A RE-ASSESSMENT OF PHOSPHORUS LOADINGS TO LOCH LEVEN, KINROSS-SHIRE AND THEIR IMPLICATIONS FOR EUTROPHICATION CONTROL BY PHOSPHORUS REMOVAL.

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C O N T E N T S

SUMMARY

1. Phosphorus (P) loadings to Loch Leven are assessed with reference to published and unpublished information including data from the current year, on loch and inflow chemistry. Findings are compared with results of a preliminary assessment by the WRC; that study was commissioned by the Forth River Purification Board to assess a proposal to control P inputs to the loch, and is largely based in 1978 loading figures.

2. For the non-specialist reader the link between phosphorus, lake enrichment (eutrophication) and algal blooms is outlined.

3. It is recommended that the aims of reducing P loadings to the loch be carefully defined; the 'improvement' (of the loch) as required by the Board and others is contrasted with 'a change in trophic status' which issue features prominently in the WRC report.

4. The industrial (L_I), atmospheric (L_A), sewage derived (L_S) and run-off (L_R) components of the total P loading (L_T) are assessed, mainly with reference to data on levels of total P as opposed to its various particulate and soluble fractions.

4.1 Studies done since 1980 on the chemistry of the South Queich show that (i) P concentrations in the lower reaches vary typically between 100 and 1,000 $\mu g\ P.l^{-1}$ whilst upstream concentrations of <u>ca</u> 25 $\mu g.l^{-1}$ are common,

(ii) high values are associated with mill effluent, and (iii) P in dye stained waters is initially unreactive (biologically unavailable) but is partially transformed within a few hours to the reactive form readily utilised by algal plankton. Recent rises in P concentrations in the South Queich, suggest that L_I is now higher than the 7.5 $kg.wk^{-1}$ given for 1978 but no accurate re-estimates are yet available; meanwhile a value of 15 $kg.wk^{-1}$ is taken.

4.2 Atmospheric inputs of 27.5 kg $P.wk^{-1}$ (for 1978) are some five times higher than values published for other localities - the estimate is retained for present purposes however, as although it cannot be accounted for by P in rain (recent collections show concentrations of $<$ 25 $\mu g.l^{-1}$), dry deposition rates are conceivably very high.

4.3 Using information from the most recent local population census, the estimate of P entering the loch in effluent from the major sewage treatment works (L_S) is <u>ca</u>. 128 $kg.wk^{-1}$ - around double the L_S for 1978.

4.4 In contrast to the low 1978 L_S value, the figure for the 1978 L_R (112.5 $kg.wk^{-1}$ in run-off <u>via</u> streams) is considered to be a gross over estimate. A current value of around only 52 kg. wk^{-1} is supported by:-

(i) calculations using loch volume, annual run-off volume and the 1978 L_R which indicate a mean inflow P concentration of 67 $\mu g.l^{-1}$ *cf* typical measured values of only 25 $\mu g.l^{-1}$, and

(ii) the application of published P export rates to measures of percentage agricultural and non-arable land in the Leven catchment - resulting in a new L_R of 51.64 kg. wk^{-1}.

4.5 The study results in a current L_T estimate of 223 kg $P.wk^{-1}$ ie:

$15 (L_I) + 28 (L_A) + 128 (L_S) + 52 (L_R)$

the similarity between this figure and the 215 $kg.wk^{-1}$ calculated for 1978 is supported by other data on algae and phosphorus. Measured annual mean algal biomass levels have shown little difference between 1978 and the present; a strong relationship exists between annual values for mean algal biomass and phosphorus loading 1968-1978. Moreover phosphorus concentrations in the loch have shown no marked changes since 1978.

5. The implications of the new assessments for decisions on phosphorus control options are discussed.

5.1 Of especial relevance is the high percentage contribution by point sources of phosphorus ie (in $kg.wk^{-1}$):-

$$\frac{128\ (=L_S) + 15\ (=L_I)}{223\ (=L_T)} \times 100 = 64\%$$

5.1.1. If 90% of the P in a combined industrial and sewage treatment effluent were removed, the L_T to the loch would be reduced to 95 $kg.wk^{-1}$

ie:-

$$223\ (= \text{present } L_T) - [0.9\ (128 + 15)] = 94.3$$

$$kg.wk^{-1} \text{ or } 0.369\ g\ m^{-2}.yr^{-1}$$

5.1.2. A loading of 94.3 $kg.wk^{-1}$ would effect a reduction in the mean concentration of P in the loch to around 57 $\mu g.l^{-1}$.

5.1.3 On the basis of an OECD algae-P model the reduced loading and mean concentration of P would be accompanied by a fall in mean chlorophyll levels from 32 $\mu g.l^{-1}$ (1982 value) to around 15 $\mu g.l^{-1}$. This predicition is supported by results of nutrient enrichment experiments on Loch Leven phytoplankton indicating that further increases in the densest populations are already limited by phosphorus availability.

6. The present assessment thus indicates that removal of P from sewage and industrial effluent would result in a considerable improvement in Loch Leven water quality; a particularly marked reduction in algal-available soluble reactive P can be expected as this fraction is a large component of P in sewage effluent. It is emphasised however that further work is necessary to obtain proper estimates of the current loadings and to assess the likely influence of phosphorus released from the sediments.

1 INTRODUCTION

This document assesses the current loadings of phosphorus (P) to Loch Leven. It comments on a recent Water Research Centre assessment (in the form of a letter from Mr R E Youngman to Mr W F Collett (FRPB), but thereafter referred to as the Report) which, on the basis of loading estimates for 1978, evaluates a proposal to control P inputs to the loch. The Report was commissioned by the Forth River Purification Board following discussions between the Board and Tayside Regional Council on the deteriorating conditions of the streams flowing into the loch. The present document firstly outlines why particularly the P content of the feed waters is an important consideration in attempts to control eutrophication. Secondly, the general evaluation by the Report of P removal proposals is considered. Thirdly, figures for different components of the total loading of P (L_T) are next examined and in most cases modified, in the light of chemical and other environmental data collected by my laboratory from 1980 to the present.

A considerable amount of information on Loch Leven could not be considered by the WRC in the time it had available for preparing its report. The data are however essential for establishing a sound base on which any further necessary research can be designed, and management proposals sensibly developed. One data set includes the information relating to conditions over the last 3 years, and referred to above. The other set is a much larger array of long-term chemical information gathered by the Freshwater Fisheries Laboratory; it concerns mainly weekly information on loch chemistry and fortnightly information on the rivers from the mid-1960's to 1973. From then until the middle of 1978 however the sampling intensity was reduced to about one half. Effluents from the main sewage treatment works were also sampled by the Pitlochry laboratory, monthly to 1974 and fortnightly January to July 1976 to supplement the routine records of the FRPB (see Holden and Caines 1974, Holden 1976, and Annual Reports). Mr R Harriman and Mr L A Caines (FFL), Mr R Sargent (FRPB), Mr I R Smith and myself (ITE) are reworking the chemical and water balance data now on the computer. The aim is to eventually combine the findings from this analysis with the results of ITE's long-term programme on Loch Leven plankton; essentially weekly sampling extending back to 1967 has been supported by experimental work to explain observed changes in algal abundance and species composition (Bailey-Watts 1974, 1976a,b, 1978, 1982 and unpublished results).

2 PHOSPHORUS AND LAKE EUTROPHICATION

The FRPB amongst others are concerned with maintaining good general water quality in the streams feeding Loch Leven, but present attention is focused on the concentrations of P. This is because the element (in certain forms - see Section 3.2 below) is an essential nutrient for plants, and in virtually all lakes is a prime controller of plant plankton (algae or phytoplankton) growth (eg Kuhl 1974 Schindler 1977).

In the life of many lakes natural enrichment may occur with nutrients and other materials being introduced by in-filling from rivers and surrounding land. This long-term process is called eutrophication, although the term tends to be reserved for the much-accelerated and relatively recent phase of enrichment associated with Man's cultural (Graham 1968a and b, Hasler 1947, 1975). Major studies of the factors involved in eutrophication have been done only during the last 40 years or so. It is now generally accepted however that our indiscriminate disposal of P-containing wastes and the increased use of nitrogenous fertilisers are prime causes of (i) the sharp increase in nitrogen (N) and P concentrations in rivers and lakes (Owens 1970, Tomlinson 1970) and (ii) the increase in problems relating to algal blooms (Lund 1971, 1972, 1978).

From a lake management viewpoint rather more interest is shown in P than in N. This is largely because major inputs of P to lakes are commonly point sources of eg sewage and industrial effluent which can be monitored and controlled (cf however Section 3.2.4 below). Contrastingly, inputs of N to the systems are usually diffuse; they include eg general run-off and seepage from land which are not easily controlled. These general considerations were reviewed by Vollenweider and his co-workers (Vollenweider 1968). The review forms the basis of progressively better defined predictive mathematical models which can aid us in evaluating various options for controlling lake eutrophication. (Vollenwieder and Dillon 1974, Jones and Bachmann 1975, Vollenweider 1976, Vollenweider and Kerekes 1980, Jones and Lee 1982).

3 THE WRC REPORT

3.1 General Considerations

The Report illustrates well an attempt to apply to the Loch Leven case the finding of a model of the type previously mentioned. The main conclusion resulting from this exercise is that removal of even a large percentage of P from sewage would not result in a change in the trophic status of Loch Leven. In assessing the value of this conclusion however, two factors need to be considered. The first can be largely ignored for the purposes of the present document, but concerns debates on the application of findings of essentially 'global' eutrophication models; these question their value for predicting algal responses to P changes in specific lakes (see eg Clasen 1980, Smith & Shapiro 1981, Anon 1982). The second point is of more immediate importance and concerns the data on which the final argument rests. Before discussing these points (Section 3.2 below) some further thought should be given to the following question:

<u>What results are to be achieved by controlling P inputs to Loch Leven?</u>

This question is posed since, whilst the WRC assessment places emphasis on changing the trophic status of the loch ie from eutrophic to oligotrophic, the main concern of the FRPB is with 'improvement of the loch' for various user purposes. Such an improvement is a realisable target. Phosphorus levels could be reduced to those characteristic of moderately, even mildly, enriched waters, but the loch would remain 'eutrophic'. Resultant changes in chemical quality, phytoplankton populations and fish would probably occur at different rates - so the paper mill operator and general tourist would experience a more immediate improvement than would the angler. Contrastingly, to effect a change to oligotrophic conditions is if possible at all, far beyond our resources (cf work on Lake Trummen, Sweden by Bjork 1972, Gelin and Ripl 1978 and Cronberg 1980, and the world-wide assessment of techniques used in lake rehabilitation work - Dunst *et al* 1974).

3.2 Components of the total loading of phosphorus

/Note: loadings of substances to a lake can be expressed as weight entering the lake per unit time eg $kg.wk^{-1}$ or $kg.yr^{-1}$; weekly values represent an average measure as these will vary considerably according to variation in eg industrial and agricultural activity, tourist numbers throughout the year. Inter-lake comparisons are facilitated by expressing the loading per unit area (usually square metre) of lake surface thus $g.m^{-2}.yr^{-1}$. In this section loadings refer mainly to total phosphorus although occasional attention is given to the contributions by various soluble and particulate fractions. Weights are always expressed as P. The total loading is designated L_T, the component derived from industry L_I, that from the atmosphere L_A, that from sewage L_S, and that from streams (run-off) L_R /.

3.2.1 Industrial inputs (L_I)

The early work of Holden and his collaborators established that industry-derived P comprised a major contribution (50%) to the total loading of P to the loch (Holden and Caines 1974). Moreover the contribution from the Todd & Duncan woollen mill could 'during active periods' (Holden 1976) comprise 65-70% of the total loading. From 1972 on, changes in the practice of disposing of mill effluent apparently led to considerable decreases in L_I and thus, in L_T. Values in Figure 1 (adapted from the Report) indicate a 20-fold decrease from 150 (not 50 as entered in the Report) $kg.wk^{-1}$ in 1967 to only 7.5 $kg.wk^{-1}$ in 1978. Industry in 1978 would thus appear to have comprised a minor (? negligible) component of the L_T ie $\frac{7.5 \times 100}{215}$ or 3.5%. Our investigations of the P content in various parts of the South Queich during recent months however indicate that this is not currently the case (Appendix 1). We are not yet in a position to calculate the actual loadings of industrial P but mill effluent effects very high concentrations in the Queich. River water above the mill contains ca 25 μg total $P.l^{-1}$ whilst in water just below the mill concentrations of 500-1,000 $\mu g.l^{-1}$ are common. Figure 2 shows how the ranges in phosphorus concentrations here have varied since 1969; maxima recorded 1982-83 are similar to those for the mid-1970's and exceed those for 1977-78. It has also been established that much of the P in dye-stained mill effluent consists of initially unreactive (and thus biologically unavailable) soluble P which within a few hours is partly transformed to the reactive and biologically available form. For present purposes an L_I estimate of 15.0 kg P wk^{-1} (double that given for 1978 in the Report) is assumed.

3.2.2 Atmospheric inputs (L_A)

Phosphorus enters a lake from the atmosphere during wet and dry weather. Dissolved and particulate fractions occur in rain - especially during the early periods of a shower (Gatz and Dingle 1971) - and particulate matter eg soil, can be blown by wind to a lake (Cooke and Williams 1970, Cullen 1974 and Pierrou (1976). Conditions introducing P in this way may occur during very short and local weather episodes; so the rates of transport of P may show extreme seasonal and even daily or shorter-term fluctuations.

Figure 1 indicates for 1978 an input from this source of 27.5 kg P. wk^{-1} or 0.107 g $P.m^{-2}\ yr^{-1}$. This is a remarkably high value and contrasts with the following annual input estimates; 0.017 $g.m^{-2}$ $.yr^{-1}$ in precipitation over Lake Michigan (calculated from figures in Murphy and Doskey 1976), 0.018 atmospheric loading for eutrophic Lough Neagh, N.I. (Jordan 1983b), 0.07 atmospheric loading for the eutrophic Grebiner See - a small (29 ha) lake in northern Germany (Ohle 1982) and 0.08 for deposition associated with a phosphoric acid factory on the bank of Richards Bay, South Africa (Archibald and Muller 1982).

The Leven estimate suggests that this loch could be classified in the eutrophic end of the oligotrophic range as a result of this input of P alone. Nevertheless, detailed work done by the FFL, (Mr R Harriman - pers. comm.) indicates that the 1978 values quoted here are not unusual; high values were obtained for other years ie 30 and 39.3 kg total $P.wk^{-1}$ in 1974 and 1975 respectively (Annual Report 1973-74, 1975). These figures suggest that concentrations of P in rainwater collections (cf those in actual rainfall - see below) are very high. This is confirmed by Holden (1976) who quotes a range of 83-1140 μg total $P.l^{-1}$ and an annual mean of 355 $\mu g.l^{-1}$. As Holden points out however, his figures for 'precipitation' include dry-deposited material. There are suggestions that deposition occurring during rain showers is far less important than that taking place in dry weather. This view is supported by our preliminary results on P in rain analysed shortly after it fell; collections made recently near the pier at Kinross show values of only 25 μg total $P.l^{-1}$. New work on this aspect of P entry to the loch has been started; the wet and dry deposition loadings will be differentiated and seasonal variation in relation to eg fertiliser application will be investigated. A method of determining particle deposition and which takes account of distance from shore (Banks & Nighswander 1982) is worthy of study. In the absence of more current data the L_A estimate given in the Report - 27.5 $kg.wk^{-1}$ - will be retained.

3.2.3 Inputs in sewage effluent (L_S)

Inputs in sewage effluent are of especial significance in lake eutrophication studies since they commonly comprise a major point source of P. The P content is often high (that is, obviously, in the absence of P stripping) with values of 5 mg $P.l^{-1}$ being fairly typical (Holden and Caines 1974) and the percentage of soluble reactive P present is also high, being commonly 50 and sometimes 90%; it is this fraction that is often considered equivalent to ortho-phosphate and algal-available P (but see eg White *et al* 1981 and Jordan 1983a).

The input of sewage P to Loch Leven remains an important component of the L_T even with a higher L_I than that indicated in the Report (Figure 1 and Section 3.2.1 above). It is important therefore that an accurate measure of L_S be obtained.

Effluent from Kinross North and Kinross South sewage treatment works enter the loch directly ie not first into any feeder stream, whilst Milnathort sewage treatment work effluent passes into the North Queich. Loadings can be estimated in two ways. One is a direct method which combines P concentration and metered effluent flow data. This method, adopted by the Pitlochry laboratory, involves considerable close time interval sampling and analytical work as there appears to be no simple relationship between concentration of P and the effluent flow rate (Mr A Reid - pers. comm.). This contrasts with the situation in rivers; the concentrations of at least some P fractions there can often be predicted from flow measurements by previously established equations relating concentrations and flow (see eg Casey *et al* 1981 and Foy *et al* 1982). The second method of estimating L_S is preferable though less direct and is based on human *per capita* P output rates. This method combines measures of sewer-served human population numbers with the *per capita* estimates. A 1978 population of around 3,200 persons is suggested if the measured L_S of 67.5 $kg.wk^{-1}$ is divided by a *per capita* P output rate of 3.0 $g.d^{-1}$ (from 2.9 $g.d^{-1}$ - Smith 1979). This is in fair agreement with population figures presented by Cuttle (1982) for Kinross-shire and Parishes 1951-1979; the Kinross town population was still around 3,000 in 1971 but had risen to nearly 4,000 by 1979. The latest estimate of the served population however is considerably greater at 6,322 ie 3,200 served by Kinross N, 1,100 by Kinross S and 2,022 by Milnathort. This figure effects a new L_S estimate of 128.3 $kg.wk^{-1}$ ie

6,322 (persons) x 2.9 (daily per capita P output in g) x 7 (days in week) ÷ 1,000 (for kg).

It is likely therefore that the current L_S is more than double that given for 1978 - especially since the extra loading from minor treatment works serving eg the Ochil Hills hospital and septic tank overflows from eg outlying hamlets and holiday caravan sites (at Hatchbank and Kirkgate) has still to be included. The estimate of 567 persons served by the Kinnesswood works has not been included since it is not absolutely certain whether the effluent from this plant enters the loch (Mr E. Parkinson - pers. comm.).

3.2.4 Inputs via run-off into feeder streams (L_R)

This input comprises particulate and soluble P entering the loch in run-off from land draining into the feeder streams. Whilst for practical purposes estimates of L_R for certain sub-catchments might include P entering via channels from eg septic tanks and farms, it should not include major L_I and/or L_S components. In the main therefore L_R values should reflect 'background' levels of P in streams draining different types of land eg rough grazing and arable.

Unless fertiliser application is immediately followed by heavy rain, the losses of P from basic soils of the type prevalent around Loch Leven are low (Cooke and Williams 1970). Phosphate fertilisers are only sparingly soluble (Hay 1981) and phosphorus in soils is relatively immobile as it precipitates as eg calcium phosphate (Armitage 1974).

Concentrations of P in soil solution vary considerably; Stennvoorden and Oosterom (1979) give a range of 20-730 $\mu g. P.l^{-1}$ for waters draining arable lands of various types in the Netherlands. Cooke and Williams (1973) quote averages of 50 $\mu g.l^{-1}$ or less from clay soils and 100-200 $\mu g.l^{-1}$ from sandy soils in Britain. Concentrations in the richest field drains entering Loch Leven (on the north side) may reach 800 $\mu g.l^{-1}$ following fertiliser application (Holden et al in Annual Report 1971). Recent analyses of the main burn in the same area also reflects the agricultural influence with concentrations of around 140 $\mu g.l^{-1}$ but this collects only 7% of the total catchment run-off to the loch (Smith 1974).

Holden (1976) states that in sharp contrast to run-off losses of nitrogen which contribute some 85% of the total nitrogen loading to Loch Leven, P losses from land amount to only 15% of the total P loading. He also considers run-off loadings of P to be of "minor consequence compared to that of industry and probably less significant than sewage". A maximum average yearly L_R value equivalent to 60 $kg.wk^{-1}$ for the period 1967-1974 is indicated in the same paper. This figure and the comments above are not reflected in the high 1978 L_R value of 112.5 $kg.wk^{-1}$ presented in the Report; even accounting for the fact that 1978 was a fairly wet year (1019 mm rainfall) this value seems very high.

For the purposes of assessing the likely current L_R the 1978 value has been examined in two ways. The first relies on the earlier findings of Holden and colleagues that concentrations of P in the major streams (ie above mill inputs in the case of the South Queich etc) are peculiarly invariable. Holden (1976) gives mean figures of 18-31 μg $P.l^{-1}$ from data extending back to 1963 (see also Holden and Caines 1974). These concentrations are quite low although they are considered to be approximately double those found in other Scottish areas where there is no agricultural activity. The maximum concentration of P in the richest of the main inflows to Loch Leven - the Gairney Water - is 63 $\mu g.l^{-1}$ but this includes septic tank discharges. The majority of other values quoted (Holden et al in Annual Reports 1970, 1971, 1972 and 1973-74) are around 25 $\mu g.l^{-1}$. Our own recent analyses indicate that the situation has not changed. These levels contrast markedly however with a mean concentration of 67 $\mu g.l^{-1}$ obtained by combining data on the volume and water balance of Loch Leven (Smith 1974) and the Report value for L_R of 112.5 kg. wk^{-1} ie:-

(i) total run-off water volume equivalent to 605 mm over a catchment area of 145 km^2 = 87.73 x $10^6 m^3$;

(ii) the mean P concentration is:

$$\frac{112.5\ (kg.wk^{-1}) \times 10^9\ (\text{for } \mu g) \times 52\ (\text{for year})\ \text{annual loading}}{87.73 \times 10^9\ (\text{litres})\ \text{annual run-off volume}} = 66.68\ \mu g.l^{-1}$$

The second way in which the value given for 1978 can be reconsidered, involves published P loss rates from different land use catchments. Dillon and Kirchner (1975) provide an extensive review of the literature which shows a wide range of values (mg to g $P.m^{-2}.yr^{-1}$) according to watershed geology and land use. The effects of agriculture and urbanisation are to increase P export. Estimates not covered by that review include 0.25 and 0.07 kg total $P.ha^{-1}$ from arable and non-arable farmland in southern England (Cooke and Williams 1973) and 0.25 $kg.ha^{-1}$ from Netherlands cropland (Steenvoorden and Oosterom 1979). A figure of 0.14 kg soluble reactive $P.ha^{-1}$ for the Lough Neagh catchment was obtained from the y axis intercept value resulting from a P export/population regression analysis; Foy et al (1982) consider 0.22 $kg.ha^{-1}.yr^{-1}$ a more applicable value. These values contrast with higher losses of eg 0.303 kg total $P.ha^{-1}$ from heterogeneous sandy clay soils in very high rainfall areas near the Great Lakes (Burton and Hook 1979) and 0.83-1.05 $kg.ha^{-1}$ from a peaty catchment (Lough Leane, Eire - Casey et al 1981). For present purposes the loss values given by Cooke and Williams are applied to recent estimates of arable and non-arable land in the Loch Leven catchment (Cuttle 1982). Ignoring the small areas represented by urban and woodland cover a new L_R estimate of 2685.4 $kg.yr^{-1}$ or 51.64 $kg.wk^{-1}$ (total P) is obtained, ie:-

[annual loss rate from non-arable land (0.07 kg $P.ha^{-1}$) x catchment area represented (0.36 x 14500 ha)] + [annual loss rate from arable land (0.25 kg $P.ha^{-1}$) x catchment area represented (0.64 x 14500 ha)].

Further work is obviously necessary to assess L_R properly. It is noteworthy however that both of these exercises suggest a current value some 60% lower than that indicated in the Report: 25 cf 67 in terms of the mean stream P concentrations and 52 cf 112.5 in terms of P loading.

3.2.5 The total input of P and the contribution from the various sources.

Figure 3 summarises the new assessment of P inputs to Loch Leven. It is constructed in the same way as Figure 1 to facilitate an easy comparison with the 1978 values in particular. The manner in which the total input is apportioned between especially L_S and L_R is different from that suggested for 1978 in the Report. The variation can be largely attributed to the availability of more recent information on stream P concentrations for knowledge about L_R (and L_I) and the population census for re-estimating L_S. The earlier assessment considers run-off P to be greater than sewage P whilst the present exercise indicates the reverse. Incidentally, the summed estimates of L_S and L_R are virtually identical for both periods.

In Figure 3 the total input of 223 $kg.wk^{-1}$ is made up as follows:

15 (L_I) + 28 (L_A) + 128 (L_S) + 52 (L_R).

Information in Section 3.2.1 and Appendix 1 suggests that the L_I is still an underestimate but the actual value does not alter conclusions presented later (Section 4) It is notable that the new L_T is similar to that given in the Report for 1978 (215 $kg.wk^{-1}$). Reasons for supporting the contention that the 1978 and current values are similar relate to observations on phytoplankton abundance (biomass) and the strong and direct relationship between algae and P loadings 1968-1978 (Holden and Caines 1974, Bailey-Watts 1978, 1982 and Holden _et al_ unpublished data). Mean annual biomass levels (expressed as chlorophyll concentration) varied between 65 and 95 $mg.m^{-3}$ ($\mu g.l^{-1}$) over the period 1968-1972 but between only 24 and 46 $mg.m^{-3}$ 1974 to the present - including a value of 32 $mg.m^{-3}$ for 1982. Levels of P in the loch in the last 3 years are similar to those recorded in the mid-1970's; each of these periods contrast with 1968-71 when much higher P concentrations were recorded (see also Smith and Shapiro 1981). Thus, neither P nor algae indicate a marked rise in L_T since the mid-to-late 1970's.

4. CONCLUSIONS

It must be emphasised that the present exercise comprises an assessment of the situation regarding Loch Leven phosphorus loadings: further field measurements are necessary for proper estimates of the various quantities. It is unlikely however that the relative importance of the different components is much different from that indicated here. Of especial relevance to phosphorus removal considerations is the contribution by point origin and thus controllable sources. Expressed as a percentage of L_T, the total point-source P loading (ie $L_S + L_I$) is:-

$$[128\ (L_S) + 15\ (L_I)] \times 100/223 = 64$$

This value is nearly double that given in the earlier Report ie:-

$$[67.5\ (L_S) + 7.5\ (L_I)] \times 100/215 = 35$$

A new prediction of the results of phosphorus removal measures obviously can now be made. The calculations performed below follow the same procedure as that adopted in the Report.

(i) Affects of phosphorus reduction on present L_T

A new L_T resulting from a 90% reduction of P in a combined sewage and industrial effluent is as follows:-

$$\text{new } L_T = \text{present } L_T - [0.9\ (L_S + L_I)]$$
$$= 223 - [0.9\ (123 + 15)]$$
$$= 94.3\ \text{kg.wk}^{-1}$$

This average weekly loading is equivalent to an annual input of 0.369 $g.m^{-2}$ calculated as follows:-

$$\frac{94.3\ (\text{kg weekly load}) \times 52 \times 10^3\ (\text{g.yr}^{-1})}{13.3 \times 10^6\ (\text{m}^2\ \text{loch surface area})} = 0.369\ \text{g.m}^{-2}.\text{yr}^{-1}$$

(ii) Expected reductions in P concentration in the loch

Table 2 in the Report equates weekly P loadings in kg to mean concentrations in $mg.m^{-3}$ in the loch: thus 215 $kg.wk^{-1}$ to 215 $mg.m^{-3}$. Mean concentrations estimated in this way however are considerably higher than even the theoretical levels; this is because no allowance is made for the flushing factor. The volume of water conveying nutrients into Loch Leven over one year is greater than one loch volume by a factor of 1.67 ie the total average annual run-off volume ($87.7 \times 10^6 m^3$ - see Section 3.2.4 above) divided by the loch volume ($52.4 \times 10^6 m^3$ - Smith 1974). Consequently the theoretical mean concentrations of P are only 0.60 (the reciprocal of 1.67) times eg 223 (from present loading assessments) and 94.3 (predicted after phosphorus removal) ie 134 and 56.58 mg $P.m^{-3}$.

In practice because many factors reduce free P concentrations in the loch water column, even these estimates are likely to be too high; Figure 4 shows that the actual mean concentration for a recent 12-month period is less than 134 $mg.m^{-3}$.

(iii) Expected reductions in chlorophyll concentrations

Table 2 in the Report relates concentrations of chlorophyll to the assessed and predicted phosphorus concentrations. Even though the P values presented are overestimates of the real situation (see (ii) above) the numerical relationship between the nutrient and pigment values is valid for the OECD model applied (Clasen 1980, Anon 1982) and this is plotted in Figure 5. The 1978 and predicted chlorophyll values in the Report must also be considered over-estimates but fortunately a measured value for 1978 chlorophyll exists - 32 $mg.m^{-3}$ (Bailey-Watts 1982 - cf 49 in the Report?). Figure 5 shows that when this value is related to the line described by the other phosphorus-chlorophyll co-ordinates, a P concentration of 137 $mg.m^{-3}$ corresponds. This is very close to the calculated phosphorus concentration of 134 $mg.m^{-3}$ (in (ii) above). Incidentally, a mean chlorophyll value of 32 $mg.m^{-3}$ has also been obtained for Loch Leven for the year 1982 (author's unpublished observations).

In Figure 5 the OECD model-based line predicts that mean chlorophyll levels of 15 $mg.m^{-3}$ would result if the L_T were reduced to around 95 $kg.wk^{-1}$ to effect a mean concentration of 57 mg $P.m^{-3}$ chlorophyll $.m^{-3}$ Coincidentally, this value is close to the 13 mg chlorophyll m^{-3} predicted in the Report; however, the latter requires 90% of sewage <u>and stream</u> P to be removed although for that part of the Report (cf the paragraph on 'critical P load') the flushing factor has been ignored. The present exercise indicates that the reduction could be achieved by treating the point sources of phosphorus alone.

Finally, a point regarding nutrient relationships of phytoplankton in the loch is of note. Nutrient enrichment experiments have been done with Loch Leven phytoplankton. The results of this work support the view drawn from comparing time curves of phosphorus concentration and algal abundance, that phosphorus already limits increases in phytoplankton densities. The limitation is particularly acute in late winter and early spring when the annual maximum algal crops are commonly recorded. It is likely that a decrease in these maxima (brought about by a reduced external loading of phosphorus) would effect a reduction in the amounts of P released from the sediments in summer (see Smith 1979). Further research will include investigations on the influence of the sediments on the annual phosphorus cycle.

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Appendix I

Phosphorus in the South Queich and the influence of mill effluent.

A variety of sampling strategies has been used to assess variation in P concentrations at different points along and across the South Queich and occasionally in the Gelly Burn tributary. Especial attention has been paid to determining if the stream of coloured effluent from the woollen mill differs in P content from clearer ie 'natural' Queich water. Table A1 shows that the 2 water types differ in total P (TP) concentration. Minimum and maximum values obtained for sets of 3 samples for mixed portions of the river or loch typically differ by $<10\%$. Dissolved silica values are included in Table A1. Even between zones of differing P content, silica shows a remarkable spatial homogeneity: this suggests (a) that the volume of mill effluent is not great enough to alter the general character of the South Queich, and (b) the P content of the effluent is very high.

Investigations into the variation in P along this river were started only recently, although from a point some 50 m upstream of its confluence with the loch the river has been sampled since 1980 - to assess the total loading to the loch of P from this single river. Recently the best likely estimates of water flow in the river have become available with the FRPB/ Edinburgh University computerised data bank on loch level, sluice gate height and outflows; these will facilitate calculations of individual river flows from catchment-proportional estimates of the total inflow rate. Even without these data however, the high concentrations of P (10^2 - 10^3 $\mu g.l^{-1}$) indicate a substantial load from the South Queich which cannot be accounted for by 'natural' - even fertiliser enhanced - run-off. Phosphorus concentrations typical of the Queich even as far down as the confluence with the Gelly Burn are <25 μg $TP.l^{-1}$.

Enquiries were made some 12 years ago about the chemicals used at the factory; these revealed that in addition to phosphoric acid (H_3PO_4), complex phosphates were involved eg sodium hexametaphosphate ($(Na\ PO_3)_6$) and tetrasodium pyro-phosphate ($Na_4P_2O_7$). As these phosphates are not completely hydrolysed before entering the loch (Holden and Caines 1974) they are included in the analysis as part of the soluble 'organic' (more strictly soluble un-reactive) fraction (SURP) which is generally considered of limited availability to algae. The high proportions of SURP in the Queich (Table A1) suggest that similar chemicals are still being used at the mill. Table A2 shows that within 24 hours some of this SURP is transformed to reactive P which is readily utilised by algae for growth.

TABLE A1. Total phosphorus concentrations (μg TP.l^{-1}), the percentage concentration by different phosphorus fractions (%) and silica concentrations (mg SiO_2.l^{-1}) in the South Queich downstream of the entry of mill effluent: dye-coloured and clear water zones compared. TP = total phosphorus, TSP = total soluble phosphorus SRP = soluble reactive phosphorus and SURP = soluble unreactive phosphorus.

SAMPLING DATE	SAMPLE	μg TP.l^{-1}	% TSP/TP	% SRP/TSP	mg SiO_2.l^{-1}
290383	Dye 1	767	112*	7	9.83
	" 2	763	85	6	9.81
	Clear 1	40	88	57	9.83
070483	Dye 1	1135	103*	4	8.80
	" 2	1029	93	4	8.62
	Clear 1	27	139*	19	8.76
180483	Dye 1	37	63	34	7.92
	" 2	23	64	44	7.94
	Clear 1	8	33	237*	7.86
260483	Dye 1	843	62	11	8.50
	" 2	721	55	12	8.47
	Clear 1	46	64	38	8.50

*An as yet unresolved analytical problem relates to these figures indicating a percentage $>$ 100.

TABLE A2. The concentrations (in $\mu g\ P.l^{-1}$) of total soluble phosphorus (TSP), soluble reactive phosphorus (SRP) and soluble unreactive phosphorus (SURP) in Loch Leven and South Queich water 260483: results of analyses done on the day of sampling and on the following day. Each value is the mean of 3 field sampling replicates except for the three samples taken from below the mill effluent entry point; here the single value for each is given to illustrate differences between dye-stained (A & B) and clear (C) stream water.

SAMPLING STATION	TSP		SRP		SURP	
	2604	2704	2604	2704	2604	2704
S. Queich						
(1) up stream of mill	7.8	7.6	6.1	4.4	1.7	3.2
(2) below mill A	525.4	516.2	57.9	123.2	467.5	393.0
" " B	398.3	402.5	49.0	108.0	349.3	294.5
" " C	29.7	29.1	11.3	17.2	18.4	11.9
(3) lower reach	235.3	229.1	38.9	78.8	196.4	150.3
Loch Leven						
(1) open water	11.2	10.5	2.8	1.6	8.4	8.9
(2) sluices	9.9	9.7	2.0	1.2	7.9	8.5

FIGURE LEGENDS

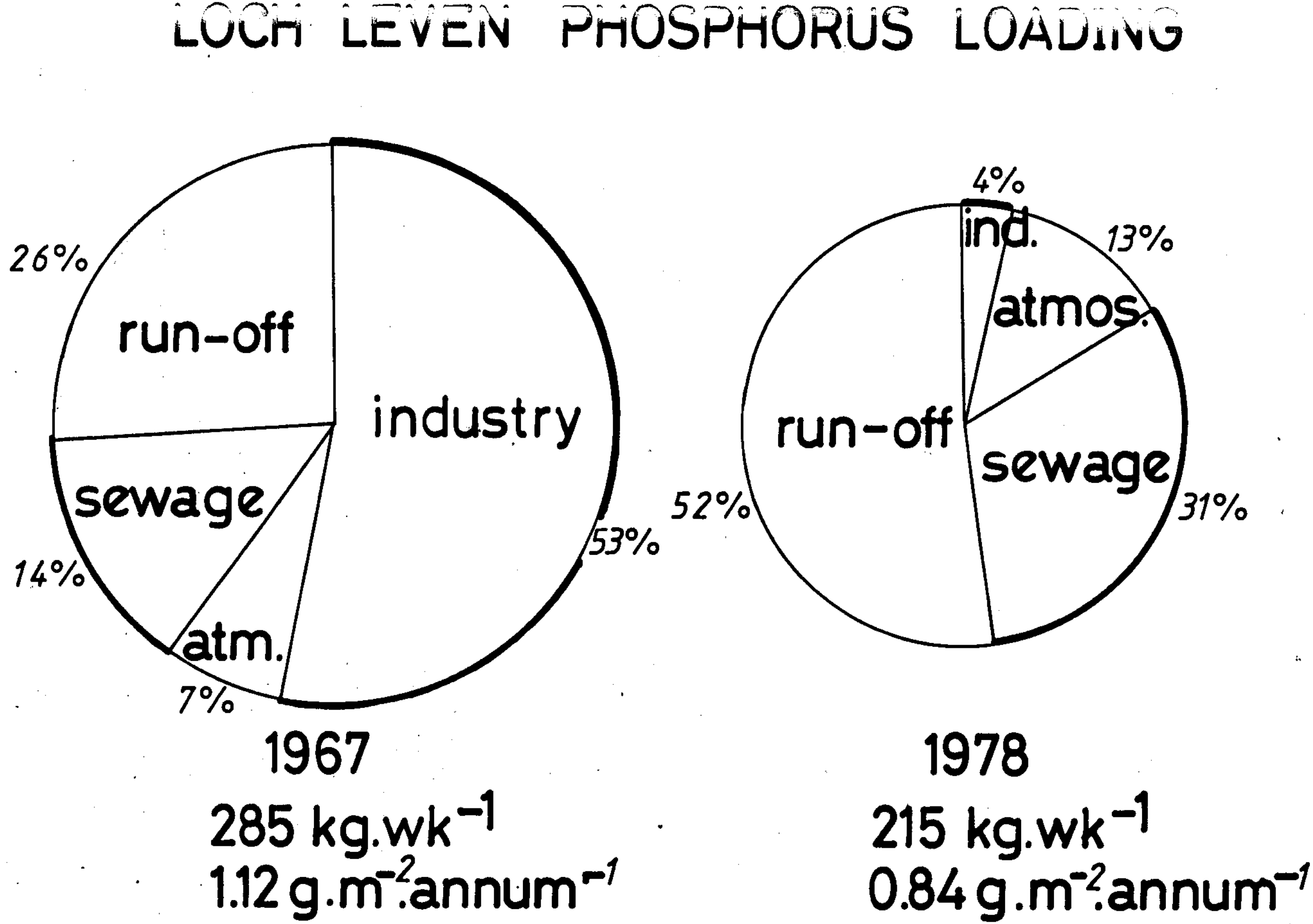
Figure 1. Loch Leven phosphorus loadings 1967 and 1978: total loading (in kg.$wk.^{-1}$ and g.m^{-2} $annum^{-1}$) and the percentage contributions from industry, the atmosphere, sewage and run-off. Thickened lines at the perimeter of the circles relate to point sources of phosphorus.

Figure 2. Ranges of total and soluble reactive phosphorus concentrations in the lower South Queich 1969 to 1983 (x, no soluble reactive figures for 1969; xx, January to August only in 1983).

Figure 3. As Figure 1: the current assessment.

Figure 4. Measured total phosphorus concentrations in Loch Leven March 1982 to April 1983: the loch is 4 m deep at the open water station (South of Reed Bower) and 1.5 m deep at the outflow (sluices).

Figure 5. Relationships between mean annual concentrations (mg.m^{-3}) of total phosphorus ($\overline{TP}$) and chlorophyll ($\overline{chl}$): Loch Leven values fitted to line described by OECD model (Clasen 1980). Co-ordinate (x_1,y_1) relates predicted $\overline{TP}$ to measured $\overline{chl}$ 1978 (and 1982); co-ordinate (x_2,y_2) relates predicted $\overline{TP}$ and $\overline{chl}$ after P-removal.



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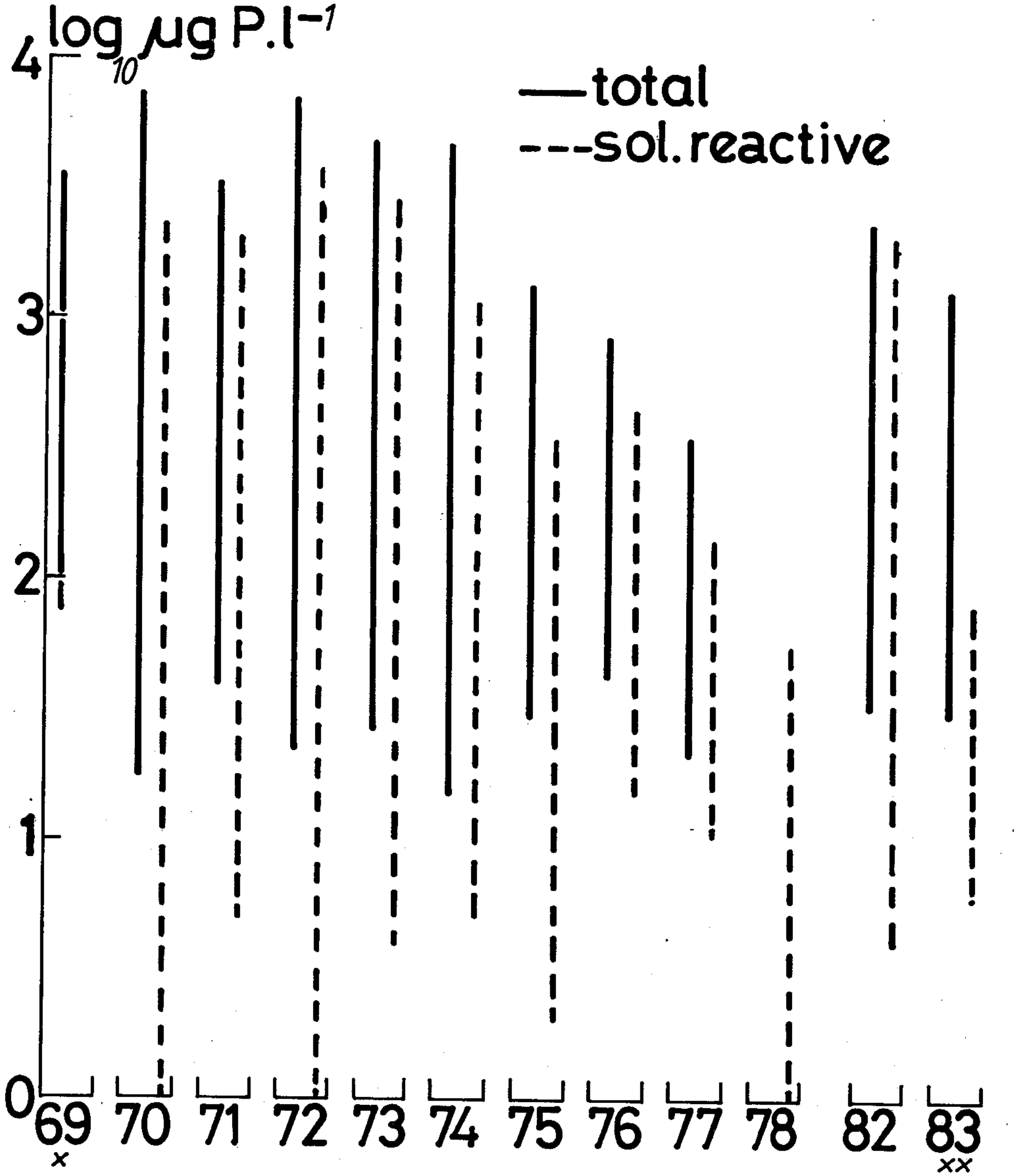

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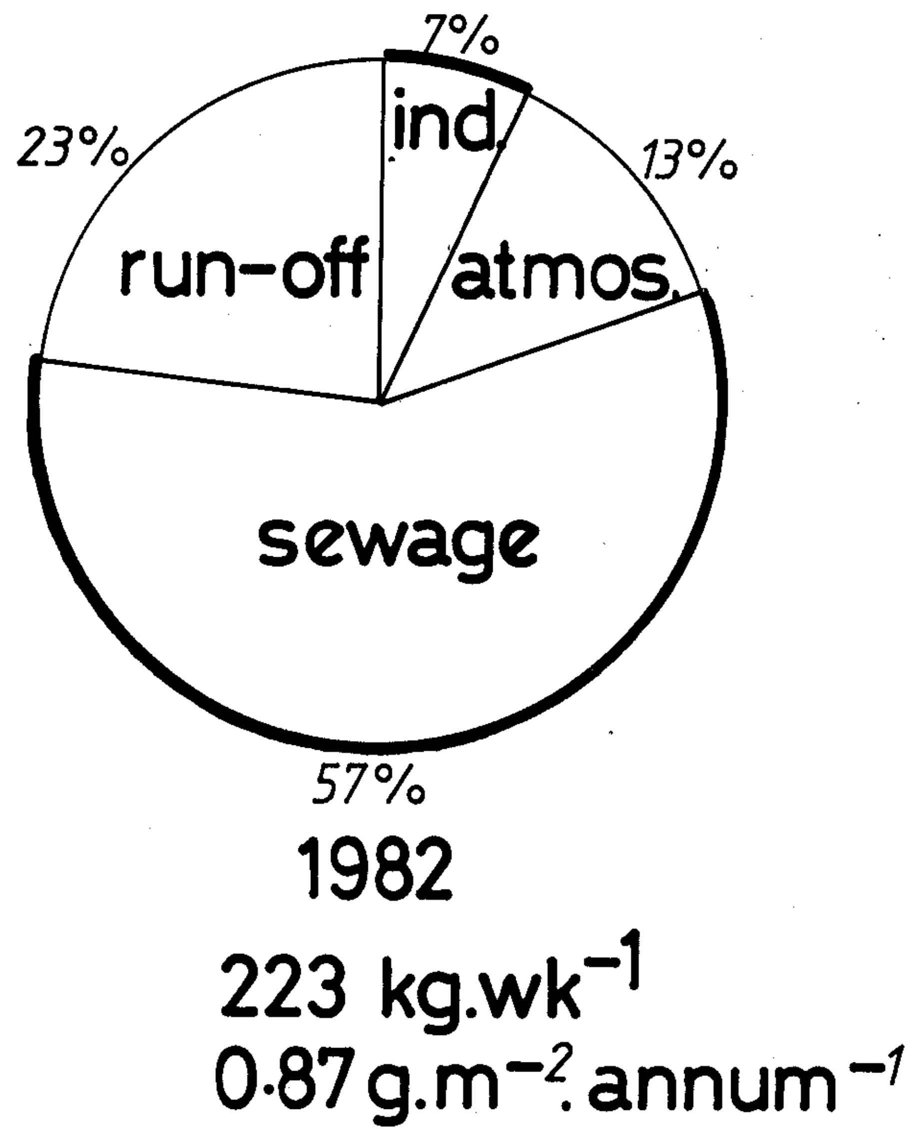

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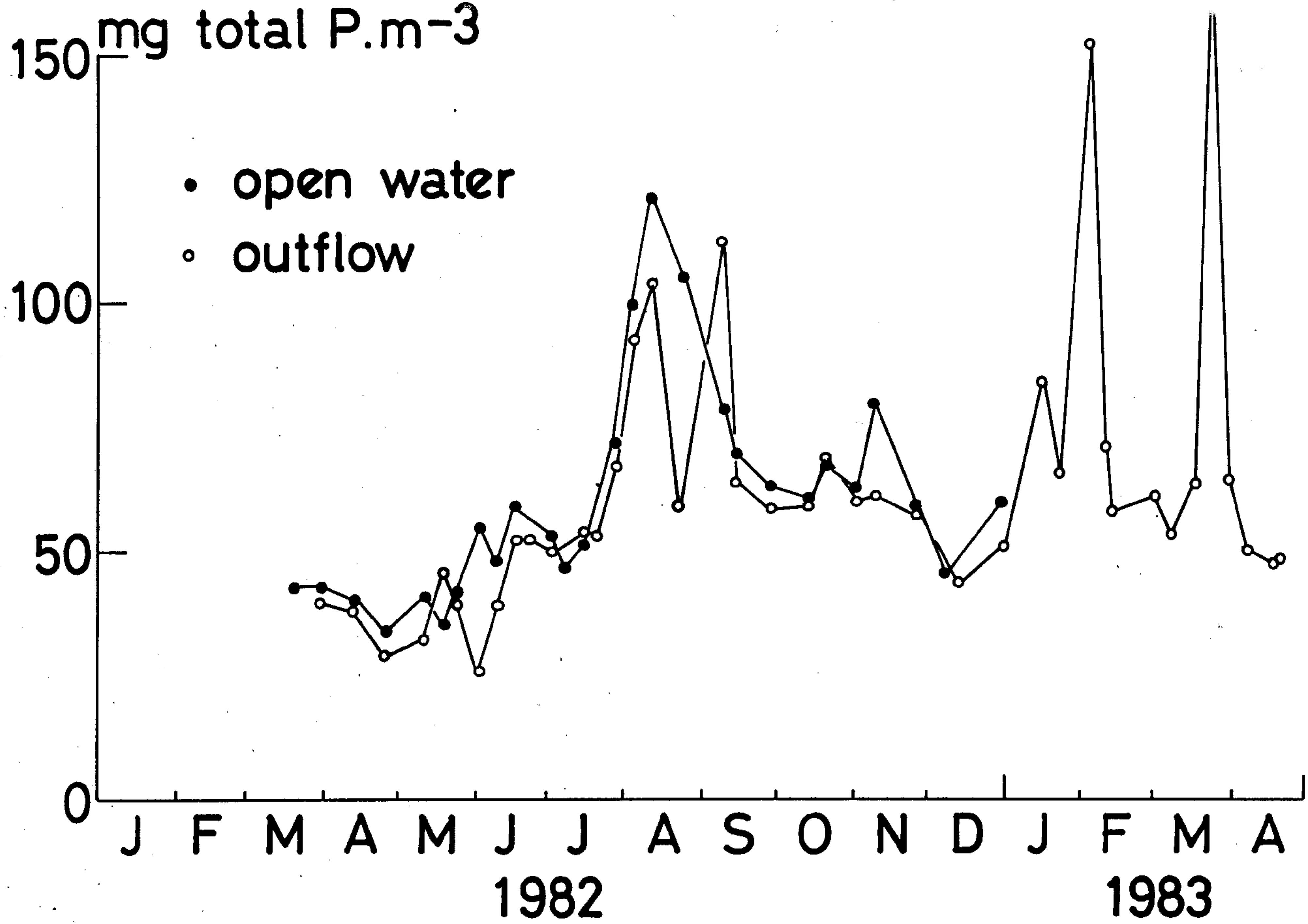

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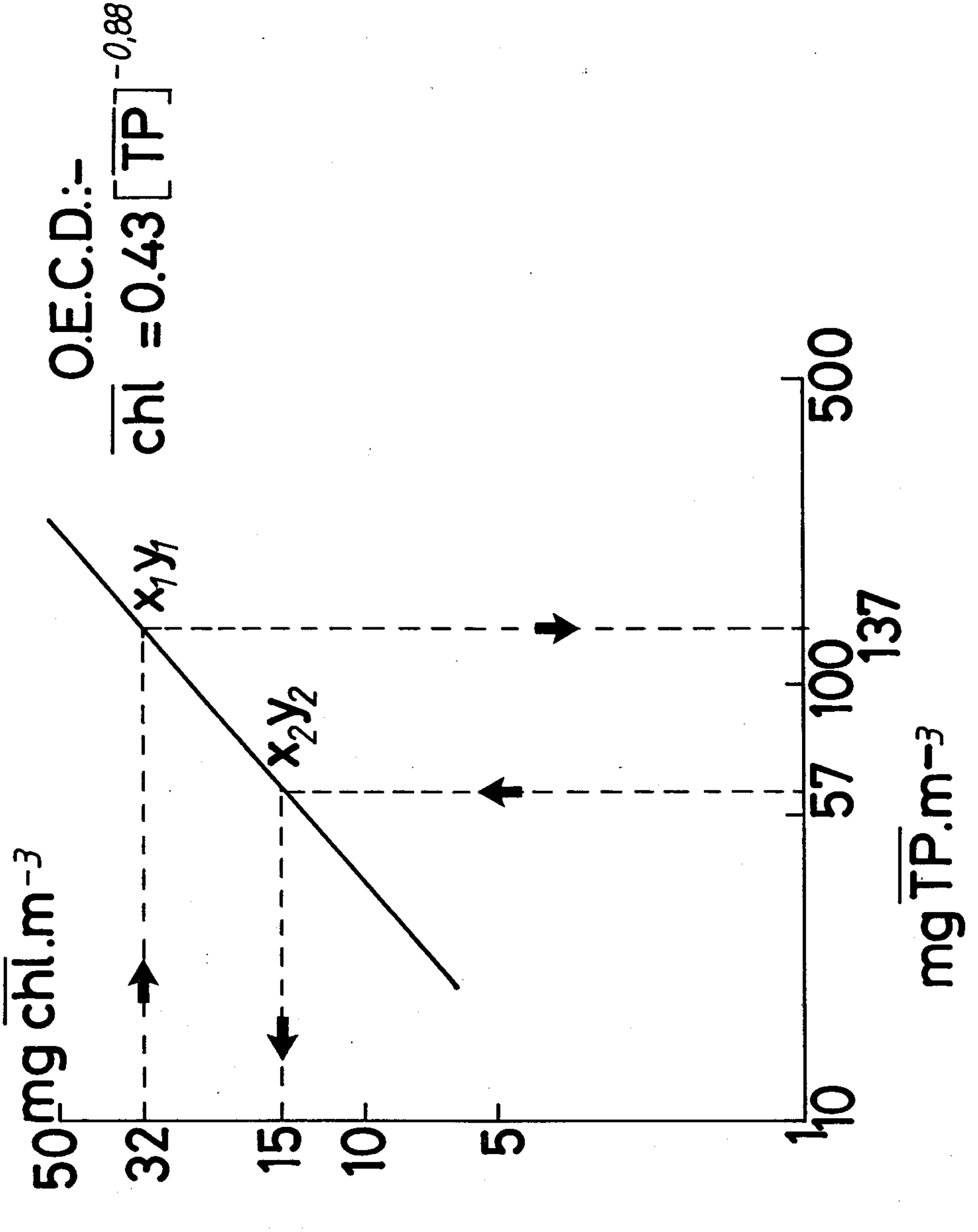

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