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An assessment of the tolerance of the Lomond and Trossachs lochs to changes in land management and water use

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SUMMARY

Demands for water for power generation, potable supply and river compensation from the Lomond and Trossachs lochs are likely to increase, as is the accommodation of an increasing tourist population in this area. It would appear that the former requirement can be met by essentially environmentally friendly engineering. The latter development however, will necessitate more thought. This is primarily because a rise in the numbers of people leads to an increase in the production of nutrient-rich waste, and if this is not prevented from passing into the surface water network, eutrophication and its biological consequences - especially an increase in algal biomass - will result.

Enrichment with phosphorus (P) - a major component of domestic effluent and some runoff waters - is of especial concern, because this nutrient is the main chemical factor limiting algal growth in many Temperate waters for most of the time.

The Lomond and Trossachs Working Party needs information on the tolerance of the different lochs to potential nutrient-enrichment. Tolerance is gauged in this report in terms of the relative efficiency with which a waterbody converts its nutrient input to algal biomass; tolerance is high where algal populations remain low in spite of high nutrient burdens. The main focus is on planktonic algae (phytoplankton) but in some situations benthic forms associated with fringing sediments or stony substrates could be of equal concern.

The major factors determining tolerance to enhanced nutrient supply are:

- *loch volume* through its effect on dilution of inputs
- *flushing rate* which controls the time available for planktonic algae to capitalise on the nutrient resources.
- *mean depth* which influences the light climate of the (photosynthetic) algae
- *the tendency to stratify* which can enhance the production of phytoplankton even in very deep lochs
- *shoreline development* which indicates the likelihood of isolated bays in which water may reside for much longer than the calculated average flushing rate would suggest.

The investigative methods are described:

- map analyses for information on land use (for gauging pressures by way of eutrophication), on rainfall (for flushing rate calculations), and on loch area and depth (for considerations about depth-of-mixing and degree of thermal stratification).

- field and laboratory procedures for the collection and analysis of samples (from near the outflow in each loch) for information on pH, conductivity and nutrient levels, and the abundance and species composition of the algal assemblages.

Extensive transfers of water within the Indicative Area and their general effects on flushing regimes, water level fluctuations and the effective size of catchments, are also noted.

The Indicative Boundary as currently proposed, encloses 2000 km^2 of which only 120 km^2 (6%) comprises the loch water surfaces. Loch Lomond dominates the standing water resource, in representing 60% of the total loch area, and, along with Katrine and Lubnaig, some 90% of the total loch volume.

The map analyses, supplemented by information on vegetation cover abutting the loch shores, suggest that the following lochs are relatively heavily pressured by way of nutrient inputs:

- Achray, Ard, Earn, Eck, Lomond, Lubnaig, Menteith and Venachar, on the basis of the high percentages of agricultural and rural land.
- Doine and Iubhair on the basis of their high catchment-to-loch area ratios
- Iubhair on the basis of high shoreline length per hectare of loch surface area.

Water quality is high overall. pH values are mainly between 6 and 7 units, and conductivity values are generally low - 33 μS cm^{-1} in Doine, to 101 μS cm^{-1} in the southern basin of Lomond. Nutrient levels are also low: from < 1 μg nitrate -N l^{-1} in Lubnaig and Menteith (the latter due to algal uptake, however) to *ca* 150 μg N l^{-1} in Eck; from < 1 μg dissolved inorganic P l^{-1} in e.g. Achray and Finglas, to 7 μg P l^{-1} in Lomond (south basin).

Phytoplankton levels are correspondingly low with < 1 μg chlorophyll *a* l^{-1} in Sloy which is a highly, and possibly erratically, flushed system; the biggest value is only 11 μg l^{-1} - in Menteith which is the shallowest loch in this series (6 m mean depth), and one in which flushing is low (11.3 loch volumes y^{-1}).

None of the waterbodies meets all the specifications for high tolerance. This is mainly because large, deep waters which are also highly flushed and non-stratifying, do not exist. Equally, there are no waters possessing the combination of attributes of a highly productive system, i.e. one that is shallow, poorly-flushed and with a high point-source (runoff-independent) nutrient loading. Regardless of the flushing regime, however, benthic mats of blue-green algae are able to take hold.

Although the (summer) phytoplankton concentrations are low, there are many species, including potentially troublesome blue-green forms (cyanobacteria), which are also found in richer i.e. eutrophic, waters.

The importance of the weather in determining water quality cannot be over-emphasised. For example, the persistance of calm, stratified conditions favouring phytoplankton growth or re-distribution, for even a few days longer in one year than another, may be critical; and there are especially serious consequences for the water treatment authorities and tourist industry.

It is concluded that none of these waters can be considered very tolerant to enhanced nutrient inputs, although the larger, deeper lochs, and the rapidly-flushed systems are likely to be better 'equipped' to suppress phytoplankton growth - though not the development of benthic algal mats. However, if large lochs are allowed to deteriorate, the prospect of restoring them would be daunting.

The report recommends that:

i) the main focus should be on maintaining the high standard of water quality; existing knowledge would allow the control of eutrophication without stemming completely any further increases in tourism, and agricultural or rural development.

(ii) to aid (i), the Indicative Boundary should be extended to include the whole catchment of each loch; at present only part of the Loch Lomond catchment for example, is included.

(iii) a programme for maintaining a thorough surveillance on water quality in these lochs should be instigated.

1. INTRODUCTION

1.1 General considerations

The deliberations of the Working Party on the Lomond and Trossachs may result in recommendations for changes in the use of, and in the management practices associated with the lochs and their catchments. A main objective will be the protection and safe-guarding of the aquatic environments, taking due consideration of the requirements of conservation authorities, fishery and angling bodies, hydro-power, water supply and tourist industries, and the local communities. However, demands for water will grow and some further rural development, and changes in agriculture, forestry and aquaculture, for example, are likely to be sought. In addition, by the very nature of the outstanding natural beauty of the Indicative Area, pressures from tourism will increase.

The meeting of the demands for more water has been successfully met so far, by a number of essentially 'environmentally friendly' hydro-power and abstraction schemes (Scottish Hydro-Electric plc; LLT/WP/92/47; LLT/WP/92/48). From these it is plain that the recycling and/or transfer of enormous volumes of water can be engineered. For example, up to 100 x 10^6 gallons of water are transferred daily fro m Loch Katrine for the water supply to Glasgow; this is equivalent to 170 x 10^6 m^3 y^{-1} or 3.2 times the volume of Loch Leven, Kinross! The situation is quite different, however, regarding the accommodation of more tourists, and rural communities. Firstly, the extent and rate of growth is not so easily modelled as the erection of a new power plant or reservoir extension. Secondly, increases in the number of people lead to increases in nutrient-rich domestic waste, the consequences of which are often not ecologically desirable. Much of this waste ultimately finds its way to, or is consciously discharged into, the surface water network. Then, although nutrients (such as phosphorus and nitrogen) *per se* are only of major concern at very high concentrations, the potential biological and chemical manifestations of this eutrophication (see LLT/WP/92/44), are a major problem, and thus, the main focus of this report.

Unfortunately, nutrients also stem from otherwise desirable, agricultural activities such as the growing of cereals, rootcrops and vegetables, and the rearing of dairy and meat animals. Forest and woodland schemes also require fertiliser and any wastage results in elevated nutrient concentrations in runoff. Cage-rearing of fish is another activity leading to eutrophication. Depending on land management practices and crop fertilisation procedures, other substances that promote plant growth may also enter the surface water network e.g. organic compounds, calcium and potassium.

Enrichment with phosphorus (P) is of particular significance because it is the main chemical factor limiting algal growth in many Temperate waters, for most of the time. It thus commonly leads to enhanced algal growths which can be unsightly and smelly, and can increase the costs of water treatment, for example, and interfere with angling activities. A number of species of blue-green algae (cyanobacteria) are known to produce dangerous toxins and their presence can affect all water-related activities. Up to now the main focus of concern in this connection has been on planktonic forms. However, as exemplified by studies including those carried out from this laboratory, on Loch Insh (Watson, 1991), very rapidly flushed waterbodies are also susceptible, although the enrichment is manifested in benthic mats of algae rather than plankton blooms.

As the components of the aquatic environment are so inextricably linked, nutrient enrichment will sooner or later affect the abundance and species composition of rooted vegetation, bottom-living and planktonic fauna, and fish, as well as the different types of algae.

To aid the Lomond and Trossachs Working Party, to decide on land and water management strategies for the proposed area, this report outlines the factors
that control the degree to which a particular waterbody is able to tolerate changes that could lead to increased nutrient burdens ie. without producing troublesome blooms of algae, for example.

The tolerance of a loch to what can be considered as pressures from its catchment, is reflected in a number of its features and 'behaviour'. The functioning of a system is, in turn, the outcome of an interaction of a large number of physical, chemical and biological factors, the parameters of major importance are relatively few. The purpose of this report is to (a) identify these tolerance indicators and (b) describe the values found for the set of 17 main lochs lying within the Lomond and Trossachs area, and provide a broad analysis of existing conditions in these waters and (c) discuss the spectrum of likely tolerance of the lochs to increased nutrient inputs, taking account of the existing use of the waters, since this will affect judgements on what is 'tolerable'.

The methods used for the desk analysis of key physical features, e.g. land use and lake bathymetry, and for the water quality survey, are described first. Second, some general features of the Lomond and Trossachs area are reviewed. Next, the results of the study are presented, primarily by using tables and graphs to illustrate the ranges of the various indicators of tolerance, and to compare and contrast the values on the basis of these factors. Finally, the major findings of the study are discussed, some general conclusions are drawn, and some recommendations for the future management and protection of the systems are outlined.

1.2 Factors affecting tolerance to enhanced nutrient loadings

For present purposes, a waterbody which produces only sparse crops of algae or a thin cover of attached and rooted plants, in spite of substantial inputs of nutrients, is considered to tolerate enrichment to a greater extent than a loch that is characterised by dense overgrowths of rooted vegetation and/or blooms of algae. The present study is thus concerned with the factors that determine the efficiency of conversion of the nutrient resources into plant matter.

In general, more nutrients will lead to more algae, although the different 'mixes' of nutrients in different inputs will effect different responses. The contrasts between 'point' and 'diffuse' sources are especially important, not least because of associated physical factors. What may be nutrient-enriched runoff (eg from an area of fertilised ground), enters a loch in an essentially large volume of water, that enhances the flushing of the waterbody at the same time. Indeed, in some situations, the heavier the rainfall runoff, the lower the concentration of nutrients. Flushing rate (see below) is very important in determining how many planktonic algae, for example, are produced per unit of nutrient supply: the faster the flushing, the shorter the time available for these populations to capitalise on the nutrients and accumulate biomass. Hence, usually sparse plankton, but not necessarily sparse benthic populations, in swiftly flowing rivers and rapidly flushed lochs, regardless of nutrient levels. By contrast, effluents from sewage treatment plants and septic tank systems, ie from people, are commonly very rich in nutrients and are of low volume. Their effect on flushing is thus minimal, while their impact on nutrient concentrations and algal abundance can be considerable. Moreover, in the Lomond and Trossachs Area, point-source inputs are likely to peak with tourist activity in summer - just when other, primarily physical, conditions (see below) are most conducive to vigorous plant growth.

Physical conditions thus determine the extent, speed and duration of the plant response, and the following factors are especially important:

(i) *loch volume*: large systems are likely to be able to tolerate greater inputs of nutrients than small-volume lochs, simply in view of their greater diluting potential. This is especially important where low-volume, nutrient-rich, point-source effluents are common.

(ii) *flushing rate*: in addition to determining the time available for planktonic plants to utilise nutrients, the rate at which water passes through a loch (units, loch volumes y^{-1}, the reciprocal of water residence time in years) plainly controls the total amount of water that is renewed each year. In this respect, the flushing volume (the product of loch volume and flushing rate), is as important a feature of the water resource as loch volume *per se*.

(iii) *loch depth*: shallow lochs tend to be more productive than deep systems, because the light climate, which by definition determines the growth of photosynthetic organisms such as planktonic algae and rooted plants, is generally the more favourable in shallow lochs. However, trends in the production of planktonic algae for example, rarely parallel trends in loch depth perfectly, and there are a number of reasons for this:

- the algal production in very shallow waters can be impaired due to wind-induced disturbance of shallow deposits 'clouding' the water,
- communities of attached (benthic) algae or rooted plants which can colonise the greater areas of lighted substrates in shallow waters, can compete with the plankton for nutrients.
- shallow waters are commonly also rapidly-flushed, and this infers further advantages on the non-planktonic plants.
- as dissolved peaty substances limit light penetration into the water, a shallow peaty water may be loss productive than a deeper clear one.

(iv) *the tendency to stratify*: this is also a factor which complicates the relationship between algal production and lake depth, but deserves separate attention. While even deep lochs may be mixed from top to bottom for some of the year, such that algal cells are forcibly circulated into deep 'dark' water at regular intervals, these same lochs often function as shallow waters in summer due to their becoming thermally stratified. A surface layer of warmer, less dense water - the epilimnion - (up to 10 m depending on loch and weather conditions) develops, in which the light is favourable for enhanced algal growth. Under such stable conditions, too, (troublesome) blue-green algae commonly dominate the scene; they can exercise their advantage over other algae in being able to adjust their bouyancy with intracellular gas vesicles, and thus move up and down through the water column to layers of preferred light intensity or nutrient content. In this connection, it should be realised that visible aggregations of algae are not the perogative of shallow, nutrient-rich waters. The classic, surface blooms are more the result of a concentrations of a populations at the surface during calm weather, than of lake-wide growth or increase in numbers *per se*. Further accumulation of material into a bay may then result from a gentle on-shore breeze. While alarming, such scums may represent the major part of the whole population in the loch. What is more, the sequence of events culminating in an unsightly scum may depend on favourable conditions persisting just a few hours longer on one day compared with another.

(v) *shoreline development*: this is a term in physical limnology which indicates the degree of departure of the shape of the surface of a loch, from a circle. The value is calculated by dividing the actual length of shoreline by the perimeter of a circle with an area equal to that of the loch. High values would therefore suggest a somewhat tortuous lake boundary, with possibly isolated arms or bays. It is in such semi-enclosed areas, that water may remain for much longer than the calculated average flushing rates would suggest. Algal growth could be enhanced in these areas, particularly if they also receive localised enrichment from a hotel, for example.

2. INVESTIGATIVE METHODS

2.1 Desk analysis

Maps of the Indicative Area have been studied to estimate the 'natural' catchment areas of the lochs (see below). Coupled with rainfall data, this information has allowed the annual volumes of water runoff to be estimated, and theoretical flushing rates to be calculated (Bailey-Watts, May, Kirika and Lyle, 1992). Supplementary data from the MLURI (1992) report on land cover around the shores of the lochs, have been used to gauge the type and extent of land use, and the general levels of human occupancy in these catchments. The freshwater systems can be compared on the basis of this information, but as the present study has not permitted a fuller catchment analysis, the actual rates of nutrient export from the land to the lochs is not yet possible.

Loch depths have been taken from the bathymetric maps produced by Murray and Pullar (1910), updated where possible with information from documents by Scottish Hydro-Electric plc, the Central Scotland Water Development Board and Strathclyde Region, Water Department. The degree to which a water column is likely to stratify in summer was examined using the following relationship found by Hanna (1990), between lake area (A_l in km^2) and the depth of the top of the thermocline (z_t, in metres) the base of the upper layer of water - the epilimnion - in which algae may be entrained at this time:

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

Then:

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

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

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

One of the main features of the Lomond and Trossachs area, is the large extent to which the water resource has been abstracted for power-generation, potable supply and flow compensation. This itself is testament to the existing generally high quality of water in this area. As a result, however, natural hydrological regimes as regards flushing rates, seasonal cycles of water inputs and outputs, and water level fluctuations, prevail in very few of these systems. **Table 1** indicates the extensive suite of changes that have been made. These data need to be analysed more fully than the time assigned to this report permits, but it is already plain that some waters will be affected, to a considerable extent - though not by any means necessarily to their detriment. Indeed, the current good quality of water in some of the lochs may well be attributable to these changes, by increasing the flowthrough of water. Some enormous transfers of water that have been engineered: for example, the two aqueducts connecting Loch Katrine with the Glasgow distribution system, transfer 170 x 10^6 m^3 y^{-1} - equivalent to 3.2 times the volume of Loch Leven, Kinross.

Table 1. Catchments and hydrological regimes of the lochs in the Lomond and Trossachs area

Loch	Catchment
Achray	Includes Loch Katrine and its drainage area, but the actual transfer of water from Katrine to Achray is limited to 5 x 10^6 mgd ~ *ca* 8.3 x 10^6 m^3 y^{-1}
Ard	Includes the Loch Chon catchment.
Arklet	Own catchment only, but supplements Katrine.
Chon	Own catchment only, therefore no alteration.
Doine	Own catchment only, therefore no alteration.
Drunkie	Own catchment only, but some water is passed by controlled flow to Venachar.
Earn	Water additional to that draining from its own catchment is fed into this loch *via* the Breadalbane hydro-power scheme, but probably enters Loch Earn very near its outflow.
Eck	Own catchment only, so no alteration.
Glen Finglas	Own catchment only, but supplements Katrine.
Iubhair	Own catchment only, so no alteration.
Katrine	Receives some water from Arklet and *ca* 20 mgd (36 x 10^6 m^3 y^{-1}) from Glen Finglas; also supplies 100 mgd (170 x 10^6 m^3 y^{-1}) to the supply system for Greater Glasgow.
Lomond	A total yield of 100 mgd (170 x 10^6 m^3) for domestic supply is available, while in 1990-1991 the demand averaged 49 mgd (81 x 10^6 m^3 y^{-1}); receives water from Sloy *via* hydro-power turbines.
Lubnaig	Includes the Voil and Doine catchments which together exceed the immediate drainage area of Lubnaig itself (9065 ha) by ca. 10%.
Menteith	Own catchment only.
Sloy	Catchment has been recently increased from *ca* 1700 ha to 8000 ha by an extensive system of aqueducts and tunnels, bringing water from areas well to the north and south.
Venachar	Receives some water from Loch Drunkie, and all of the discharge from Achray, (including the 50 mgd (83 x 10^6 m^3 y^{-1}) from Katrine).
Voil	Includes the Doine catchment.

2.2 **Field work**

In order to obtain some up-to-date data on the nutrient status and general quality of these waters, samples were taken from the outflow of 16 of the lochs. Loch Eck was omitted due to shortage of time, but IFE data from summer 1991 are available, and these have been included in the results presented below. The information from all the lochs is comparable, although it is only a 'snapshot' of the conditions. Also, in the case of Loch Lomond, the outflow is representative of the shallower and richer southern basin and not the deeper, nutrient-poor northern trench (see Bailey-Watts and Duncan, 1981; Maitland, Smith, Bailey-Watts, Smith, and Lyle, 1981).

The opportunity was taken to assess the levels of planktonic algae (phytoplankton). The abundance and species composition of the assemblages are good indicators of water quality and of some of the physical features of the lochs, such as the tendency to stratify. They thus provide further information on the likely tolerance of a system to the pressures from the catchment. In addition, the phytoplankton studies give data on the incidence (at this time) of blue-green species, some of which are of particular concern to health departments and water supply authorities.

Two 500-ml bottles were filled. Subsamples were treated immediately by e.g. filtering for dissolved nutrient analysis, and fixing with Lugol's Iodine for algal investigations. As a routine, the temperature, pH, dissolved oxygen and total ionic content (specific conductivity) were measured, using a Corning 'Check Mate' probe system.

2.3 **Laboratory procedures**

The method of Mullin and Riley (1955) with procedures outlined in Golterman, Clymo and Olmstad (1978), were used for the determination of dissolved silica which is an important nutrient for diatoms and many chrysophycean algae. Murphy and Riley (1962) were followed for dissolved inorganic phosphorus (DIP) which is the fraction of P most immediately available for algal growth. Nitrate was measured by reduction with copper-cadmium to nitrite, and then by addition of acidified sulphanilamide solution, followed by N-(1-naphthyl-ethylene-diamine dihydrochloride (IFE modification A.P.H.A. of 1976). These methods are all based on the spectrophotometric measurement of coloured solutions produced by chemical reactions with the particular nutrient ions. In the case of the generally dilute, nutrient-poor Lomond and Trossachs waters, special attention was paid to obtaining repeatable results down to e.g. 1 μg P l^{-1} and 10 μg N l^{-1}. The concentration of total P which includes the fractions adsorbed onto, or incorporated in, particles including algae, was determined as for DIP, but on an unfiltered sample submitted firstly to strong acid digestion to convert all of the P to the dissolved form.

Chlorophyll *a* was determined as an index of total phytoplankton abundance; a measured volume of water was filtered onto Whatman Glass Fibre Grade C pads; the pad with the trapped material was then steeped in 90% methanol overnight at *ca* 4°C before the resulting green solution was centrifuge-cleared. The absorbance of the solution at a wavelength of 665 nm, was measured in a Phillips PU 8670 spectrophotometer, and the equation of Talling and Driver (1963) was used to convert these readings to chlorophyll *a* concentrations. The algae in the iodine-fixed samples were concentrated 10-fold by centrifugation, before introducing an aliquot into a Lund nanoplankton counting chamber. The number of individuals of the dominant species recorded at a range of magnifications from 40x to 600x, were estimated by counting under a Vickers Photoplan microscope, according to the procedures described by Bailey-Watts (1978).

2.4 Data analysis

The data gathered during this study have been mounted on μVax computer at the Edinburgh Laboratory of the Institute of Freshwater Ecology. Custom-designed programmes have been used for sorting the data, and the 'MINITAB' and 'SAS' packages have been used for statistical analysis and preparation of graphs.

3. RESULTS

3.1 General features of the study area and the relative pressures on the lochs as regards nutrient inputs from the catchments

The Indicative Area covers approximately 2000 km^2 only 6% of which comprises the surface of the lochs. Some 37% of the total area is occupied by the Lomond system, and this loch is by far the largest of the 17 standing waters, accounting for nearly 60% of the total loch area, ie 71 km^2 of 120 km^2. It is some 130 times the area of the smallest waterbodies covered here - Doine and Iubhair.

The area is dominated very much by semi-natural vegetation ie heath, grass and peatland (MLUIRI 1992, Plate 2 suggests a value of *ca* 90% of the land cover). However, woodland is prominent around Loch Ard and Loch Drunkie, and agricultural land is especially important around the southern end of Loch Lomond, and in a number of smaller areas e.g. the eastern end of Loch Venachar and both ends of Lubnaig. Nevertheless, MLUIRI (1992) found that woodland dominated the cover within the 1-km strip abutting the loch shores with more than 60% of the shore lengths of Achray, Ard, Chon, Drunkie, Earn, Eck and Lomond so covered. Contrastingly, ≥ 60% of the shorelines of Arklet (nearly 100%), Iubhair (65%) and Sloy (92%) face onto semi-natural vegetation.

The two categories of land from which potentially, the most nutrients could be lost that is, in terms of weight of material per unit area overtime (e.g. kg P ha^{-1} y^{-1}), are agricultural and rural developed land. Each of these, and especially the rural developed class, cover much smaller areas in total than woodland and semi-natural heathland and grassland etc., but they are locally important. For example, 42% of land abutting the Lake of Menteith shoreline is put over to agriculture, while the corresponding values for Achray, Venachar and Earn are all around 30%. Apart from Lubnaig (24%), the remaining waters gave values of < 20%. Contrastingly, Loch Lomond gave the highest value for developed rural land, i.e. 4%, much of which is concentrated at the south-western corner of the loch near the outflow. MLUIRI (1992) identified only 4 other lochs with this type of cover abutting the shorelines, ie Ard (3.7%), Earn (2.5%), Eck (1.3%) and Lubnaig (1.6%). On the basis of this preliminary consideration of the catchment characteristics, the following 8 waters are considered to be the most pressured in terms of the focus of this report: Achray, Ard, Earn, Eck, Lomond, Lubnaig, Menteith and Venachar.

It is probable that a better indication of the potential impact of the catchments on the lochs is obtained if catchment size and shore length are related to size of loch. This is done in **Table 2** using surface area as the measure of size.

Even if the loss coefficient of, for example, P from the catchments were very moderate e.g. 0.06 kg ha^{-1} y^{-1} - a rate characteristic of high altitude terrain, devoid of agriculture and human habitation (see e.g. Bailey-Watts, May, Kirika and Lyle 1992) - the total annual inputs of this nutrient to some of these lochs would be very high: for example 3.9 t to Loch Lomond, and *ca* 1.0t to Venachar and Lubnaig.

Table 2. Indices of likely pressures on the lochs as regards nutrient burdens from the catchments*: the catchment areas (A_c), the catchment-to-loch area ratio (A_c/A_l) and the length of shoreline per unit area of loch surface S/A_l

Loch	A_c(ha)*	A_c*/A_l	S/A_l (m ha^{-1})
Achray	12020	145.0	67.1
Ard	4450	18.3	51.4
Arklet	1910	8.1	47.2
Chon	1610	14.5	70.0
Doine	7470	136.0	not measured
Drunkie	570	10.0	126.0
Earn	13710	13.5	24.8
Eck	9890	22.5	54.0
Glen Finglas	3980	28.4	71.1
Iubhair	11750	218.0	153.0
Katrine	9400	7.6	32.1
Lomond	78100	11.0	20.0
Lubnaig	19020	76.4	67.1
Menteith	1620	6.1	35.5
Sloy	8000	69.0	63.8
Venachar	20260	48.6	35.1
Voil	9950	43.7	85.5

*The catchment areas for the lochs affected by water transfers (see Table 1) are often difficult to estimate, but as far as is known, the values shown here are good approximations.

The highest catchment-to-loch area ratios are calculated for Achray, Doine and Iubhair, but the value for Achray (145:1) is likely to be misleading. Firstly, while we have included in the 'natural' catchment of this loch, the catchment of Loch Katrine, a considerable volume of water (*ca* 170 x 10^6 m^3 y^{-1}) passing into Katrine does not reach Achray, because it is diverted for treatment for the population of Greater Glasgow. Indeed, the outflow of Katrine to Achray is also very carefully controlled. Secondly, all lochs retain a certain percentage of e.g. P entering them, and there is reason to believe that the value for Loch Katrine, which is essentially a very low-flushed system (see below) is 80%-90%. In this way, Katrine (the upper loch in the series) reduces the 'pressures' on Achray (the lower loch of this pair).

On the basis of the figures tabulated for metres of shoreline per hectare of loch surface, it appears that Iubhair - a relative long and narrow waterbody - has the longest stretch of land-water interface *via* which materials may enter the loch. By contrast, the larger waters such as Lomond and Katrine have the shortest interfaces with the land.

The other features of these waters that influence their tolerance to nutrient inputs, e.g. depth and flushing rate, are discussed in the following section. But it is noteworthy that the proposed set of Lomond and Trossachs Lochs range over an order of magnitude in mean depth ie from 6 m (Menteith) to 61 m (Lomond), some 10-fold in maximum depth ie from 19.5 m (Iubhair) to 189.9 m (Lomond), and *ca* 600-fold in volume ie from 4.2 x 10^6 m^3 (Iubhair) to 2631 x 10^6 m^3 (Lomond). The total volume of water held by the 17 lochs is *ca* 4.2 x 10 m^3. Loch Lomond accounts for approximately 63% of this (2.6 x 10^9 m^3), Katrine a further 18% (0.75 x 10^9 m^3) and Earn an additional 10% (0.43 x 10^9 m^3) ie > 90% in all. While some of the smaller waters such as Iubhair and Doine are extremely well-flushed (see below), because the total resource is so heavily dominated by the poorly-flushed, large basins of Lomond and Katrine (with water residence times of 2 and 4 years respectively), the total volume of water passing through the 17 lochs is probably little in excess of the total loch volume.

Aspects of water quality will also be considered later in this report in an attempt to relate the perceived pressures on the systems to e.g. summer nutrient levels. However, perhaps as a reflection of the extensive use of these waters for potable supply, and the proposals for protecting them, the current quality is high (**Table 3**). The waters are generally of circumneutral pH and low in total ion content. The low concentrations of nutrients measured in summer are likely to be reasonably typical of the waters, while if anything, the chlorophyll results are perhaps more indicative of the higher levels achieved than the mean year-round values.

Table 3. pH, conductivity (μScm^{-1}), nutrient and chlorophyll levels measured near the outflow in each of the Lomond and Trossachs Lochs in July 1992.

Loch	**pH**	**μS cm^{-1}**	**nitrate N (mg l^{-1})**	**dissolved PO_4.P (μg l)**	**dissolved CiO_2 (mg l^{-1})**	**chlorophyll *a* (*μg l^{-1}*)**
Achray	5.9	68.5	30	0.3	0.50	3.1
Ard	6.1	69.7	60	3.8	0.82	2.1
Arklet	5.8	50.9	31	0.0	0.32	4.4
Chon	5.8	53.0	57	1.2	0.92	5.2
Doine	6.5	32.8	2	0.4	0.37	3.1
Drunkie	5.3	71.7	107	0.0	1.40	2.3
Earn	6.8	72.1	31	1.0	0.71	4.4
Eck	6.9	49.0	150	1.8	1.12	1.3
Finglas	5.9	75.6	15	0.5	0.93	1.7
Iubhair	6.8	77.6	1	1.0	0.43	1.6
Katrine	5.9	48.1	46	0.2	0.52	1.4
Lomond	8.1	101.4	35	6.9	0.34	3.8
Lubnaig	6.7	70.9	1	1.6	0.39	3.0
Menteith	6.5	102.6	1	0.0	0.41	11.1
Sloy	6.0	45.5	10	0.3	0.73	0.9
Venachar	5.5	41.0	31	0.0	0.63	2.1
Voil	6.5	66.0	6	1.6	0.27	2.4

3.2 An assessment of the relative tolerance of the lochs to nutrient enrichment.

Values for the 5 factors identified as being of considerable importance in determining the tolerance of a waterbody to nutrient enrichment, are listed in **Table 4.**

Table 4. Major factors determining the tolerance of a loch to nutrient enrichment: volume (V_l), flushing rate (p), mean depth (z_{mean}) tendency to stratify as indicated by the thermocline depth (z_t) predicted from loch area, the ratio of z_t to z_{mean} (z_t/z_{mean}), and the shore line development coefficient (SLD).

Loch	V_l ($m^3 10^{-6}$)	p (loch volumes y^{-1})	z_{mean} (m)	z_t (m)	z_t/z_{mean}	SLD
Achray	9.1	6.3	11.0	6.72	0.61	1.725
Ard	32.6	1.5	13.4	8.19	0.61	2.260
Arklet	6.3	*	7.3	8.13	1.11	2.038
Chon	10.1	2.0	9.0	7.09	0.79	2.080
Doine	5.6	26.3	10.1	6.22	0.62	*
Drunkie	6.2	1.48*	10.8	6.26	0.58	2.683
Earn	408	0.5	42.0	10.67	0.25	2.231
***Eck**	67.4	3.4	15.3	9.14	0.60	3.198
***Finglas**	19.1	*	13.6	7.40	0.54	2.375
***Iubhair**	4.2	45.1*	7.7	6.20	0.80	3.163
***Katrine**	860	0.3	60.7	11.07	0.18	3.189
Lomond	2630	0.5	37.0	15.30	0.41	4.749
Lubnaig	32.4	11.8	13.0	8.23	0.63	2.986
Menteith	15.9	1.3	6.0	8.32	1.39	1.627
***Sloy**	*	*	*	7.14	*	2.010
Venachar	53.9	3.3	12.9	9.05	0.70	2.021
Voil	28.3	6.7	12.5	8.10	0.65	3.641

* denotes no data or values based on very rough estimates.

From the foregoing considerations about whether low or high values of these parameters enhance or inhibit the conversion of nutrients to phytoplankton biomass, it would appear that a waterbody with the highest degree of tolerance to increased nutrient inputs would have the following features:

(i) large in terms of volume - like Lomond, Katrine and Earn, for example.

(ii) rapidly flushed (ie with short hydraulic residence time) - like Lubnaig and Doine.

(iii) deep - like Lomond, Earn and Katrine

(iv) well-mixed even in summer, to a depth exceeding the mean depth - like Arklet and Menteith

(v) have a low shoreline development coefficient - like Achray and Menteith.

Peat staining of the water would also impair the conversion of nutrients to algal biomass.

None of the waterbodies in the present series meets all these specifications. There are 2 primary features that are unlikely to occur together in this part of the world: rapid flushing and large size, either as volume (**Figure 1**), or depth (**Figure 2**). Nevertheless, particularly in a wet summer which is the surface epilimnion potentially the most productive zone of a deep loch, may well be rapidly flushed; **Figure 3** identifies the lochs that are likely to stratify, ie where $z_t < z_{mean}$ and **Figure 4** relates the fraction z_t/z_{mean} to flushing rate, to show which of the stratifying lochs are highly flushed, and thus unlikely to produce dense algal populations even in summer. The abundance of summer algal populations depend very much on the weather. This means that while a run of wet summers could well ameliorate effects of increased nutrient loadings, a dry summer may trigger the return of troublesome blooms.

From the above analysis, it is plain that none of the Lomond and Trossachs Lochs conform in all respects to the 'ideal'. Nevertheless, the tolerance of a rapidly flushed loch of any size to nutrient burdens, is likely to exceed that of a system in which the water resides for many months, even years. A fuller investigation of the water input-output regimes of these waters is necessary. For example, in the apparently low-flushed Loch Katrine, the various transfers of water and other perturbations to the natural outflow may effect fluctuations in water depth rather than flushing *per se*.

While there appear to be no waters in this set that can be considered highly tolerant to nutrient enrichment, equally, there are no lochs possessing all the major physical attributes conforming to what would be viewed as a potentially highly productive system, ie of extremely low tolerance, by being small, shallow and poorly flushed (Figures 1 and 2). Such systems do exist in Scotland, however, eg Coldingham Loch, Berwickshire which is highly productive and prone to algal blooms (Bailey-Watts 1987) although also far richer in nutrients than any of the Lomond and Trossachs waters (Bailey-Watts, Lyle, Kirika and Wise 1987).

It is emphasised again that the tolerance of these lochs to nutrient enrichment is quite different if the criterion centres on the likelihood of enhanced benthic algal growths. The results of the studies on Loch Insh (Watson 1991) show how, even in a rapidly flushed lake, unsightly, smelly mats and highly toxic cyanobacteria can develop. The main requirements then are nutrients and areas of sediment which are of suitable physical structure and (presumably) lie within the illuminated zone.

3.3 Summer phytoplankton levels and species composition in relation to physical features of the lochs

None of the lochs appeared to have very dense crops of phytoplankton in July 1992, and this is not surprising considering the generally low levels of nutrients and major ions recorded (see Table 3). Menteith had the highest chlorophyll concentration i.e. 11.1 $\mu g\ l^{-1}$ which was more than double the value of 5.2 $\mu g\ l^{-1}$ recorded in the next richest loch on this basis, ie Chon. It is noteworthy that Menteith conforms nearest to the type of waterbody that is likely to be reasonably efficient in producing algae; it is the shallowest loch in this series at 6.0 m mean depth (**Figure 5**) and one of the least rapidly flushed with a value of 1.3 loch volumes y^{-1} (**Figure 6**). It is however, one of the waters identified as being potentially rich because of the agricultural land abutting a considerable portion of its shoreline - and it contains a fish cage from which further nutrient burdens can be expected (see IoA, IFE and ITE 1990).

Loch Earn also features high in the list of summer chlorophyll levels and it has agricultural land and some rural development on it shores. It is fairly large ($V_l = 408 \times 10^6\ m^3$) and deep ($z_{mean}$ = 42.0 m - Figure 5) but it also stratifies. Above all, it is probably very poorly flushed (0.5 loch volumes y^{-1}- Figure 6), and like Menteith, it contains fish cages.

At the other end of the spectrum of chlorophyll concentrations is Sloy ($0.9\ \mu g\ l^{-1}$). This is not surprising in that the water draining into this reservoir comes mainly from high altitude, nutrient-poor terrain. In any event too, even in the absence of sound information on the hydrological regime, it is likely to be rapidly and possibly erratically flushed. Similar considerations about flushing rate would explain the algal levels of $\leq 2\ \mu g$ chlorophyll *a* l^{-1} in Finglas, Iubhair and even Eck. The value for Katrine is also $< 2\ \mu g\ l^{-1}$, yet, as far as can be ascertained, at present, it has a very long water residence time, and although it is very deep, it is likely to stratify in summer, and its nutrient content is not markedly lower than those of a number of the other waters (see Table 3).

The generally sparse nature of the phytoplankton in these waters is in keeping with the oligotrophic character of the area. Only Menteith would be classified as other than oligotrophic, and then only mildly mesotrophic. Nevertheless, the microscopic examination of the algae has revealed some interesting features. Firstly, there are a number of waters in which there are some species which are known to thrive in richer eg. eutrophic waters - but then at much higher population densities than recorded during this study. These 'eutrophic' indicators are included in **Table 5**. Secondly, there are some very high concentrations, albeit of small-celled species, in a few locations eg. 8.4×10^4 colonies ml^{-1} ($= 8.4 \times 10^7\ l^{-1}$) of the blue-green alga *Merismopedia tenuissima* in Chon. Other 'classic' blue-green algae such as *Anabaena* , are also present in a number of the waters.

Table 5. Some main features of the phytoplankton assemblages in the Lomond and Trossach Lochs - July 1992

Loch	**Phytoplankton composition: figures in parentheses indicate the number of individuals per millilitre of water**
Achray	Eutrophic forms include the blue-green *Anabaena flos-aquae* (3), *Aphanothece clathrata* (2000) and *Merismopedia tenuissima* (1400), and the green algae *Raphidonema* (40) and *Monoraphidium minimum* (650). [2 rotifers characteristic of eutrophic water were also recorded - *Keratella cochlearis* and a *Polyarthra* species].
Ard	*M. tenuissima* (4200) and *A. flos. aquae* (2), but also a dense background of 'picoplankton' cells *ca* 1 μm (34200), plus cryptomonads (150), chrysoflagellates (1500) and an occasional desmid (*Staurodesmus indentatus* - $< 1\ ml^{-1}$).
Arklet	Eutrophic *Raphidonema* sp. (540) and *Ankistrodesmus*, nr. *A. falcatus* (270), plus a background of small chrysoflagellates (4200), picoplankters (4800) and *M. tenuissima* (11100).
Chon	A few chrysoflagellates (40), but otherwise a near-pure stand of *M. tenuissima* (84000).
Doine	A 'poor' flora, but one in which an *Anabaena* - possibly the *treleasii* form of *A. flos-aquae* - is most prominent (12).

Table 5 Continued

Drunkie	A highly eutrophic assemblage dominated by green algae of the genus *Oocystis* (1800) and ?*Crucigenia fenestrata* (1500), an unidentified green algae ?nr *Crucigenia* (160), plus picoplankters (28000) and small chrysoflagellates (3600).
Earn	A very diverse assemblage, with at least 20 species recorded during the routine counting. Mesotrophic-eutrophic diatoms e.g. colonial *Asterionella formosa* (46) and *Fragilaria crotonensis* (11) and unicellular forms (400). Background of cryptomonads (110), green algae including the colonial *Pseudosphaerocystis lacustris* (110), some desmids (2-4) and a background of picoplankters (4800) and small chrysoflagellates (80).
Eck (from July 1991)	Eutrophic *A. flos-aquae* (15) and green algae including *Ankistrodesmus closterioides* (2), *Monoraphidium contortum* (480), *Oocystis* species (200); yet also the oligotrophic-mesotrophic diatom *Tabellaria fenestrata* (2 colonies) and the chrysoflagellate *Dinobryon* (<1 colony).
Glen Finglas	*A. formosa* (2), *A. flos-aquae* (2), picoplankters (1800) and small chrysoflagellates (300) - a very sparse crop.
Iubhair	Sparse, e.g. *Tabellaria flocculosa* (2 colonies), cryptomonads (75) and small chrysoflagellates (180).
Katrine	Picoplankters are numerous (ca 7200) and the crop is very sparse, but a mixture of oligotrophic indicators such as the desmid *Staurodesmus ?subulatus* (3), the diatom *Rhizosolenia* (<5) and the chrysoflagellate *Ochromonas* (50). Also, eutrophic types e.g. the green algae *Oocystis* (60) and *Monoraphidium* (30), and the blue-green *Aphanothece clathrata* (60).
Lomond	The sample is likely to mirror conditions in the southern, shallow, mesotrophic basin rather than the northern, deep oligotrophic sector, but it is a very sparse crop. The following species may reflect the relatively high pH and conductivity values (see Table 2): the filamentous diatom *Aulacoseira subarctica* (1) the colonial diatoms, *Tabellaria fenestrata* (1) and *T. flocculosa* (2), the colonial cyanobacterium *Coelosphaerium* (<1), the desmid *Cosmarium botrytis* (1), plus cryptomonads (10) in addition to picoplankters (9100).
Lubnaig	Eutrophic faces are evident with the blue-green *Anabaena flos-aquae* (7) and small colonies of *Microcystis aeruginosa* (<1) and *Aphanothece* (2100) in addition to small green algae e.g. *Monoraphidium minimum* (80), and unicellular diatoms (250).

Table 5 Continued

Menteith	Probably the richest of the lochs in this series, and with the densest algal crop (and the lowest nitrate and dissolved phosphate levels - see Table 3); eutrophic' forms are prominent e.g. the diatoms *Fragilaria crotonensis* (60 colonies), *Asterionella formosa* (9 colonies), and *Aulacoseira subarctica* (11); the cyanobacteria *Anabaena flos-aquae* (7), *A. spiroides* (2) and *Oscillatoria ?bornetii* (2); Unicellular green flagellates (180). Another blue-green alga, the colonial *Gomphosphaeria lacustris* is also present; in iodine, however, this alga fragments, and while 36 000 cells ml^{-1} were estimated, this probably represents < 10 colonies ml^{-1}.
Sloy	A mucky sample, with picoplankters (4800), small chrysoflagellates (400), small cryptomonads (100) dominating a thoroughly uninspiring assemblage.
Venachar	Another sparse, but this time, diverse crop: *Tabellaria fenestrata* (5), *Anabaena flos-aquae* (<1), *Anabaena* ?sp (<1), the diatom *Cyclotella comta* (5) and cryptomonads (40), along with a background of very small-celled aggregations of species of *Microcystis/Aphanothece.* These indicate a mildly enriched system.
Voil	Also sparse, but dominated by *Dinobryon bavaricum* (100), a colonial chrysoflagellate indicating nutrient-poor conditions. Small green unicells (3-7 μm in diameter) also abundant (1200), along with very tiny (*ca* 2 μm), possibly colourless, flagellates (1200).

*Many of the counts from which the population densities are estimated, are very low; this means that 95% confidence intervals of the figures shown, may be ± 200%; even this, however, does not alter the general impression gained about these assemblages.

4. CONCLUDING DISCUSSION

4.1 Major findings and general conclusions

None of the lochs within the proposed Lomond and Trossachs Indicative Area is eutrophic, and indeed, high water quality is a general hallmark. This is primarily due to the relatively small amounts of intensive agriculture, rural development and urbanisation in these catchments. At the same time, most of the waters are either deep or well-flushed - features leading to a generally low conversion of nutrient supplies to potentially troublesome populations of planktonic algae. The flushing rates of some of the lochs may also be enhanced by water transfer schemes, even though the latter often increase the effective catchment areas and thus nutrient loadings. These considerations do not apply to benthic algae, however; problems with dense mats of these forms can arise even in rapidly flushed waters as long as nutrients and suitable substrates are available.

In spite of generally oligotrophic conditions, the concentrations of planktonic algae, albeit small species, can be considerable - with 10^3 - 10^4 cells ml^{-1} - and a number of the types recorded are also found (in greater numbers) in much richer, even eutrophic, waters.

The importance of the weather in determining water quality *vis a vis* algal levels, cannot be over-emphasised. There are 3 main considerations here. Firstly, rainfall patterns through their effect on water runoff, control flushing regimes, while wind and temperature control water movements, the depth of mixing and thus, the extent of thermal layering (stratification). Secondly, even quite minor year-to-year variation in weather patterns can effect marked differences in algal growth. If, for example, conditions favouring the increase in numbers of some species, persist for a week or two longer than usual, double the 'usual' biomass may be achieved. Thirdly, the dynamics of weather patterns over very short timescales e.g. days, even hours, may also be significant. Good examples are the build-up of some of the classic, potentially troublesome, blue-green algae at the surface of a loch and/or on a windward shore. As these accomulations are largely the result of a re-distribution of the populations rather than growth *per se*, they can cause problems even in waters as intrinsically dilute as many of those in the Lomond and Trossachs Area.

The weather is also a major determinant of temporal variability in the abundance of benthic algae. The development of the mats of particularly toxic and odorous species of cyanobacteria in Loch Insh, coincided with the recent warm summers. Nevertheless, they also follow an extraordinary sequence of 25-year and 100-year floods in successive winters 1989 and 1990, which also inundated local sewage treatment works and septic tank systems (Watson 1991).

The apparent severity of the effects of increases in the levels of any algae depends on the time of year, and especially on how many people are present, and on how the water is used. Plainly, where the major points of focus are, as here, on (i) draw-off of water destined for potable supply, (ii) water sports and (iii) conservation of communities of rate aquatic plants and fish, the consequences of factors inducing even slight increases in algal biomass can be very serious.

Finally, none of these lochs can be considered very tolerant to enhanced nutrient inputs, although plainly the larger, deeper waters, or the well-flushed systems are likely to be relatively better 'equipped' to suppress phytoplankton growth at least. However, if the larger waters are allowed to deteriorate, even though this might take a long time, the prospect of restoring them would be daunting in the extreme.

4.2 Recommendations for the future protection of the Lomond and Trossachs waters

It is recommended that:

(i) the main thrust of the management of this Area should be on maintaining the present high quality of water; thus, while every effort should be made to reduce the present loadings, the priority should be given to ensuring that the rates of input of nutrients do not increase; the potential sources of greatest significance in the Lomond and Trossachs Area, are hotels, restaurants and toilets, although any proposals for intensifying agriculture - especially near the loch margins - should be stemmed; existing knowledge, expertise and technology facilitate the control of eutrophication without placing complete embargos on tourism, rural development and agriculture etc.

(ii) to aid (i) the proposed Indicative Boundary should be extended to include all parts of the catchments of the lochs; the present perimeter excludes a large portion of the southern part of the Loch Lomond catchment, for example.

(iii) chemical and biological aspects of water quality should be carefully monitored and in this case, a highly proficient approach is necessary, and one that takes account of benthic algae as well as the plankton; some of the organisms recorded during the present study, would not be noticed/detected by a casual observer.

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FIGURES

Figure 1. The absence of points in the top right hand sector of this graph, illustrates that there are no large lochs which are rapidly flushed. Note that because of the similarity between Venachar and Eck, the 3-letter labels for these lochs overlap.

Lomond and Trossachs lochs – flushing rate related to loch volume

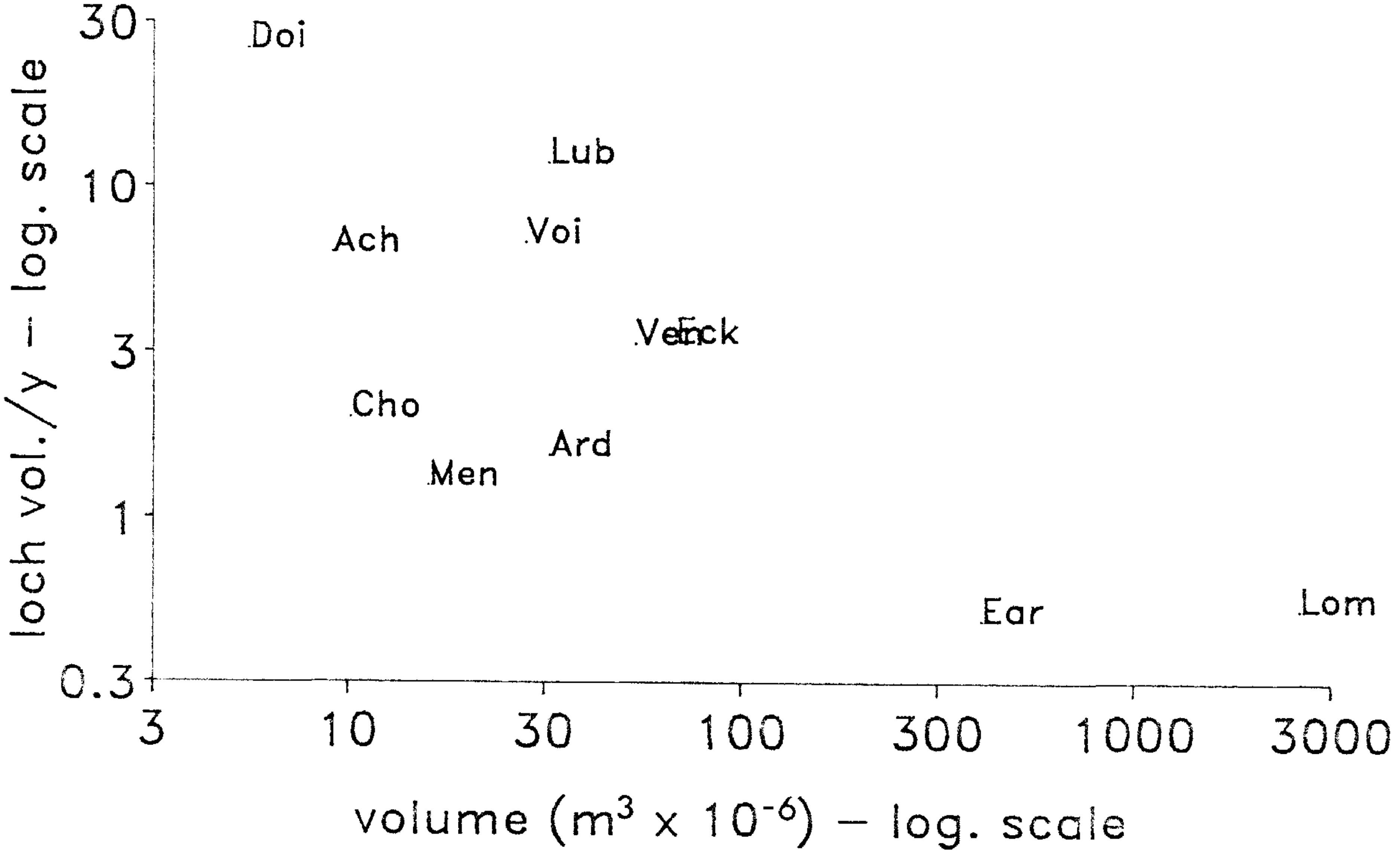

Figure 2. As Figure 1 to illustrate the absence of deep, rapidly flushed lochs. Due to similarities between the following pairs of lochs, their labels overlap: Achray and Voil, Venacher and Eck, and Lomond and Earn

Lomond and Trossachs lochs – flushing rate related to loch mean depth

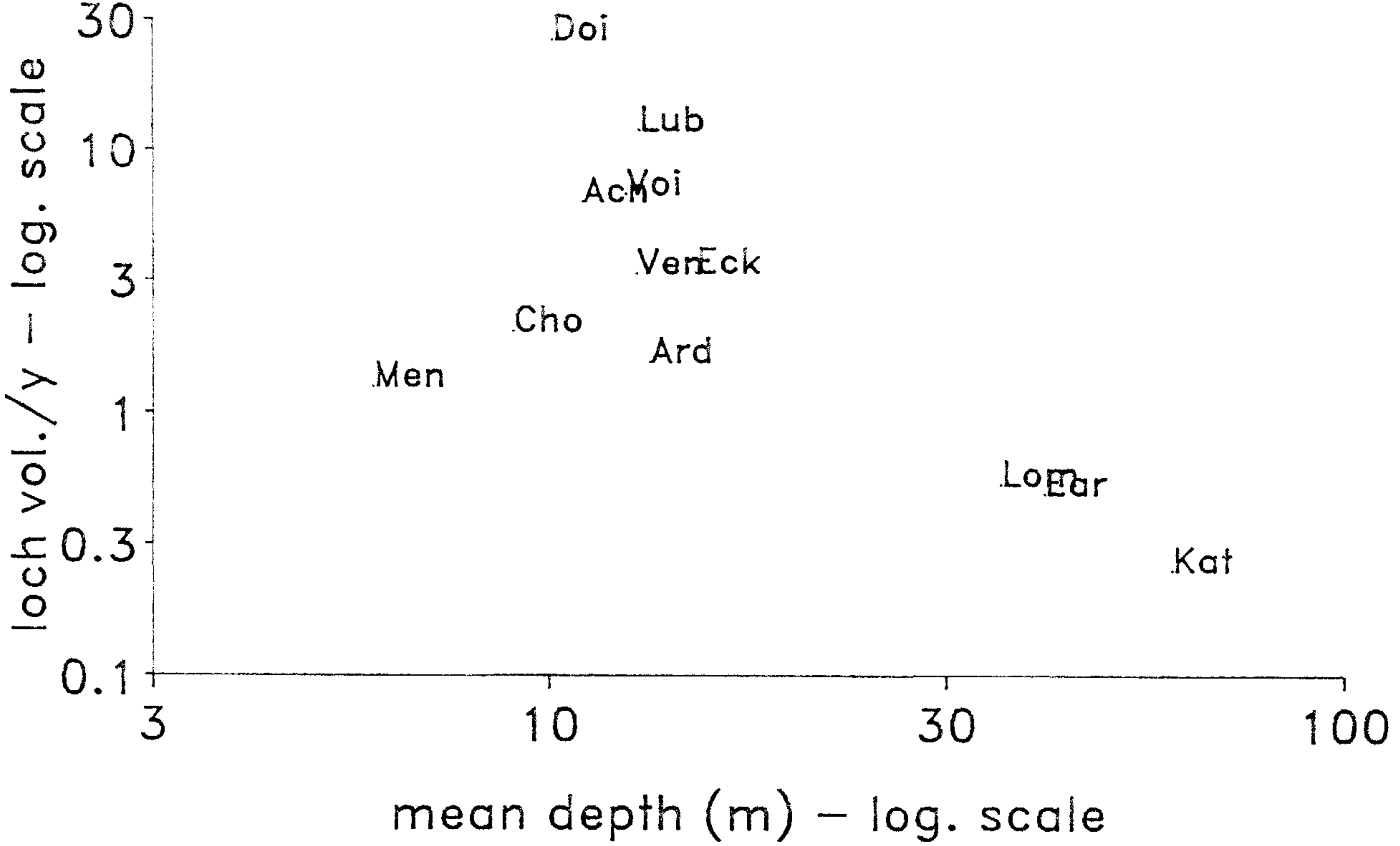

Figure 3. The majority of these lochs are likely to stratify in summer, especially those corresponding to the points furthest right of the line which represents the condition where the thermocline depth equals the mean depth. Thus, only in the Lake of Menteith and Loch Arklet is thermal stratification unlikely. Note that because the pairs of values plotted for Doine and Drunkie, and for Voil, Ard and Lubnaig, their labels overlap

Lomond and Trossachs lochs – predicted depth of thermocline related to loch mean depth

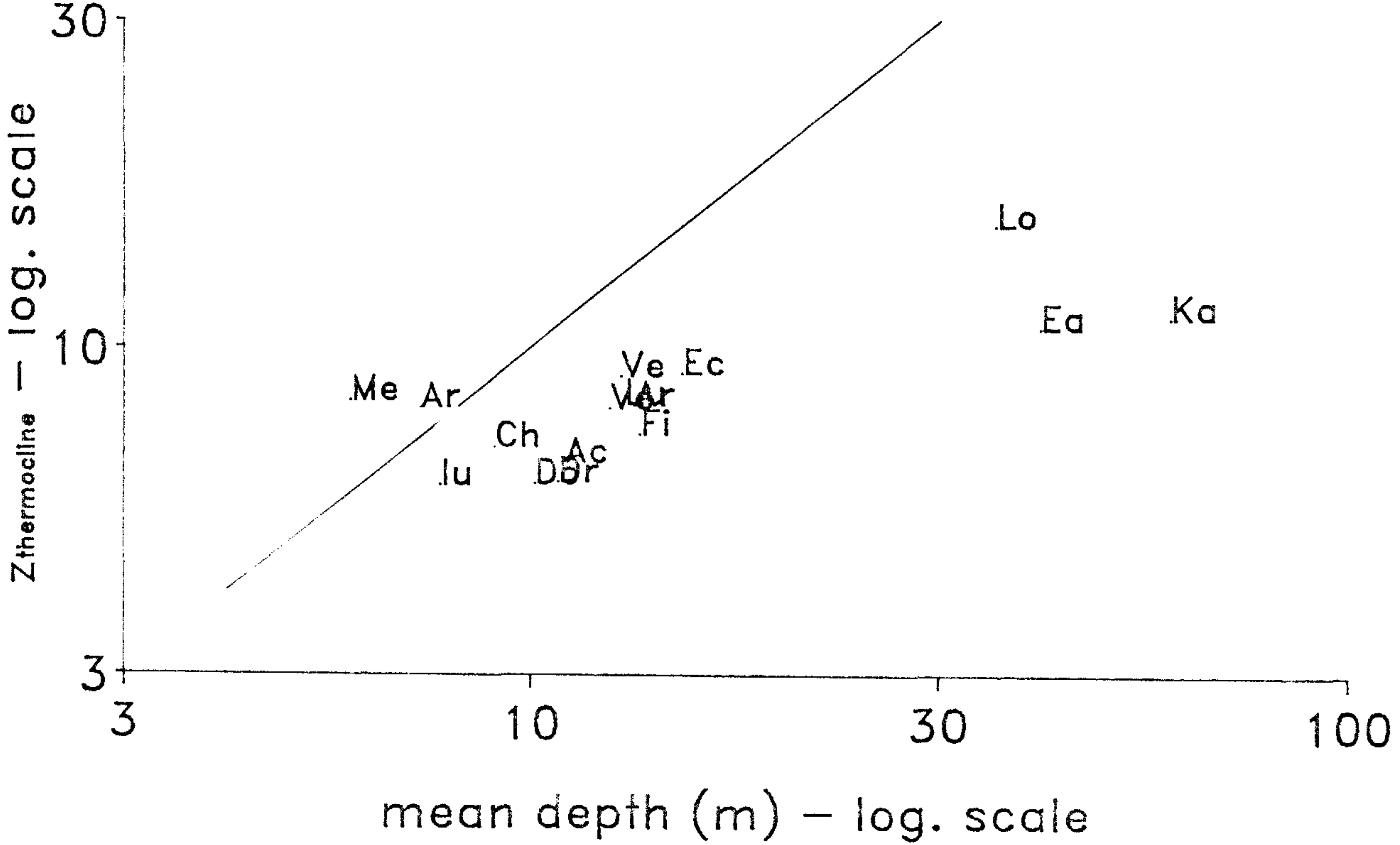

Figure 4. Apart from the Lake of Menteith, where $z_\tau/z_{mean} > 1$ the lochs referred to in this plot stratify in summer. The higher the flushing rate, the greater the susceptibility of the summer epilimnetic populations of algae, in these lochs, to losses by washout.

Lomond and Trossachs lochs – thermocline depth/mean depth, related to loch flushing rate

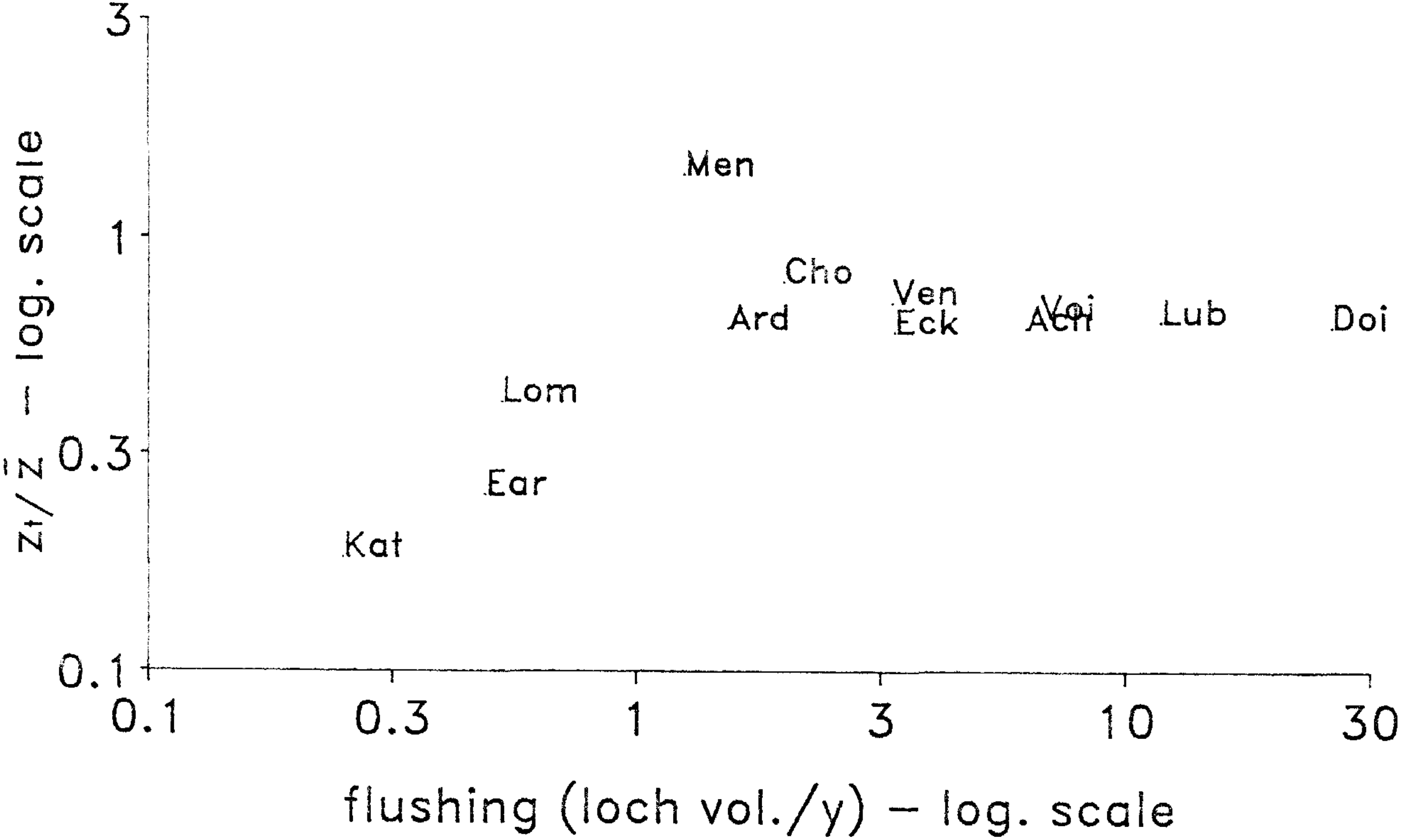

Figure 5. Two distinct groups of waters are revealed when the summer chlorophyll concentrations are related to loch mean depth, with, in each group, phytoplankton abundance generally declining with depth of loch.

Loch Lomond and Trossachs Area – summer phytoplankton concentration related to loch mean depth

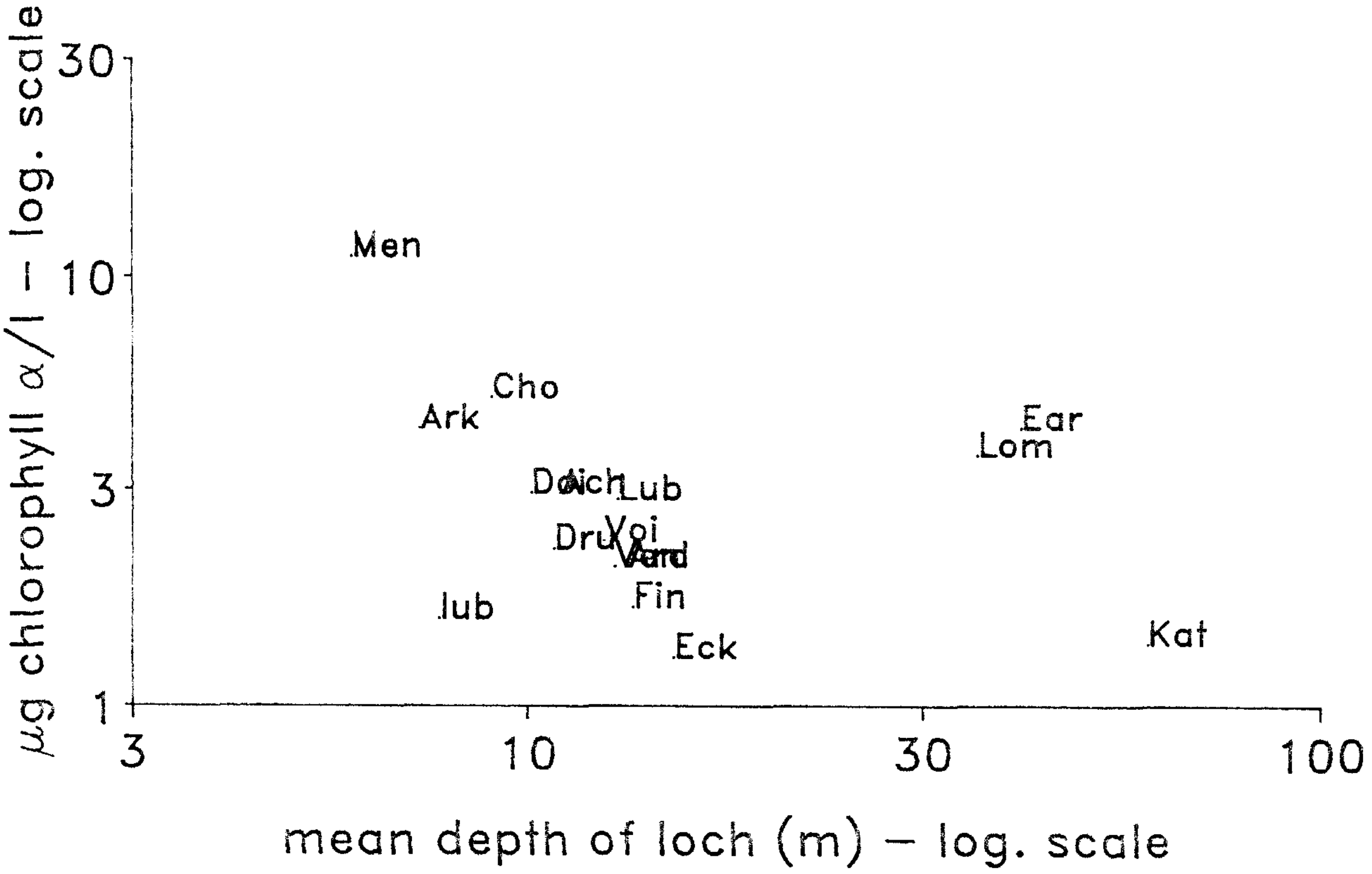

Figure 6. There appears to be no consistent relationship between summer phytoplankton abundances and the mean annual flushing rates of this series of lochs, although the absence in the top right sector of the graph is predictable.

Loch Lomond and Trossachs Area – summer phytoplankton concentration related to flushing rate