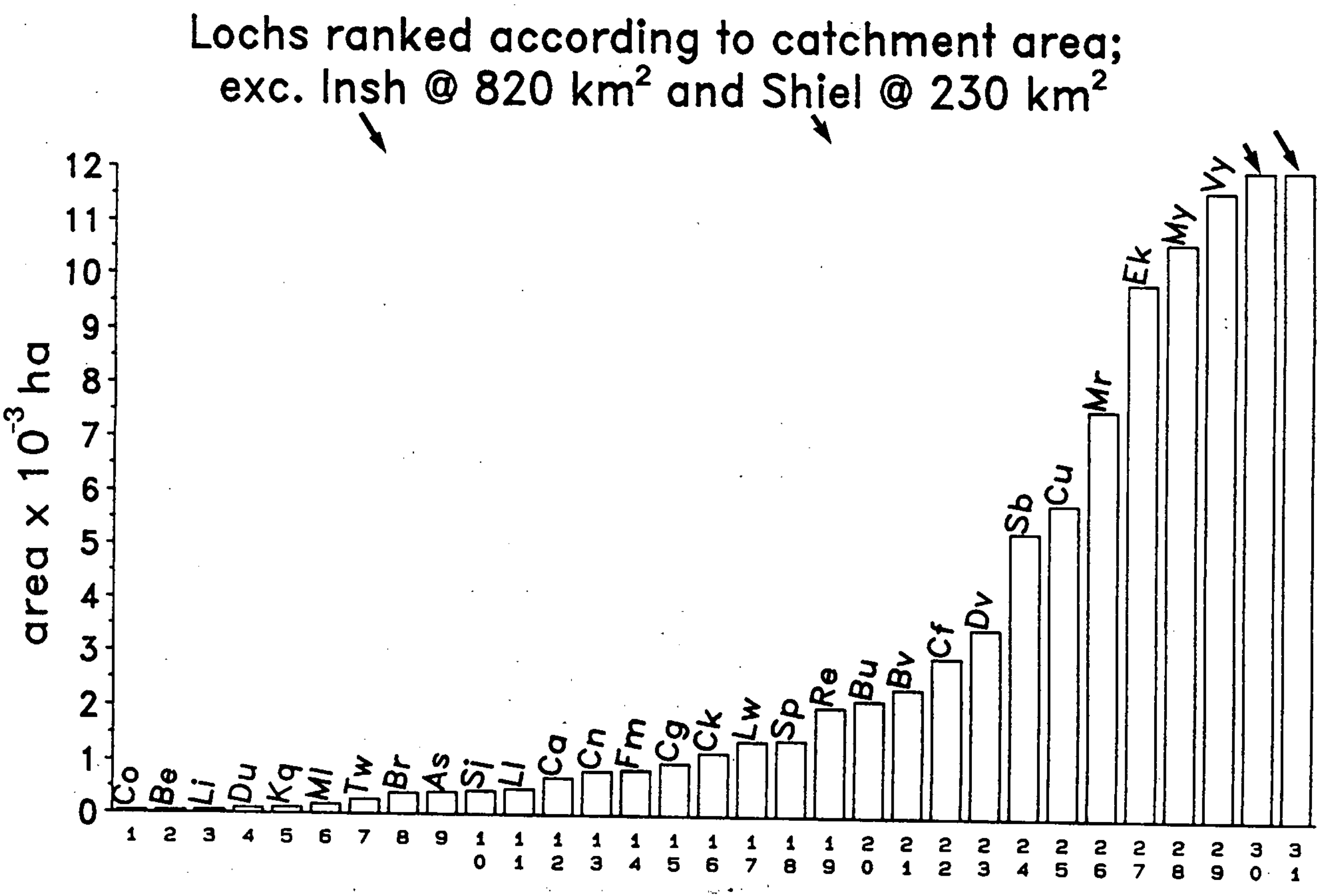

Lochs ranked according to catchment area;
exc. Insh @ 820 km2 and Shiel @ 230 km2
area x 10-3 ha
0
1
2
3
4
5
6
7
8
9
10
11
12
Co
Be
Li
Du
Kq
Ml
Tw
Br
As
Si
Ll
Ca
Cn
Fm
Cg
Ck
Lw
Sp
Re
Bu
Bv
Cf
Dv
Sb
Cu
Mr
Ek
My
Vy
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

Figure 11a.

Co - Coldingham	11 June *
Li - Lindean	13 June *
Be - Branxholme Easter	13 June *
Myn - St Mary's (north)	18 June *
Mys - St Mary's (south)	18 June
Kq - Kilconquhar	25 June *
Lle - Linlithgow (east)	26 June
Llw - Linlithgow (west)	26 June *
Bve - Balgavies (east)	2 July *
Bvw - Balgavies (west)	2 July
Ree - Rescobie (east)	2 July
Rew - Rescobie (west)	2 July *
Mre - Marlee (east)	3 July *
Mrw - Marlee (west)	3 July
Cu - Clunie	4 July *
Bu - Butterstone	5 July *
Lw - Lowes	6 July *
Cg - Craiglush	6 July *
Sbe - Strathbeg (east)	16 July
Sbw - Strathbeg (west)	16 July
Dv - Davan	17 July *
Ekn - Eck (north)	23 July *
Eks - Eck (south)	24 July *
Shn - Shiel (north)	24 July *
Shs - Shiel (south)	25 July *
Ml - Mill (open water dip only)	31 July
Sp - Spiggie	5 August *
Br - Brow	5 August *
As - Asta	6 August *
Twn - Tingwall (north)	6 August *
Tws - Tingwall (south)	6 August *
Sj - St John's	10 August *
Vye - Veyatie (east)	21 August *
Vyc - Veyatie (central)	21 August
Vyw - Veyatie (west)	21 August *
Vya - Veyatie (arm)	21 August *
Ine - Insh (east)	18 July *
Inw - Insh (west)	18 July *
Cfc - Cliff (centre)	7 August *
Cfa - Cliff (arm)	7 August *
Cfe - Cliff (c/e confluence)	7 August *
Du - Duddingston	not sampled
Ca - Castle	not sampled
Ck - Carlingwark	not sampled
Cn - Cran	not sampled
Fm - Flemington	not sampled

Lochs ranked on annual P load predicted purely from the altitude characteristics of the catchment

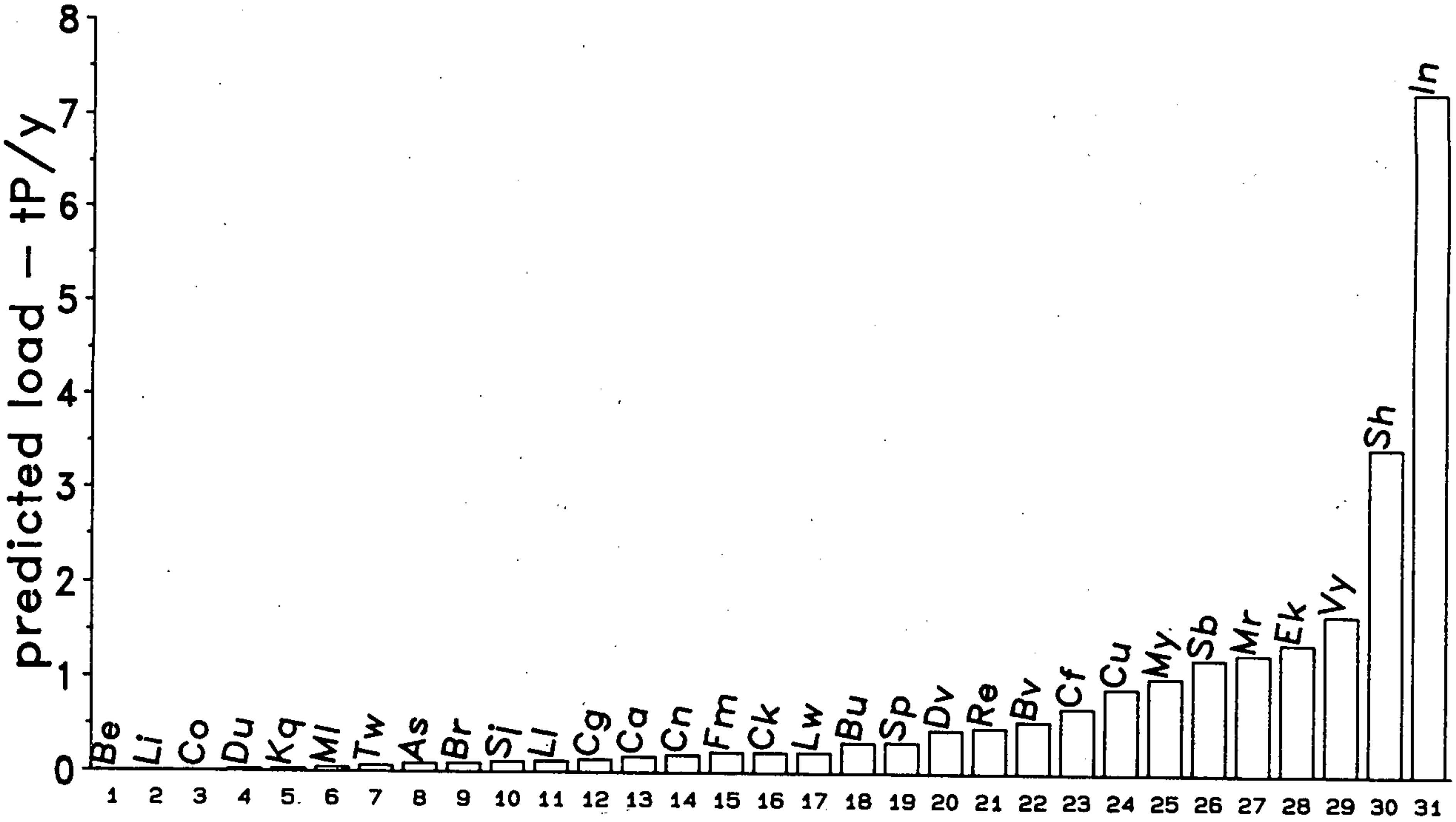


Figure 11b.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled

Lochs ranked on annual P load predicted from land use in the catchment i.e. exc. people etc.

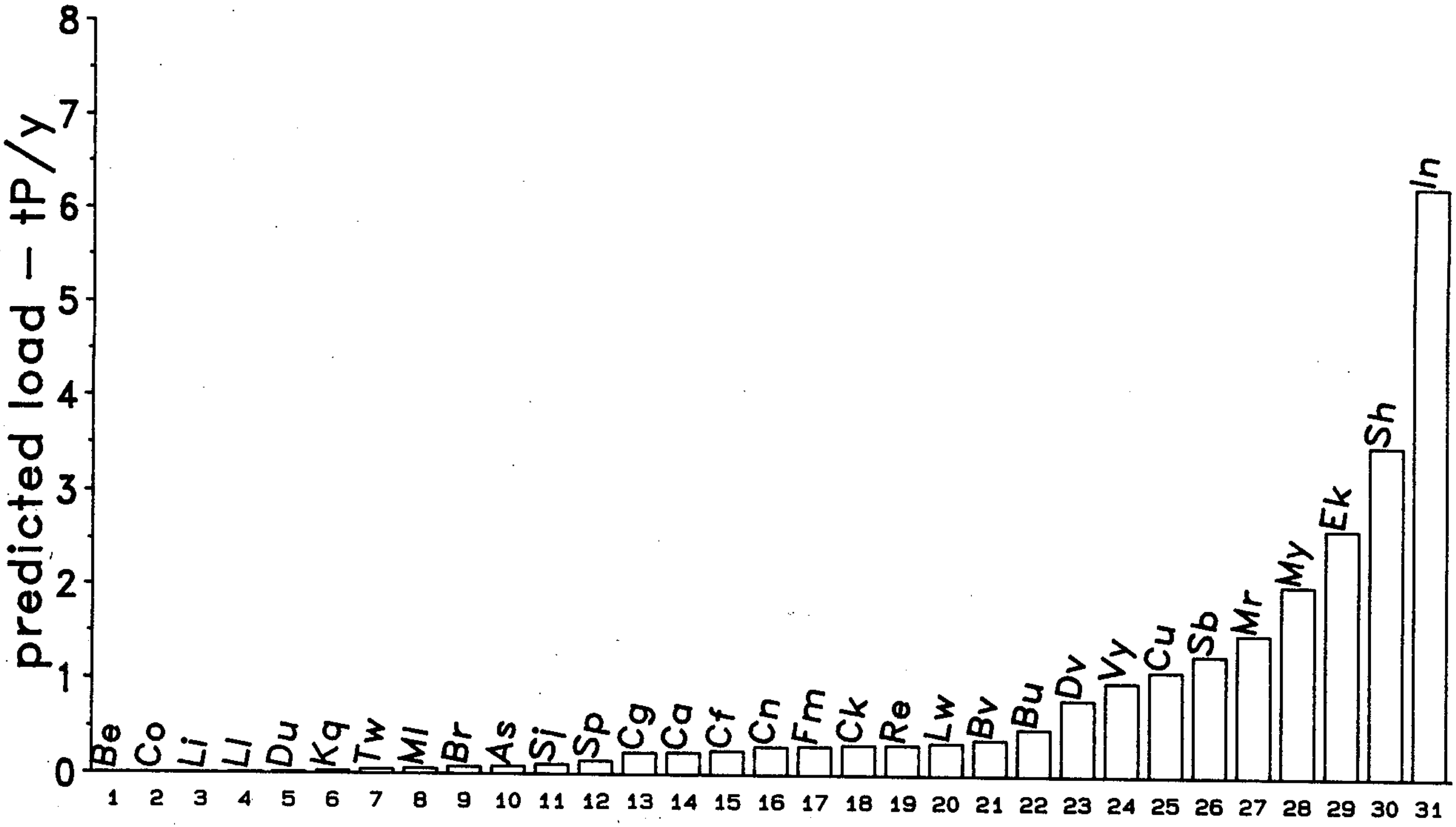


Figure 12a.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25. July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Lochs ranked on P load predicted from altitude plus the nos. of people, wildfowl and caged fish

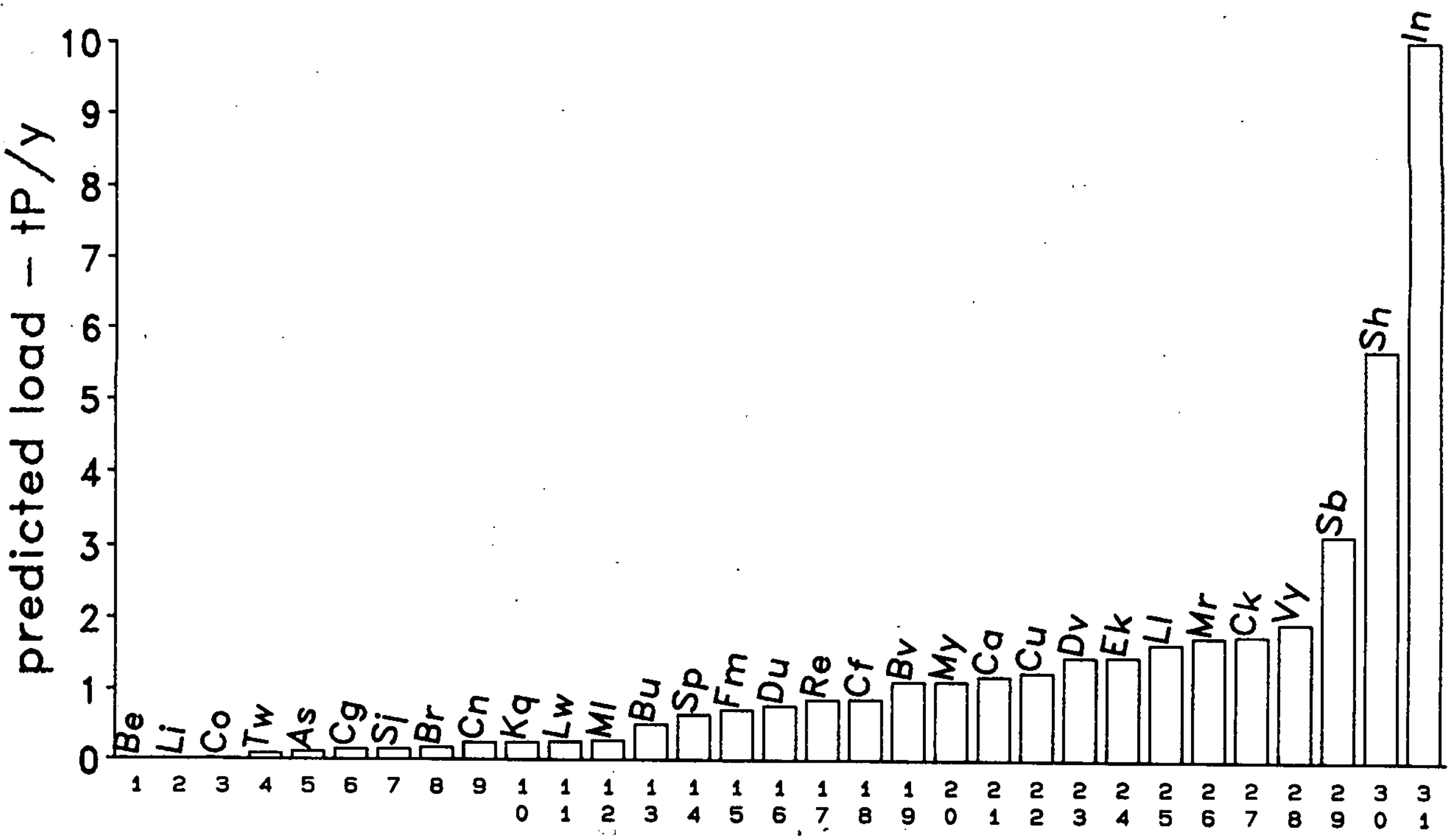


Figure 12b.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

Lochs ranked on P load predicted from land use plus the nos. of people, wildfowl and caged fish

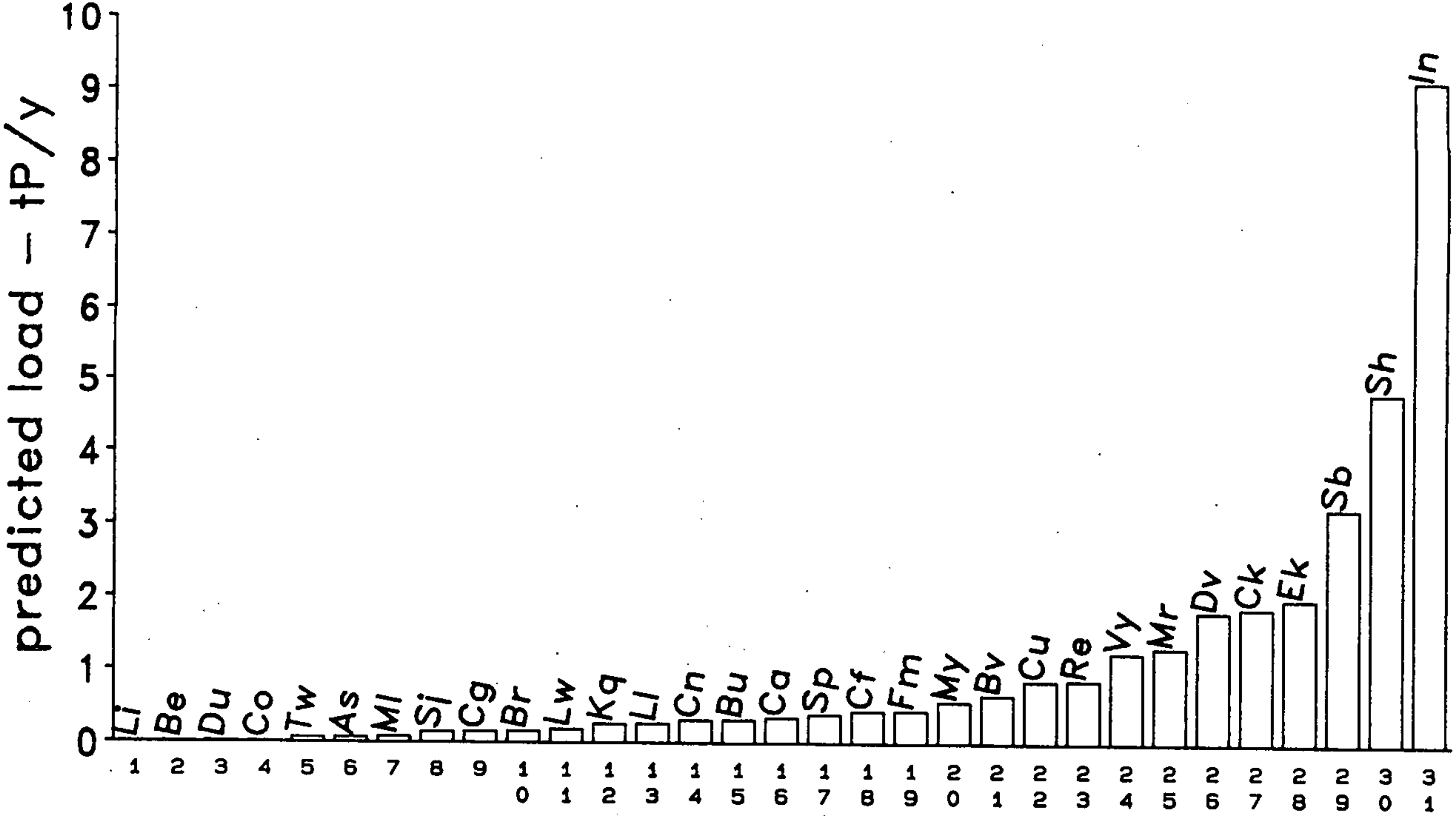


Figure 13a.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

P loads predicted from land use etc., related to loch area

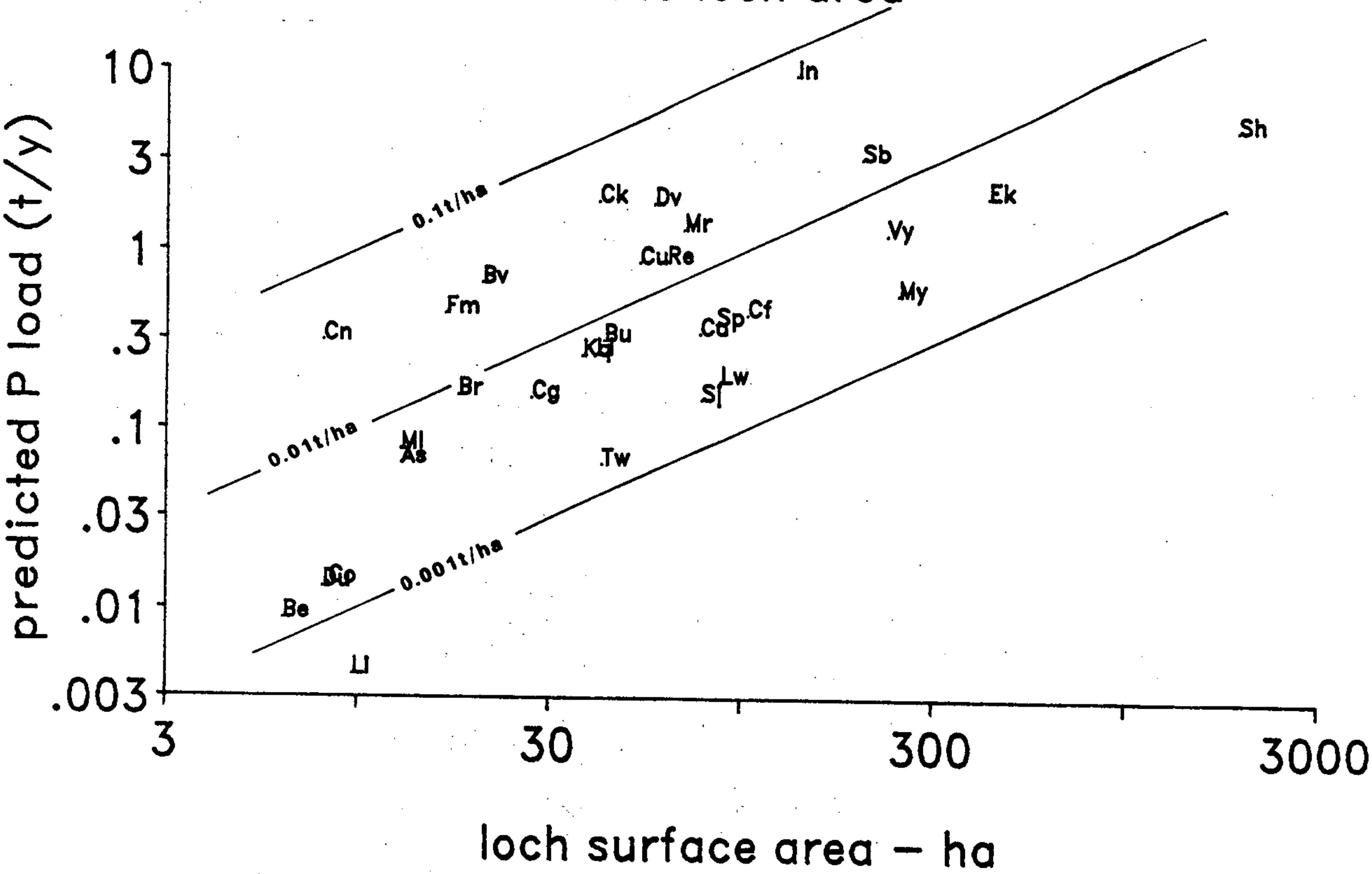


Figure 13b.

Co	- Coldingham	11 June *
Li	- Lindean	13 June *
Be	- Branxholme Easter	13 June *
Myn	- St Mary's (north)	18 June *
Mys	- St Mary's (south)	18 June
Kq	- Kilconquhar	25 June *
Lle	- Linlithgow (east)	26 June
Llw	- Linlithgow (west)	26 June *
Bve	- Balgavies (east)	2 July *
Bvw	- Balgavies (west)	2 July
Ree	- Rescobie (east)	2 July
Rew	- Rescobie (west)	2 July *
Mre	- Marlee (east)	3 July *
Mrw	- Marlee (west)	3 July
Cu	- Clunie	4 July *
Bu	- Butterstone	5 July *
Lw	- Lowes	6 July *
Cg	- Craiglush	6 July *
Sbe	- Strathbeg (east)	16 July
Sbw	- Strathbeg (west)	16 July
Dv	- Davan	17 July *
Ekn	- Eck (north)	23 July *
Eks	- Eck (south)	24 July *
Shn	- Shiel (north)	24 July *
Shs	- Shiel (south)	25 July *
Ml	- Mill (open water dip only)	31 July
Sp	- Spiggie	5 August *
Br	- Brow	5 August *
As	- Asta	6 August *
Twn	- Tingwall (north)	6 August *
Tws	- Tingwall (south)	6 August *
Sj	- St John's	10 August *
Vye	- Veyatie (east)	21 August *
Vyc	- Veyatie (central)	21 August
Vyw	- Veyatie (west)	21 August *
Vya	- Veyatie (arm)	21 August *
Ine	- Insh (east)	18 July *
Inw	- Insh (west)	18 July *
Cfc	- Cliff (centre)	7 August *
Cfa	- Cliff (arm)	7 August *
Cfe	- Cliff (c/e confluence)	7 August *
Du	- Duddingston	not sampled
Ca	- Castle	not sampled
Ck	- Carlingwark	not sampled
Cn	- Cran	not sampled
Fm	- Flemington	not sampled

P loads predicted from land use etc., related to loch mean depth

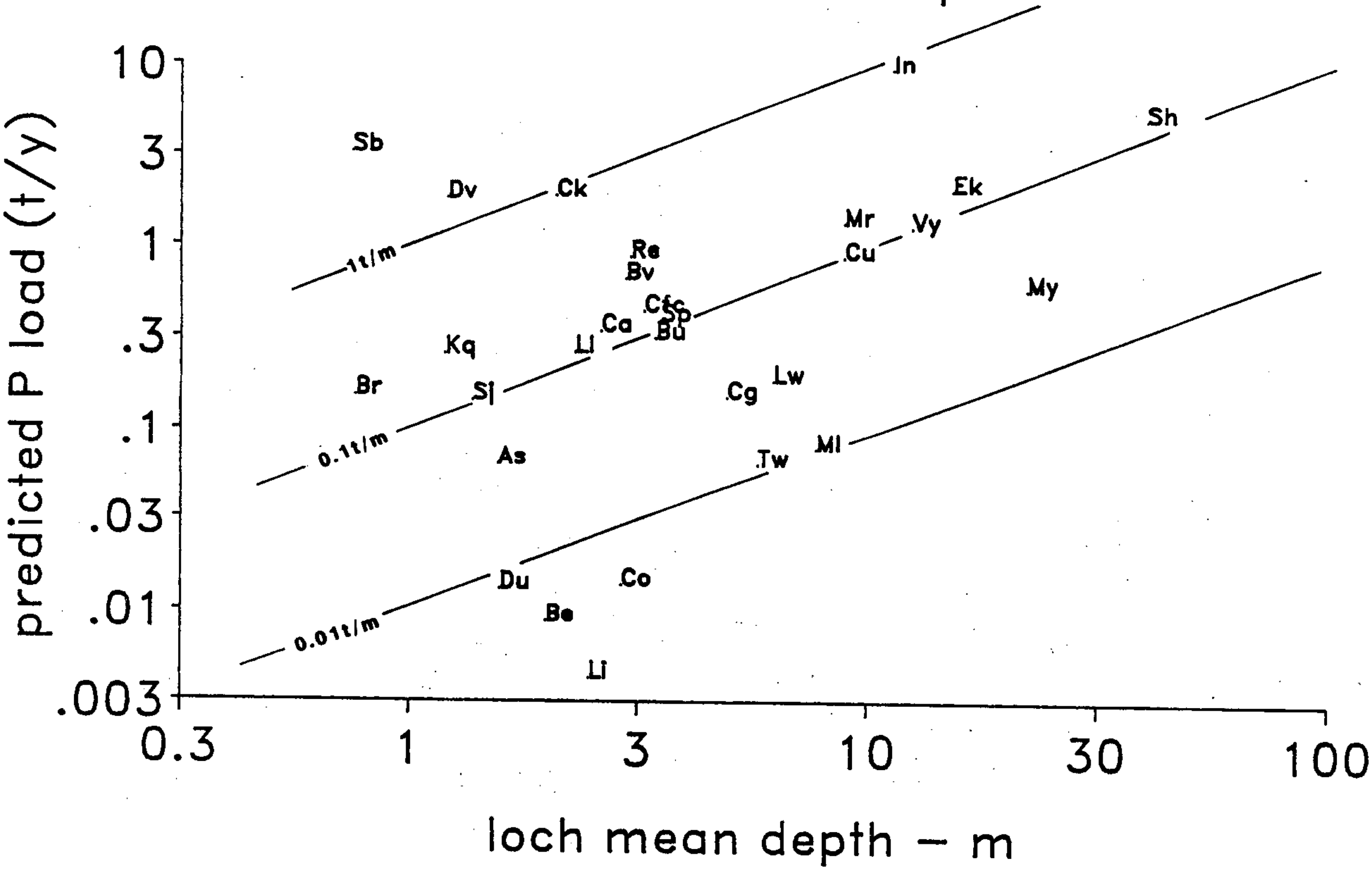


Figure 13c.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Astà	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

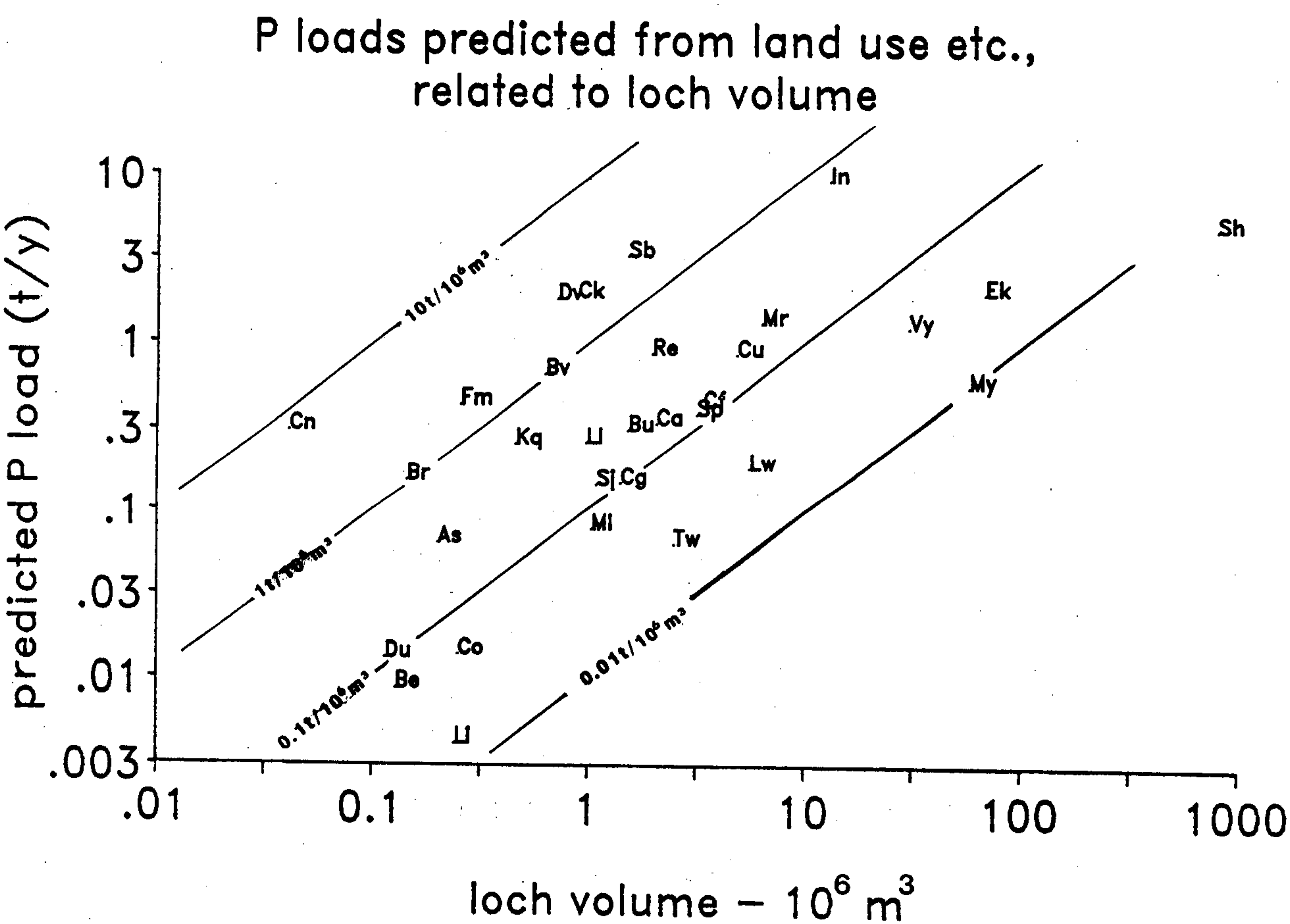

P loads predicted from land use etc.,
related to loch volume
predicted P load (t/y)
10
3
1
.3
.1
.03
.01
.003
.01
0.1
1
10
100
1000
loch volume – 10^6 m^3
10t/10^6 m^3
1t/10^6 m^3
0.1t/10^6 m^3
0.01t/10^6 m^3
In
Sh
Sb
DvCk
Ek
Mr
Vy
Re
Cu
Bv
My
Fm
Cn
Bu
Ca
Sp
Kq
Ll
Br
Lw
Sl
Cg
Ml
As
Tw
Du
Co
Be
Ll

Figure 14.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

specific areal P loads predicted from land use etc., related to loch mean depth

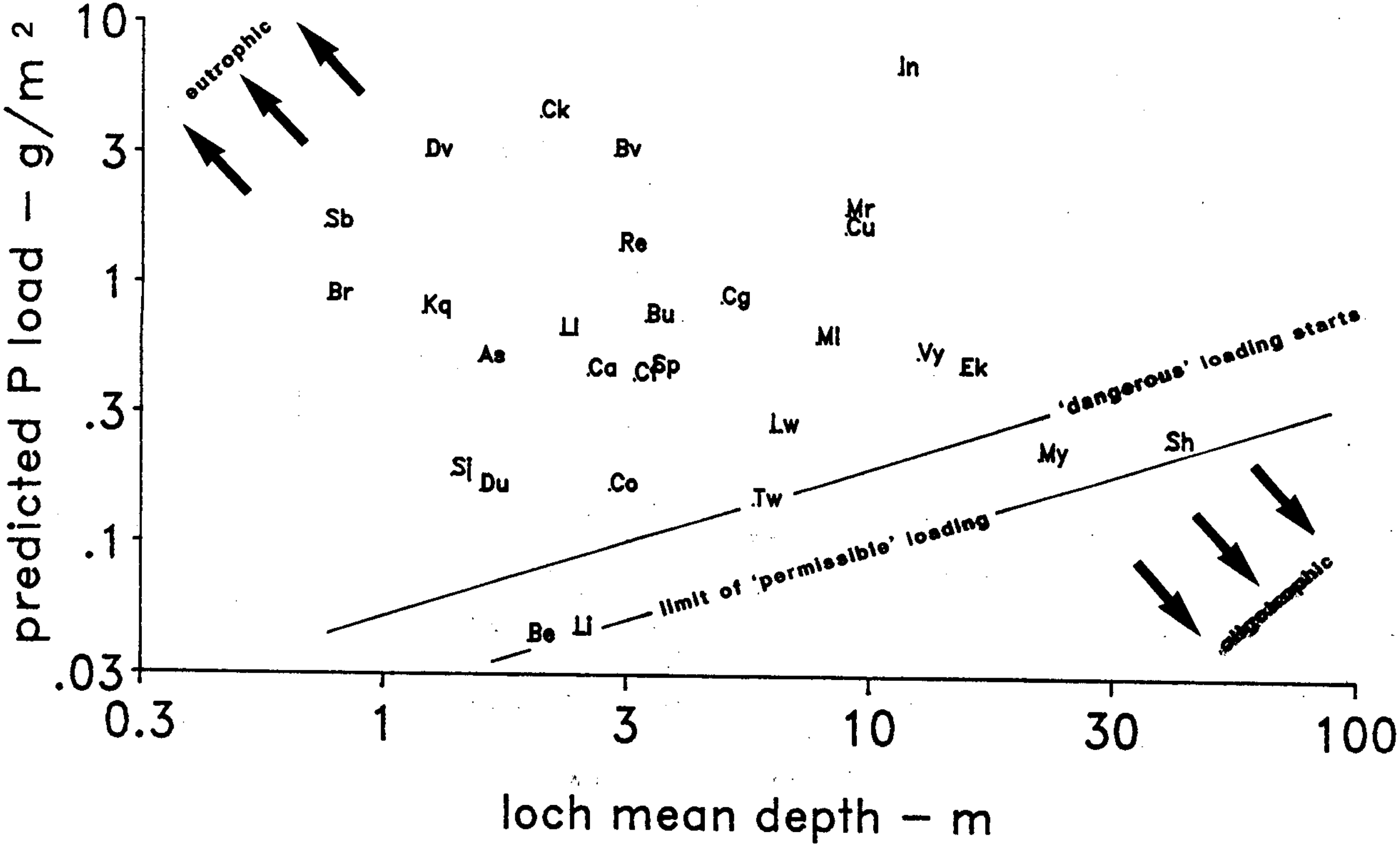


Figure 15a.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

Surface area related to the mean depth of 29 Scottish lochs

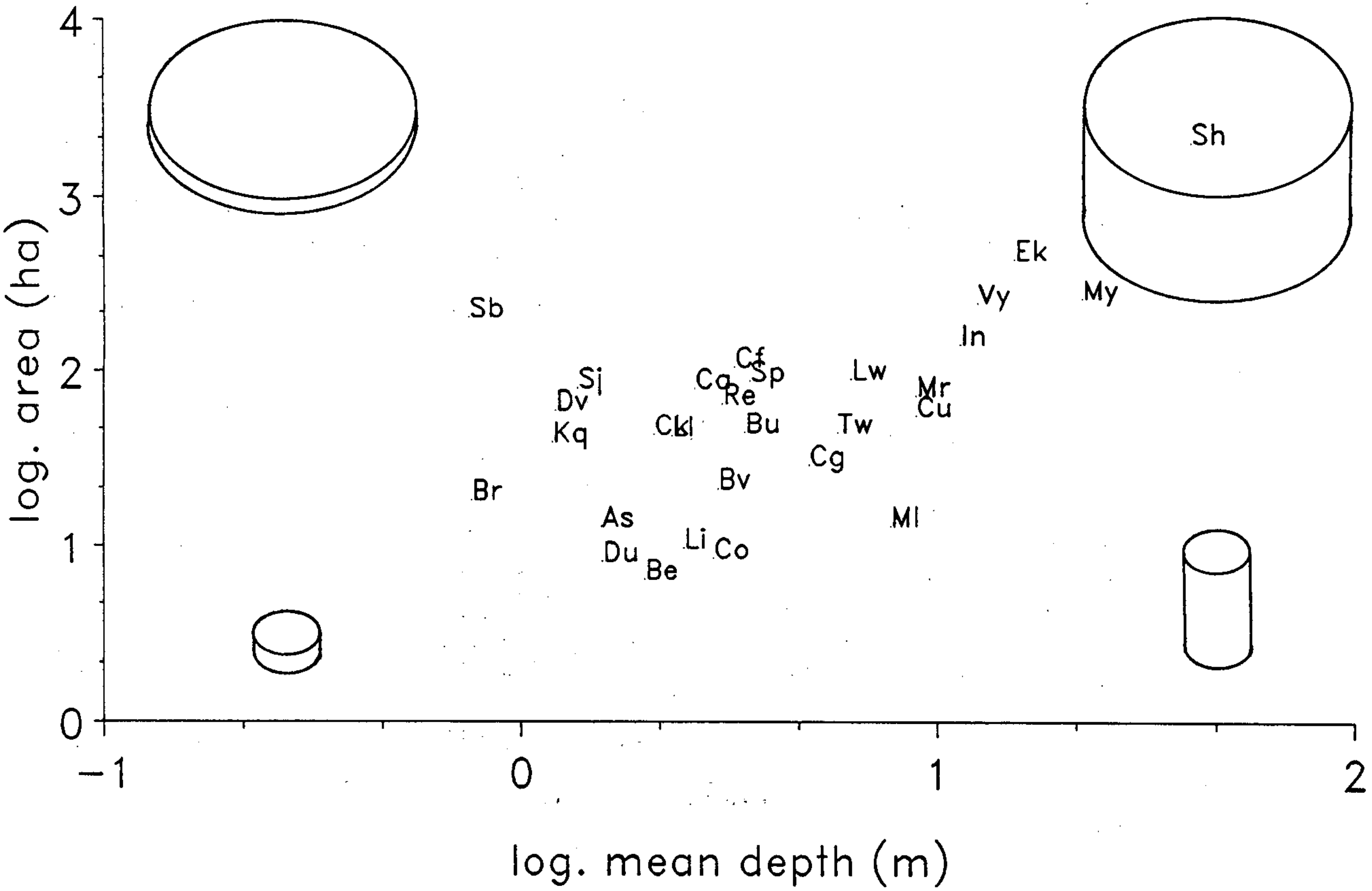
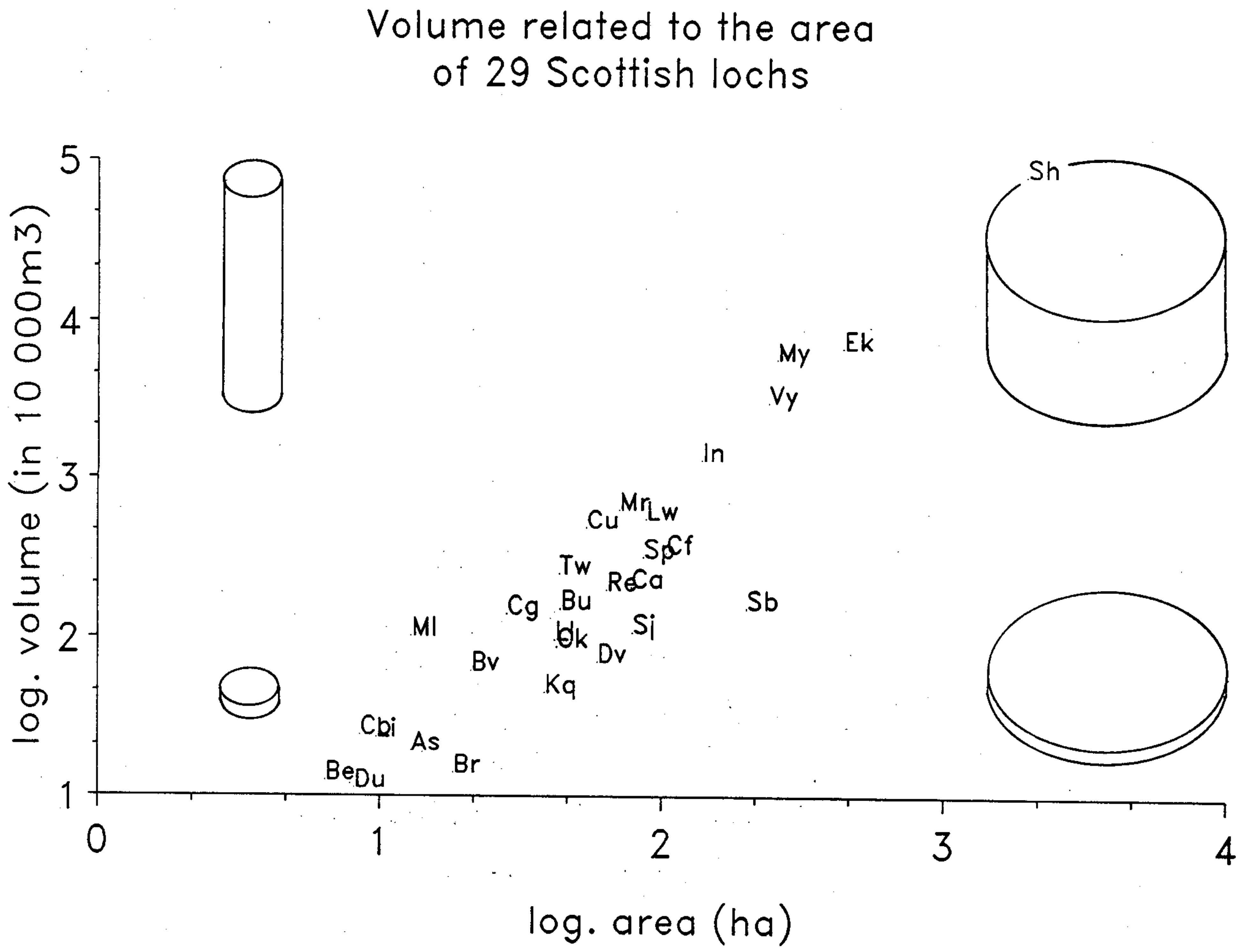


Figure 15b.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	



Volume related to the area
of 29 Scottish lochs
log. volume (in 10 000m3)
log. area (ha)
0
1
2
3
4
5
Sh
Ek
My
Vy
In
Mr
Lw
Cu
Sp
Cf
Tw
Re
Ca
Sb
Cg
Bu
Si
Ml
Ok
Dv
Bv
Kq
Cbi
As
Br
Be
Du

Figure 15c.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Volume related to the mean depth of 29 Scottish lochs

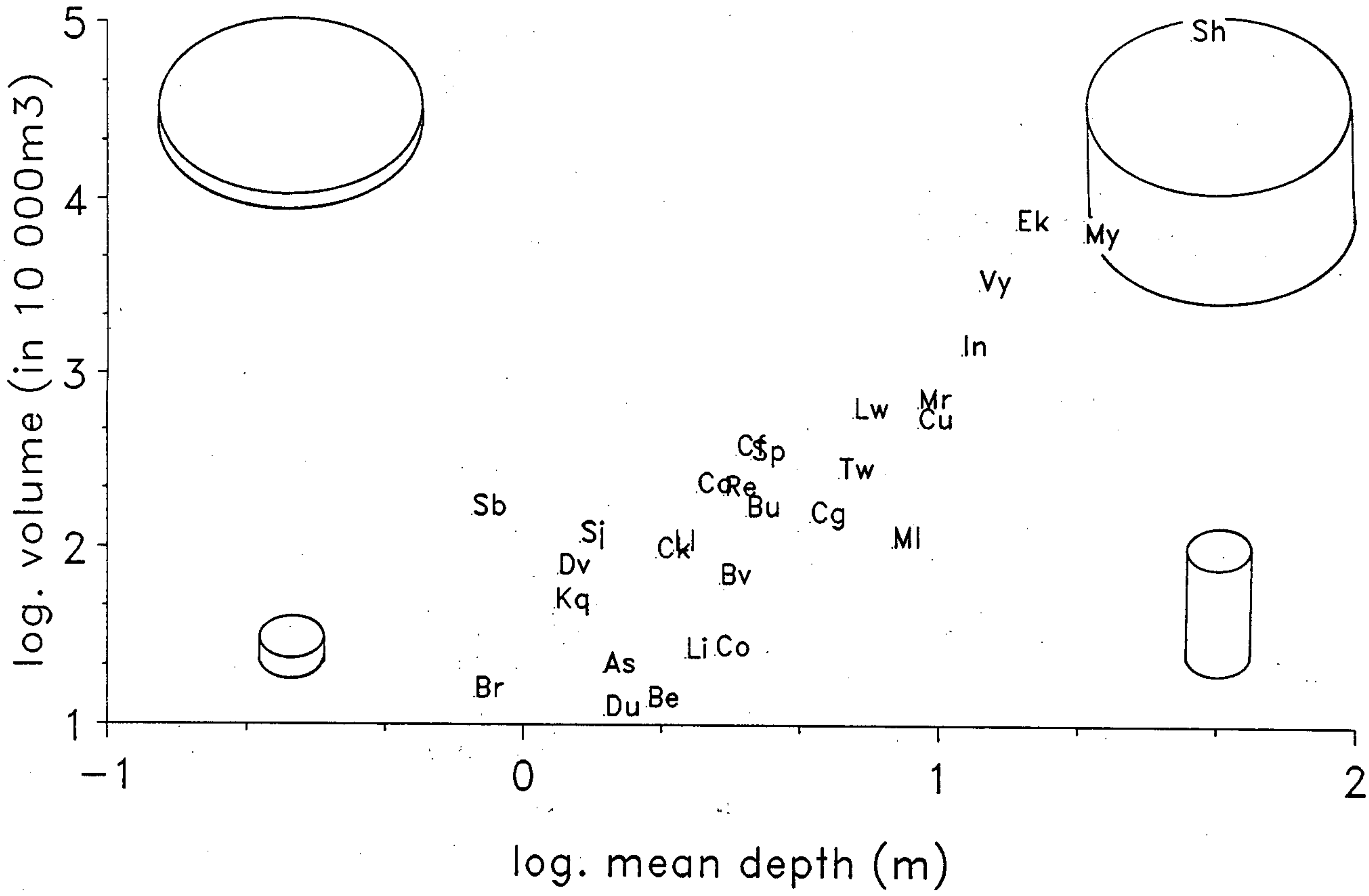


Figure 16.

Co - Coldingham	11 June *
Li - Lindean	13 June *
Be - Branxholme Easter	13 June *
Myn - St Mary's (north)	18 June *
Mys - St Mary's (south)	18 June
Kq - Kilconquhar	25 June *
Lle - Linlithgow (east)	26 June
Llw - Linlithgow (west)	26 June *
Bve - Balgavies (east)	2 July *
Bvw - Balgavies (west)	2 July
Ree - Rescobie (east)	2 July
Rew - Rescobie (west)	2 July *
Mre - Marlee (east)	3 July *
Mrw - Marlee (west)	3 July
Cu - Clunie	4 July *
Bu - Butterstone	5 July *
Lw - Lowes	6 July *
Cg - Craiglush	6 July *
Sbe - Strathbeg (east)	16 July
Sbw - Strathbeg (west)	16 July
Dv - Davan	17 July *
Ekn - Eck (north)	23 July *
Eks - Eck (south)	24 July *
Shn - Shiel (north)	24 July *
Shs - Shiel (south)	25 July *
Ml - Mill (open water dip only)	31 July
Sp - Spiggie	5 August *
Br - Brow	5 August *
As - Asta	6 August *
Twn - Tingwall (north)	6 August *
Tws - Tingwall (south)	6 August *
Sj - St John's	10 August *
Vye - Veyatie (east)	21 August *
Vyc - Veyatie (central)	21 August
Vyw - Veyatie (west)	21 August *
Vya - Veyatie (arm)	21 August *
Ine - Insh (east)	18 July *
Inw - Insh (west)	18 July *
Cfc - Cliff (centre)	7 August *
Cfa - Cliff (arm)	7 August *
Cfe - Cliff (c/e confluence)	7 August *
Du - Duddingston not sampled	
Ca - Castle not sampled	
Ck - Carlingwark not sampled	
Cn - Cran not sampled	
Fm - Flemington not sampled	

Lochs ranked on P concentration predicted from land use etc.
but not ρ−corrected; Cran @ 8 mg/l excluded

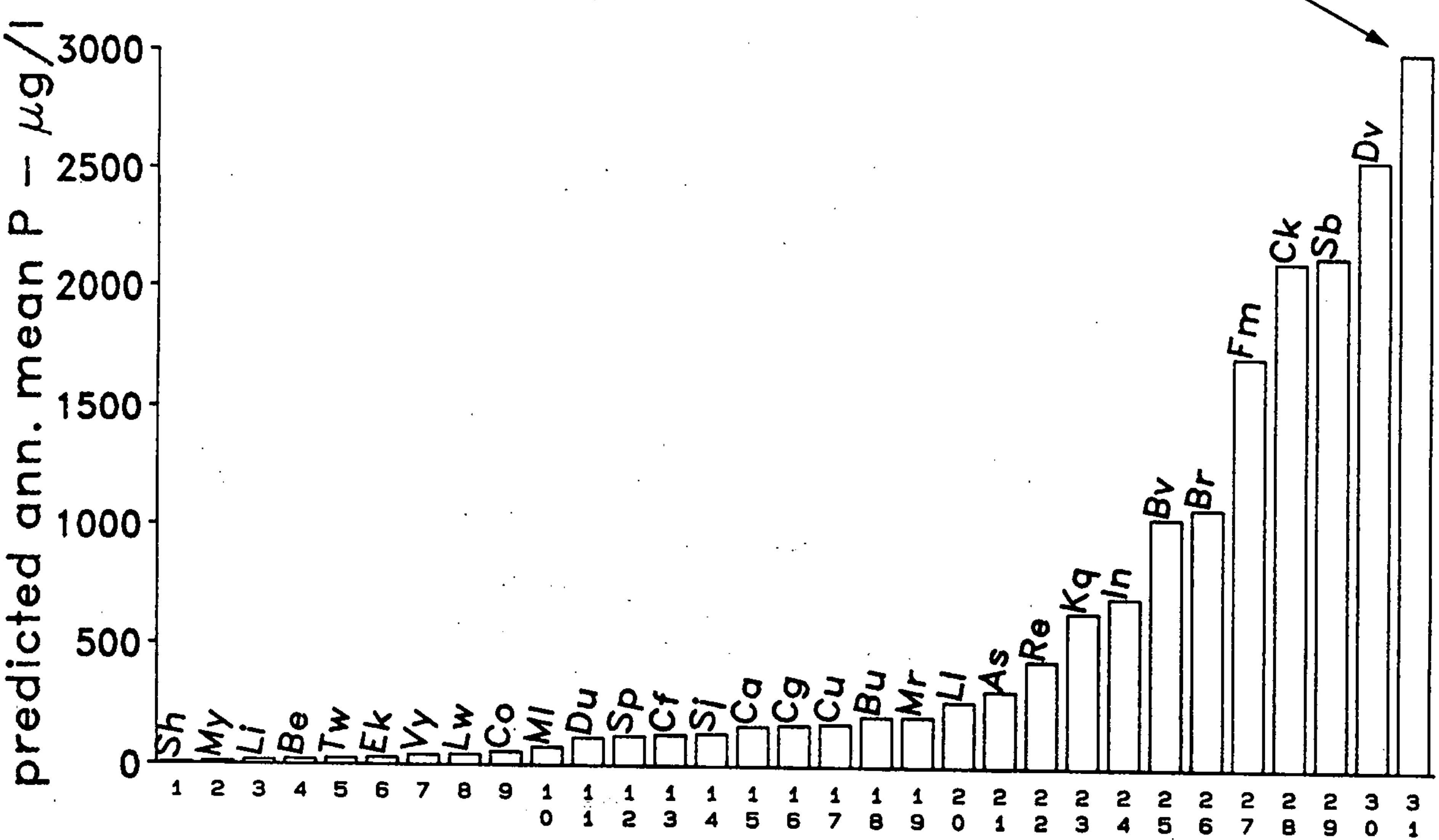


Figure 17.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

P loads predicted from land use etc., related to loch flushing rate

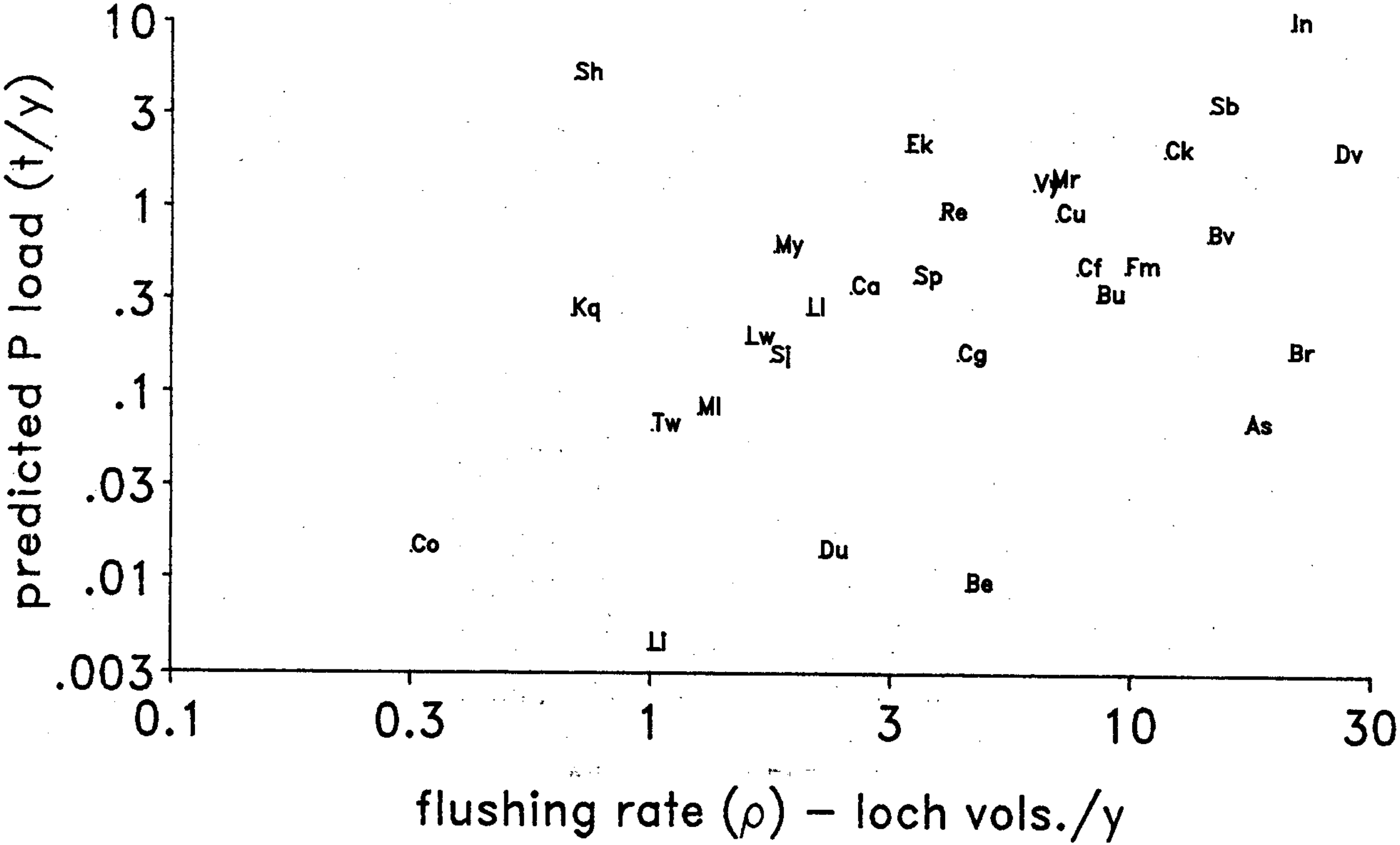


Figure 18a.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Lochs ranked on the annual mean, loch–wide, ρ–corrected, P concentration predicted from land use etc.

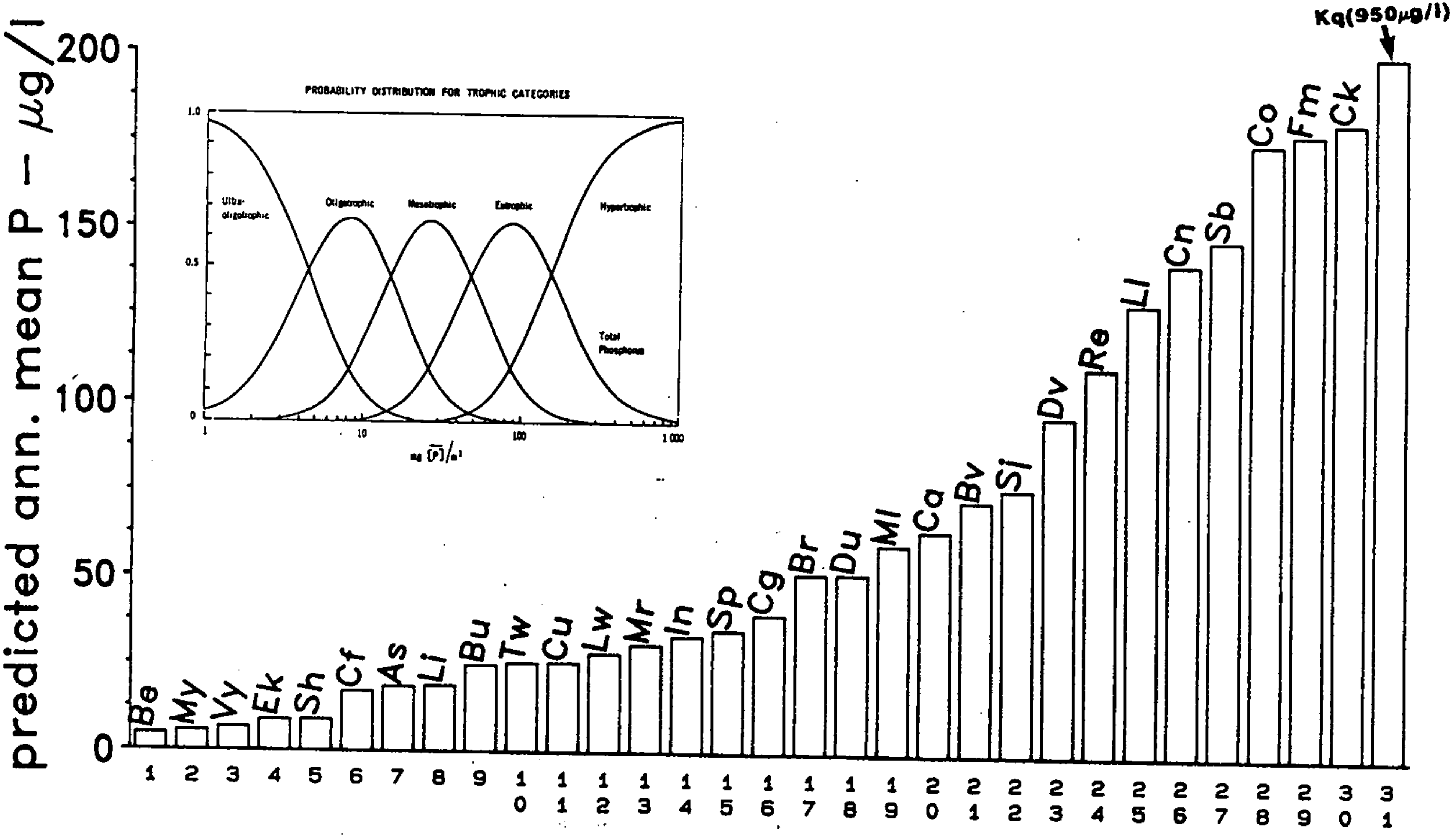


Figure 18b.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

specific areal load predicted from land use etc., related to the product of mean depth and flushing rate

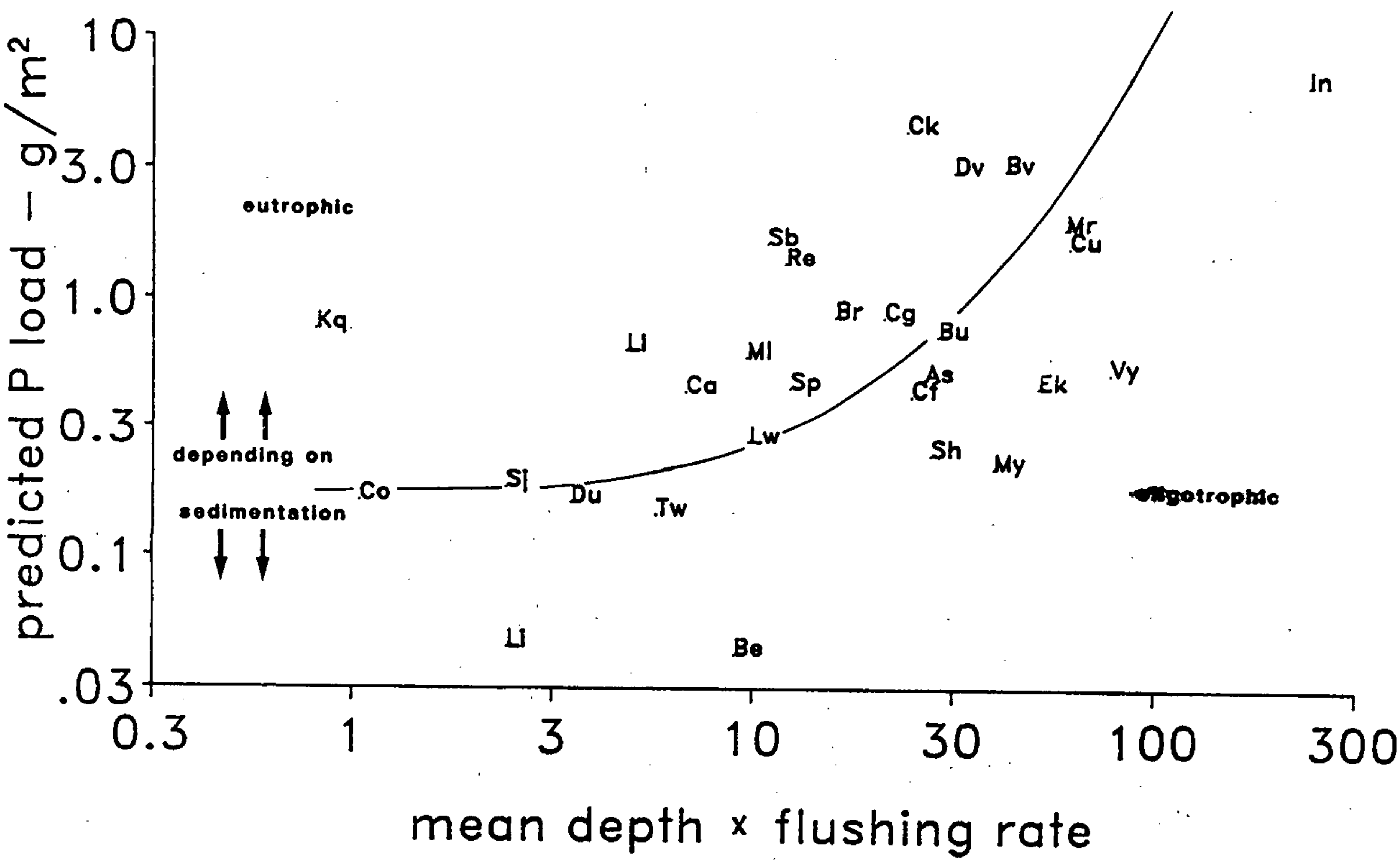


Figure 19.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

Loch volume related to the flushing volume of 29 Scottish lochs

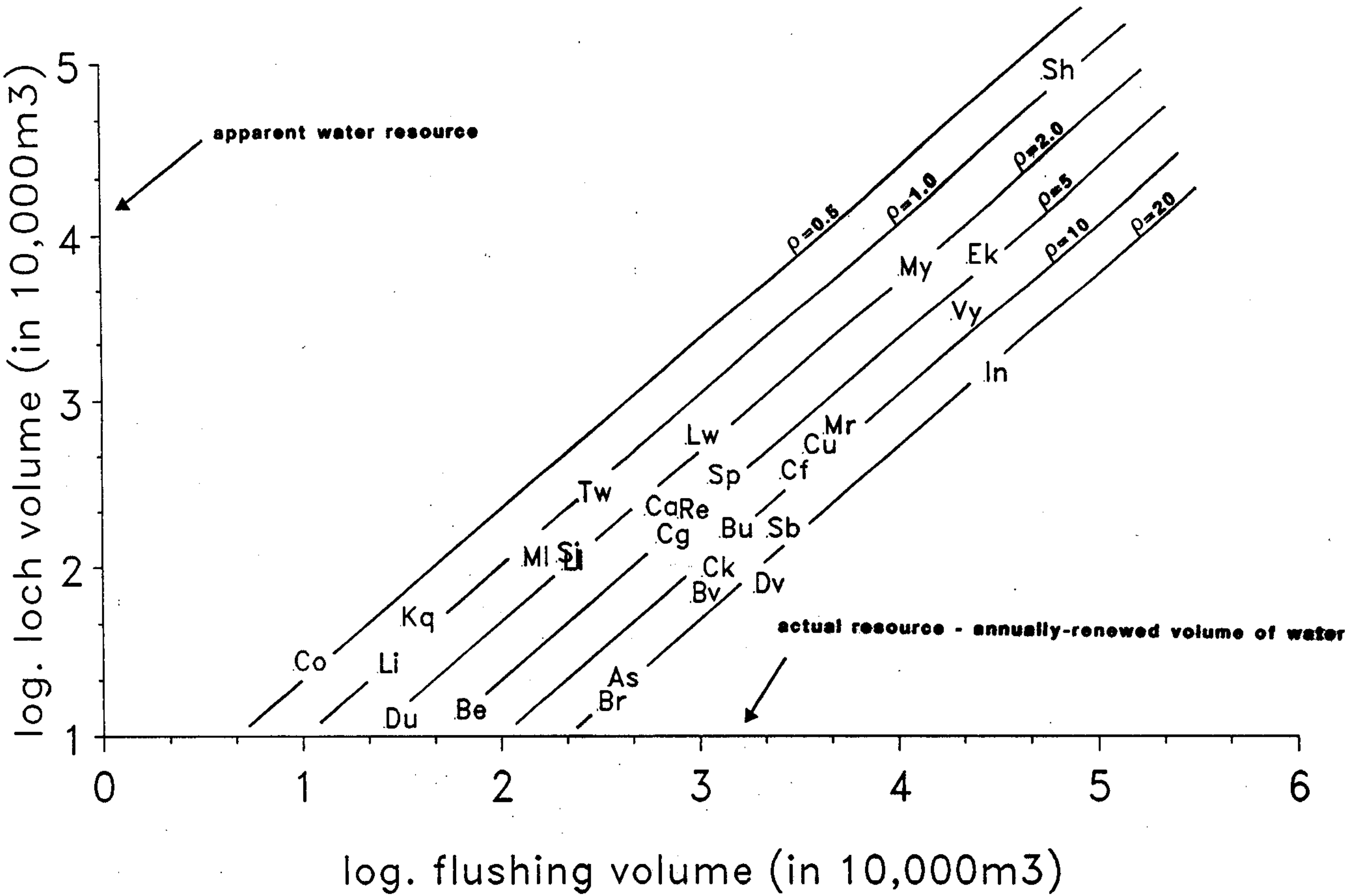


Figure 20a.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Flushing rate related to the mean depth of 29 Scottish lochs

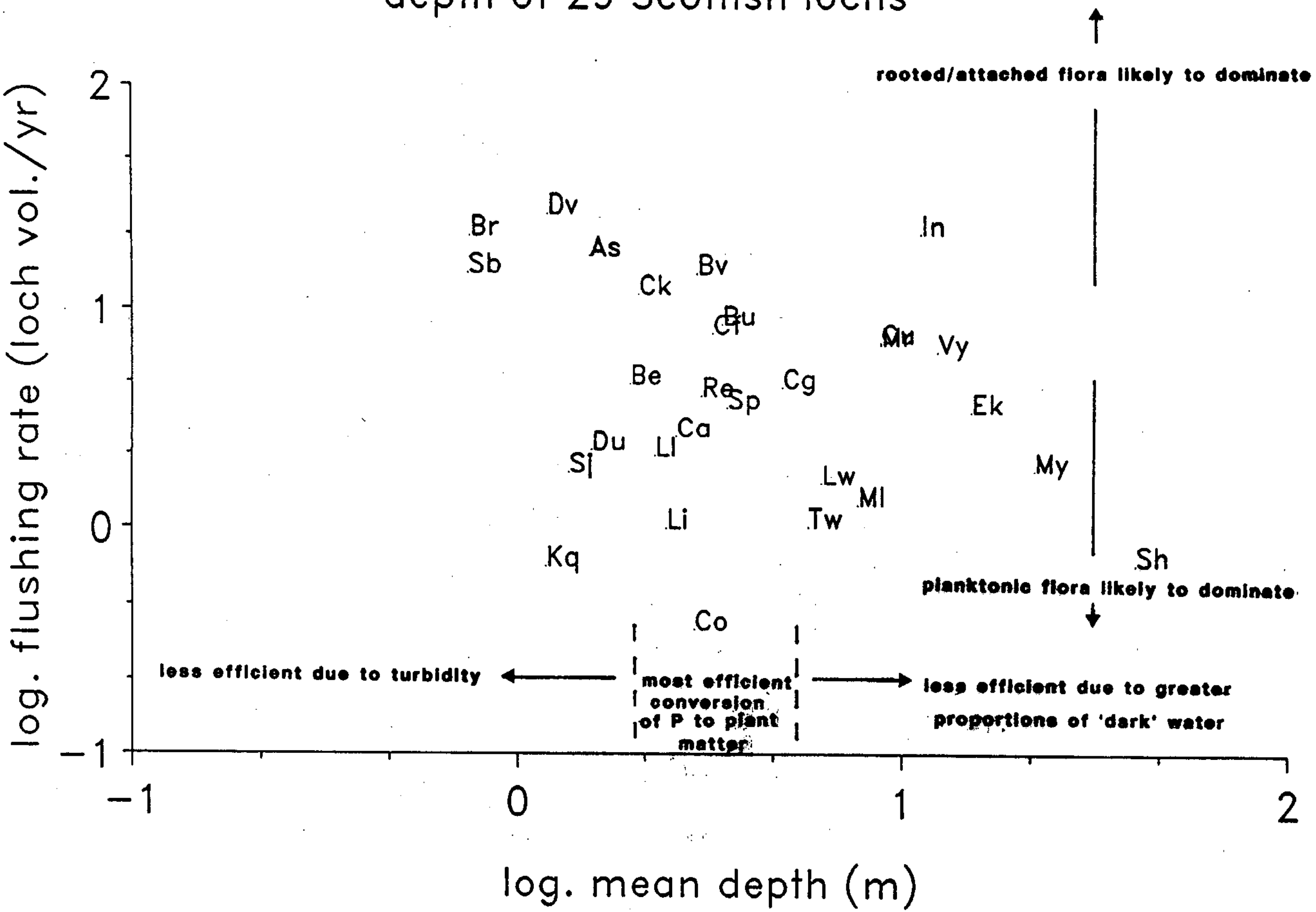


Figure 20b.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Flushing rate related to the volume of 29 Scottish lochs

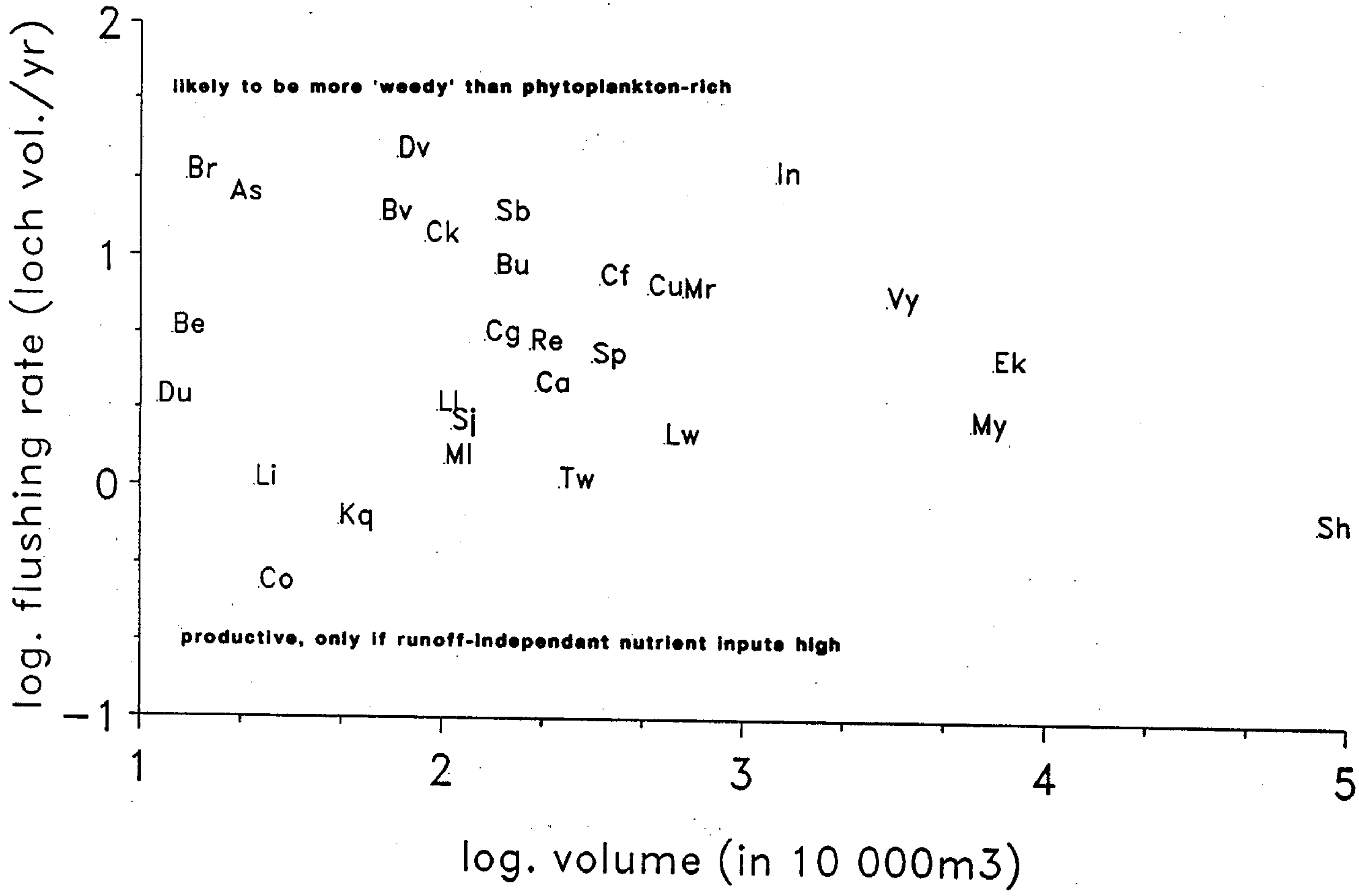
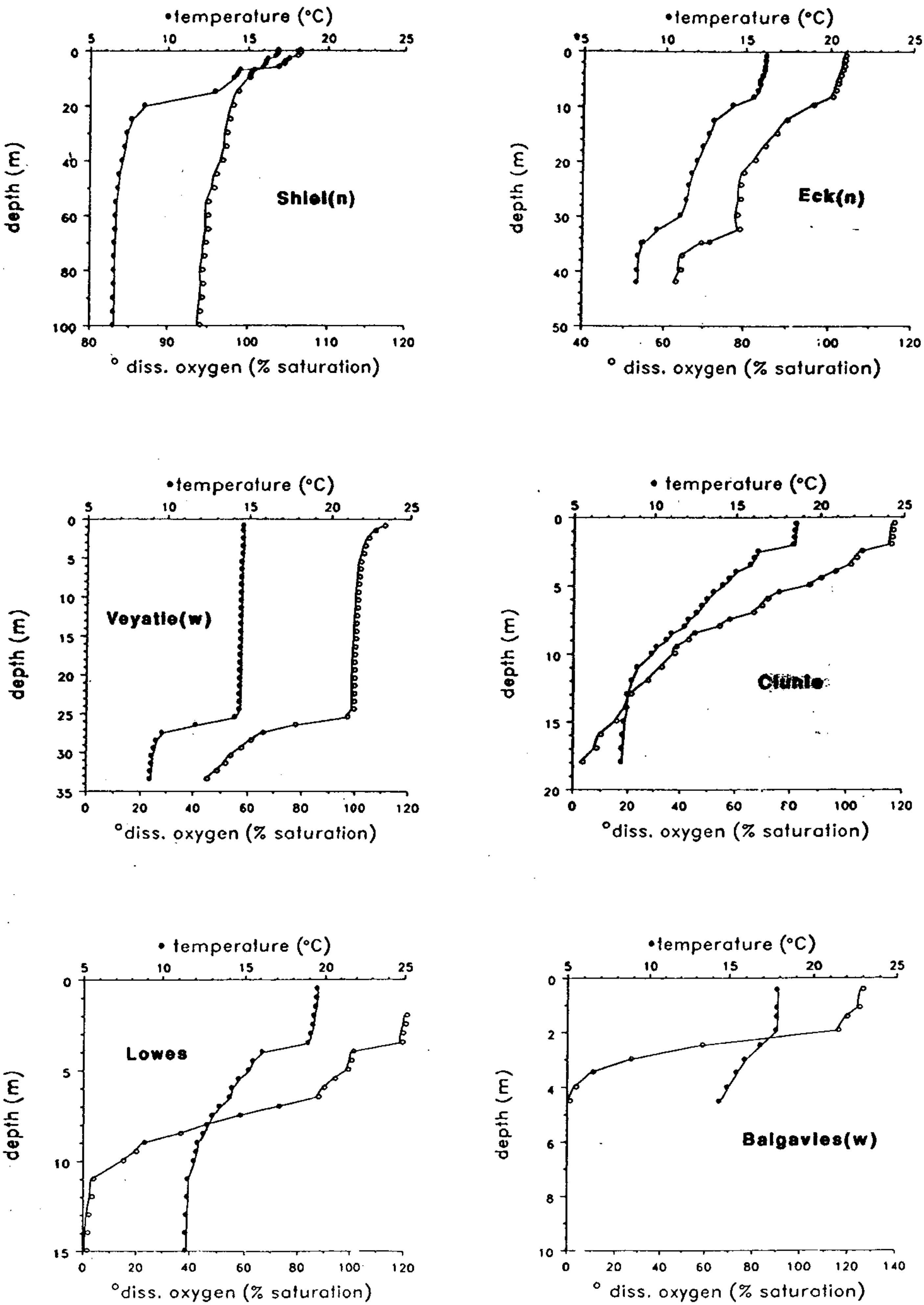


Figure 21.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled



•temperature (°C)
depth (m)
Shiel(n)
° diss. oxygen (% saturation)
•temperature (°C)
depth (m)
Eck(n)
° diss. oxygen (% saturation)
•temperature (°C)
depth (m)
Veyatie(w)
°diss. oxygen (% saturation)
• temperature (°C)
depth (m)
Clunie
°diss. oxygen (% saturation)
• temperature (°C)
depth (m)
Lowes
°diss. oxygen (% saturation)
•temperature (°C)
depth (m)
Balgavies(w)
° diss. oxygen (% saturation)

Figure 22.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled

Lochs ranked on the P retention coefficient predicted by the Kirchner & Dillon model

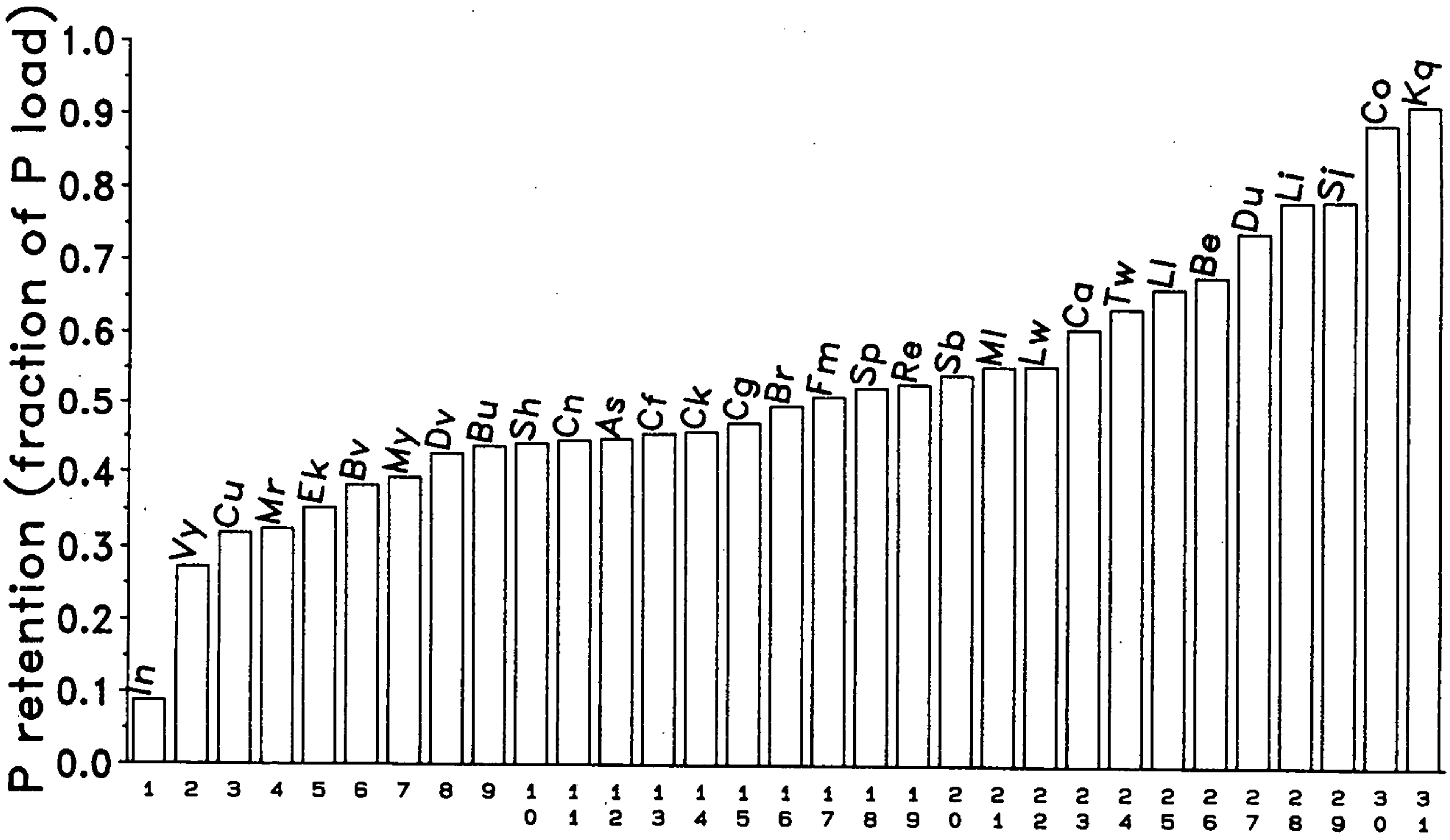


Figure 23.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

pH related to conductivity in 30 Scottish loch basins

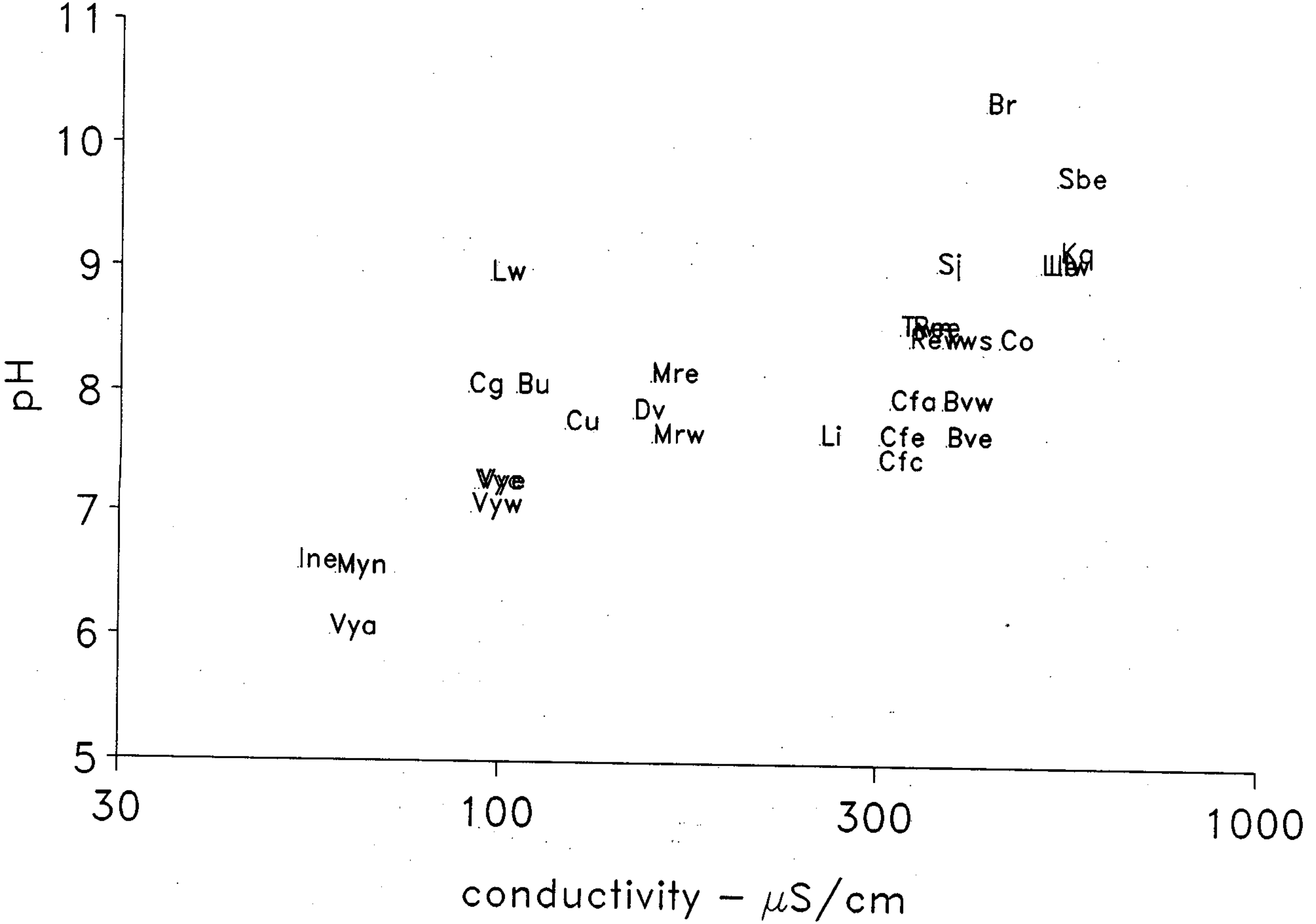


Figure 24.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Loch basins ranked on open water P levels measured in summer 1991; set excludes Kilconquhar (1250 μg/l).

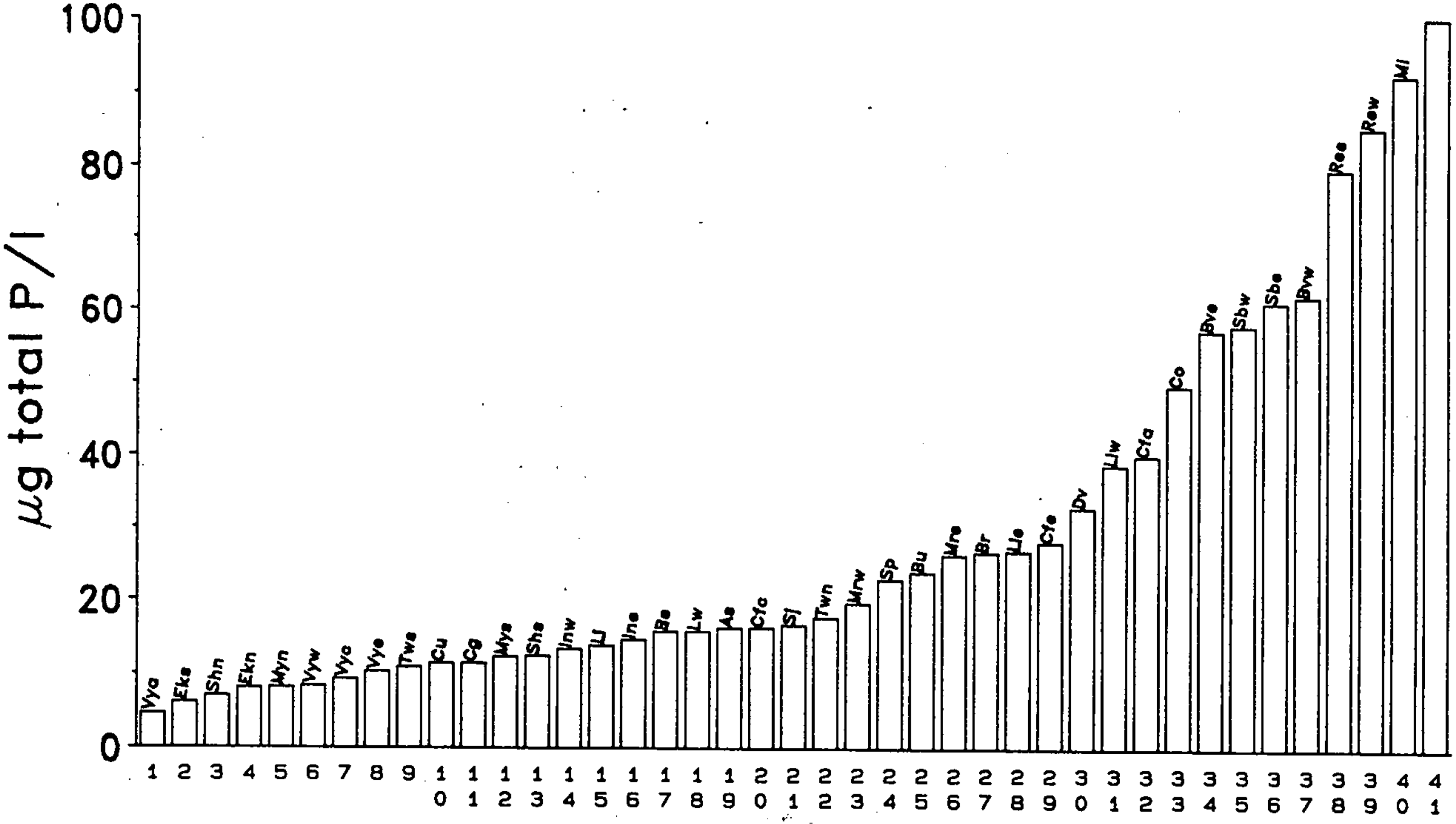
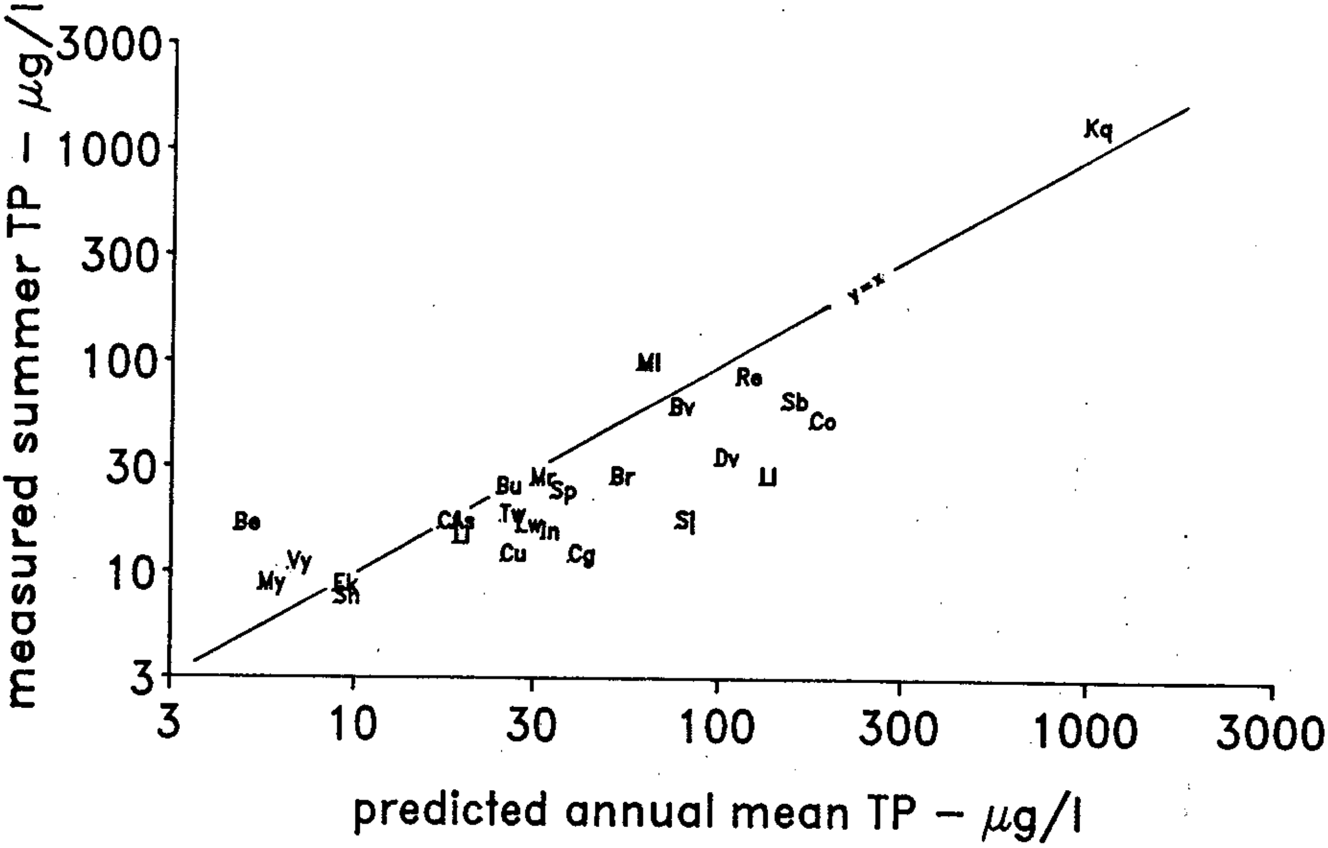


Figure 25a.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

measured summer P related to the mean annual P calculated from the loading predicted from land use



measured summer P related to the mean annual P calculated from the loading predicted from land use

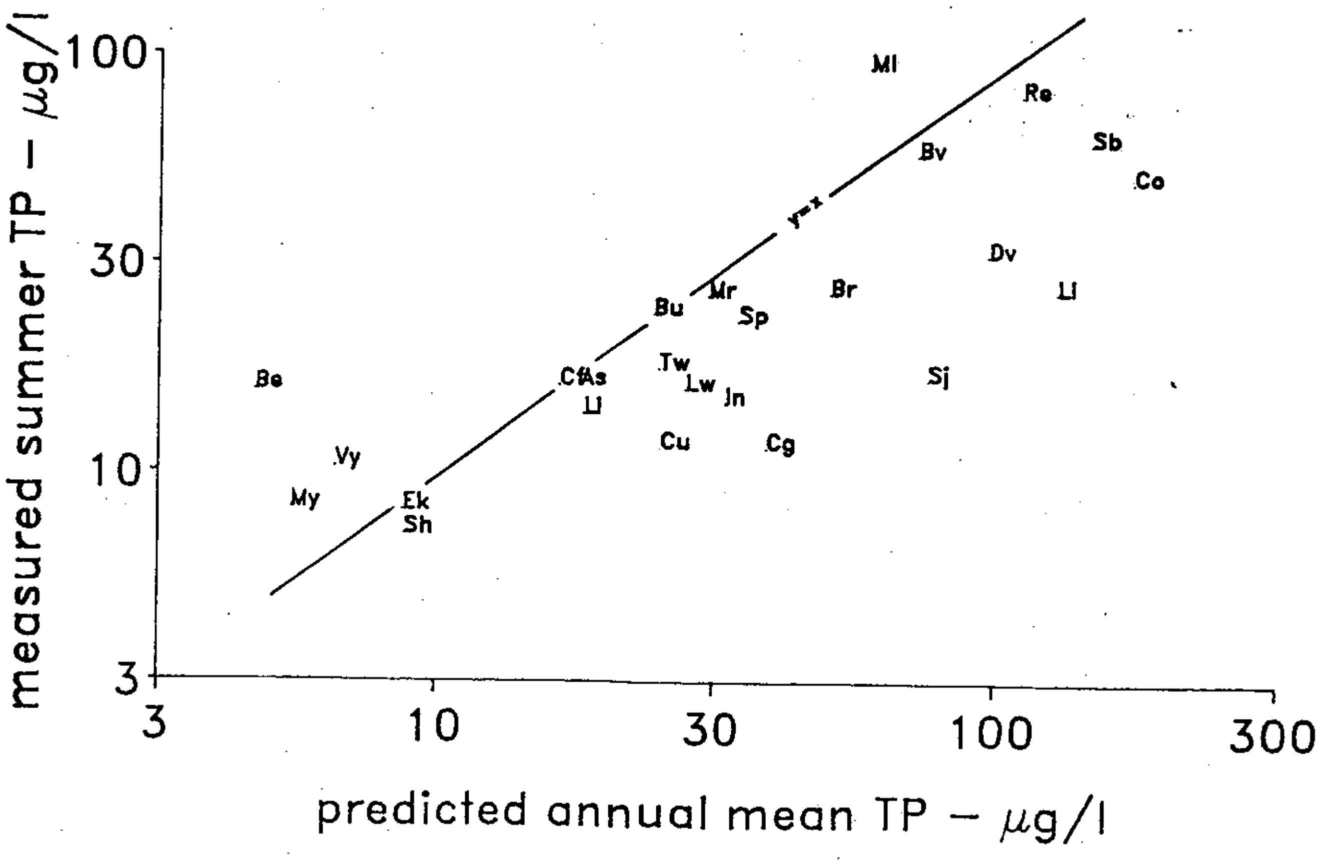
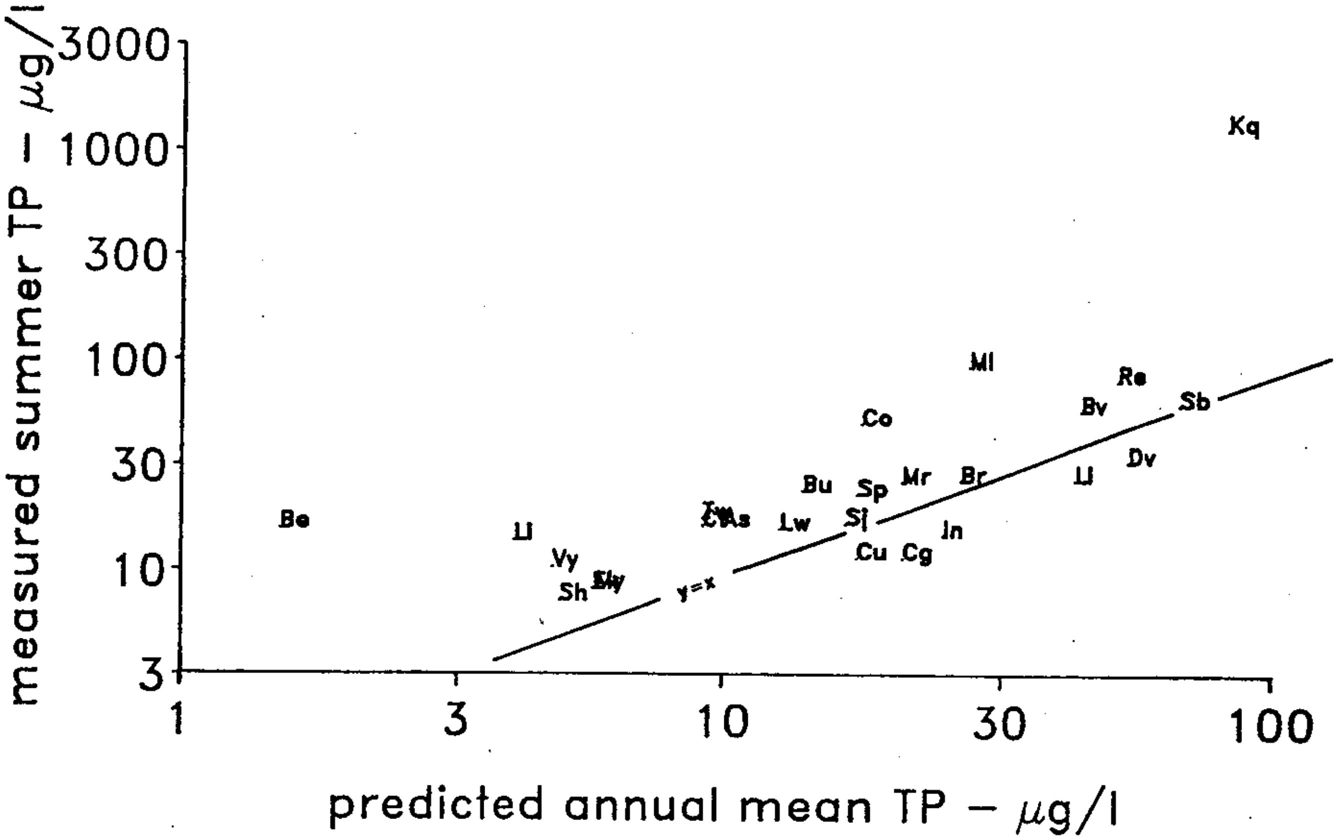


Figure 25b.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled

measured summer P related to the predicted mean annual P corrected for P retention according to Dillon & Rigler



measured summer P related to the predicted mean annual P corrected for P retention according to Dillon & Rigler

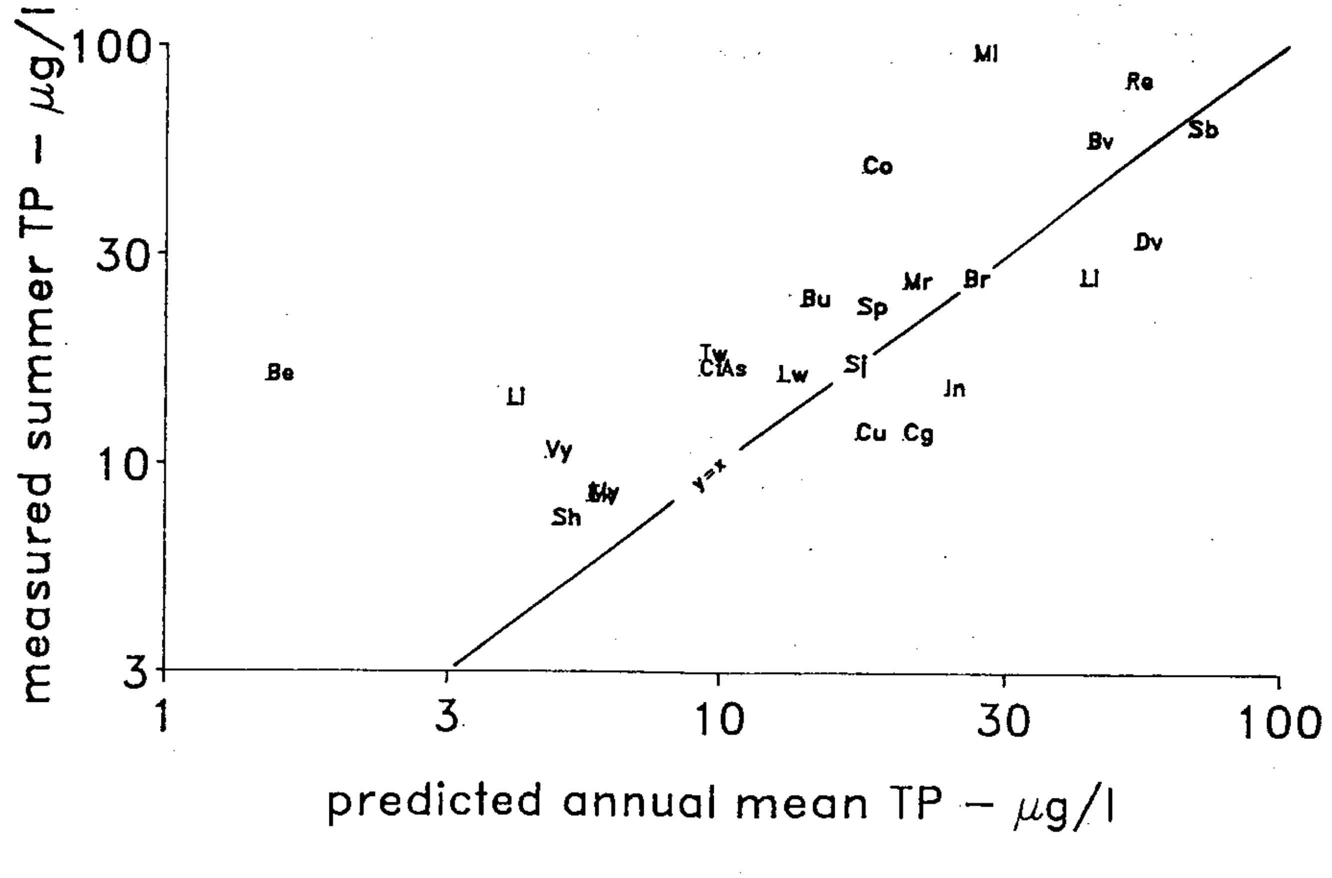


Figure 26.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

Loch basins ranked on open water clarity values measured in summer 1991

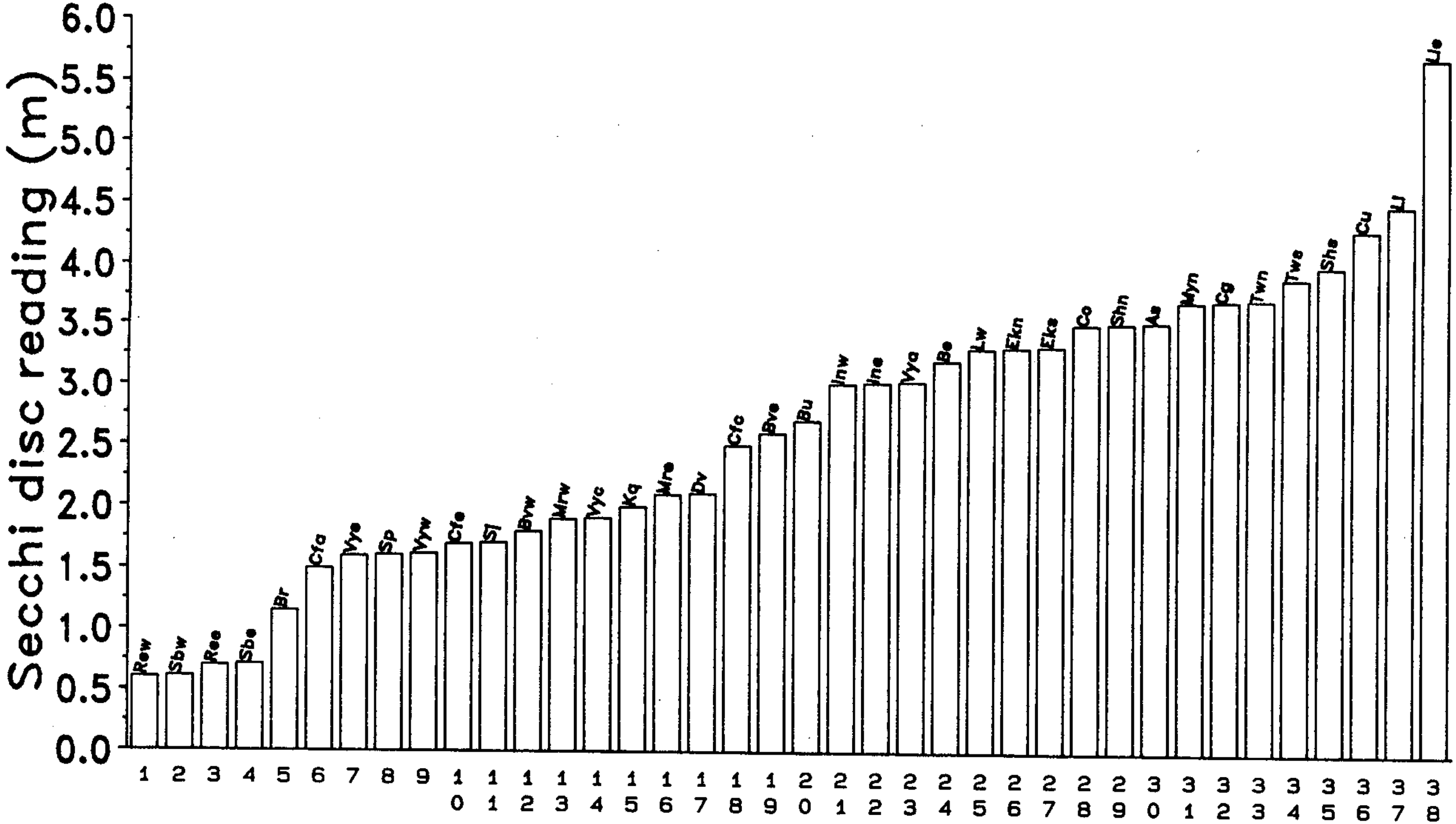


Figure 27.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

Loch basins ranked on surface water nitrate concentrations measured in summer 1991

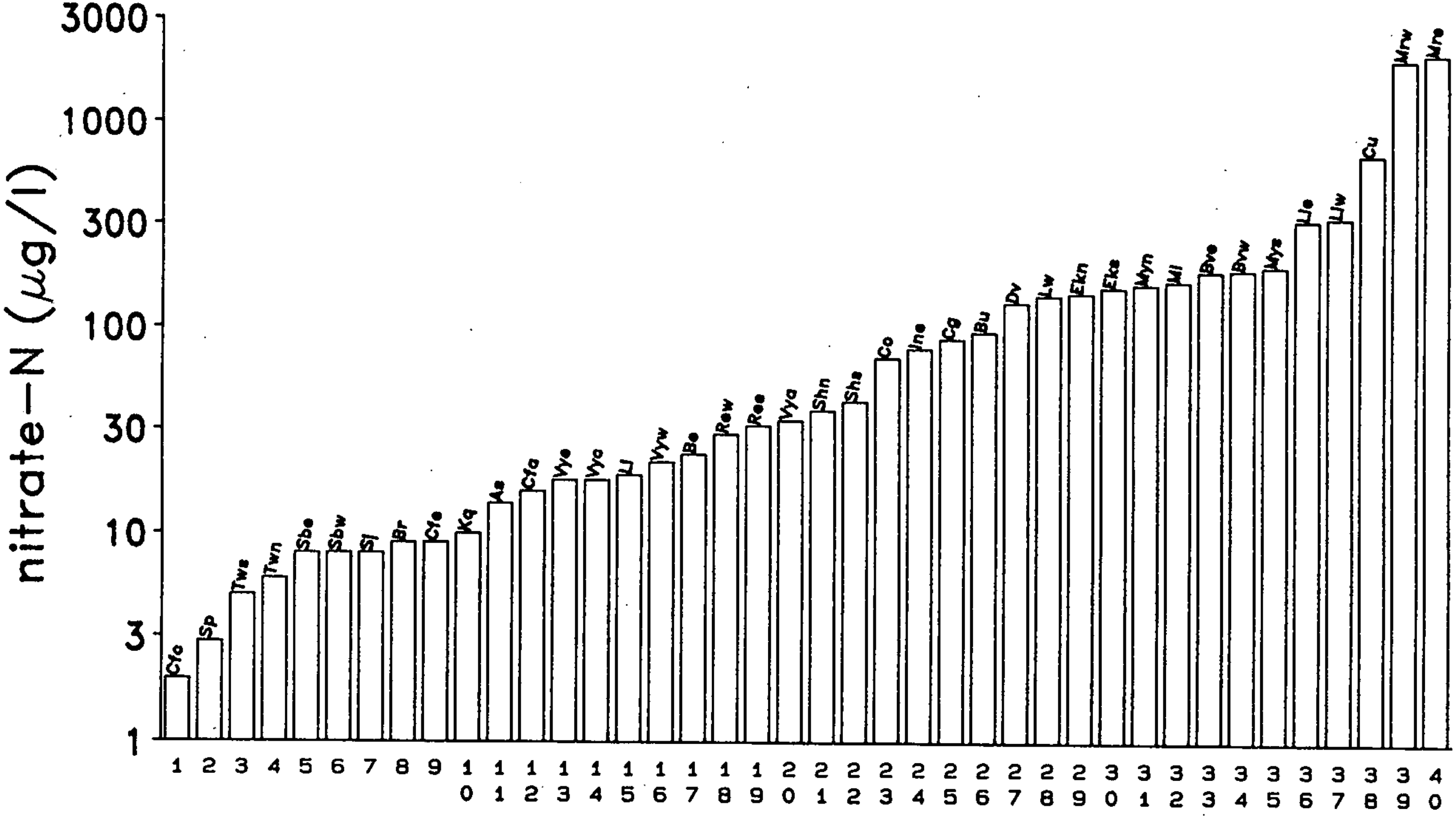


Figure 28a.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

Loch basins ranked on sol.react.P level in the pore water of the top 5cm of sediment (summer 1991)

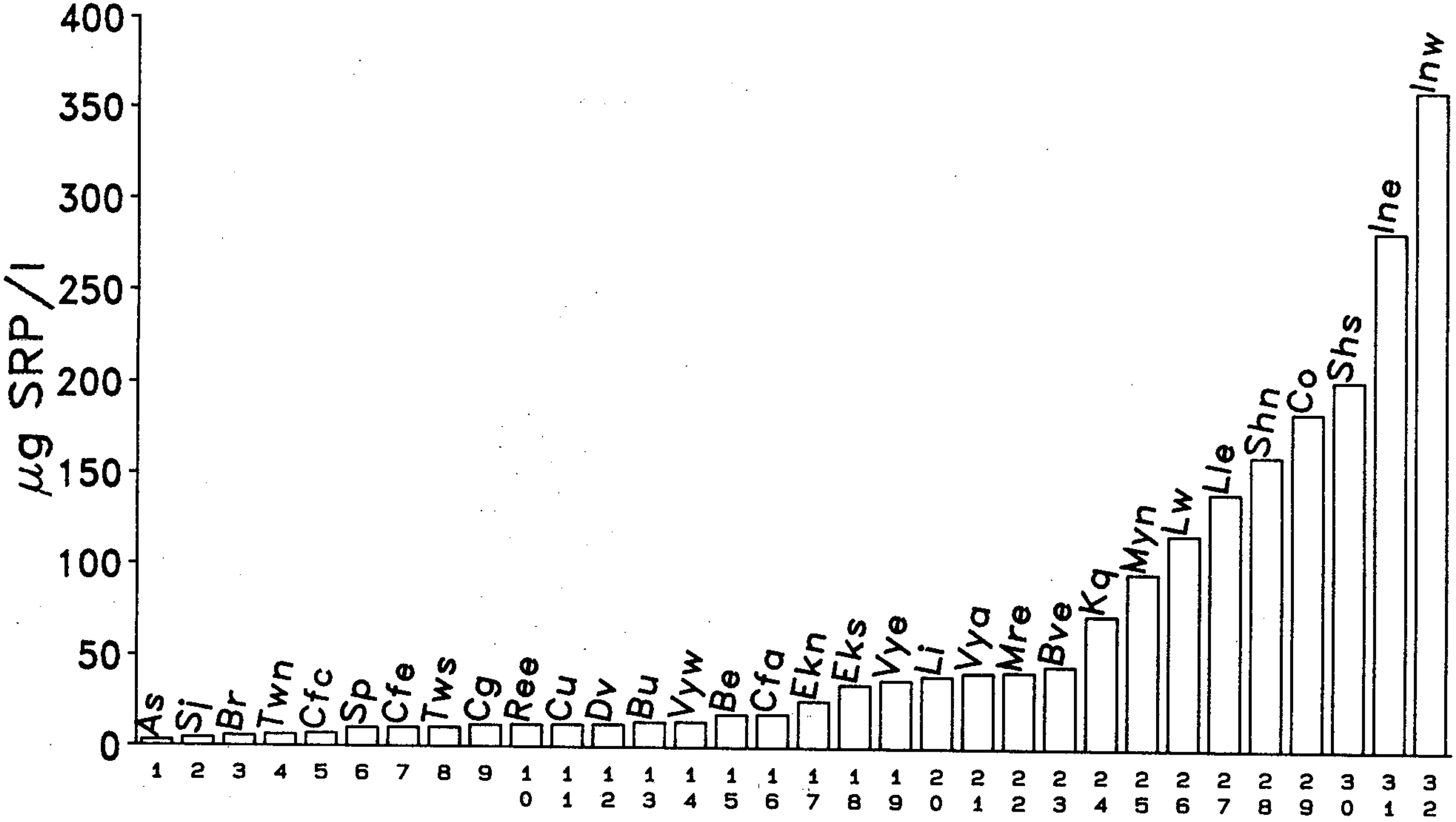


Figure 28b.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

summer pore water SRP in the top 5 cm of sediment, related to the P loading predicted from land use etc.

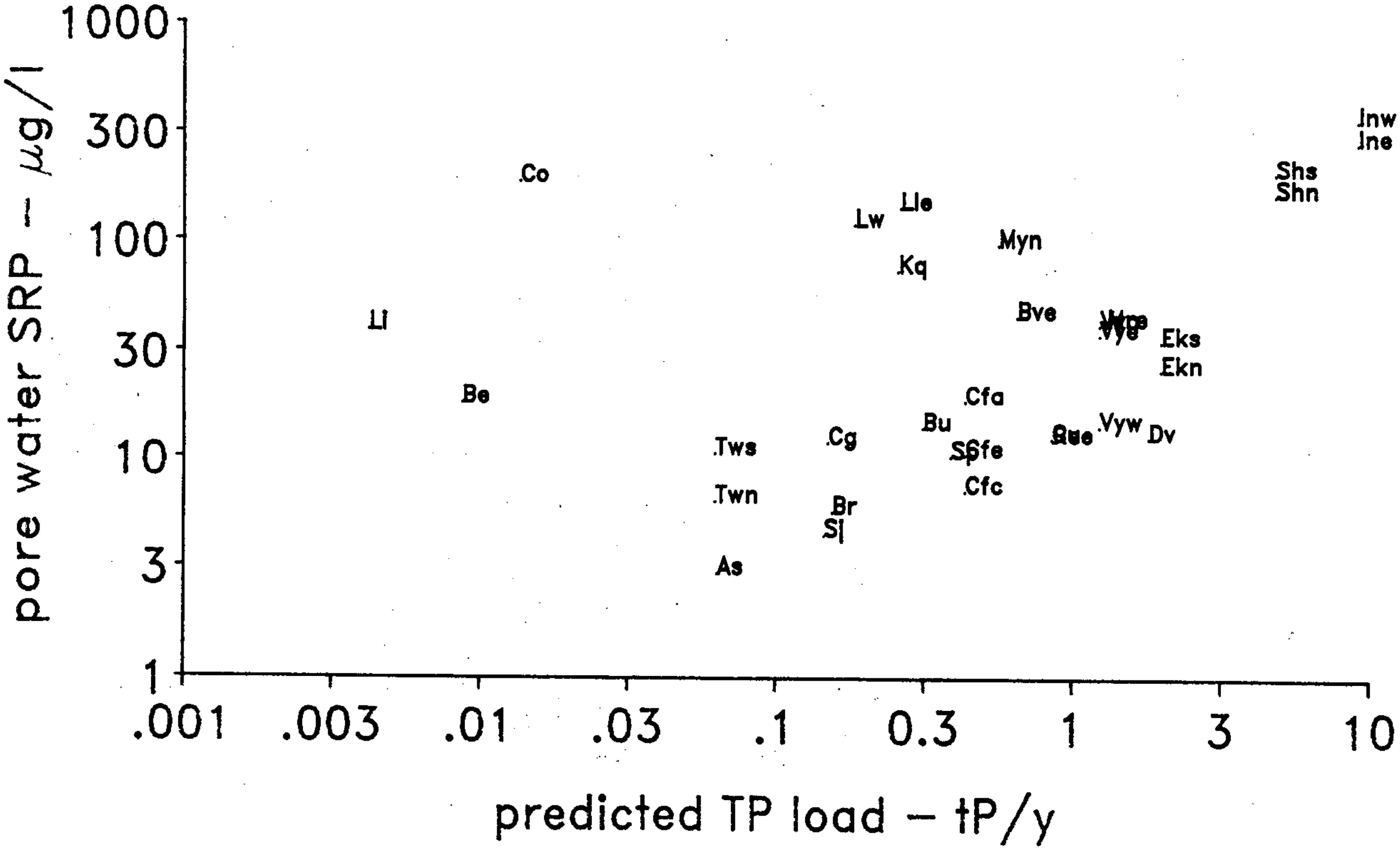


Figure 29a.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Loch basins ranked on the phosphorus content (% DWt) of the top 5cm of sediment (summer 1991)

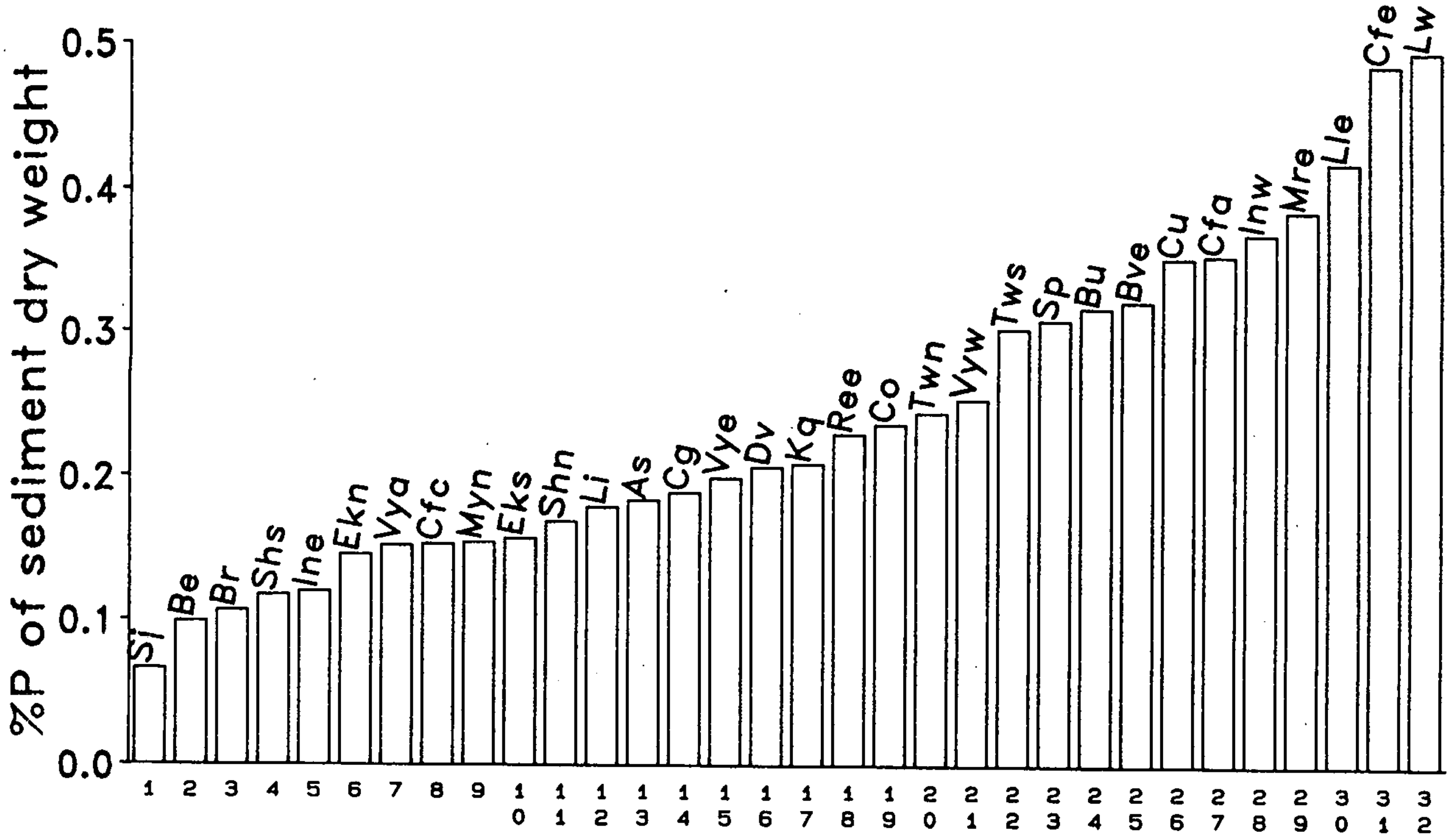


Figure 29b.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

mean %P of dry wt. in the top 5 cm of sediment, related to the P loading predicted from land use etc.

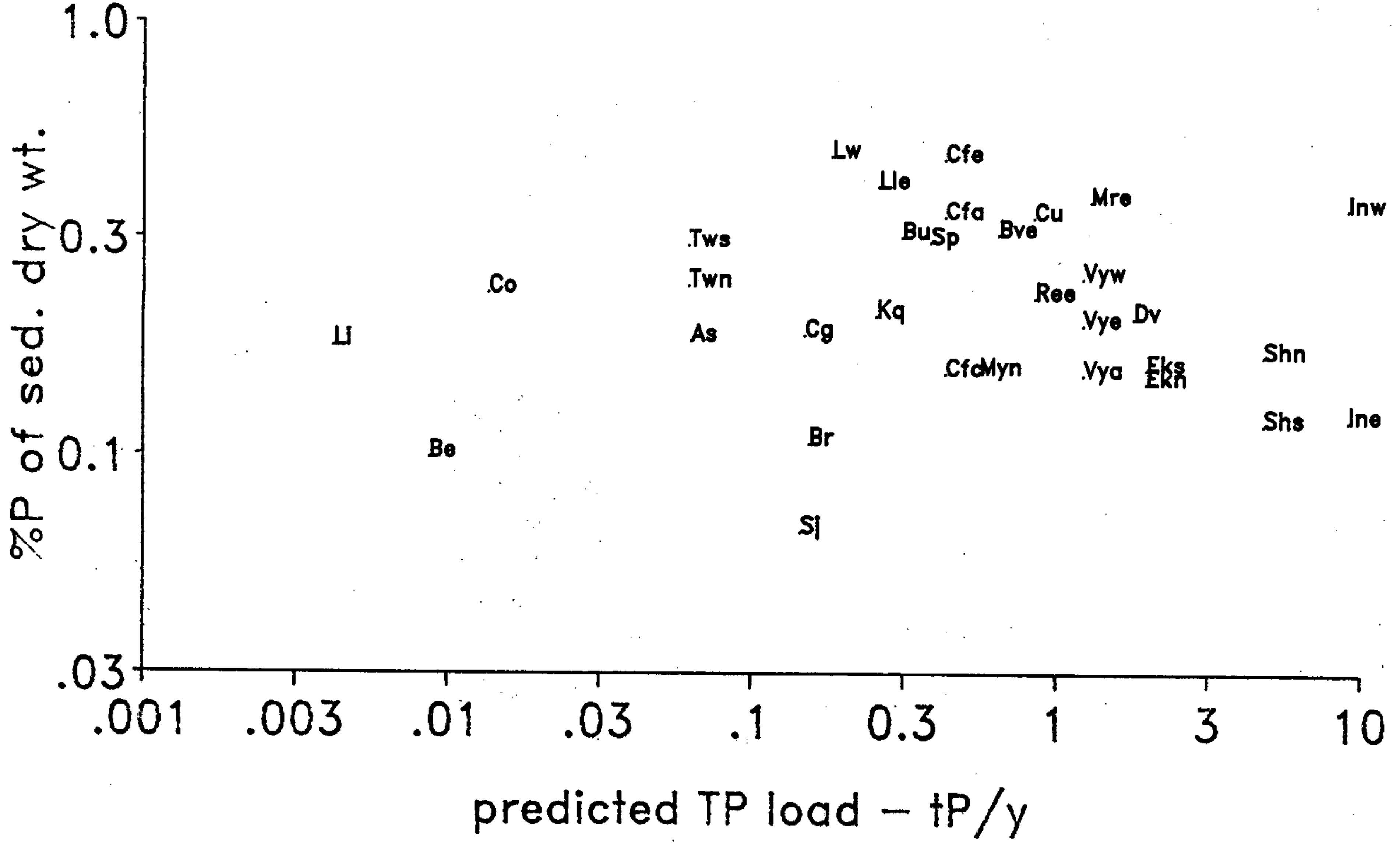


Figure 30.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine-	Insh (east)	18 July *
Inw-	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

Loch basins ranked on open (surface) water chlorophyll levels in summer 1991; Mill value of 145 $\mu g/l$ excluded

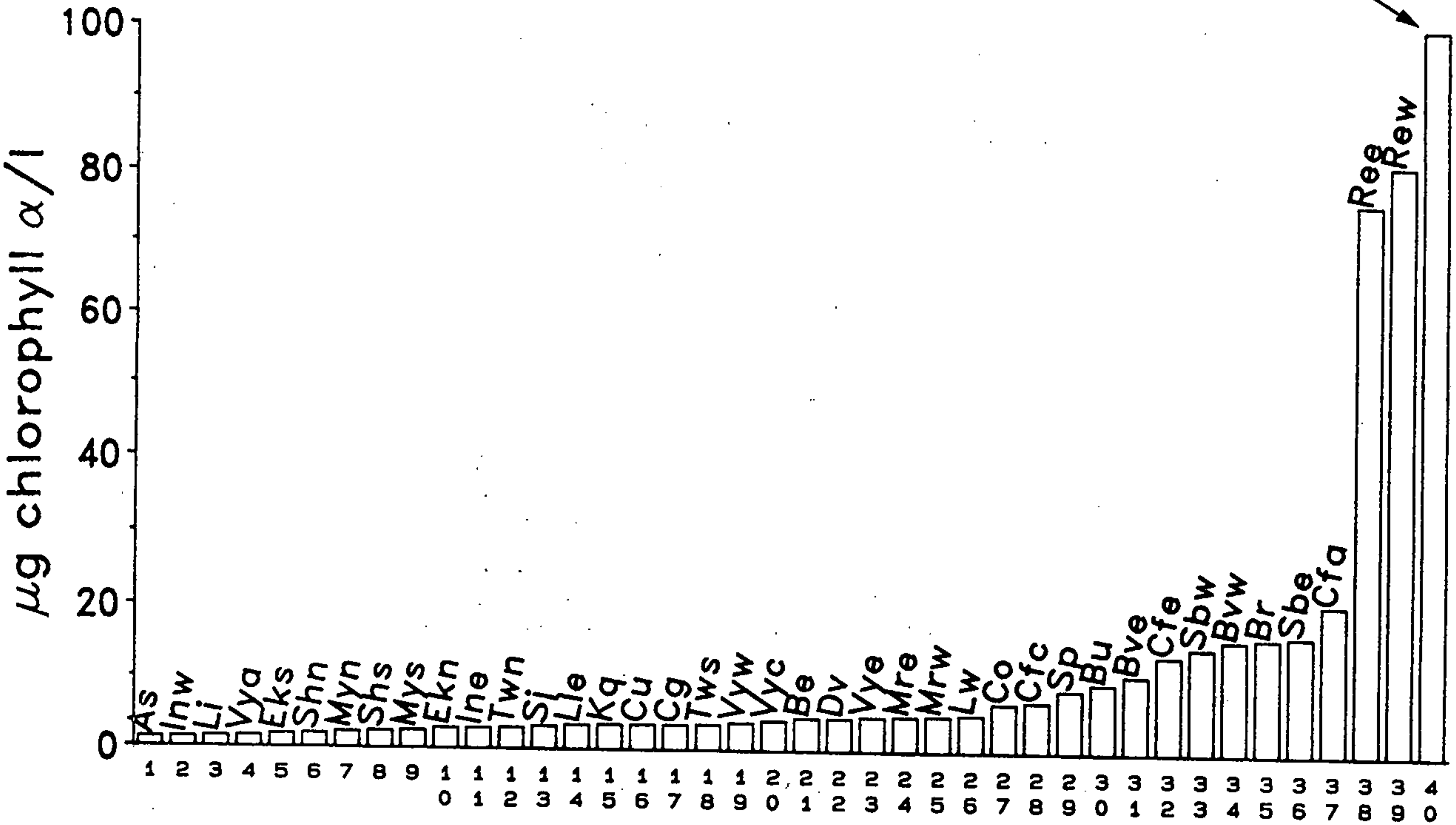


Figure 31.

Co	Coldingham	11 June	*
Li	Lindean	13 June	*
Be	Branxholme Easter	13 June	*
Myn	St Mary's (north)	18 June	*
Mys	St Mary's (south)	18 June	
Kq	Kilconquhar	25 June	*
Lle	Linlithgow (east)	26 June	
Llw	Linlithgow (west)	26 June	*
Bve	Balgavies (east)	2 July	*
Bvw	Balgavies (west)	2 July	
Ree	Rescobie (east)	2 July	
Rew	Rescobie (west)	2 July	*
Mre	Marlee (east)	3 July	*
Mrw	Marlee (west)	3 July	
Cu	Clunie	4 July	*
Bu	Butterstone	5 July	*
Lw	Lowes	6 July	*
Cg	Craiglush	6 July	*
Sbe	Strathbeg (east)	16 July	
Sbw	Strathbeg (west)	16 July	
Dv	Davan	17 July	*
Ekn	Eck (north)	23 July	*
Eks	Eck (south)	24 July	*
Shn	Shiel (north)	24 July	*
Shs	Shiel (south)	25 July	*
Ml	Mill (open water dip only)	31 July	
Sp	Spiggie	5 August	*
Br	Brow	5 August	*
As	Asta	6 August	*
Twn	Tingwall (north)	6 August	*
Tws	Tingwall (south)	6 August	*
Sj	St John's	10 August	*
Vye	Veyatie (east)	21 August	*
Vyc	Veyatie (central)	21 August	
Vyw	Veyatie (west)	21 August	*
Vya	Veyatie (arm)	21 August	*
Ine	Insh (east)	18 July	*
Inw	Insh (west)	18 July	*
Cfc	Cliff (centre)	7 August	*
Cfa	Cliff (arm)	7 August	*
Cfe	Cliff (c/e confluence)	7 August	*
Du	Duddingston not sampled		
Ca	Castle not sampled		
Ck	Carlingwark not sampled		
Cn	Cran not sampled		
Fm	Flemington not sampled		

water transparency (Secchi disk reading) related to phytoplankton biomass (chlorophyll α) – summer 1991

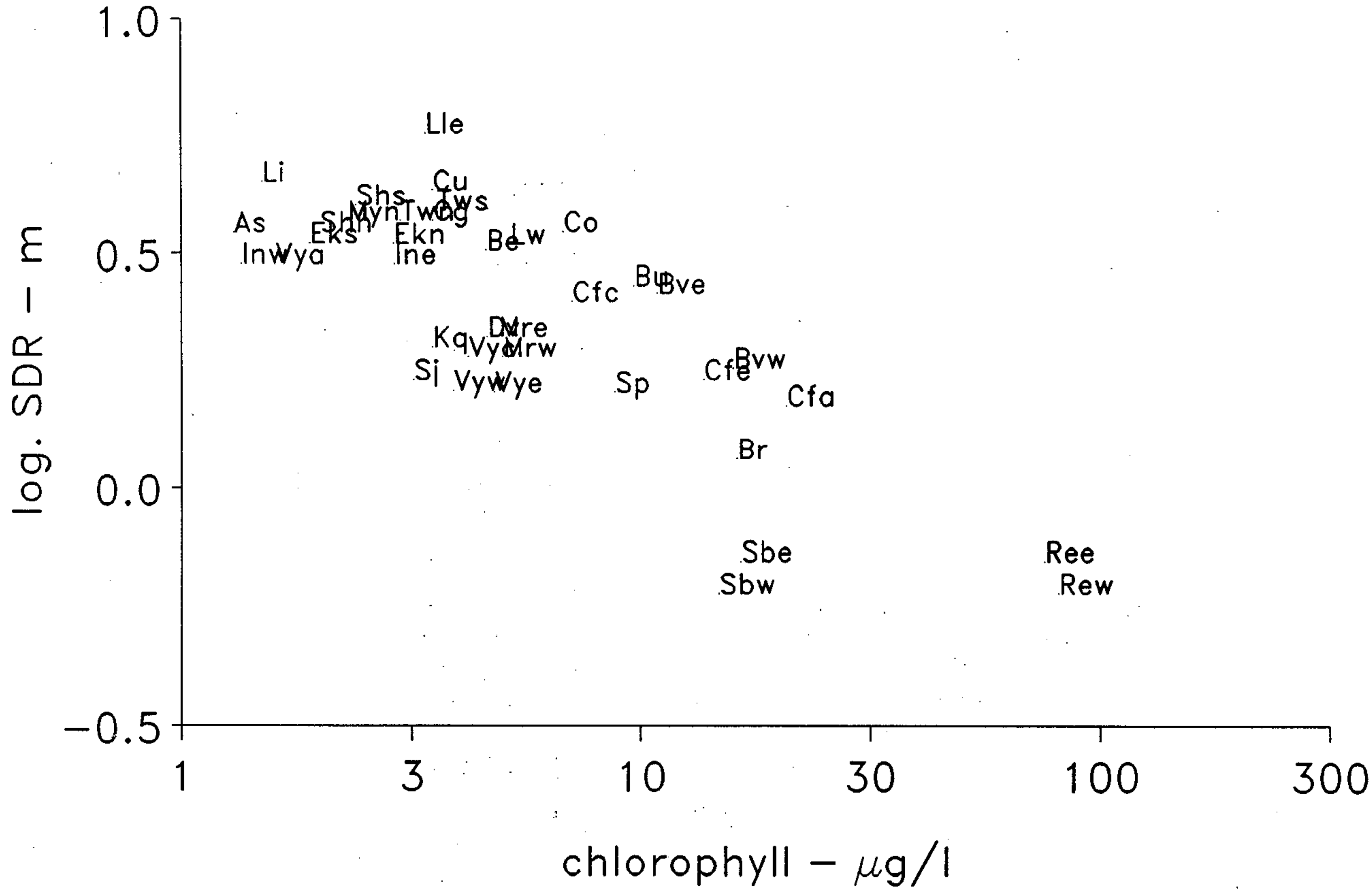


Figure 32.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Phytoplankton biomass (chlorophyll α) – summer 1991
related to loch mean depth

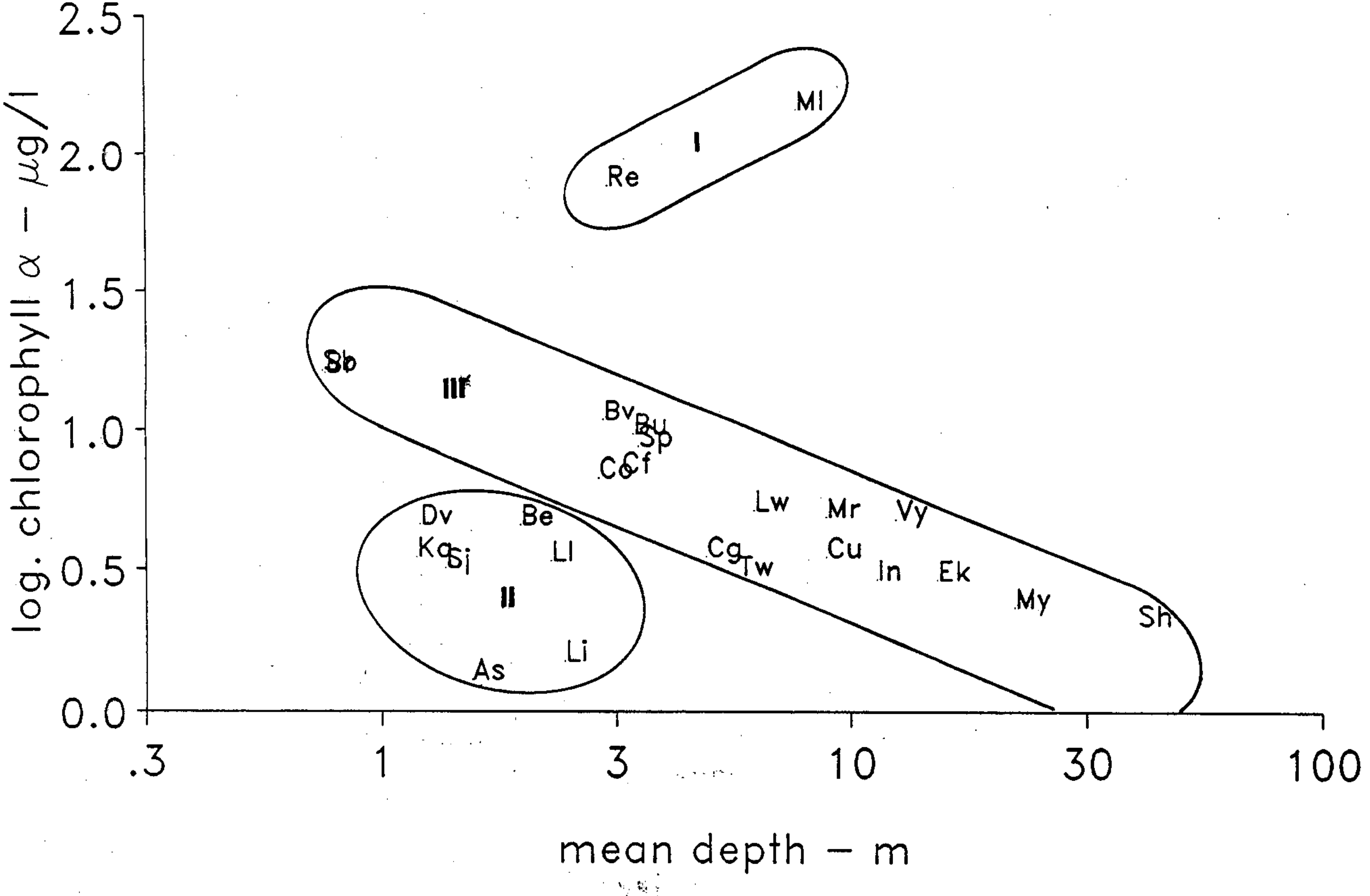


Figure 33.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Phytoplankton biomass (chlorophyll α) – summer 1991
related to depth of epilimnion

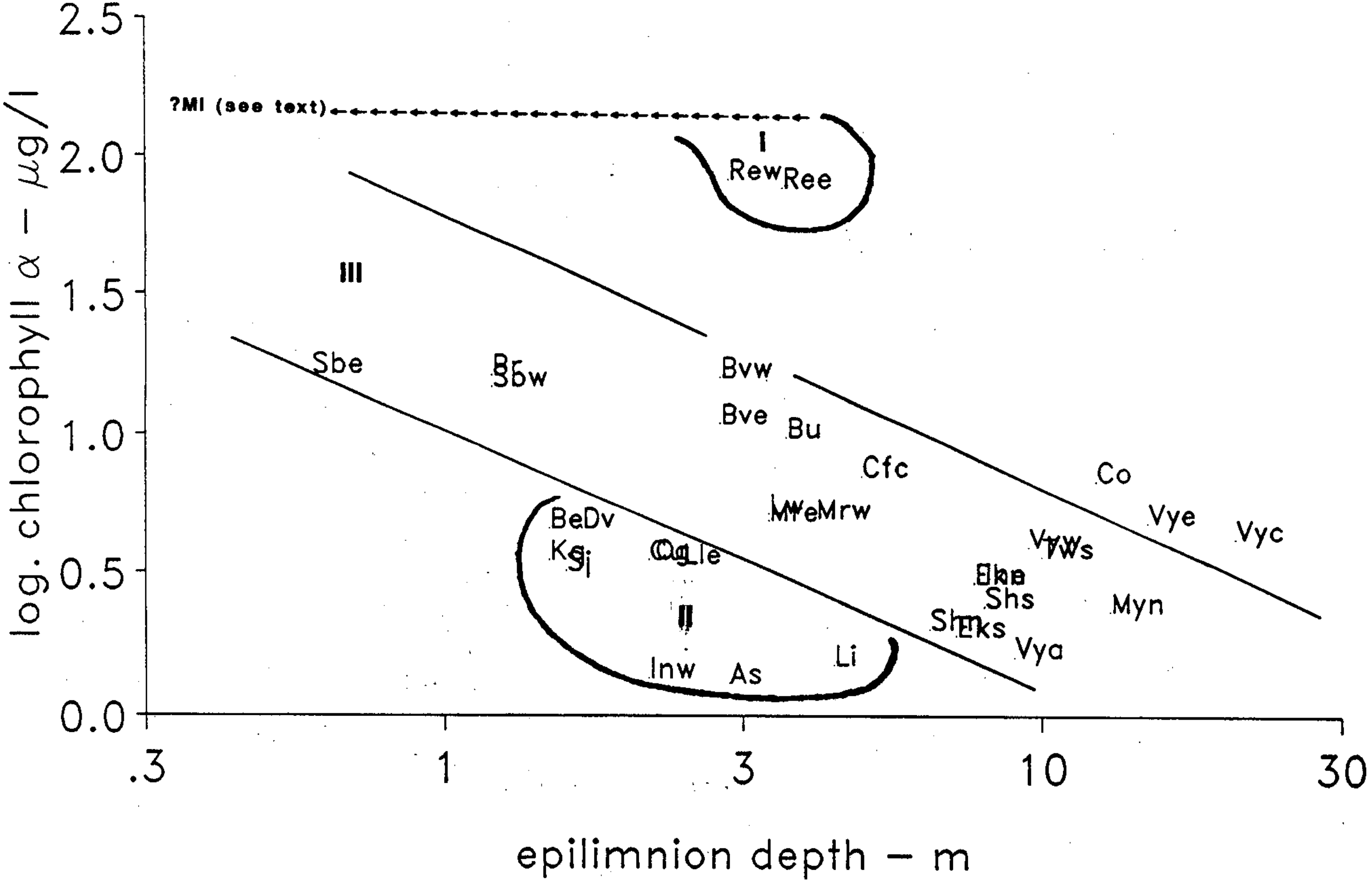


Figure 34.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston not sampled	
Ca	Castle not sampled	
Ck	Carlingwark not sampled	
Cn	Cran not sampled	
Fm	Flemington not sampled	

summer phytoplankton biomass (chlorophyll α)
related to the P loading predicted from land use etc.

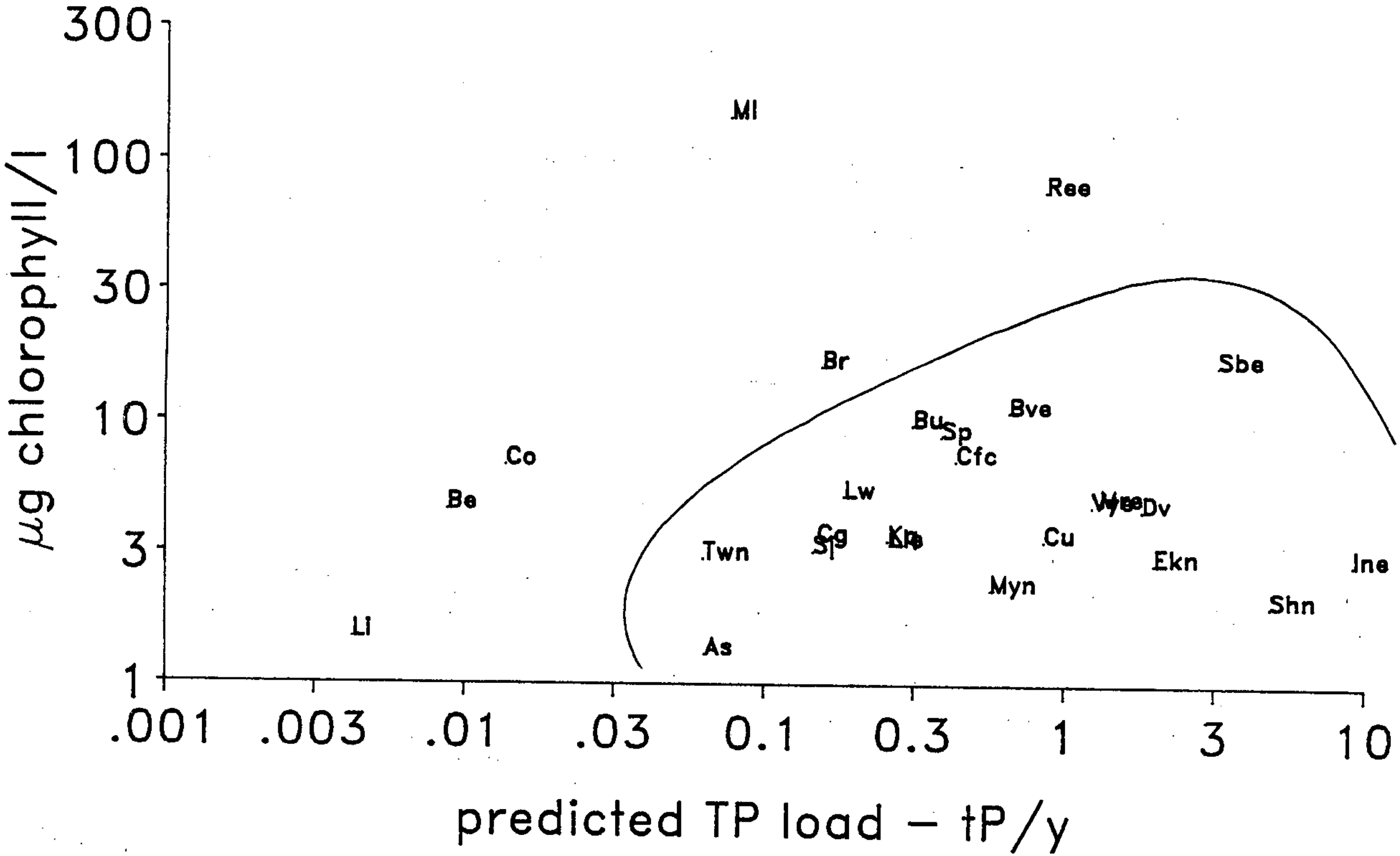


Figure 35.

Co	Coldingham	11 June *
Li	Lindean	13 June *
Be	Branxholme Easter	13 June *
Myn	St Mary's (north)	18 June *
Mys	St Mary's (south)	18 June
Kq	Kilconquhar	25 June *
Lle	Linlithgow (east)	26 June
Llw	Linlithgow (west)	26 June *
Bve	Balgavies (east)	2 July *
Bvw	Balgavies (west)	2 July
Ree	Rescobie (east)	2 July
Rew	Rescobie (west)	2 July *
Mre	Marlee (east)	3 July *
Mrw	Marlee (west)	3 July
Cu	Clunie	4 July *
Bu	Butterstone	5 July *
Lw	Lowes	6 July *
Cg	Craiglush	6 July *
Sbe	Strathbeg (east)	16 July
Sbw	Strathbeg (west)	16 July
Dv	Davan	17 July *
Ekn	Eck (north)	23 July *
Eks	Eck (south)	24 July *
Shn	Shiel (north)	24 July *
Shs	Shiel (south)	25 July *
Ml	Mill (open water dip only)	31 July
Sp	Spiggie	5 August *
Br	Brow	5 August *
As	Asta	6 August *
Twn	Tingwall (north)	6 August *
Tws	Tingwall (south)	6 August *
Sj	St John's	10 August *
Vye	Veyatie (east)	21 August *
Vyc	Veyatie (central)	21 August
Vyw	Veyatie (west)	21 August *
Vya	Veyatie (arm)	21 August *
Ine	Insh (east)	18 July *
Inw	Insh (west)	18 July *
Cfc	Cliff (centre)	7 August *
Cfa	Cliff (arm)	7 August *
Cfe	Cliff (c/e confluence)	7 August *
Du	Duddingston	not sampled
Ca	Castle	not sampled
Ck	Carlingwark	not sampled
Cn	Cran	not sampled
Fm	Flemington	not sampled

Dissolved oxidised N concentrations related to the levels of soluble reactive P in 30 loch basins in summer 1991

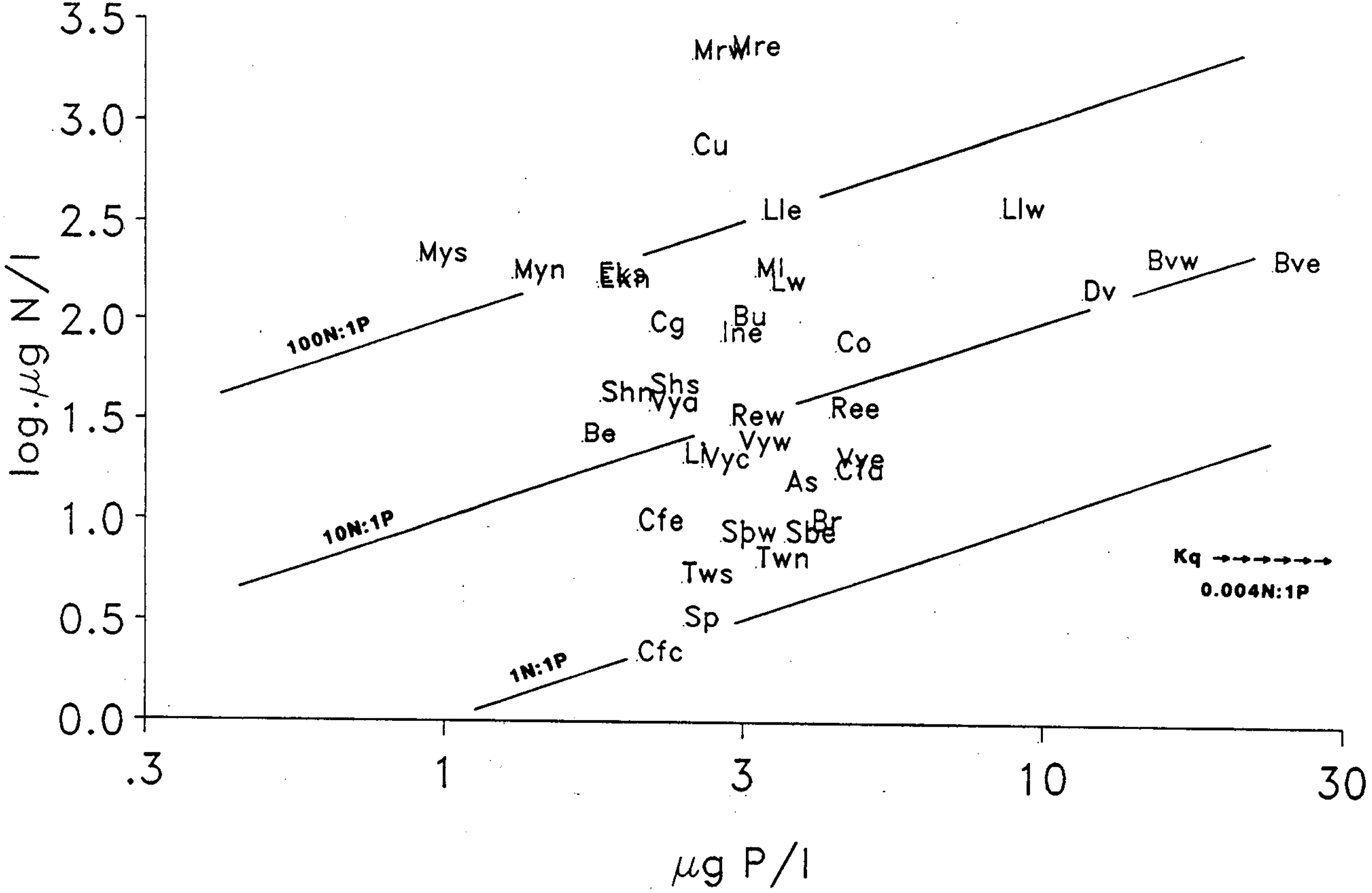


Figure 36.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine-	Insh (east)	18 July *
Inw-	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston not sampled	
Ca -	Castle not sampled	
Ck -	Carlingwark not sampled	
Cn -	Cran not sampled	
Fm -	Flemington not sampled	

Loch basins ranked on open water silica concentrations measured in summer 1991

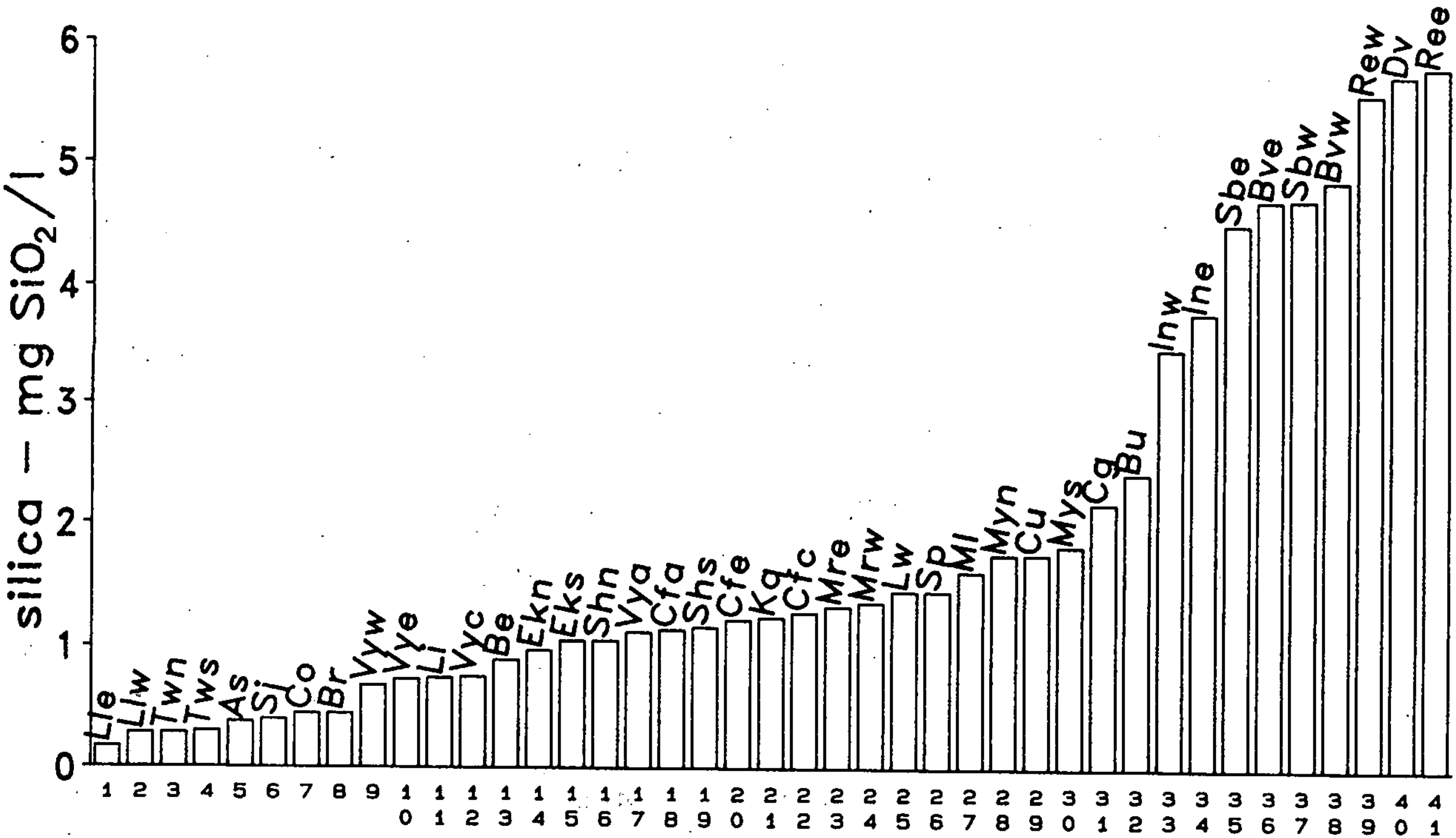


Figure 37.

Co -	Coldingham	11 June *
Li -	Lindean	13 June *
Be -	Branxholme Easter	13 June *
Myn -	St Mary's (north)	18 June *
Mys -	St Mary's (south)	18 June
Kq -	Kilconquhar	25 June *
Lle -	Linlithgow (east)	26 June
Llw -	Linlithgow (west)	26 June *
Bve -	Balgavies (east)	2 July *
Bvw -	Balgavies (west)	2 July
Ree -	Rescobie (east)	2 July
Rew -	Rescobie (west)	2 July *
Mre -	Marlee (east)	3 July *
Mrw -	Marlee (west)	3 July
Cu -	Clunie	4 July *
Bu -	Butterstone	5 July *
Lw -	Lowes	6 July *
Cg -	Craiglush	6 July *
Sbe -	Strathbeg (east)	16 July
Sbw -	Strathbeg (west)	16 July
Dv -	Davan	17 July *
Ekn -	Eck (north)	23 July *
Eks -	Eck (south)	24 July *
Shn -	Shiel (north)	24 July *
Shs -	Shiel (south)	25 July *
Ml -	Mill (open water dip only)	31 July
Sp -	Spiggie	5 August *
Br -	Brow	5 August *
As -	Asta	6 August *
Twn -	Tingwall (north)	6 August *
Tws -	Tingwall (south)	6 August *
Sj -	St John's	10 August *
Vye -	Veyatie (east)	21 August *
Vyc -	Veyatie (central)	21 August
Vyw -	Veyatie (west)	21 August *
Vya -	Veyatie (arm)	21 August *
Ine -	Insh (east)	18 July *
Inw -	Insh (west)	18 July *
Cfc -	Cliff (centre)	7 August *
Cfa -	Cliff (arm)	7 August *
Cfe -	Cliff (c/e confluence)	7 August *
Du -	Duddingston	not sampled
Ca -	Castle	not sampled
Ck -	Carlingwark	not sampled
Cn -	Cran	not sampled
Fm -	Flemington	not sampled

Lochs ranked according to total rotifers (ind l^{-1})

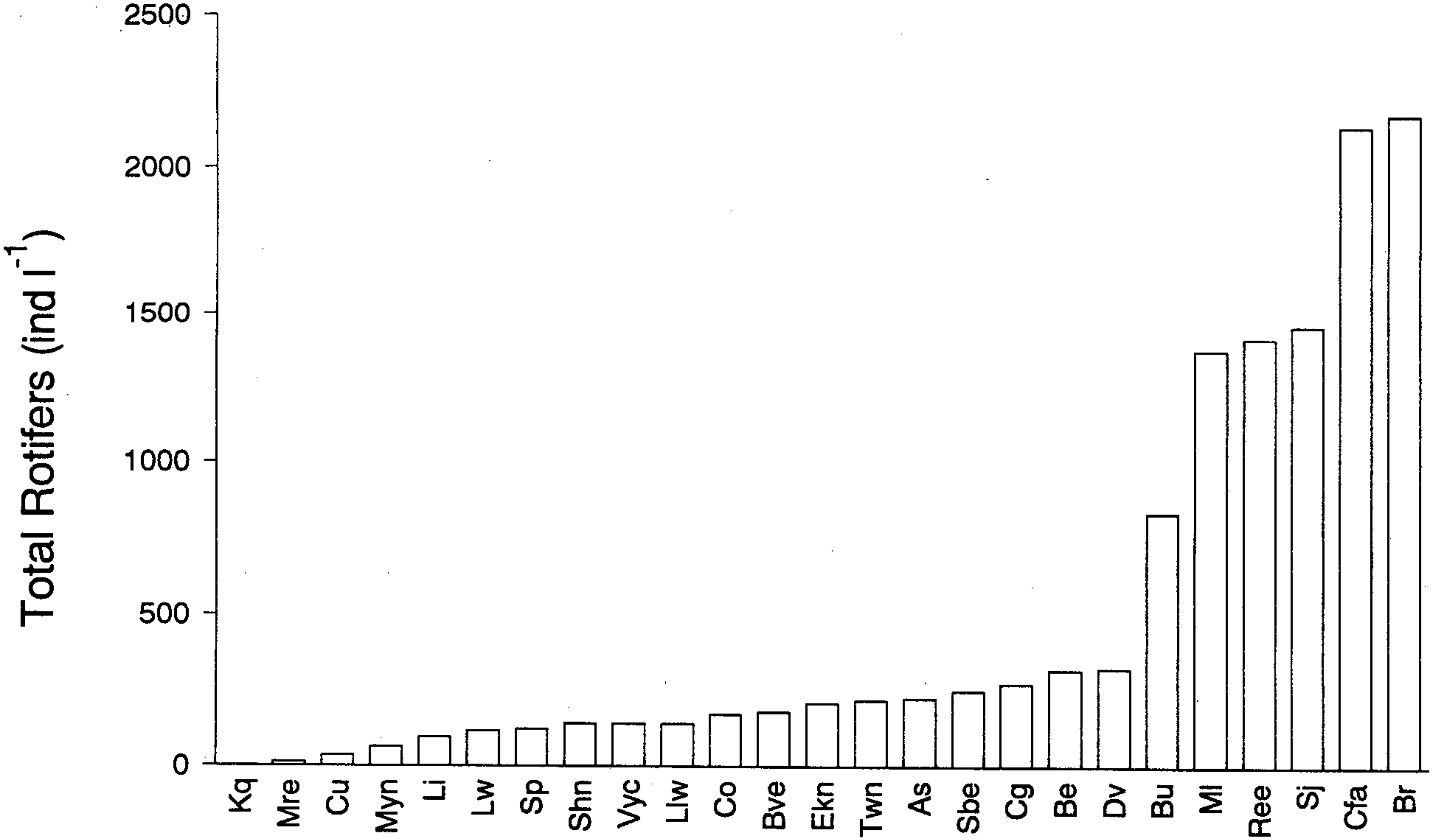


FIGURE 38

Total rotifers in relation to loch surface area

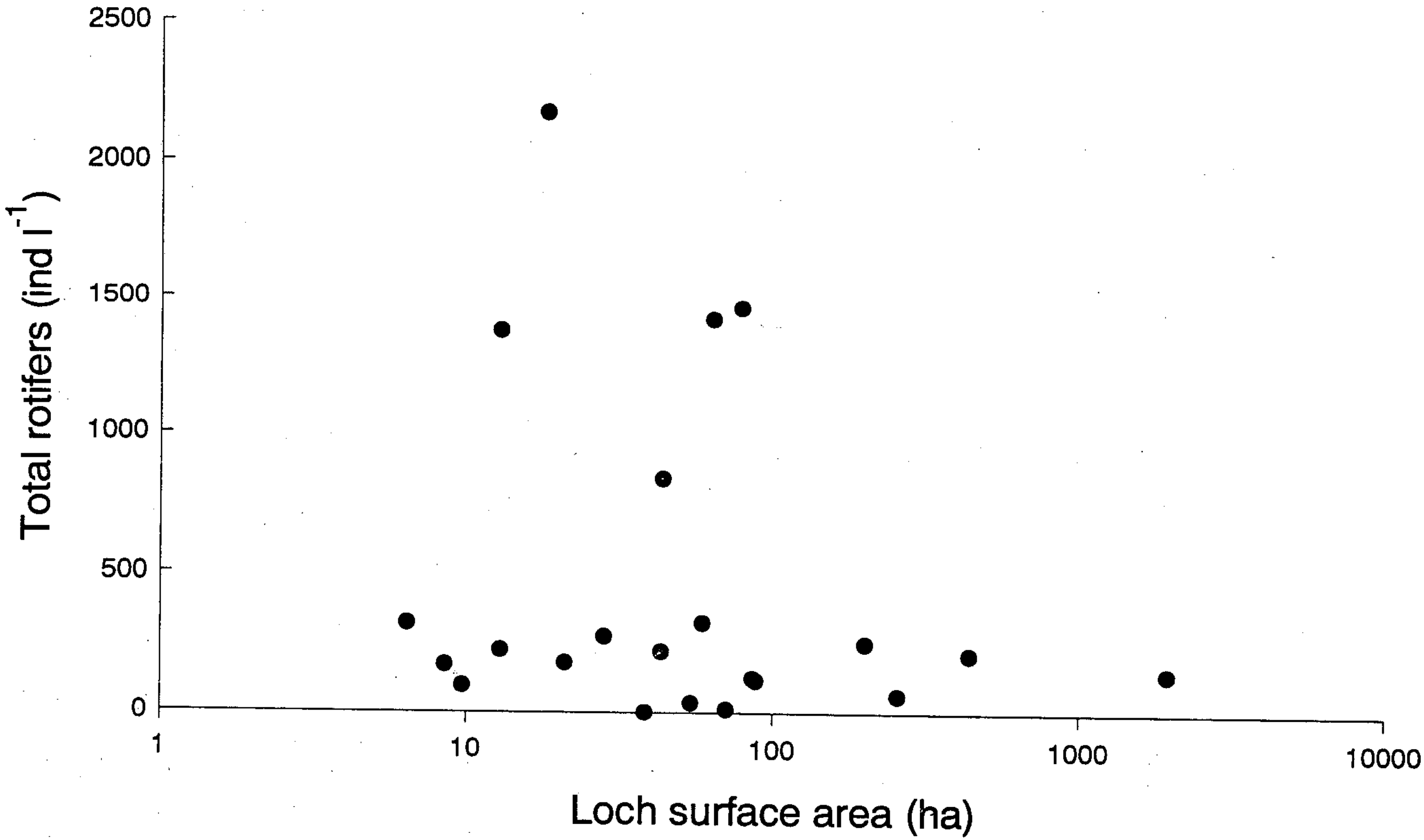


FIGURE 39

Total rotifers in relation to loch mean depth

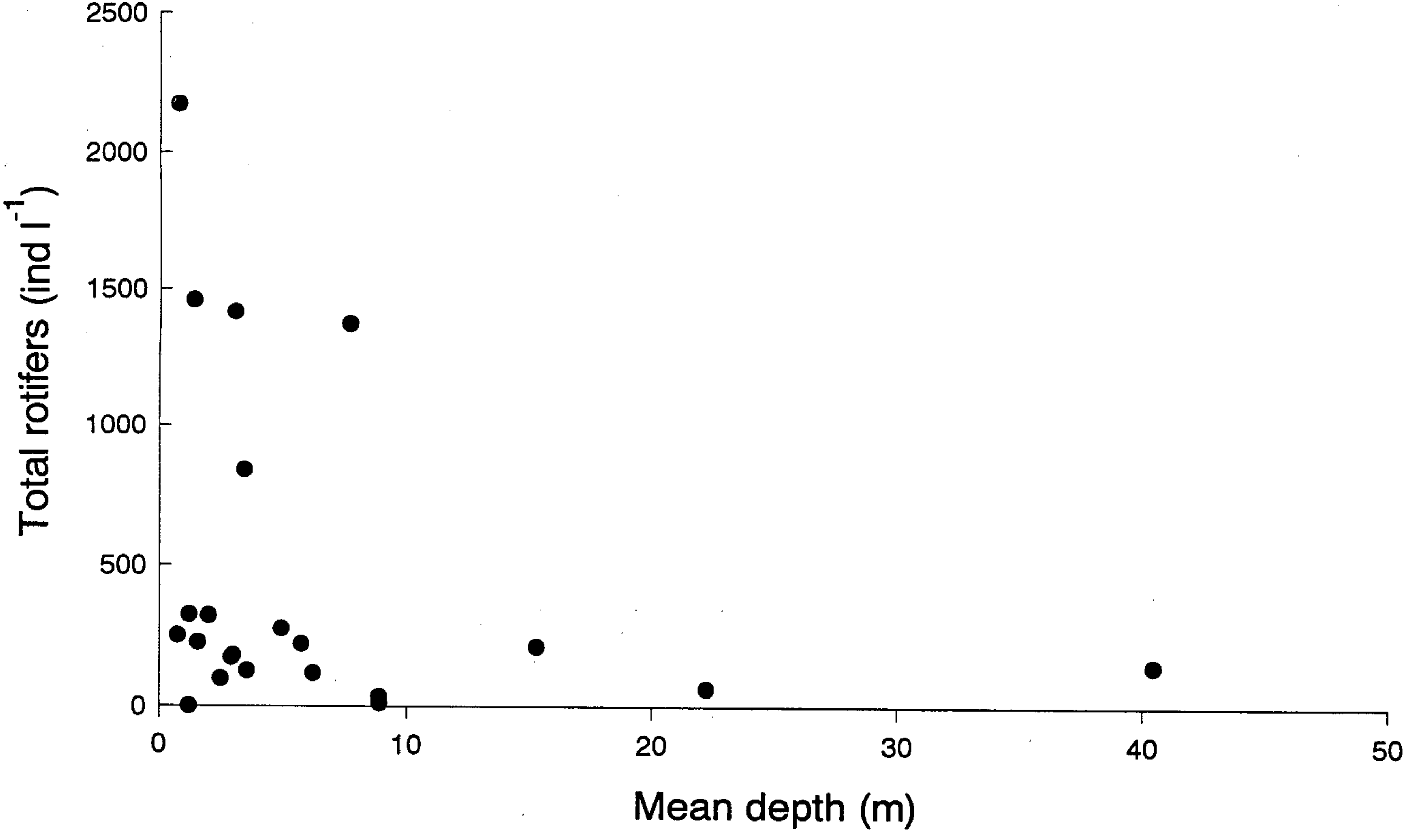


FIGURE 40

Total rotifers in relation to Secchi disk reading

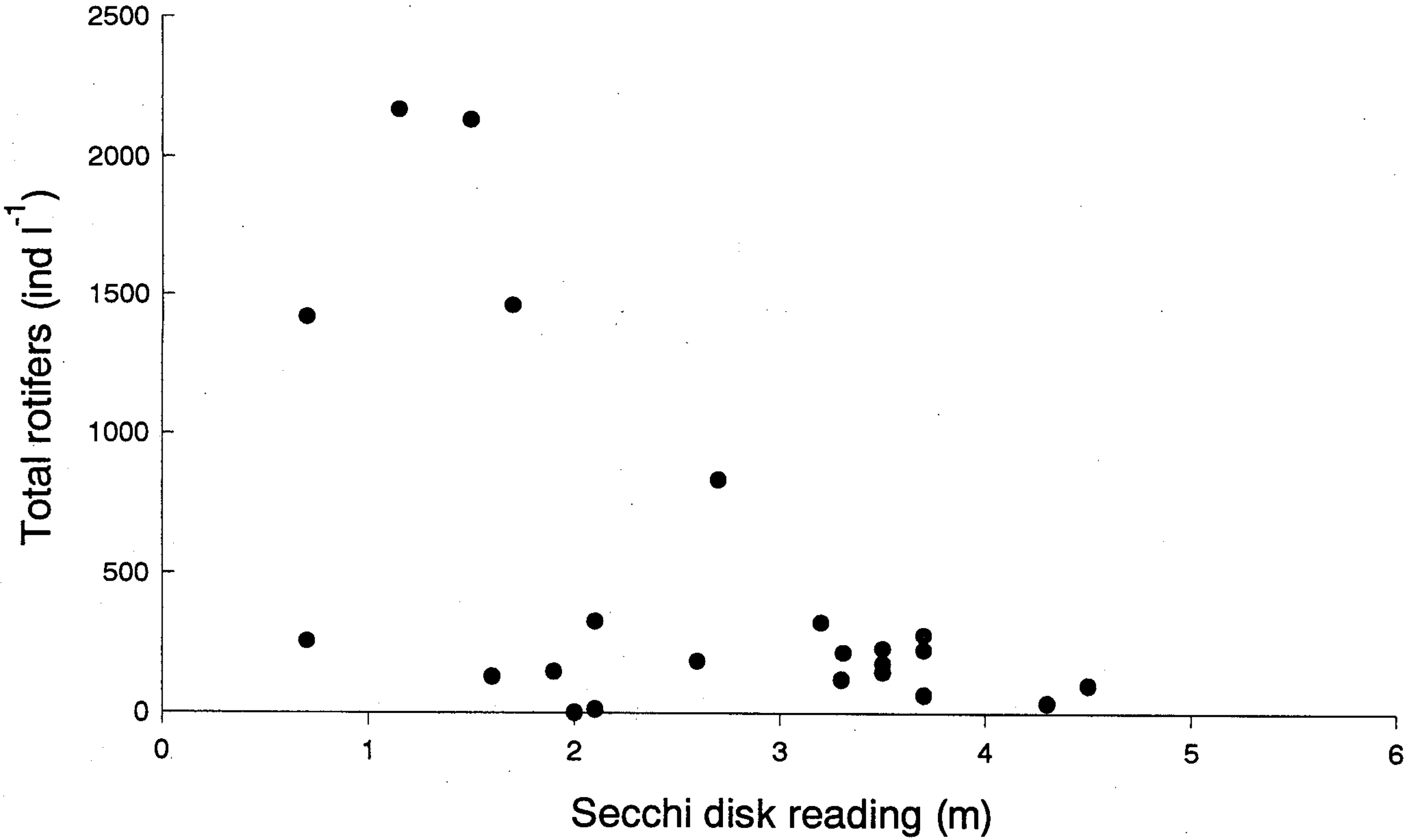


FIGURE 41

Total rotifers in relation to surface water temperature