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ASSESSMENT OF THE NUTRIENT STATUS AND ASSOCIATED ALGAL PRODUCTIVITY OF MALHAM TARN, YORKSHIRE

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1. INTRODUCTION

Concern about a possible increase in nutrients to Malham Tarn, N. Yorks, with biological consequences, led in 1982 to a commissioned Report (Talling & Hilton 1982) by the Freshwater Biological Association to the Nature Conservancy Council. As a mainly desk-study, it assessed the chemical evidence then available. This strongly suggested an increase since 1960 in the winter nitrate content of the Tarn water, but the situation with respect to phosphorus - potentially the most influential enrichment - was uncertain. Quantitative recent information was lacking for several major sources of input and compartments of storage. Among the latter algal communities of the plankton and benthos are important, and are also indicators of biological response to nutrients.

To remedy these deficiencies in knowledge, a field investigation was carried out from March 1985 to March 1987. The present Report describes and assesses its findings. The Tarn is treated as a chemical system of input, largely transient storage, and output; seasonal cycles of inflow and outflow concentrations are traced and compared with reference to the dynamics of algal biomass and averaged nutrient concentrations in the Tarn. Algal biomass in plankton and benthos is characterised for elemental composition, and the phytoplankton resolved into seasonally varying species components with distinct patterns of environmental response. Very rough estimates are attempted of the nutrient inputs from atmospheric precipitation, migrant birds, agricultural fertiliser, and domestic sewage. Internal nutrient loading is also considered. Finally the susceptibility to long-term change is discussed, partly with reference to older records.

2. METHODS

Sampling of Tarn and inflow was generally at 2-week intervals from March January 1985 to March December 1987, with less regularity in mid-winter. Water samples for chemical and algal analysis were collected from six two regular stations, five one around on the Tarn margin at the outflow and one from on the main inflow (Fig. 1). Three stations along the northern shore were designed to detect possible pollution from the Field Station above. On two occasions (6 March 85 and 11 June 85) series of chemical samples were collected further upstream along the inflow. Samples of rainwater (as bulk precipitation, collected at a north-short e site by plastic funnel) for chemical analysis were obtained on most sampling visits during 1986-87, by courtesy of staff of the Field Studies Council (FSC). Bore-hole water, from High Trenhouse, was sampled on 16 February 1987. Samples for phytoplankton were preserved on site with Lugol's iodine fixative; those for pH and CO_2 quantities were analysed later the same day on return to Windermere; other chemical analyses were performed on unfiltered or (for PO_4-P) GF/C-filtered samples after one or more days storage in darkness at c. 10°C; chlorophyll a estimations were made after one day of such storage.

Field measurements were routinely made of lake level, as cm of depth at the west side of the outflow spillway, and of surface water temperature by mercury thermometer at the same outflow station 1 D. The outflow discharge was measured infrequently some distance downstream by dilution gauging, using brine additions and the 'gulp method' (Water Research Association 1970) applied to continuous records of conductivity. The requisite time-integrals of conductivity increment were obtained directly by integrating millivoltmeter, connected across the recorder output, and calibrated by known dilution-time combinations. Earlier and less reliable estimates of discharge obtained by a rotating vane current meter were discarded. Daily measurements of rainfall and wind-run, from a site near the north shore of the Tarn, were kindly provided by the F.S.C. Field Studies Council

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described in Appendix 03.

Samples of bottom sediment, and of overlying Chara beds, were obtained on two occasions from a northern offshore area with a Jenkin mud sampler.

Methods of subsequent laboratory analysis were as follows. Water analyses included Ca^{2+} and K^+ by atomic absorption spectroscopy; alkalinity, CO_2-acidity, and pH by acidimetric titration followed by Gran transformation; NO_3-N by reduction with hydrazine to nitrite and spectrophotometric estimation; NH_4-N by the indophenol blue reaction and spectrophotometric estimation; soluble reactive Si (expressed as SiO_2) by reaction with molybdate, reduction to silicomolybdenum blue and spectrophotometric estimation; soluble reactive phosphorus (PO_4-P) by the molybdate reaction followed by hexanol extraction of the molybdenum blue complex and spectrophotometry; total P, on filtered and unfiltered samples, by the molybdenum blue reaction after prior digestion with persulphate under pressure; electrical conductivity by a Philips conductivity meter after temperature equilibration to 25°C. The principles and many working details of these methods are described in Mackereth, Heron & Talling (1978), who also give limits of detection - here especially relevant for PO_4-P (0.6 $\mu g\ l^{-1}$), Si as SiO_2 (9 $\mu g\ l^{-1}$), NO_3-N (11 $\mu g\ l^{-1}$), NH_4-N (4 $\mu g\ l^{-1}$), and K^+ (15 $\mu g\ l^{-1}$).

Analyses of some elements were made in three types of dry particulate matter - suspended seston on glass-fibre, Whatman grade GF/C, filter discs; sediment from the 0-5 cm layer; and the macrophyte alga Chara globularis var. virgate. In all, total C and N were measured after high temperature oxidation and gas chromatography with a Carlo Erba CHNS analyzer, and total P after acid digestion. For surface sediment the readily exchangeable PO_4-P and NH_4-N were also estimated after elution with 0.125 M NaOH and 6% NaCl respectively within 24 h of collection. A further PO_4-P fraction was then extracted with 0.5 M H_2SO_4. Exchangeable K was estimated after elution with 1 M ammonium acetate. The contents of Ca, Mg, K, Na, Fe and Mn were measured in sediment and Chara samples treated by acid extraction, applied as sequential digestions with nitric, perchloric, and hydrofluoric acids.

Phytoplankton numbers were counted on 0.25, 1, 5, or 20 ml samples after iodine sedimentation under the inverted microscope. Larger, 100 ml samples were similarly examined and the species abundances qualitatively graded on a 4-point scale given weightings of 2, 4, 6, and 8 relative units. Chlorophyll a content of Tarn water was estimated by spectrophotometry after extraction in hot methanol, following an initial separation of plankton on glass-fibre (GF/C) filters.

The site

3. THE TARN AND CATCHMENT : GENERAL FEATURES AND WATER BALANCE

The Tarn (Fig. 1) is situated at an altitude of 375 m (1297 ft) in Pennine uplands largely composed of Carboniferous Limestone with an area of slate adjoining the Tarn. It is underlain by more impervious clays of glacial drift, with an accumulation of c. 8 m of lake sediment offshore (Pigott & Pigott 1959). The shallow and largely unstratified water-mass has the following characteristics:

area = $0.61\ km^2$* volume = $1.46 \times 10^6\ m^3$*
max depth = 4.4 m catchment area = $6.1\ km^2$
mean depth = 2.4 m*

(* by planimetry of a 1956 survey map)

Depth contours (Fig. ~~2~~1) indicate a generally steeply-shelving marginal region to 2 m, with gentle gradients offshore. There is a detailed literature on the local geology (Shaw 1982), geomorphology (Clayton 1966), soils (Bullock 1971), general vegetation (Sledge 1936, Sinker 1960, Proctor 1974), land-use (Williams 1963, Disney 1975), and freshwater biology (Holmes 1965) including algae (Lund 1961, Round 1953, Pentecost 1978, 1984). Earlier water analyses of Tarn and major inflow are summarised by Lund (1961), ~~and~~ Talling & Hilton (1982), and Talling (1987).

The Tarn receives water from a single major inflow and several minor ones, fed from calcareous springs that emerge at the junction of limestone and slate. Its level was artificially raised last century by a concrete weir at the southern outflow, whose considerable width ensures that the typical annual range in lake level is small (c. 15 cm). The small catchment (~~only~~ 10 x the Tarn area) consists mainly of limestone grassland, with some calcareous fen (NW side) and acid raised bog (W side). Of relevance for nutrient income are (i) western areas of improved pasture with annual additions of artificial fertiliser ~~(Fig. 7)~~ (ii) periodic grazing of cattle along the southern shore (iii) some incursions of seagulls, especially in autumn (iv) various small settlements ~~(see Fig. 1)~~ that include an active farm (Home Farm) with cattle and a Field Centre with numerous visitors, both with soak-away drainage to the Tarn.

The general climate (Manley 1956) is wet-oceanic and windy. Occasional strong winds induce appreciable re-suspension of sediment in the Tarn. This is especially true for daily wind-runs of > 500 km day^{-1} (Fig. ~~3~~ 2). Ice-cover, of varying duration, extends over most or all of the Tarn each winter. The summer water temperature (Fig. ~~3~~ 2) is depressed by several degrees from the altitude factor.

The water balance of the Tarn over unit time period can be expressed as

$$q_i + q_t = q_o + q_e + q_s$$

where quantities of water (q) are referred to surface inflow (i), precipitation on the tarn (t), surface outflow (o), evaporation (e), and Tarn storage (s). These quantities were estimated for successive 2-week periods centred on the normal sampling dates, with interpolation during the few irregular winter periods. Values of q_t were obtained from daily records of rainfall at the Field Centre; of q_o from Tarn level and the flow-gauging relationship in Talling (1987) ~~shown in Fig. 4~~; of q_s from change in Tarn level after linear interpolation between sampling dates; of q_e by using rough estimates (liable to errors of c. ± 50%)

for mean evaporation rates of 1, 2 and 3 mm day^{-1} applicable to winter (Nov-Feb.), spring and autumn (Mar-April, Sept-Oct), and summer (May-Aug) respectively. The remaining term q_i was then estimated by difference, and its quotient (q_i/q_c) with the annual catchment rainfall (q_c) evaluated as the catchment run-off factor. Tabulations for the two years of measurements are given in Table 1.

With due allowance for error-uncertainties, the following conclusions can be drawn. The quantities q_t, q_e and q_s are very subordinate ones. The annual outflow quantity q_o is consistent with the independently measured rainfall if the mean run-off factor is 0.9. The last value is not atypical for northern Britain. Hydrological differences between the two years are large, primarily because of the heavy rainfall in late-summer 1985 and in autumn during 1986 (Fig. 3). The mean retention time, as lake volume/discharge, is 11 weeks.

4. NUTRIENT INPUTS

(a) Inflow concentrations

The main inflow, sampled at a bridge near the Tarn, is the main input of solutes - but not necessarily of all nutrients - to the Tarn. The nutrient elements C, Ca, N, P, K and Si are here considered with reference to seasonal changes in concentrations over two years. Estimates of the corresponding elemental loadings for the total inflow are given later (Tables 4-9). On two occasions (6 March 1985, 11 June 1985) concentrations were traced over a sequence of upstream stations, but the variations encountered were not substantial. However there were slightly higher concentrations of PO_4-P (9.8 µg l^{-1}) and total P (11.8 µg l^{-1}) at station a below farm and housing with septic tank drainage.

Concentrations of inorganic carbon and calcium are always high, from denudation of a limestone catchment. The pH levels of 7.3 - 7.8 (Fig. ~~5~~ 3) are such that the total alkalinity range of 2.1 - 4.3 meq l^{-1} (Fig. ~~5~~3) is probably synonymous with the range of HCO_3^- in the same units. They also imply considerable concentrations of free CO_2, far above those (c. 15-25 µmol l^{-1}) expected at air-water equilibrium, that are also estimated by the free CO_2 acidity. The last is equal to $-V_1$ where V_1 is a directly measured titrimetric quantity. Its seasonal variation, shown in Fig. ~~5~~3, implies concentrations of free CO_2 of between 100 and 360 µmol l^{-1}, with maxima in autumn (organic decomposition) and minima in spring - early summer (plant growth). The concentrations of calcium are similar to those of alkalinity, and the time-variations are closely correlated.

Potassium (Fig. ~~5~~3) fluctuates, apparently irregularly, about a mean level of c. 0.5 mg l^{-1} (13 µeq or µmol l^{-1}) that is only slightly higher than the mean concentration in rainwater (see (b) below).

Inorganic nitrogen is probably present almost entirely as NO_3-N and NH_4-N (Fig. ~~6~~4). The former is quantitatively predominant, with a late winter-spring concentration~~s~~ above 800 µg l^{-1}. Concentrations decline in summer (1985) or autumn-early winter (1986), but even the lowest concentrations of c. 400 µg l^{-1} are considerable and similar to the most probable mean estimate for rainwater (see (b) below). The similarity may have a causal origin as the variably-timed minima in the inflow occur during seasons of heavy rainfall, when run-off is rapid. The higher levels probably arise mainly from soil nitrification and possible accumulation during low flow in underground channels feeding the springs.

Ammonium-nitrogen shows little evidence of a seasonal cycle, with limited fluctuations about a mean level of only c. 40 µg l^{-1}.

Phosphorus is known from analysis for its total quantity and its particulate, soluble-reactive (PO_4-P) and soluble-unreactive components (Fig. ~~6~~5). The total phosphorus concentration is low by general standards, with only two values > 20 µg l^{-1}. Its short-term fluctuations are largely due to a variable particulate component that is probably influenced by wind and rainfall. Concentrations of soluble reactive P are almost always detectable (unlike those of the Tarn) and generally between $\overset{1}{\cancel{2}}$ and $\overset{4}{\cancel{5}}$ µg l^{-1}. Together the two soluble (i.e. filter-passing) components constitute a fairly stable and low aggregate quantity of c. $\overset{5}{4}$ µg l^{-1}, which does not indicate major phosphate-rich effluents upstream.

Soluble silicon, here expressed as silica SiO_2 (Fig. $\overset{5}{6}$), also fluctuates
a marked depletion in late winter – spring.
without obvious regularity or relation to rainfall and season. Almost all concentrations fall between 1 and 2 mg SiO_2 l^{-1}.

(b) Catchment sources

Nutrient sources in the catchment are principally from atmospheric bulk precipitation (= wet and dry deposition), surface chemical denudation, ground water, agricultural fertilisers, visiting birds, and domestic sewage.

Atmospheric precipitation

Analyses for Malham Tarn are included in Appendix 03, Table .

~~Table 2 gives chemical analyses for atmospheric precipitation collected over the year March 1986 - March 1987. A large variability of concentrations is indicated by the standard deviations, which are either similar to the means (SiO_2, total P, K) or c. 0.6 of them (NO_3-N, NH_4-N). Samples of very small volume, after low rainfall, generally show high concentrations and are not included here. The only noticeable evidence of seasonality in the concentrations concerns total P, for which levels > 50 µg l^{-1} were limited to four consecutive samples in summer.~~

Comparison of the mean nutrient concentrations in precipitation with those for the major surface inflow can give an indication of the importance of the atmospheric contribution. This appears strong (probably above 50%) for N, P, and K but insignificant for Si. The relative proportions of NH_4-N and NO_3-N in precipitation and inflow are reversed, as would be expected from the lability of NH_4-N and its conversion to NO_3-N by soil nitrification. The magnitude of the atmospheric P input is very dependent upon the weighting given to the four high concentrations measured over May-August 1986, but is considerable with or without these values. Rough estimates of the atmospheric fluxes are derived later (Tables 4, 5, 7) by combining mean nutrient concentrations with the measured rainfall, of which 10% falls directly on the Tarn surface.

Surface chemical denudation, especially from limestone areas, must account for almost all of the large inputs of Ca^{2+} and HCO_3^- via the inflow. Comparison between inflow concentrations and known catchment sources of N, P and K suggests that for these elements it is subordinate.

Ground water is not known to have a significant direct influx to the Tarn, but its total-P concentration was checked by a single sampling on 16 Feb 1987 of bore-hole water from High Trenhouse. The analysis yielded 5.3 µg total-P l^{-1}, a low value not indicative of significant P accumulation.

Agricultural fertiliser

Of the total catchment of c. 6.1 km^2, 1.0 km^2 consists of improved pasture grassland to which inorganic fertiliser and often farmyard manure are added (Fig. 7). Fertiliser is an N-P-K mixture, mostly "Compound 20:10:10", with these ratios expressed as N, P_2O_5, and K_2O, equivalent to the elemental composition of 20% N, 4.4% P, and 8.3% K. Roughly equal areas receive dressings at levels of c. 2 and 3 cwt $acre^{-1}$ yr^{-1}, or c. 250 and 380 kg km^{-2} yr^{-1}. Allowing for nutrient contributions from unspecified but fairly light dressings of farmyard manure (with some recycled hay nutrients) over c. two-thirds of the fertilized area, the higher figure above is here taken as applicable to the whole area. Allowing for a loss of c. half the nutrient additions before ultimate entry by drainage to the Tarn, order-of-magnitude estimates of these nutrient element contributions are 38 kg N yr^{-1}, 8.4 kg P yr^{-1}, and 16 kg K yr^{-1}. From the disposition of the fertilised pastures (Fig. 7) roughly half these quantities will drain to the Tarn via the main inflow and be represented in its estimated nutrient inputs, and about half will be an independent contribution via other land run-off.

Birds

The Tarn is visited in spring and autumn by flocks of black-headed gulls (Larus ridibundus) whose excreta make an input of N and P, sometimes sufficient to appear as a whitening of distant slopes (K. Iball, pers. comm.). A possible estimate of the more critical P component is derived below. From observations by E. Jackson (FSC), an exceptional count of > 10,000 birds is known, but more typical estimates (K. Iball, pers. comm.) rate the spring and autumn visits as c. 1000-2000 birds for 1-2 weeks each. A median estimate is thus 1500 x 1½ x 7 x 2 = 31500 bird-days per year. Adopting, as by Moss & Leah (1982), an excretory output per bird of 38 mg P per 24 h, and assuming a near-Tarn residency of about 16 h per day, the estimate of P input is 0.80 kg yr^{-1}. Values for N can be expected to be about one order of magnitude greater. However, for both elements the quantities are hardly significant in comparison with other inputs.

Domestic sewage

Sewage input of P is roughly estimated below, using a generalized per capita contribution of 1.8 g P day^{-1} (Alexander & Stevens 1976). Although settlements in the catchment are sparse, the FSC Field Centre has a large occupancy and its effluents drain (via a septic tank and a soak-away) direct to the Tarn and not to the main inflow. Records for 1986 show an average Nov.-Feb. occupancy of c. 15 staff + 10 visitors, and an average March-October occupancy of c. 15 staff + 49 visitors. Allowing a 50% interception loss during drainage, the P input to the Tarn can be estimated as about 1.8 [(25 x 120) + (64 x 245)] x 0.5 x 10^{-3} = 17 kg P yr^{-1}. Applying a similar calculation to mean year-long occupancy of other settlements (Waterhouses, National Trust, High Trenhouse, Low Trenhouse), estimated to be c.30 persons, an estimated input of $1.8 \times 30 \times 365 \times 0.5 \times 10^{-3} = 9.9$ kg P yr^{-1} is obtained. Most of this latter input will enter the Tarn via the main inflow.

Nitrogen fixation

An input by N_2- fixation is likely to be chiefly due to the activity of heterocystous blue-green algae - mainly Gloeotrichia echinulata - common in the summer plankton of the Tarn (Figs 12, 16). The nitrogen content of this algal component can be roughly estimated from the highest Tarn-mean chlorophyll a content, when the latter appears chiefly derived from a dominant Gloeotrichia component. This mean content was c. 38 µg chl-a l^{-1} in 1985 and c. 26 µg l^{-1} in 1986, if overweighting by secondary inshore accumulations is avoided. Adopting representative percentages of dry weight of 8% and 2% for N and chlorophyll a respectively, a turn-over factor of 2 for the season involved and assuming that the main biomass increment depends upon N-fixation, a very rough estimate of planktonic N fixation is 0.3 mg N l^{-1} y^{-1} or - for a well-mixed Tarn - 400 kg N yr^{-1}. Although small compared to the annual N-input from other sources (Table 5), this quantity is probably important for algal growth under summer N depletion.

Seasonal chemical changes : - - - - - - - - growth

5. THE TARN AS A CHEMICAL REACTOR

(a) Inflow-outflow concentration changes

A guide to net chemical activity in the Tarn is provided by the seasonally varying differences in concentrations measured at the main inflow (station 5) and outflow (station 1). These are summarized in Figs ~~5~~ 4 and ~~6~~ 5. Some allowance is necessary for the time factor in retention, and that a divergence indicative of a certain Tarn activity is likely to be reduced in periods of high water through-put. These features, and some other Tarn inputs of varying significance, are expressed in the nutrient budget (Tables 4-9).

A large *summer removal of $CaCO_3$* is evidenced by Tarn reductions in Ca^{2+} and alkalinity (largely HCO_3^-), and the correlated variable of conductivity (Fig. ~~5~~4), despite increases in the inflow. This feature was already known from earlier years (1949 - 1953: Lund 1961; 1964-1965: Pitty 1971; 1980: Pentecost 1984; 1985-6 : Talling 1987). The mainly ~~June~~ May-July reduction in Tarn concentrations of Ca^{2+} and HCO_3^- (as alkalinity) varies from year-to-year, and can account for about half of the preceding winter stocks (e.g. in 1986). In 1987 it was exceptionally small, probably due to the exceptionally wet summer and consequently high water flux. A general relation to plant growth and photosynthetic CO_2 assimilation in the Tarn was suggested by Lund (1961). Pentecost (1985) showed that in timing and probably in quantity the removal is ascribable to the benthic summer growth of *Chara globularis*, an interpretation supported (Talling 1987) by the ~~present~~ chemical analyses ~~(Table 3)~~ and budgets for Ca^{2+} and alkalinity ~~(Tables 8, 9)~~.

A further loss of inorganic carbon as *free CO_2* in the Tarn is indicated by the much lower values of CO_2-acidity (V_1) and higher values of pH there compared to the inflow. Direct loss of CO_2 to the atmosphere must occur, augmented by the photosynthetic consumption of CO_2 by aquatic plants.

Compared with Ca^{2+} a proportionately still larger *summer removal of K^+* occurs (Fig. ~~5~~4)~~, although the absolute quantities involved are less by a factor of 10^2~~. Its seasonal phasing is similar to that of the $CaCO_3$ removal. A common cause in the seasonal growth of *Chara* is supported by analyses of this plant (mean K content 1610 mg g^{-1} dry weight : ~~Table 3~~ Talling 1987) and the overall K budget (Table ~~7~~1). However the residual K^+ concentrations of c. 40 µg or 1 µeq l^{-1} are - unlike those of Ca^{2+} and HCO_3^- - low enough to be suspect of a growth-limiting effect. From information reviewed by Sutcliffe (1978), they may also affect the ionic exchange of such Tarn invertebrates as the freshwater shrimp (*Gammarus* ~~*pulex*~~ lacustris) and crayfish (*Austropotamamobius pallipes*).

A major *removal of soluble reactive silicate* (here expressed as SiO_2) can be deduced from the near-consistent depression of Tarn concentrations below those (c. 1-2 mg SiO_2 1^{-1}) of the inflow (Fig. ~~6~~ 4) and the corresponding budget (Table 6). The most intensive removal is late winter-early spring, utilising stocks built up during the winter. Its predominant cause is almost certainly the growth of benthic diatoms, as was earlier deduced by Lund (1961) from records of Si depletion in 1949-1953. Such diatoms are abundant; their species-representation and seasonal abundance during 1949-1953 were described by Round (1953).

Of the two main forms of inorganic nitrogen, shown separately in Fig. ~~6~~ 5 and summed in Table 5, nitrate-nitrogen has a strong summer depletion in the Tarn below the generally high (400-1100 µg 1^{-1}) inflow concentrations. The latter also show some seasonal decline but phased later than that of April-June in the Tarn, where the resulting summer concentrations are often at or below the limit of detection (10 µg 1^{-1}). As in many productive lakes, the summer uptake could reflect temperature-sensitive bacterial denitrification and incorporation in plant biomass. In view of the large benthic biomass of Chara in the Tarn, its influence here is probably considerable.

For ammonium-nitrogen there is evidence (Fig. ~~6~~ 4) of a net Tarn uptake below inflow concentrations during summer, 1986 but little during summer 1985. In all these periods the concentration differences involved, and the estimated net transfers of NH_4-N, were small compared to the corresponding changes of NO_3-N. More considerable are Tarn increases of NH_4-N above inflow concentrations during October-December in both years 1985, 1986 and 1987. The maxima reached, circa 200 µg 1^{-1}, would only be expected in an unpolluted surface water if transfers from organic decomposition were occurring. Sufficiently large organic sources occur only in the sediments, the benthic Chara biomass, and the adjacent raised bog; the available evidence (Section 5d) suggests one or both of the last two sources.

Among the various forms of phosphorus examined, only soluble reactive phosphorus (PO_4-P) showed consistent divergence between inflow and outflow

(Fig. $\overset{4}{6}$). The Tarn outflow concentrations were almost always near the limit of detection of 0.$\overset{6}{7}$ μg l^{-1}, whereas inflow concentrations were generally between 1 and $\overset{4}{5}$ μg l^{-1}. All these levels are very low for surface waters, and because of the larger quantities in other interrelated fractions the inflow-outflow difference need not imply a net removal of P in the Tarn. The input-output budget for phosphorus (Table 4) has been based upon total-P concentrations, but these are susceptible to local algal (esp. Gloeotrichia) accumulations and local sediment disturbance induced by wind. Thus strong maxima of total-P are associated with maxima of particulate-P (Fig. $\overset{4}{6}$) and, in the Tarn, both are correlated with phytoplankton abundance indicated by chlorophyll-a (Figs 9, 11) and particulate-C (Fig. 11). During 1985 the concentrations of total-P in inflow and outflow were very similar. In 1986-7 the outflow concentrations (and particulate P) were generally somewhat higher, but because of significant estimated inputs other than by the main inflow there is an estimated net P retention in the Tarn during both years (Table 4).

(b) Nutrients: within-Tarn variation and water-mass content

Five sampling stations around the Tarn were used to detect possible horizontal variation of nutrient concentrations and to improve the estimate of a mean concentration in the water-mass as a whole. Such near-shore stations, however, are prone to yield some overestimate of particulate-P concentrations. The largest examples concern not silt but inshore and downwind accumulations of the colonial buoyant alga Gloeotrichia echinulata, also reflected in chlorophyll-a concentrations. Thus on 9 September 1985 at station 1, after a south wind, extreme and transient concentrations of 3.1 μg l^{-1} for particulate P and 3.0 μg l^{-1} for chlorophyll a were found. Corresponding concentrations at the northern and opposite station 3 were 20.1 and 28.0 μg l^{-1} respectively.

Horizontal inequalities of concentration for dissolved components were generally relatively small. There was no reliable evidence of local increases at stations 2 - 4 on the northern shore that might relate to nearby sewage inputs from the Field Centre. At times the influence of inflow water at the nearer stations (especially nos. 4 and 6) could be recognised for constituents seasonally depleted in the Tarn and then more abundant in the inflow. Examples included Si, K, NO_3-N, and alkalinity, for which the lowest concentrations were recorded at the outflow (station 1). Pentecost (1981) refers to appreciable variation of alkalinity in transects across the Tarn, which he believes was probably induced by a horizontally variable removal of $CaCO_3$ by beds of Chara.

Arithmetic mean values for five (rarely fewer) stations are used in Figs 8 and 9 to show changes in time over two years for various constituents. Information on alkalinity, CO_2-acidity, and pH is from station 1 only. Almost all major changes appear to be of biological origin, although their timing is likely to be indirectly regulated by such physical factors as solar radiation input and temperature and their extent conditioned by the water input-output flux. Examples already described in (a) above include strong seasonal depletions of Ca^{2+}, HCO_3^-, K^+, Si, and NO_3-N, and a seasonal release of NH_4-N. Strong winds are known to disturb surface sediment, but their incidence (Fig. 3) has no clear impact on the concentrations of constituents likely to be released from interstitial water (e.g. K^+, NH_4-N, PO_4-P, Si). The limited variation (at station 1) of pH, range 7.7-8.7, must be induced by CO_2 inputs or removal. However only the first major fall in July 1985 is correlated with a major influx of CO_2-rich stream water.

(c) Benthic nutrient stocks

The Tarn holds large stocks of nutrients in its bottom sediments and, at least seasonally, in dense benthic stands of Chara globularis var. virgata

(Kütz.) R.D. Wood (incl. C. delicatula Agardh: Moore 1986). These were sampled simultaneously on two dates, 12 May and 20 Oct. 1986, and their composition determined for the various chemical fractions given in Table 3.

The sediment was from the 0-4 cm layer, with duplicate cores analysed on each occasion. Differences between cores and between sampling dates are generally minor, although the October samples showed substantially higher contents of K, Na, Mg, and Fe. The contents of Ca and inorganic C indicate a high $CaCO_3$ content of c. 50% of sediment dry weight, for which the mineral residues of Chara are probably the main source. The organic C content shows that organic material contributes another c. 25% of the dry weight. The mild extraction procedures also applied to PO_4-P, NH_4-N, and K indicate that potentially exchangeable forms of these nutrients are present in substantial amounts.

For comparison with other Tarn stocks, area-based quantities are desirable. These were calculated (Table 10) for the 0-4 cm sediment layer, assuming a specific gravity for sediment of 1.05 g ml^{-1} that is based upon the known water content and the specific gravity of principal sediment components.

Corresponding estimates of nutrient stocks in Chara require assessments of its biomass as dry weight and analyses of element quantities in unit biomass. The former were kindly made available by FSC staff, based on sampling by divers of the Ribblesdale BritishSub-Aqua Club in August and September 1985 and July, August, September and October 1986. Mean stand densities were calculated from four well-spaced stations over the Tarn for Aug-Sept 1985 (1.57 kg m^{-2}) and Aug-Sept 1986 (1.27 kg m^{-2}). Combining these values, the summer maximum of Chara was estimated to correspond to a mean stand density of 1.42 kg dry weight m^{-2} (cf. station of Pentecost 1984: 1.4 kg m^{-2}) or a Tarn total of 870 x 10^3 kg. Multiplication of these values by the mean relative elemental contents yields estimates of the maximum seasonal stocks of organic and inorganic C, N, and S, and of total P, K, Ca, Mg, Fe, and Mn (Table 10).

The maximum Chara biomass is clearly much larger than the maximum seasonal biomass of phytoplankton, and will incorporate correspondingly larger quantities of C, N, P, and K. If the maximum, phytoplankton density is roughly estimated, from Fig. 9, as c. 25 µg chl-a l^{-1} or c. 2.5 mg dry weight l^{-1}, and is evenly distributed, the Tarn total is c. 3.6 x 10^3 kg dry weight (cf. Chara: 870 x 10^3 kg). A corresponding comparison of particulate-P stocks in Tarn water (seasonal maximum 20 µg l^{-1}: Fig. 9), Chara (summer maximum), and sediment (0-4 cm layer) gives values of 29, 1400 and 3090 kg respectively.

(d) Internal nutrient loading

Internal loading, by redistribution of nutrients from pre-existing quantities that were unavailable for spatial or chemical reasons, is seasonally important for plant production in many lakes. In the Tarn, lacking a persistent thermocline with hypolimnion, the opportunities for redistribution are (i) from sediment to water column and (ii) by release in breakdown of biomass. Both processes occur continuously at low and unquantified rates, but evidence for large periodic inputs is considered below.

There are visual signs, in water turbidity, for disturbance of surface sediment under strong winds. Accelerated transfer of nutrients from sediment to water-column might then result. If present, this is not manifest in increases of the dissolved nutrients measured (PO_4-P, NO_3-N, NH_4-N, K^+) at the times of strong winds shown in Fig. 3. Connexions with total- and particulate-P are inconsistent, as shown by strong increases in these P-quantities during the windy period 1-14 April 1986 but not during that of 3 March - 1 April 1986. The increased turbidity is unlikely to greatly exceed that (5 mg l^{-1}) expected by resuspension of the uppermost 1 mm of sediment. Quantities of readily elutable PO_4-P, NH_4-N, and K^+ from this layer would - if in concentrations similar to those measured for the 0-4 cm layer - raise concentrations in the well-stirred Tarn by 6.7, 2.7, and 9.0 µg l^{-1}

respectively. These amounts would be increased by a factor of 40 if the entire 0-4 cm layer was involved in release, as is documented for Lake George in Uganda (Ganf & Viner 1973). In proportion to pre-existing concentrations, the calculated quantity of PO_4-P would be much the most significant.

The succession of phytoplankton species implies that nutrients released by an abundant precursor species must often be reincorporated in its successor(s). However large correlated changes in measured nutrient concentrations are generally lacking. The situation is possibly otherwise for the much larger benthic biomass of Chara globularis var. virgata, which from observations of Pentecost (1984) may partially die down in autumn. Of its large incorporations of N, P, K, and Ca, early releases of the first three are then possible. A large autumn-winter increase of NH_4-N in the Tarn water, above inflow concentrations, can be so interpreted, but a post-summer K^+ increase there can also be related to a replenishment by inflow. A release of P is not reflected in observed concentrations, and if present must be otherwise removed (e.g. by adsorption on sediments). It is possible that the autumn decline depicted by Pentecost (1984) is not a regular annual feature, as over-winter persistence of C. globularis sensu lato in Britain is known (Moore 1986). Apparently dense and healthy beds of the species were encountered during the sampling of 20 October 1986, immediately before increased concentrations of NH_4-N occurred (cf. the August increase in 1985). An alternative explanation of the increase in both years is by run-off of bog-water from Tarn Moss rich in NH_4-N, after the onset of persistent rains in late-July 1985 and in October 1986. Such water would probably be of low P content.

(e) Components of the annual nutrient budget

Estimates of component fluxes or stock changes of nutrients in the Tarn system are given in Tables 4 - 9. They are based on (i) a combination of water budget fluxes and measured concentrations, (ii) estimates of nutrient inputs from agricultural fertiliser and domestic effluents, and gulls, (iii) changing concentrations in the Tarn water-mass, (iv) maximum stand-densities of benthic Chara beds and their nutrient content per unit biomass, and (v) sediment nutrient stocks in the 0-4 cm layer. Most of these quantities have already been assessed individually. The present object is to delimit their interaction in terms of tentative budgets (with input, output, and storage) for the elements P, N, K, Ca, and Si, and from relative magnitudes assess possible susceptibility to change. Some principal quantities are summarized in diagram form (Fig. 10) and in the comparative Table 10.

The P-economy is distinctive in that Tarn-water stocks are invariably deficient in the most readily available fraction of PO_4-P, and so seasonal phases of its depletion by uptake are lacking. This condition may be due to the persistence of considerable benthic biomass (Chara, diatoms) and possibly to adsorption on surfaces of $CaCO_3$ (analysed elsewhere by House et al. 1986a, b). The input by atmospheric precipitation appears predominant, although the variability between analyses is large and an overestimation by contamination of exposed collectors is possible. The human contribution from field-fertiliser and sewage is probably appreciable (> 20%). The Tarn has a small annual net retention. It contains a very large stock in the benthic Chara biomass, whose seasonal growth can not be sustained from current Tarn input or pelagic P stock but must require translocation from old cells to young shoots or via rhizoids from the large sediment stock.

The N-economy is mainly supported by large inputs (of NH_4-N and NO_3-N) in atmospheric precipitation. The human contribution from fertiliser and sewage appears relatively minor. A seasonal contribution of NH_4-N from the adjacent raised bog is possible. The Tarn-water stocks of inorganic N (mainly NO_3-N) are large in winter but almost exhausted in summer, when a transient and probably small input flux by planktonic N-fixation occurs. The benthic

Chara biomass is again a large stock-component, greatly exceeding the maximum phytoplankton stock. If the large and unmeasured flux of dissolved organic N is little utilised during transit, the Tarn has a net N retention.

The K-economy is also predominantly supplied by inputs from atmospheric precipitation. The contribution of field-fertiliser is minor. In summer most of the Tarn stock in solution is removed; the quantity and timing indicate an uptake by the benthic Chara biomass, rather than by phytoplankton or phytobenthos.

The Ca economy is almost entirely supplied by chemical denudation from a partly limestone catchment, a process subject to seasonal variation that is probably related to CO_2 release. The Tarn stock in solution shares a summer uptake which (like those of K^+ and HCO_3^-) is ascribable to the growth of Chara biomass, containing c. 50% $CaCO_3$ in dry weight. The quantities of Ca^{2+} and HCO_3^- involved greatly exceed those of any other ion subject to biological transfer. There is a strong net accumulation of $CaCO_3$ in the Tarn.

The Si economy depends upon input by chemical denudation. Depletion of the dissolved stock in the Tarn occurs below inflow concentrations throughout almost all the year. It is ascribable to benthic rather than planktonic diatom growth, and is most extensive in February-March after a winter build-up of the dissolved stock. There is a strong net retention of Si as SiO_2 in the Tarn; its recycling is conjectural.

Summarizing, all five elements show strong biological depletions from the Tarn water-mass, with varying seasonal incidence. Except for Ca^{2+}, the low residual concentrations may be suspected as possibly limiting for algal growth rates unless (Chara?) an alternative and quantitatively adequate translocation from sediment stocks is feasible.

6. PHYTOPLANKTON DYNAMICS

(a) Total biomass

Assessments of total phytoplankton concentration are here based mainly upon chlorophyll a (chl-a) estimations (Figs 9, 13-16 7–10), with which concentrations of particulate phosphorus and particulate carbon are closely correlated (Figs 9, 11). During 1985 the 5-station Tarn mean for chl-a was almost consistently low, exceeding 8 µg l^{-1} on only one occasion in September when wind-drift induced secondary inshore accumulations of a buoyant alga (Gloeotrichia echinulata). The annual average level in 1986 was about three times higher. There ~~is~~ were evidence of a late-February to early April increase in 1985, 1986, and 1987, and a more extended summer to autumn phase of higher concentration that often included uneven horizontal distribution. Other brief and apparently irregular maxima can occur, as in June 1986.

Overall, the mean concentrations are low (1985) to moderate (1986) and would compare with values encountered in moderately productive or mesotrophic lakes. The post-winter increase shows an early timing that is known from shallow lakes elsewhere and can be related to an earlier onset of more favourable light conditions in such water-masses.

Relationships between chlorophyll a content and concentrations of particulate C and P are further illustrated in Fig. 11. Estimates of the highest total-Tarn contents during 1986 of chl-a and suspended particulate P, based on all 5 stations on 18 August, are 38 and 23 kg or 62 and 38 mg m^{-2}. The phosphorus quantities have already been shown to be are much lower than the corresponding estimates for the P stock in benthic Chara beds, about 1400 kg (Talling 1987).

(b) Relative species composition

The phytoplankton biomass is contributed by species whose seasonal quantities and persistence vary greatly. A summary based on subjective grading of abundance at stations 2 and 3 appears in Fig. 12. 6

During much of the year flagellates are predominant; they include the very persistent *Rhodomonas lacustris* plus *Cryptomonas* spp., *Trachelomonas* spp., *Dinobryon divergens*, and an unidentified small chlamydomonad. Dinoflagellates, as species of *Peridinium* and *Gymnodinium*, are regularly abundant though rarely dominent in a late winter-early spring phase. They are probably derived by excystment from overwintering cysts, as cell contents are often bipolar. Diatoms are rarely dominant, the most characteristic and persistent species being *Diatoma elongatum* and its var. *elongatum*. *Stephanodiscus hantschii* has brief periods of abundance, and two normally benthic genera - *Navicula* and *Cymbella* - are also frequent yet never dominant. Green algae, best developed in summer, include the persistent *Pediastrum boryanum* and a small *Scenedesmus* sp., '*Sphaerocystis* agg.' (now assignable to other species), *Asterococcus superbus*, *Volvox* sp., and various large desmids of the genera *Staurastrum*, *Cosmarium*, and *Xanthidium*. Such desmids are more characteristic of acid than calcareous alkaline water, and are possibly recruited from the adjacent raised bog of Tarn Moss. The buoyant *Botryococcus braunii* is also common in summer-autumn. Only two blue-green algae (cyanobacteria) are of significance, also in summer-autumn, *Gloeotrichia echinulata* and *Anabaena flos-aquae* forma (= *A. lemmermanii*). The former is present as large buoyant colonies which often accumulate on down-wind shores, producing locally elevated concentrations of chl-*a* (1 colony averages c. 0.15 µg chl-*a*). A variety of other algae occur in small quantities; they include the green *Pseudoquadrigula* sp., the chrysophytes *Mallomonas akrokomos* and another *Mallomonas* sp., the dinoflagellate *Ceratium hirundinella*, *Oscillatoria* spp., and dislodged benthic diatoms.

The floristic composition is notable for the absense of common large colonial diatoms such as *Asterionella formosa* (previously abundant in 1949-53: Lund 1961), *Tabellaria flocculosa* var. *asterionelloides*, and *Melosira* spp. for the abundance of flagellates and limited representation of diatoms and blue-green algae; and for the occasional occurrence of the diatom Stephanodiscus hantschii usually characteristic of eutrophic or enriched lakes.

(c) Population cycles

More quantitative information on algal population cycles is based on counts for station 2 1. It is shown as semi-logarithmic plots, with corresponding quantities of chl-a, in Figs 13-16 7-10. Parallelism between a species pattern and that of chl-a could imply either predominance of that species in the total biomass or a similar limitation of a subordinate species biomass with that of the total biomass. The first cause is probably applicable to Rhodomonas lacustris for long periods and to Gloeotrichia echinulata, Stephanodiscus hantzschii, and 'Sphaerocystis agg'. for short periods of abundance. The second cause probably applies for long periods to Cryptomonas spp. and for the mid-winter period of low abundance to most species.

Inspection of Figs 13-16 7-10 suggests that most patterns of seasonal abundance tend to fall into three major groups. These feature: (i) a strong winter minimum with an extended abundance (dynamic range c. 10:1) over most other seasons, (ii) a strong maximum in early spring plus a generally lesser one in autumn, and (iii) an extended single main maximum in summer-autumn. To these groups may be attributed the following species:

group (i) - Rhodomonas lacustris, Cryptomonas spp., Trachelomonas spp.

group (ii) - the diatom Diatoma elongatum plus (in 1986) Navicula radiosa, Cymbella spp., and Gomphonema sp.; the chrysophyte Dinobryon divergens; and the dinoflagellates Peridinium spp. and Gymnodinium sp.

group (iii) - the green algae Volvox sp., Pediastrum boryanum, Scenedesmus sp., 'Sphaerocystis agg.', Asterococcus superbus, and Botryococcus braunii; the blue-greens Anabaena flos-aquae and Gloeotrichia echinulata.

Besides these differences of seasonal pattern, the amplitude of well-attested temporal variation ranges from a low value of c. 1.7 $\log_{10}$ units for Rhodomonas lacustris to values of > 3 $\log_{10}$ units (i.e. factor of > 1000:1) for Diatoma elongatum, Asterococcus superbus, and Cryptomonas spp. The corresponding amplitude for total algal biomass, as indicated by chl-a concentration, is c. 1.6 $\log_{10}$ units. Its comparatively low value will be influenced by temporal species replacement, as illustrated elsewhere by Talling (1986).

(c) Controlling factors

In the absence of direct experimental evidence, factor influences are here discussed from time-correlative behaviour supplemented by considerations of chemical budgets.

Among the probable controlling factors, Temperature in the Tarn is depressed by altitude (Manley 1956), and values > 12°C exist for only 9-10 weeks each year (Fig. ~~3~~ 2). As there is experimental evidence that some algae (e.g. Ceratium hirundinella : Appendix 0) ~~Heaney, Chapman & Morison 1983)~~ achieve little vegetative growth below 10°C, it is possible that their summer growth is severely restricted. The much lower levels of winter temperature (< 4°C) can not be directly responsible for the winter minimum of phytoplankton, as an active early-season increase of some algae can occur at such levels (e.g. February, - March 1987). Further, the main October - November decline occurs at higher temperature. However the presumed excystment of dinoflagellates in spring may well be conditioned by temperature increase, as known elsewhere (Heaney, Chapman & Morison 1983).

Light income (Fig. 3) is lowest during the winter season of reduced phytoplankton and, from experience elsewhere (e.g. Talling 1971) is likely to be a principal determining factor.

Water-flushing, expressable as low retention time and deducible from water-level (Fig. 3), was particularly strong during mid-winter periods. Values of < 25 days retention time were then estimated to prevail for several weeks. The corresponding loss rates would be > 0.28 ln units week^{-1}, and are likely to be significant for net population increase already reduced by low temperature-light conditions. A lesser restriction would be expected in the wet summer-autumn of 1985.

Wind-stress is accentuated by the altitude and exposure of the Tarn. Daily wind-runs of 500-1000 km day^{-1} occur periodically (Fig. 3), equivalent to mean velocities of 5.8 - 11.6 m s^{-1}, with some disturbance of sediment and possible nutrient release. Regular correlations with phytoplankton changes are not apparent, but there are examples of major increases of some species after high winds (e.g. *Asterococcus superbus*, May 1986).

Phosphorus is the nutrient element for which the closest (though controversial) measure of a soluble available component (PO_4-P) is consistently in very low concentration (Fig. 9). From correlative experience in deeper lakes elsewhere (e.g. Dillon & Riger 1974) the winter-spring concentrations of total P - c. 8 µg l^{-1} in 1985-86 - would not be expected to be associated with later summer concentrations of chl-*a* greater than the maximum observed Tarn mean values of c. 20 µg l^{-1}. In the Tarn partly accessible sedimentary reserves exist, but the relatively large benthic plant growth will be in competition for phosphorus. It is notable that the correlation between suspended particulate P and chl-*a* is strong (Fig. 11b), and that values of both in 1986 are generally higher than in 1985.

Inorganic nitrogen consists of two main components, both reduced to concentrations of < 30 µg l^{-1} in summer. The much longer depletion in 1986 occurs with denser phytoplankton and a lesser inflow supply. A dominant component of the summer phytoplankton is the heterocystous Gloeotrichia echinulata, likely to fix N_2 and so - with the accompanying Anabaena flos-aquae - be probably unrestricted by the reduced supply of $NO_3 + NH_4$-N. Restrictions on other algal growth are possible but conjectural in the absense of information on N-recycling. In other seasons the large reserves of NO_3-N make an N-limitation unlikely.

Dissolved silicon is largely consumed in late-winter to early spring by diatom growth, but the timing (e.g. in 1986) indicates that benthic rather than planktonic populations are mainly involved. Earlier evidence for this conclusion is given by Lund (1961). If, as is likely, the varying depletions of Si throughout the year are mainly due to benthic diatoms, the latter may introduce periodic limitation of planktonic diatom growth. This supposition is supported by the main occurrence of planktonic species outside the periods of stronger depletion (cf. Figs 9 and 14).

Dissolved potassium has a strong annual summer depletion to 30-50 µg l^{-1}, probably from uptake during growth of the benthic Chara beds. From unpublished experiments of G. Jaworski (pers. comm.), such concentrations would be unlikely to support growth of one test diatom (Asterionella formosa) beyond increments of c. 80 µg chl-a l^{-1}. As this quantity is some 3 to 4 times higher than the maximum Tarn-mean concentrations, it is unlikely that there is even a brief summer phase of K-limitation for phytoplankton in the Tarn, ascribable to competition from the phytobenthos.

Inorganic carbon is always present in high total concentration, though also subject to summer reduction by Chara. This does not exclude possible limitations operating via greater reduction of free CO_2 levels, but the observed upward shifts of pH (Fig. 8) are too small to make appreciable limitation likely.

Grazing by zooplankton cannot be quantified. Inshore swarms of cladocerans were occasionally met but are unlikely to extend over much of the water-mass. Probably more significant are periodic and large maxima of two planktonic ciliates, seen with ingested small algae whose populations they may influence.

7. SUSCEPTIBILITY TO CHANGE

(a) Records over time

A limited number of earlier records can be compared with those from 1985-7 as evidence of stability or historical change. Earlier evidence on nutrient status comes from four main sources: Lund (1961) - the most extensive with 1949-53 information, unpublished analyses from 1971 by the Freshwater Biological Association given in Talling & Hilton (1982) and Woof & Jackson (1988), routine analyses by the Yorkshire Water Authority, and a few unpublished analyses of the Central Electricity Generating Board from 1980-1. They, with records of $CaCO_3$ removal by Pitty (1971) and Pentecost (1971), are reviewed in the previous report to the NCC by Talling & Hilton (1982). Combining them with analyses of major ions in 1980-1 by Woof & Jackson (1988) and the present information, it appears that (i) the base status (Ca^{2+}, alkalinity) of the Tarn has shown no long-term change (ii) concentrations of PO_4-P have been consistently low, (iii) concentrations of NO_3-N have always been depleted in summer but in winter have increased by a factor of about 2 from 1949 to 1985, and (iv) concentrations of dissolved silicon have throughout been subject to periodic depletion by benthic diatom growth but not by appreciable long-term change. As the low PO_4-P concentrations could result from secondary removal, there is no firm evidence - requiring total P analyses - on the crucial issue of long-term P inputs.

Of the biological communities in the Tarn, the phytoplankton has shown some qualitative change since 1949-53, notably by the apparent disappearance of the once-dominant diatom Asterionella formosa. An older record of net phytoplankton by West & West (1909) is less easily compared. An indicator of nutrient-rich waters, Stephanodiscus hantzschii, showed sporadic maxima in 1949-53 as in 1985-7. Surface blooms of blue-green algae are known from 1949-53 and 1983 (aerial photographs) as well as 1985-7. An abundant and floristically diverse benthic community of diatoms has been known since 1949-53 (Round 1953, Lund 1961, Barber 1982; also unpublished 1980 records of E.Y. Haworth and the late H.G. Barber), admixed with macroscopic growths of some blue-green algae studied by Pentecost (1978, 1987).

A well-developed benthic community of macrophytes, dominated by Chara spp., has been recorded since the 1930's (Sledge 1936, Holmes 1956, Sinker 1960, Lund 1961). There are subjective impressions of a quantitative increase of Chara growth (C. Newbould and K. Iball, pers. comm.) and some extensions in the distribution of other macrophytes that include Elodea canadensis and Potamogeton spp. (K. Iball, pers. comm.).

(b) The nutrient-flux network and biological responses

The biological systems of the Tarn are maintained by fluxes of nutrients with inputs from atmosphere, surface chemical denudation, and local human activities. A current issue is whether increasing inputs are likely to greatly alter the quantitative and qualitative character of community stocks, including the relative importance of phytoplankton and benthic macrophytes. For this attention must centre on input changes that are clearly large or concern a critical limiting nutrient.

The largest established changes are of NO_3-N, almost certainly due to an increased N content in atmospheric precipitation influenced by distant and increasing oil consumption (reviewed in Royal Society 1983). As the summer consumption of the Tarn NO_3-stock is virtually complete, it is possible that the increase in input has been translated into increased plant production.

However it may have principally supported increased loss by bacterial denitrification, here favoured by the ratio of sediment area to water volume.

Experience with enriched temperature lakes is that phosphorus is the crucial element in most instances. Here evidence for increased P input is largely indirect, as the historical analytical record is deficient for total-P and merely establishes the lack (possibly partly by interaction with $CaCO_3$) of a marked rise of PO_4-P in inflow and Tarn. Present estimates of input have large uncertainties due to the variance of total-P concentration in atmospheric precipitation and the uncertain transmission factor through soil to Tarn of domestic and agricultural additions. However the atmospheric input is apparently dominant, and the human influence appreciable (Table 4). Recent increases in the latter, especially by detergents and large human numbers may therefore increase the biological P stocks. These are quantitatively much more susceptible to relative increase in the phytobenthos (Chara) than in the phytoplankton. The possible opportunities for more interannual accumulation in overwintering benthos and sediments further emphasise this route, but a future transfer of greater production to the phytoplankton (as occurred in the Norfolk Broads) cannot be excluded. However it would not be favoured by the inevitably short-retention time. At present several elements (P, N, Si) in the nutrient time-sequences and budgets appear to demonstrate competition between phytoplankton and phytobenthos.

Experience elsewhere (e.g. Loch Leven) is that the phytoplankton of shallow lakes has less long-term stability than that of deep lakes as regards species composition and annual cycles. This is consistent with some features of the Tarn phytoplankton (e.g. loss of Asterionella formosa; biomass differences between 1985 and 1986), and adds a further uncertainty into a competitive situation with the phytobenthos.

8. SUMMARY

1

(a) Malham Tarn is a shallow upland water-body of small catchment in a Pennine limestone area, here studied by 2-weekly sampling from March 1985 to March 1987. The aims were to assess nutrient input, storage, and output and to relate them to the composition and seasonal dynamics of the phytoplankton.

(b) General features of morphometry, catchment, and the water-budget are described. Quantitative features of the latter are based upon water level, the level-outflow flux relationship (here determined), and the rainfall from F.S.C. records. The rainfall-inflow relationship indicates a mean run-off factor of 0.9, and the outflow-lake volume relationship a mean retention time of 11 weeks.

2

(c) Nutrient inputs for the elements C, N, P, K, Ca and Si were estimated from regular sampling of the single major inflow and assessed sources of supply to the catchment, which involved analyses of rainwater. Seasonal variations of concentrations in the inflow were generally less than those in the Tarn and most systematic for inorganic C, N, and Ca. The main source of inorganic C, Ca, and Si was chemical surface denudation. and of inorganic N, K and probably P atmospheric precipitation. Rough estimates were made of the P-input from visiting gulls and domestic sewage, and of P, N, and K inputs from grassland fertiliser. The sewage-P input (from per capita estimates) was the most significant of these. There was some summer input of N, probably small, from N-fixation by planktonic blue-green algae.

3

(d) The nutrient exchanges and nutrient stocks for the Tarn are considered from five lines of evidence. Comparison of seasonal inflow and outflow concentrations demonstrated phases of strong net removal. Those of Ca^{2+}, HCO_3^-, and K^+ are probably mainly due to summer growth of the benthic macrophyte Chara globularis (incl. C. deliculata); of NO_3-N to plant growth plus bacterial denitrification in summer; and of Si to benthic diatoms, especially in early spring. Concentrations of PO_4-P were reduced in the Tarn to around the limit of detection (0.7 μg l^{-1}), but those of total-P were generally not reduced and were correlated via particulate-P with phytoplankton abundance (as chlorophyll-a).

Variation of nutrient concentrations over the Tarn was mainly affected by proximity to the inflow and by down-wind, near-shore accumulations of buoyant algae in summer. Large stocks of nutrients (C, N, P, and K) were incorporated in a dense benthic biomass of Chara and in the surface sediments, for which analyses from two seasons are given. Seasonal or episodic release from either reservoir could constitute internal loading. Release from Chara may account for autumn increases of NH_4-N, but run-off from an adjacent raised bog is also a possible cause; occasional phytoplankton increase after windy periods may reflect sediment disturbance with nutrient release.

Nutrient concentrations measured for inflow, Tarn, and atmospheric precipitation are combined with the corresponding hydrological quantities, and an estimated Tarn input by sewage, to produce rough nutrient budgets for P, inorganic N, K, Si, Ca, and alkalinity. The main features are summarized in tabular form, supporting conclusions regarding the input-origin and seasonal uptake of individual elements.

4

(e) The total phytoplankton density, as chl-a concentration, is generally moderate. It is regularly depressed in winter, and develops maxima mainly in early spring and summer-autumn. Year-to-year differences are significant for quantity but less so for qualitative composition. The changes of species representation and species numbers that underlie these features are described from subjective gradings and absolute counts. The latter are also used to associate patterns of seasonal abundance into three major groups. ~~Relations to probable~~ The rôle of temperature as a causative factor~~s, including nutrients, are~~ is discussed.

(f) The few long-term records available provide evidence on past susceptibility of the Tarn to change. Increase of nutrient concentrations, in inflow and Tarn, is best established for NO_3-N since 1949-53. If P input has increased, it is not shown in the low concentrations of PO_4-P; the situation for total-P is not known. There are probably no recognisable trends of phytoplankton species occurrence that can be associated with nutrient changes, but a common indicator of eutrophy (Stephanodiscus hantzschii) is known since 1949-53. The apparent loss of another once abundant diatom, Asterionella formosa, is evidence of some long-term instability. Benthic Chara beds have existed at least since the 1930's, but recently they have probably increased and some other aquatic macrophytes (including Elodea canadensis) have spread in the Tarn.

(g) Interrelations between some earlier subject-components are discussed, with particular reference to phosphorus as a probable (though not proven) critical nutrient. Its additional inputs from recent human activities are probably significant in the P-budget. A nutrient-competition now exists between the phytoplankton and the much larger biomass stocks of benthic Chara. If an over-year cumulative situation for phosphorus (not clearly established by the present budget) were to develop in the Tarn, a reversal of these relative abundances is conceivable from experience elsewhere.

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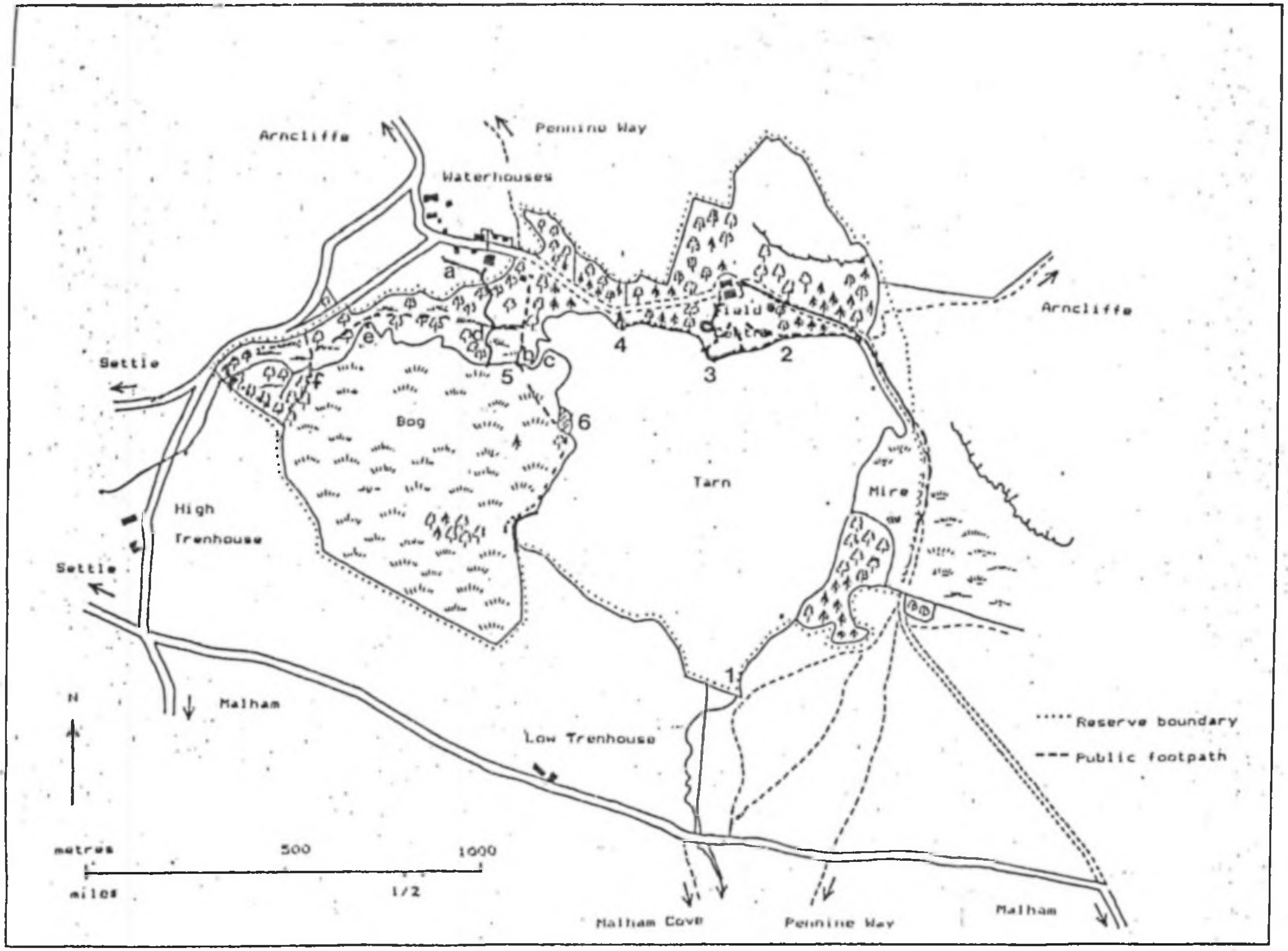

Fig. 1. Map of Malham Tarn showing adjacent drainage settlements; also stations 1–6 used in regular sampling, and additional inflow stations a–f.

FIG. 1

FIG. 2

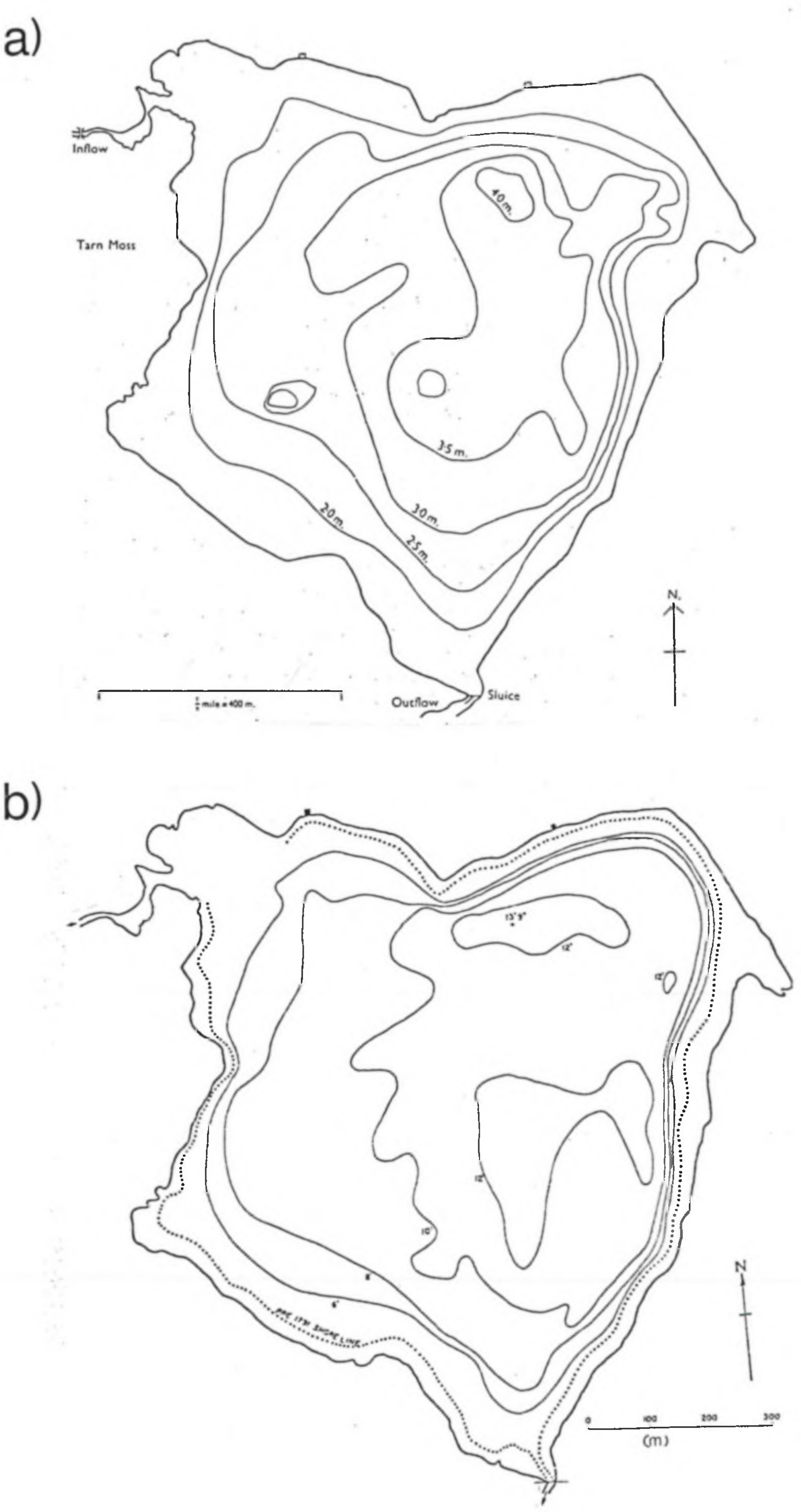

Fig. 2. Maps of Malham Tarn showing depth contours:
(a) from Round (1953), contours in m (b) from July 1956 survey, contours in feet.

FIG.3

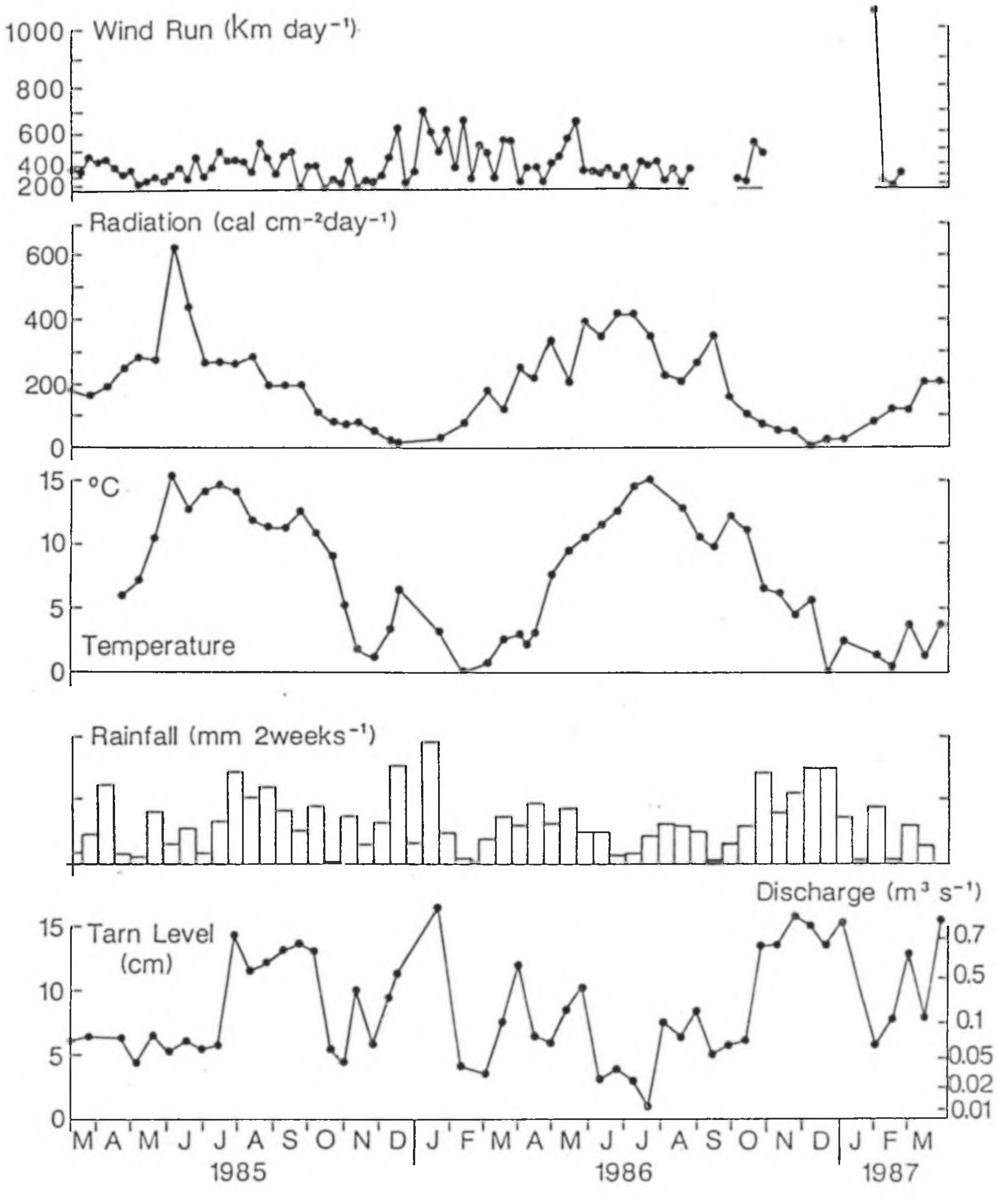

Fig. 3. Seasonal variation of meteorological and physical factors (solar radiation at Windermere, rainfall, lake surface temperature, Tarn level and estimated discharge, daily wind run), expressed as individual readings (temperature, level) or as average values over 1-week or 2-week periods.

FIG. 4

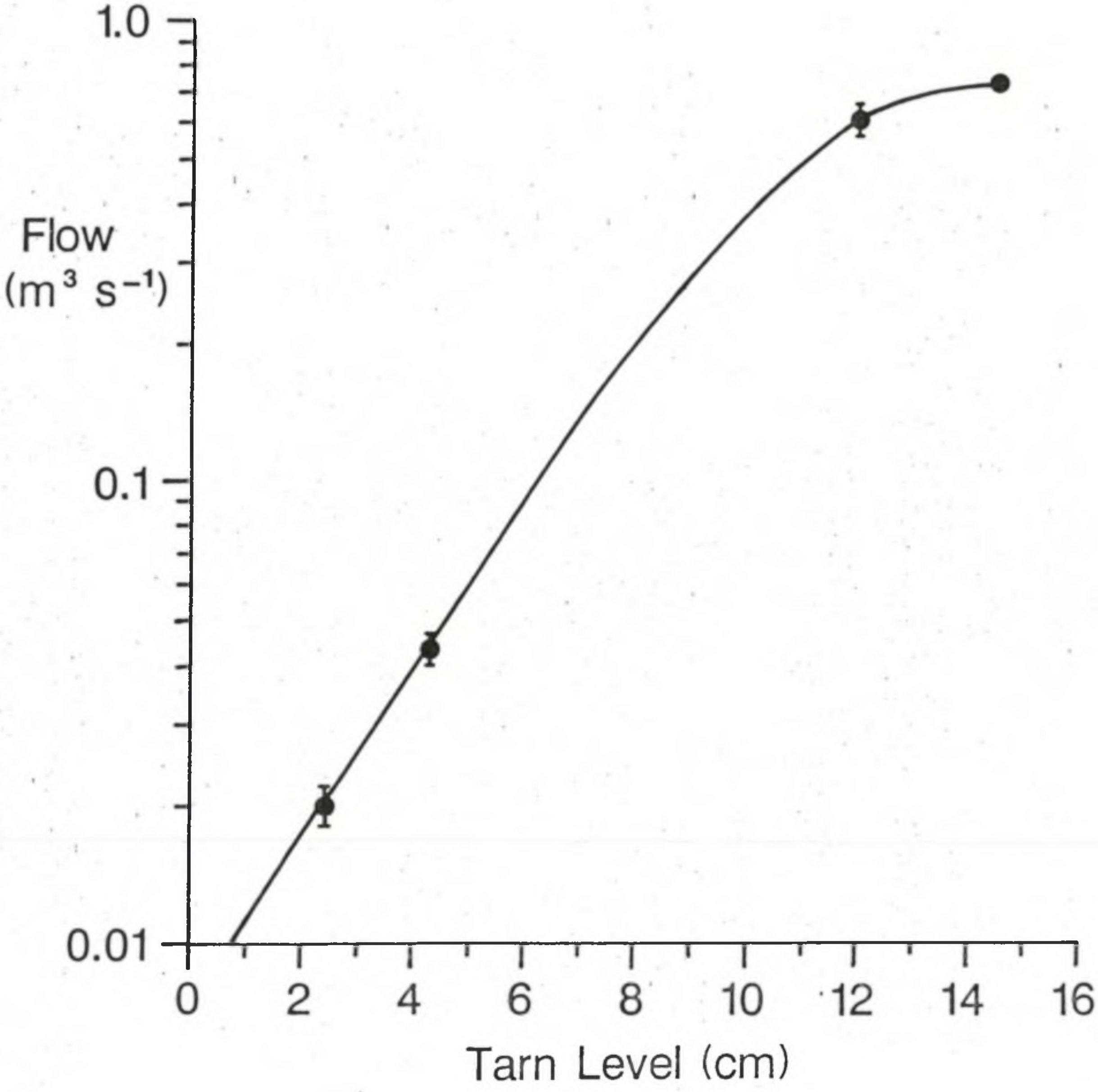

Fig. 4. Relationship between Tarn level (as cm above outlet sill) and discharge estimated by dilution gauging.

FIG. 5

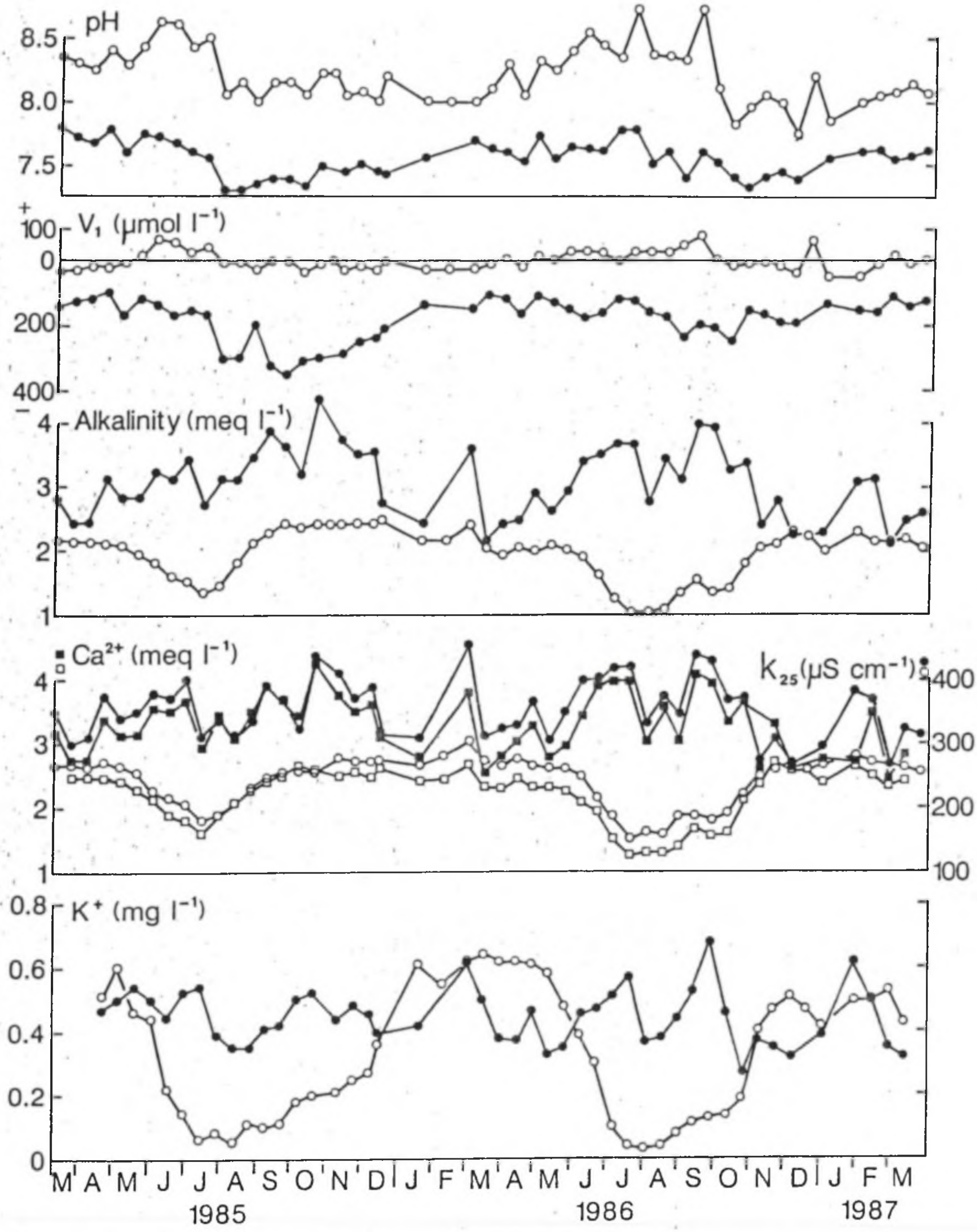

Fig. 5. Seasonal variation of chemical characteristics of the main inflow (●) and outflow (o): pH, CO_2-acidity ($-V_1$), alkalinity, conductivity (k_{25}) and concentrations of Ca^{2+} and K^+.

FIG. 6

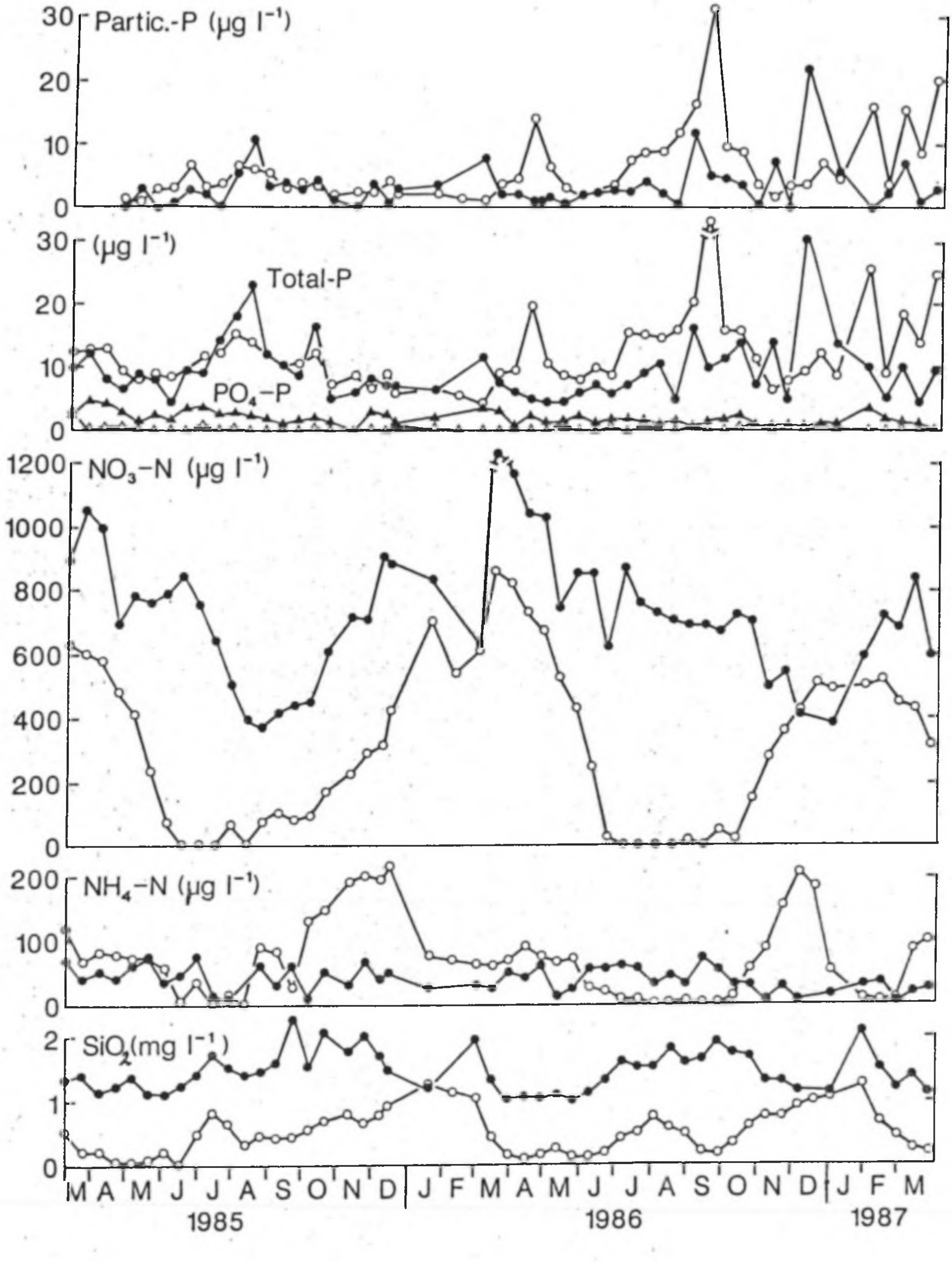

Fig. 6. Seasonal variation of nutrient concentrations of the main inflow (●) and outflow (o): particulate-P, PO_4-P and total P, NO_3-N, NH_4-N, and Si expressed as SiO_2.

FIG. 7

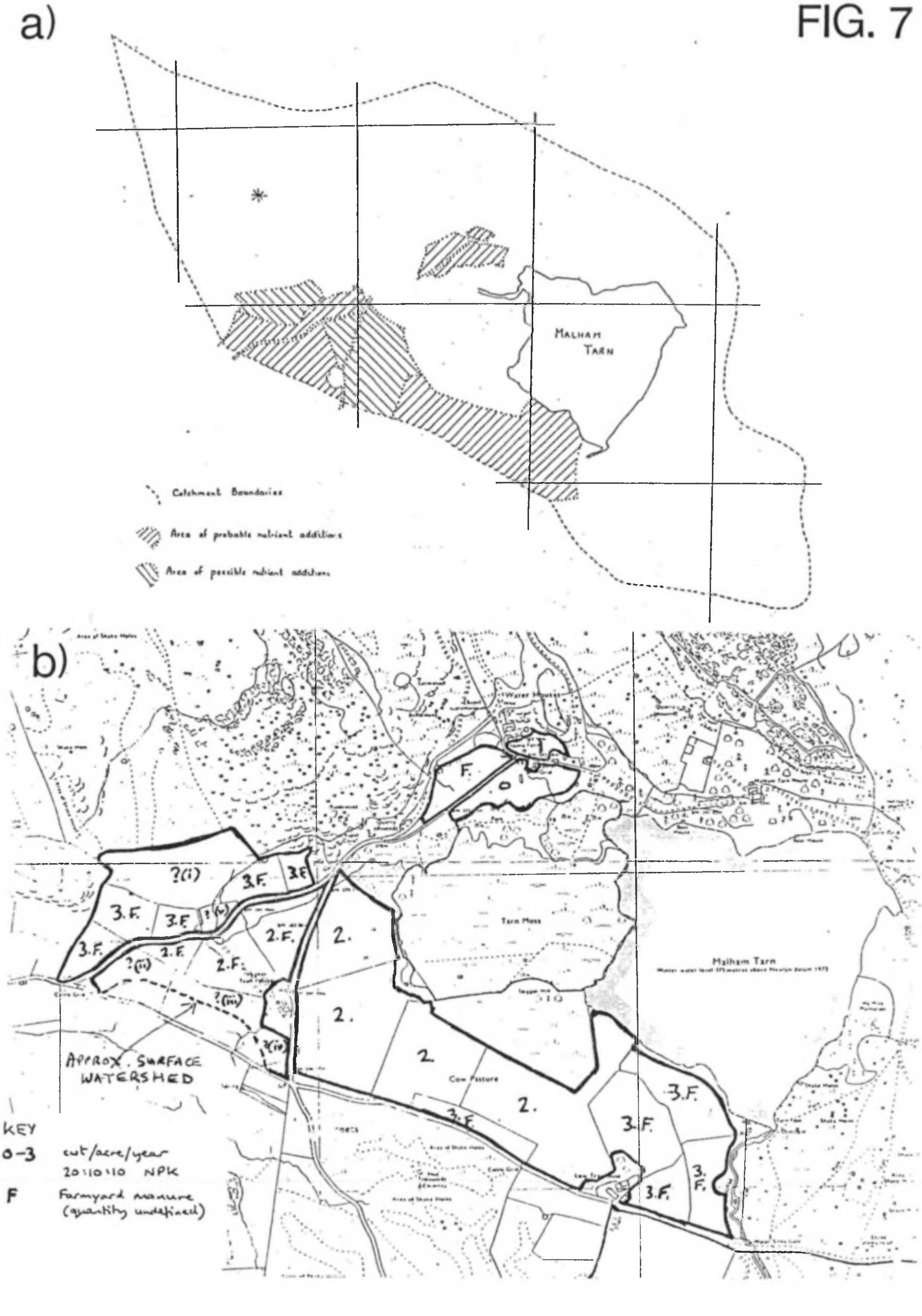

Fig. 7. The Tarn catchment: (a) total extent, with areas of agricultural enrichment shaded (b) very approximate extent of additions of NPK fertiliser and of farmyard manure. Maps prepared in November-December 1986 by Kingsley Iball & Sheelagh McDade (a) and Ben Mercer (b).

FIG. 8

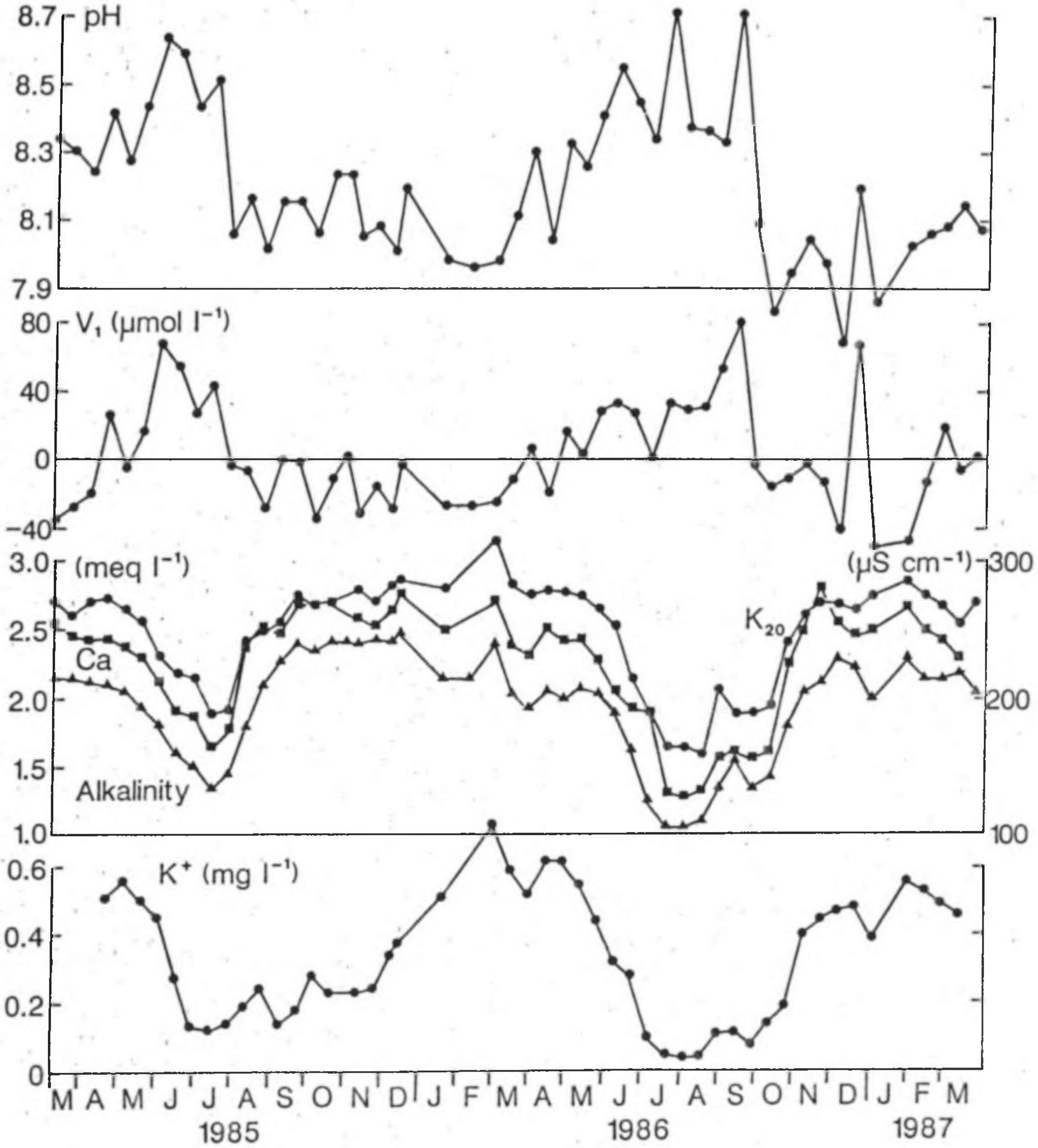

Fig. 8. Seasonal variation of chemical characteristics of Tarn water, measured from station 1 only (pH, CO_2-acidity as $-V_1$, alkalinity) or as mean values for 5 Tarn stations (conductivity k_{20}, concentrations of Ca^{2+} and K^+).

FIG. 9

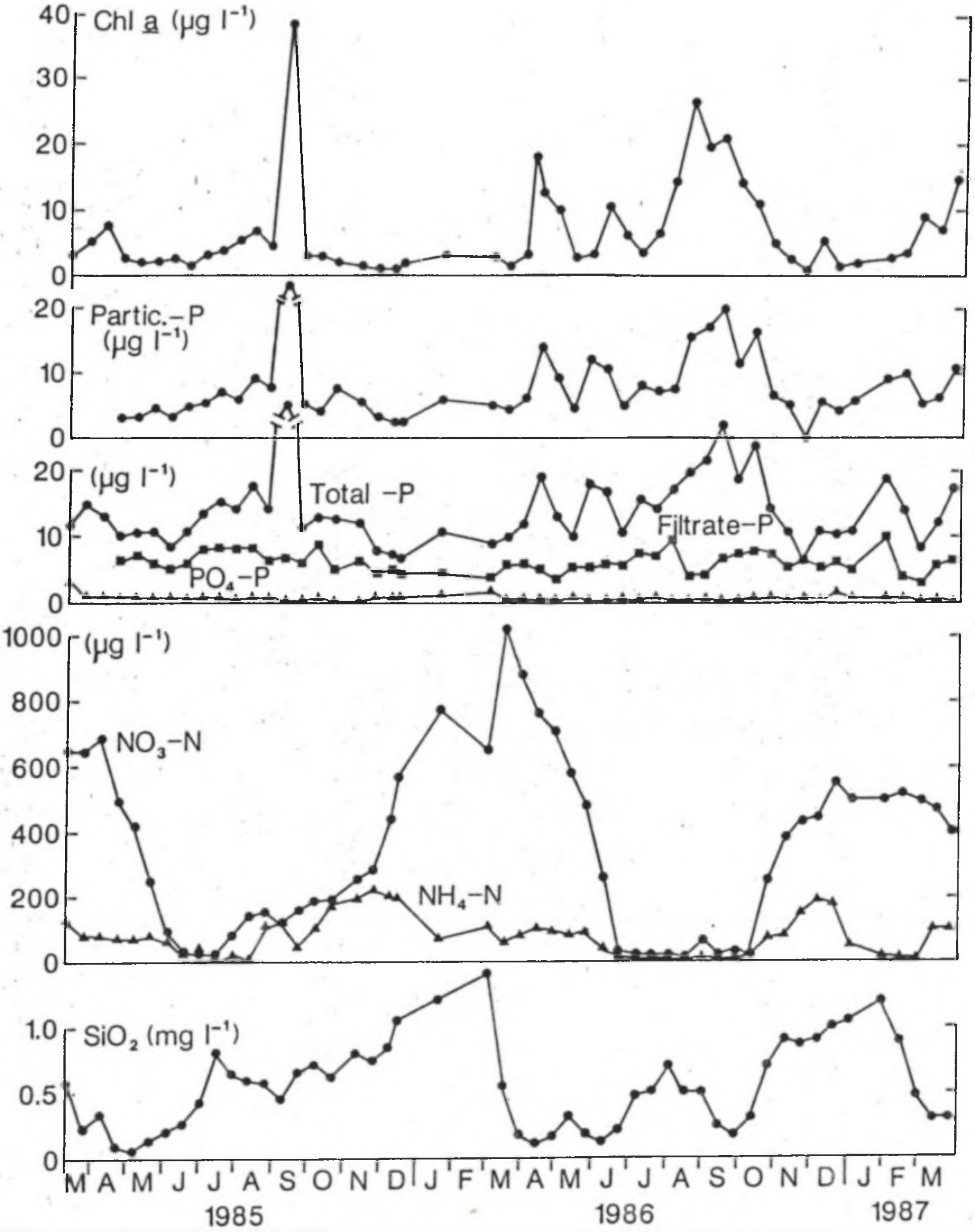

Fig. 9. Seasonal variation of mean Tarn concentrations (from 5 stations) of chlorophyll a and various P-fractions, NO_3-N, NH_4-N, and Si expressed as SiO_2.

FIG. 10

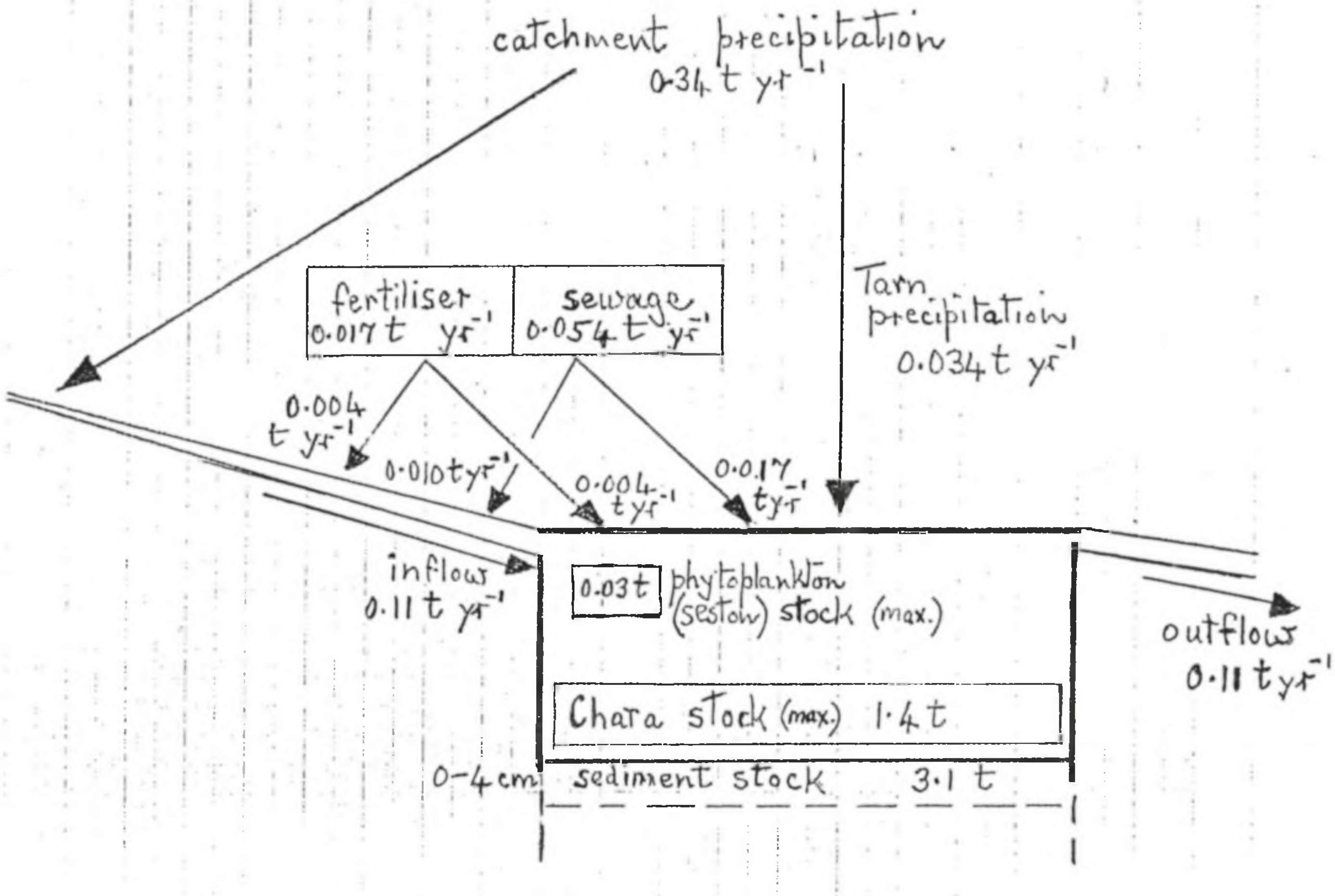

Fig. 10. Diagram of the main input-output pathways for water and nutrients at Malham Tarn and its catchment, with estimated annual fluxes of P inserted.

FIG. 11

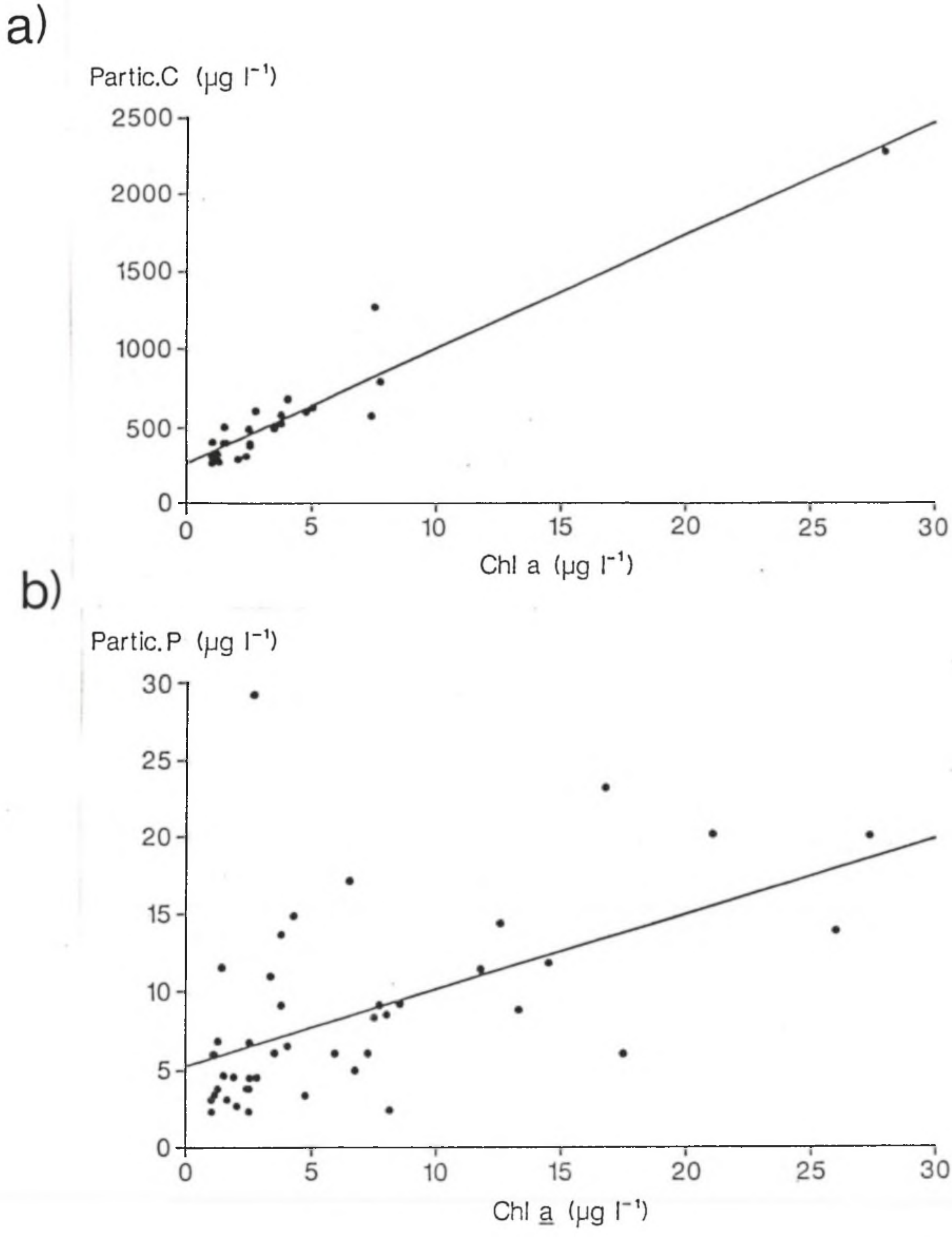

Fig. 11. The interrelation of concentrations of chlorophyll a with (a) particulate-C and (b) particulate-P in Tarn water at station 3.

FIG. 12

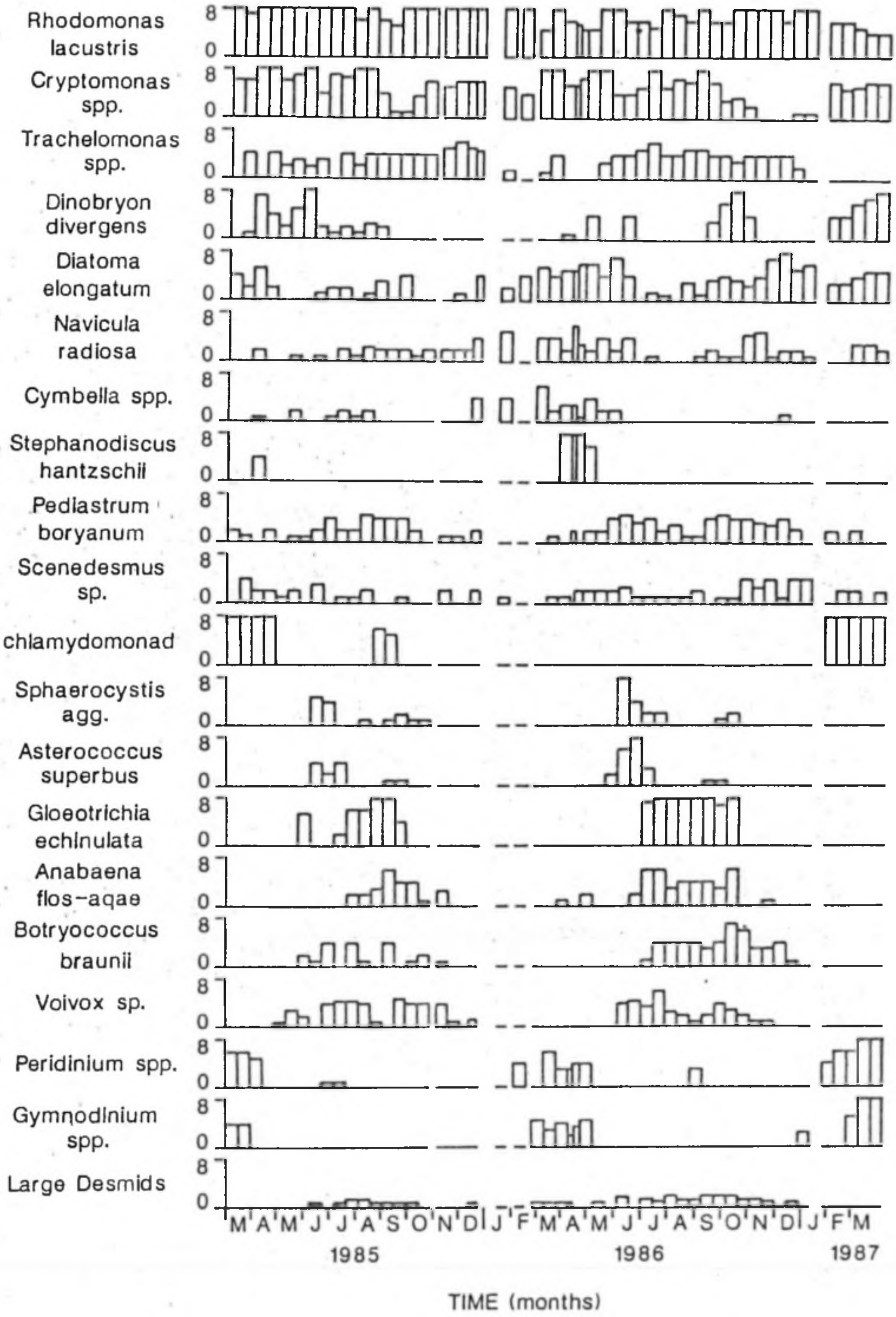

Fig. 12. Seasonal variation in the relative proportions of major phytoplankters, expressed on a 4-point scale (dominant = 8, common = 6, occasional = 4, rare = 2) as mean values from stations 2 and 3.

FIG.13

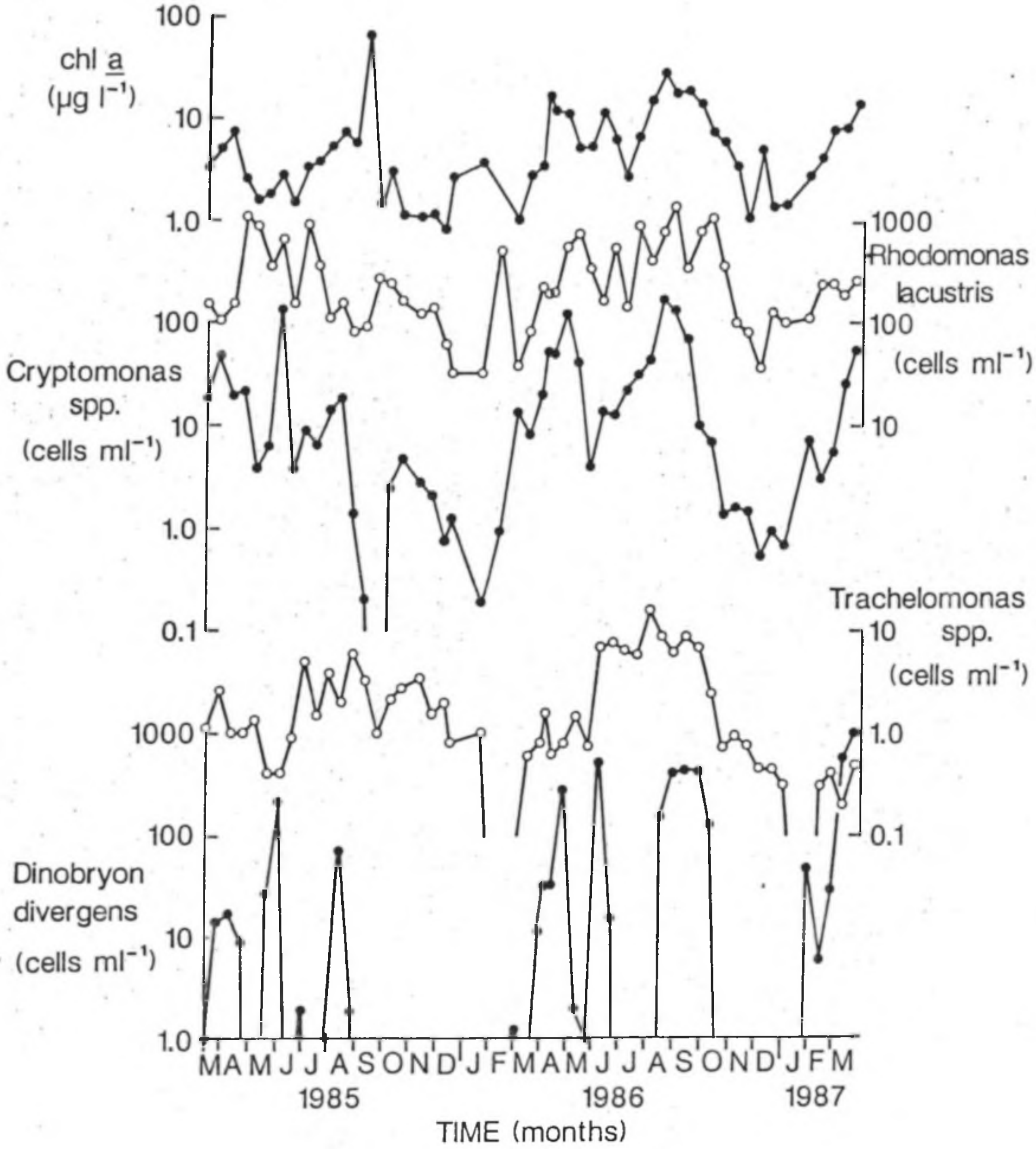

Fig. 13. Planktonic phytoflagellates: seasonal variation in population densities at station 2 in relation to that of total phytoplankton as indicated by chlorophyll a.

FIG.14

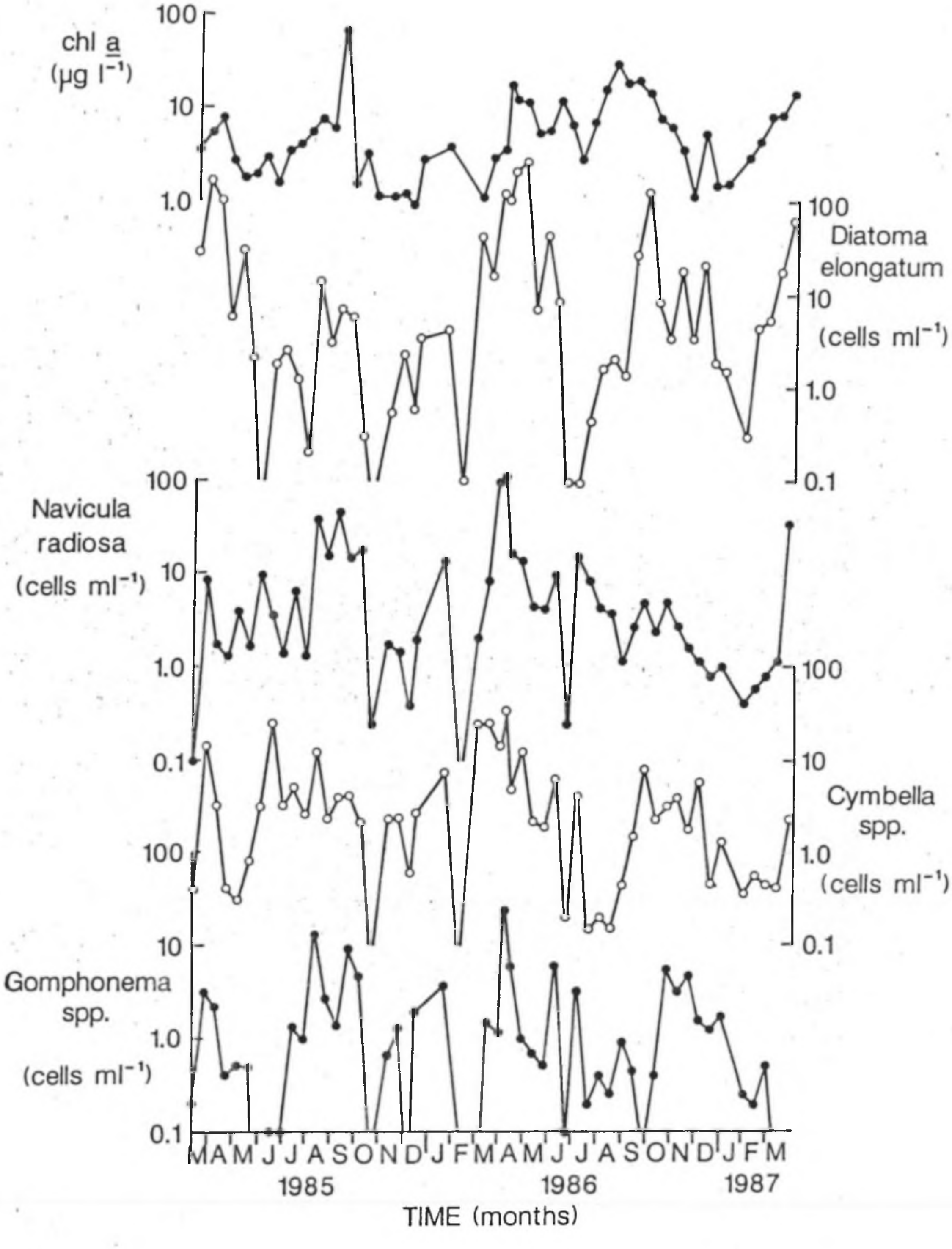

Fig. 14. Planktonic diatoms: seasonal variation in population densities at station 2 in relation to that of total phytoplankton as indicated by chlorophyll a.

FIG.15

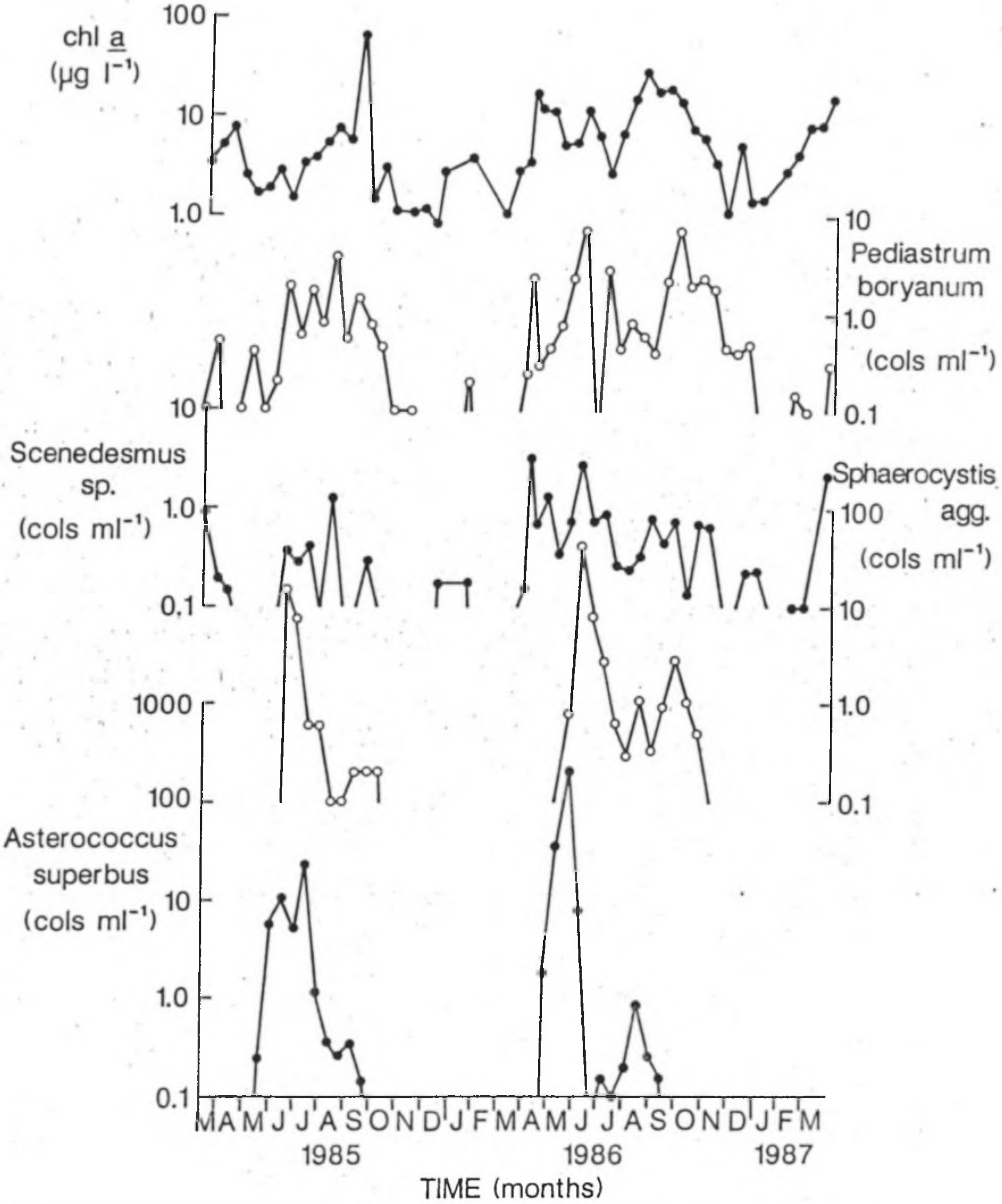

Fig. 15. Planktonic green algae: seasonal variation in population densities at station 2 in relation to that of total phytoplankton as indicated by chlorophyll a.

FIG.16

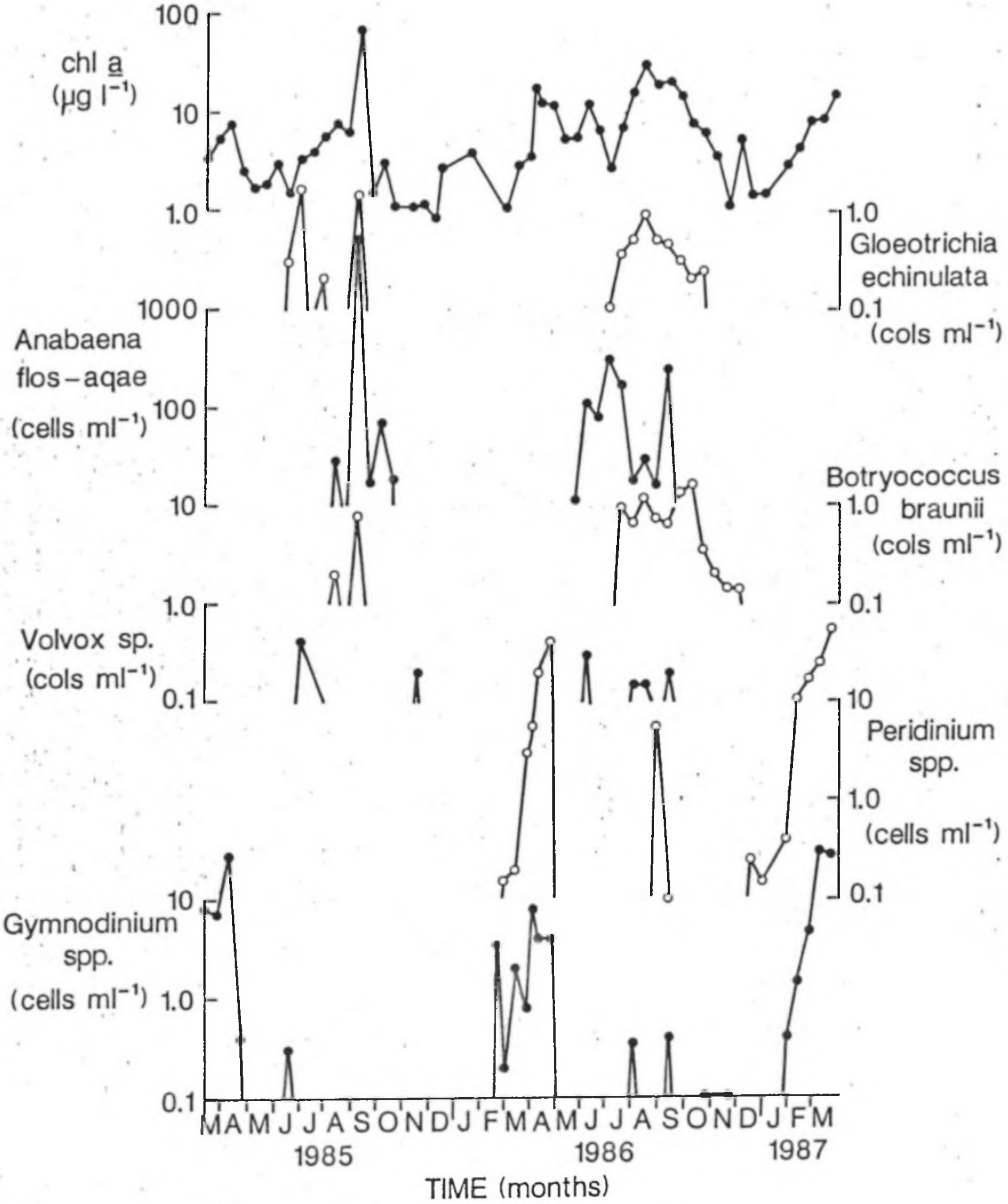

Fig. 16. Planktonic green algae (Volvox, Botryococcus), blue-green algae (Anabaena, Gloeotrichia) and dinoflagellates (Peridinium, Gymnodinium): seasonal variation in population densities at station 2 in relation to that of total phytoplankton as indicated by chlorophyll a.

Table 1. Factors and water-flux components of the water-budget of Malham Tarn, assessed for successive 2-week periods during (a) March 1985 - February 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Interpolated values of water-level are used throughout to assess water storage and of other quantities during irregular winter sampling.

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	OUTFLOW (flow m³ s⁻¹)	OUTFLOW ($10^4 m^3$/2wks) m³/sec × 3600 × 24 × 14 × 10^{-4}	LEVEL (cm)	Δ (rise) (cm)	Δ STORAGE (rise, $10^4 m^3$) ⑤ × 0.61	RAINFALL (mm/2wks)	TARN RAINFALL ($10^4 m^3$/2wks) ⑦ × 0.61 × 0.1	CATCHMENT RAINFALL ($10^4 m^3$/2wks) ⑦ × 6.1 × 0.1	EVAPORATION FROM TARN a) 1mm/day b) 2mm/day c) 3mm/day ($10^4 m^3$/2wks)	INFLOW ($10^4 m^3$/2wks) ③ − (⑧ + ⑥ + ⑩)
	①	②	③		④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
11.3.85	1		0.086	10.4	6.0		(0)	14.2	0.87	8.7	1.71	11.24
		1a			(6.2)							
25.3.85	2		0.1	12.1	6.4	0.2	0.12	44.4	2.71	27.1	1.71	11.22
		2a			(6.4)							
7.4.85	3		0.1	12.1	(6.4)	0	0	121.9	7.44	74.4	1.71	6.37
		3a			(6.4)							
22.4.85	4		0.096	11.6	6.3	-1.1	-0.67	14.2	0.87	8.7	1.71	11.77
		4a			(5.3)							
6.5.85	5		0.043	5.2	4.3	0.1	0.06	10.8	0.66	6.6	2.56	7.16
		5a			(5.4)							
20.5.85	6		0.105	12.7	6.5	0.5	0.31	81.5	4.97	49.7	2.56	10.6
		6a			(5.9)							
3.6.85	7		0.062	7.5	5.2	-0.2	-0.12	29.7	1.81	18.1	2.56	8.13
		7a			(5.7)							
17.6.85	8		0.039	10.3	6.1	0	0	60.8	3.71	37.1	2.56	9.65
		8a			(5.7)							
1.7.85	9		0.064	7.7	5.3	-0.2	-0.12	15.3	0.93	9.3	2.56	9.21
		9a			(5.5)							
15.7.85	10		0.076	9.2	5.7	4.5	2.75	65.5	4.00	40.0	2.56	10.51
		10a			(10)							
29.7.85	11		0.74	89.5	14.3	2.9	1.77	142.5	8.69	86.9	2.56	85.14
		11a			(12.9)							
12.8.85	12		0.55	66.5	11.5	-1.1	-0.67	101.2	6.17	61.7	2.56	62.22
		12a			(11.8)							
26.8.85	13		0.6	72.6	12.0	0.7	0.43	118.4	7.22	72.2	2.56	68.37
		13a			(12.5)							
9.9.85	14		0.66	79.8	13.0	0.8	0.49	80.9	4.93	49.3	1.71	77.07
		14a			(13.3)							
23.9.85	15		0.69	83.5	13.5	0	0	50.8	3.10	31.0	1.71	82.11

3

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	OUTFLOW ($10^4 m^3$/2wks) m^3/sec × 3600 × 24 × 14 × 10^{-4}	LEVEL (cm)	Δ (rise) (cm)	Δ STORAGE (rise, $10^4 m^3$) ⑤ × 0·61	RAINFALL (mm / 2wks)	TARN RAINFALL ($10^4 m^3$/2wks) ⑦ × 0·61 × 0·1	CATCHMENT RAINFALL ($10^4 m^3$/2wks) ⑦ × 6·1 × 0·1	EVAPORATION FROM TARN a) 1mm/day c) 2mm/day b) 3mm/day ($10^4 m^3$/2wks)	INFLOW ($10^4 m^3$/2wks) ③ - ⑧ + ⑥ + ⑩
	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
		15a	[illegible]	(13·3)							
7·10·85	16		0·66 79·8	13·0	-4·1	-2·50	87·5	5·34	53·4	1·71	73·67
		16a		(9·2)							
21·10·85	17		0·067 8·1	5·4	-2·6	-1·59	0·4	0·02	0·2	1·71	8·20
		17a		(6·9)							
(4·11·85)			0·22 26·6	(8·5	3·1	1·89	73·9	4·51	45·1	0·85	24·83
11·11·85	18			10·0							
(18·11·85)		18a	0·185 22·4	[illegible]	-4·3	-2·62	26·7	1·63	16·3	0·85	19·00
25·11·85	19			5·7							
(2·12·85)		19a	0·16 19·4	(7·6)	3·7	2·26	64·3	3·92	39·2	0·85	18·59
9·12·85	20			9·4							
16·12·85	21	20a	0·51 61·7	11·2	2·8	1·71	152·7	9·32	93·2	0·85	54·94
				(12·2)							
(30·12·85)			0·68 82·3	(13·3)	2·1	1·28	32·7	2·00	20·0	0·85	82·43
		21a		(14·3)							
(13·1·86)			0·78 94·3	(15·4)	2·1	1·28	191·1	11·66	116·6	0·85	84·77
20·1·86	22			16·4							
(27·1·86)		22a	0·62 75·0	(12·2)	-8·3	-5·06	46·3	2·82	23·2	0·85	67·97
				(8·1)							
10·2·86	23		0·036 4·4	3·9	-4·3	-2·62	6·2	0·38	3·8	0·85	2·25
		23a		(3·8)							
(24·2·86)			0·032 3·9	(3·6)	-0·3	-0·18	7·5	0·46	4·6	0·85	4·11
3·3·86	24		0·031 3·8	3·5	1·9	1·16	36·9	2·25	22·5	1·71	4·42
		24a		(5·5)							
17·3·86	25		0·155 18·8	7·5	4·2	2·56	71·5	4·36	43·6	1·71	18·71
		25a		(7·7)							
1·4·86	26		0·59 71·4	11·9	-0·5	-0·31	57·1	3·48	34·8	1·71	69·32
		26a		(9·2)							

Table 2. Measured concentrations of plant nutrients in atmospheric precipitation collected over days immediately preceding the dates given.

1986		SiO_2	NO_3-N	NH_4-N	Total P	K
		mg l^{-1}	μg l^{-1}	μg l^{-1}	μg l^{-1}	mg l^{-1}
March	24	-	91	172	5.7	0.12
	30	-	350	365	6.1	0.52
April	8	0.10	640	833	16.0	0.30
	14	0.06	795	1297	17.9	0.13
May	13	0.03	311	704	6.1	0.12
	27	0.52	164	794	129.1	0.49
June	9	0.28	401	801	-	1.15
	23	0.09	689	585	81.3	0.28
July	7	0.04	301	495	54.3	0.24
August	4	0.04	709	486	106.8	0.22
Sept	1	0.02	87	77	17.5	0.08
	29	0.22	482	1104	19.0	0.40
Oct	27	0.02	292	384	18.6	0.23
Nov	10	0.02	139	309	8.0	0.17
	24	0.06	118	172	10.6	0.47
Dec	8	0.06	306	464	9.1	0.16
1987						
Jan	5	0.04	215	371	4.9	0.23
Feb	2	0.04	839	1282	57.8	0.54
Mar	30	0.08	502	736	22.8	0.26
Mean		0.10	391	602	32.9	0.32
Standard deviation		(n=17) 0.13	(n=19) 244	(n=19) 356	(n=18) 37.6	(n=19) 0.25

SAMPLE DATE	SAMPLE NO.	PERIOD No.	OUTFLOW	($10^4 m^3$ / 2wks) m^3/sec × 3600 × 24 × 14 × 10^{-4}	LEVEL (cm)	Δ (rise) (cm)	Δ STORAGE (rise, $10^4 m^3$) ⑤ × 0.61	RAINFALL (mm / 2wks)	TARN RAINFALL ($10^4 m^3$/2wks) ⑦ × 0.61 × 0.1	CATCHMENT RAINFALL ($10^4 m^3$/2wks) ⑦ × 6.1 × 0.1	EVAPORATION FROM TARN a) 1mm/day c) 2mm/day b) 3mm/day ($10^4 m^3$/2wks)	INFLOW ($10^4 m^3$/2wks) ③ - ⑧ + ⑥ + ⑩
	①	②	③		④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
			(flow ($m^3 s^{-1}$))									
14.4.86	27		0.1	12.1	6.4	-2.9	-1.77	92.3	5.63	56.3	1.71	6.41
		27a			(6.3)							
28.4.86	28		0.089	10.8	6.1	1.0	0.61	60.1	3.67	36.7	1.71	9.45
		28a			(7.3)							
12.5.86	29		0.23	27.8	8.4	2.1	1.28	63.9	3.90	39.0	2.56	27.74
		29a			(9.4)							
27.5.86	30		0.41	49.6	10.3	-2.7	-1.65	47.7	2.90	29.0	2.56	47.61
		30a			(6.7)							
9.6.86	31		0.026	3.1	3.1	-3.2	-1.95	47.2	2.88	28.8	2.56	0.83
		31a			(3.5)							
23.6.86	32		0.036	4.4	3.9	0	0	13.4	0.82	8.2	2.56	6.14
		32a			(3.5)							
7.7.86	33		0.025	3.0	3.0	-1.4	0.85	16.6	1.01	10.1	2.56	5.40
		33a			(2.1)							
21.7.86	34		0.012	1.5	1.1	2.2	1.34	42.1	2.57	25.7	2.56	2.83
		34a			(4.3)							
4.8.86	35		0.15	18.1	7.4	2.5	1.53	63.9	3.90	39.0	2.56	18.29
		35a			(6.8)							
18.8.86	36		0.092	11.1	6.2	0.5	0.31	57.8	3.53	35.3	2.56	10.44
		36a			(7.3)							
1.9.86	37		0.23	27.8	8.4	-06	-0.37	49.9	3.04	30.4	1.71	26.1
		37a			(6.7)							
15.9.86	38		0.055	6.7	4.9	-1.3	-0.79	4.3	0.26	2.6	1.71	7.36
		38a			(5.4)							
29.9.86	39		0.078	9.4	5.3	0.6	0.37	29.5	1.80	18.0	1.71	9.68
		39a			(6.0)							
13.10.86	40		0.092	11.1	6.2	3.8	2.32	58.0	3.54	35.4	1.71	11.59
		40a			(9.8)							
27.10.86	41		0.68	82.3	13.4	3.6	2.20	142.3	8.68	86.8	1.71	77.53

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	OUTFLOW $(10^4 m^3 / 2wks)$ $m^3/sec \times 3600 \times 24 \times 14 \times 10^{-4}$	LEVEL (cm)	Δ (rise) (cm)	Δ STORAGE (rise, $10^4 m^3$) ⑤ × 0·61	RAINFALL (mm / 2wks)	TARN RAINFALL $(10^4 m^3 / 2wks)$ ⑦ × 0·61 × 0·1	CATCHMENT RAINFALL $(10^4 m^3 / 2wks)$ ⑦ × 6·1 × 0·1	EVAPORATION FROM TARN a) 1mm/day c) 2mm/day b) 3mm/day $(10^4 m^3 / 2wks)$	INFLOW $(10^4 m^3 / 2wks)$ ③-⑧+⑥+⑩	RUN-OFF FACTOR [⑪/⑨]
	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫
		41a	Flow $(m^3 s^{-1})$	(12.2)								
10.11.86	42		0·68 82·3	13·4	1·2	0·73	76·9	4·69	46·9	0·85	79·19	
		42a		(11·6)								
24.11.86	43		0·8 96·3	15·8	0·8	0·49	108·0	6·59	65·9	0·85	91·55	
		43a		(15·4)								
8.12.86	44		0·76 91·9	14·9	- 1·2	- 0·73	147·7	9·01	90·1	0·85	83·01	
		44a		(14·2)								
22.12.86	45		0·7 84·7	13·5	0·2	0·12	146·9	8·96	89·6	0·85	76·71	
		45a		(14·4)								
5.1.87	46		0·78 94·4	15·3	-1·5	- 0·92	70·9	4·33	43·3	0·85	90·0	
				(12·0)								
19.1.87		46a	0·43 52·0	(10·5)	-4·8	- 2·93	6·1	0·37	3·7	0·85	49·55	
				(8·1)								
2.2.87	47		0·076 9·2	5·7	- 1·3	-0·79	86·5	5·28	52·8	0·85	3·98	
		47a		(6·8)								
16.2.87	48		0·175 21·2	7·8	3·5	2·14	6·5	0·40	4·0	0·85	23·79	
		48a		(10·3)								
2.3.87	49		0·64 77·4	12·7	-0·1	- 0·06	59·1	3·61	36·1	1·71	75·44	
		49a		(10·2)								
16.3.87	50		0·17 20·6	7·7	1·3	0·79	27·9	1·70	17·0	1·71	21·4	
		50a		(11·5)								
Σyr1			969·1				1641·4	100·14	1001·4	44·37	900·31	0·90
Σyr2			1003·3				1691·0	103·16	1031·6	47·80	954·47	0·93
mean			986·2				1666·2	101·65	1016·5	46·09	927·39	0·91

Table 3. Chemical characteristics of bottom sediment from the 0-4 cm layer, and of whole shoot systems of the macrophyte <u>Chara globularis</u> var. <u>virgata</u>, referred to unit dry weight and relating to (a) total content (b) exchangeable fractions of K (extraction with 1 M ammonium acetate at pH 9), PO_4-P (alk - extraction with 0.125 M NaOH; acid - sequential extraction with 0.5 M H_2SO_4), and NH_4-N (extraction with 1 M NaCl).

CHEMICAL QUANTITY	SEDIMENT					CHARA				
	12.v.86		20.x.86		mean	12.v.86		20.x.86		mean
TOTAL										
% : C (total)	18.1	18.3	19.5	19.6	18.9	20.4		20.4	20.8	20.5
C (org.)	10.5	12.0	14.3	14.5	13.1	13.1		12.7	12.8	12.9
C (inorg.)	6.6	6.3	5.2	5.1	5.8	7.2		7.7	8.0	7.6
N	1.27	1.31	1.46	1.45	1.37	1.61		1.43	1.41	1.48
S	0.62	0.60	0.97	0.59	0.70	0.78		0.0	0.73	0.50
Water	90.3	90.5	89.9	90.2	90.2					
loss on ignition	24.8	25.7	28.0	28.4	26.8	33.3	33.2	27.4	27.8	30.4
mg g^{-1} : K	2.64	2.95	4.73	4.80	3.78	8.01	8.92	8.91	7.17	8.25
Na	0.59	0.66	5.91	6.95	3.53	1.46	1.38	6.59	-	3.14
Ca	173.0	173.8	149.1	145.7	160.4	215.8	215.9	210.9	211.6	213.6
Mg	1.35	1.46	5.64	6.51	3.74	1.89	1.95	5.22	-	3.02
Fe	10.8	12.5	22.0	21.5	16.7	3.18	2.76	1.54	1.56	2.26
Mn	0.47	0.33	0.67	0.63	0.53	1.46	1.35	0.47	0.51	0.95
P	1.01	1.13	1.41	1.35	1.23	1.70	1.72	1.51	1.51	1.61
EXCHANGEABLE:										
(µg g^{-1}) K	281	212	173	169	209					
PO_4-P (alk.)	105	168	175	172	155					
PO_4-P (acid)	258	307	411	457	358					
NH_4-N	63	50	66	71	62					

Table 3. Chemical characteristics of bottom sediment from the 0-4 cm layer, and of whole shoot systems of the macrophyte Chara globularis var. virgata, referred to unit dry weight and relating to (a) total content (b) exchangeable fractions of K (extraction with 1 M ammonium acetate at pH 9), PO_4-P (alk - extraction with 0.125 M NaOH; acid - sequential extraction with 0.5 M H_2SO_4), and NH_4-N (extraction with 1 M NaCl).

CHEMICAL QUANTITY	SEDIMENT					CHARA				
	12.v.86		20.x.86		mean	12.v.86		20.x.86		mean
TOTAL										
% : C (total)	18.1	18.3	19.5	19.6	18.9	20.4		20.4	20.8	20.5
C (org.)	10.5	12.0	14.3	14.5	13.1	13.1		12.7	12.8	12.9
C (inorg.)	6.6	6.3	5.2	5.1	5.8	7.2		7.7	8.0	7.6
N	1.27	1.31	1.46	1.45	1.37	1.61		1.43	1.41	1.48
S	0.62	0.60	0.97	0.59	0.70	0.78		0.0	0.73	0.50
Water	90.3	90.5	89.9	90.2	90.2					
loss on ignition	24.8	25.7	28.0	28.4	26.8	33.3	33.2	27.4	27.8	30.4
mg g^{-1} : K	2.64	2.95	4.73	4.80	3.78	8.01	8.92	8.91	7.17	8.25
Na	0.59	0.66	5.91	6.95	3.53	1.46	1.38	6.59	-	3.14
Ca	173.0	173.8	149.1	145.7	160.4	215.8	215.9	210.9	211.6	213.6
Mg	1.35	1.46	5.64	6.51	3.74	1.89	1.95	5.22	-	3.02
Fe	10.8	12.5	22.0	21.5	16.7	3.18	2.76	1.54	1.56	2.26
Mn	0.47	0.33	0.67	0.63	0.53	1.46	1.35	0.47	0.51	0.95
P	1.01	1.13	1.41	1.35	1.23	1.70	1.72	1.51	1.51	1.61
EXCHANGEABLE:										
($\mu g\ g^{-1}$) K	281	212	173	169	209					
PO_4-P (alk.)	105	168	175	172	155					
PO_4-P (acid)	258	307	411	457	358					
NH_4-N	63	50	66	71	62					

Tables 4 - 9. General notes.

(i) Chemical fluxes of outflow (column 16) and inflow (column 13) are based on water flux terms in Table 1 multiplied by concentrations measured on (or interpolated for) the dates given, being mid-times for successive 2-week periods. Concentrations measured for the major surface inflow are assumed to be representative for the total surface inflow.

(ii) Chemical fluxes for on-Tarn atmospheric deposition (column 14) are based on rainfall terms in Table 1, column 8, multiplied by the mean concentrations measured in bulk collectors over the period March 1986 - March 1987 (Table 2). Dry deposition is not separately distinguished. Corresponding values for the entire catchment (Table 10) are estimated, in proportion to area, as 10-times greater.

(iii) For P, sewage inputs from the Field Centre (column 15) are estimated from two mean seasonal levels of occupancy as described in the text and shown separately for successive 2-week periods. Sewage input from other houses and agricultural field dressings independent of the main inflow, and from gull excreta, are shown as final annual estimates.

(iv) Total Tarn input is calculated as the sum of columns 13, 14, and 15; Tarn retention as the difference between columns 17 and 16; and Tarn stock increase as the concentration increment between successive dates multiplied by the mean Tarn volume.

Table 4. Component fluxes of the P-budget of Malham Tarn, assessed in kg (2 weeks)$^{-1}$ as input, output, storage and water-stock increase quantities for successive 2-week periods during (a) March 1985 - March 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Use is made of columns 3, 8 and 11 of the water budget in Table 1.

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N kg (2 weeks)$^{-1}$ ⑥ × conc^n ÷ 100	kg (2 wks)$^{-1}$ RAINFALL ON TARN × MEAN CONC'N ⑤ × conc^n ÷ 100	kg (2 wks)$^{-1}$ HOUSE SEEPAGE [person - days] × FACTOR winter: 0.3, rest: 0.8	OUTFLOW kg (2 wks)$^{-1}$ ③ × conc^n ÷ 100	INPUT kg (2 wks)$^{-1}$ ⑬ + ⑭ + ⑮	TARN RETENTION kg (2 wks)$^{-1}$ ⑰ - ⑯	TARN STOCK INCREASE kg (2 wks)$^{-1}$ $(\bar{C}_2 - \bar{C}_1) \times 1.46$
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
11.3.85	1		1.11	0.29	0.8	1.3	2.20	0.90	
		1a							4.8
25.3.85	2		1.37	0.89	0.8	1.6	3.06	1.46	
		2a							-2.3
9.4.85	3		0.51	2.46	0.8	1.6	3.77	2.17	
		3a							-4.7
22.4.85	4		0.30	0.29	0.8	1.5	1.89	0.39	
		4a							0.9
6.5.85	5		0.62	0.22	0.8	0.5	1.64	1.14	
		5a							0.2
20.5.85	6		0.85	1.64	0.8	1.2	3.29	2.09	
		6a							-2.9
3.6.85	7		0.37	0.60	0.8	0.6	1.77	1.17	
		7a							3.1
17.6.85	8		0.92	1.22	0.8	1.0	2.94	1.94	
		8a							3.9
1.7.85	9		0.84	0.31	0.8	0.9	1.95	1.05	
		9a							2.7
15.7.85	10		1.48	1.32	0.8	1.1	3.6	2.50	
		10a							-1.6
29.7.85	11		15.24	2.87	0.8	13.6	18.91	-5.31	
		11a							4.8
12.8.85	12		14.19	2.04	0.8	9.4	17.03	7.63	
		12a							-5.0
26.8.85	13		8.07	2.38	0.8	8.9	11.25	2.35	
		13a							65.7
9.9.85	14		7.94	1.63	0.8	8.2	10.37	2.17	
		14a							-69.6
23.9.85	15		7.14	1.02	0.8	8.9	8.96	0.06	

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		15a							2.2
7.10.85	16		12.01	1.76	0.8	9.7	14.57	4.87	
		16a							-0.4
21.10.85	17		0.40	0.66	0.8	0.6	1.21	0.61	
		17a							-0.26
(4.11.85)			1.37	1.49	0.3	2.1	3.16	1.06	
11.11.85	18								-2.25
(18.11.85)		18a	1.33	0.54	0.3	1.7	2.17	0.47	
25.11.85	19								-2.5
(2.12.85)		19a	1.39	1.29	0.3	1.5	2.98	1.48	
9.12.85	20								-0.9
16.12.85	21	20a	3.74	3.08	0.3	3.8	7.12	3.32	
									1.4
(30.12.85)			5.56	0.66	0.3	5.1	6.52	1.42	
		21a							1.75
(13.1.86)			5.51	3.35	0.3	6.1	9.66	3.56	
20.1.86	22								0.5
(27.1.86)		22a	4.21	0.93	0.3	4.9	5.44	0.54	
									-0.5
10.2.86	23		0.20	0.13	0.3	0.3	0.63	0.33	
		23a							-0.5
(24.2.86)			0.43	0.15	0.3	0.2	0.88	0.68	
3.3.86	24		0.50	0.74	0.8	0.2	2.04	1.54	
		24a							1.3
17.3.86	25		1.42	1.44	0.8	1.7	3.66	1.96	
		25a							2.9
1.4.86	26		4.23	1.15	0.8	6.8	6.18	-0.62	
		26a							10.8

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [PERSON - DAYS × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
14·4·86	27		0·31	1·86	0·8	2·4	2·97	0·57	
		27a							−9·1
28·4·86	28		0·44	1·21	0·8	1·1	2·45	1·35	
		28a							−4·1
12·5·86	29		1·28	1·29	0·8	2·4	3·37	0·97	
		29a							11·1
27·5·86	30		2·90	0·96	0·8	4·0	4·66	0·66	
		30a							−1·3
9·6·86	31		0·06	0·95	0·8	0·3	1·81	1·51	
		31a							−9·3
23·6·86	32		0·35	0·27	0·8	0·4	1·42	1·02	
		32a							7·3
7·7·86	33		0·39	0·33	0·8	0·5	1·52	1·02	
		33a							−1·8
21·7·86	34		0·26	0·85	0·8	0·2	1·91	1·71	
		34a							4·1
4·8·86	35		1·94	1·29	0·8	2·7	4·03	1·33	
		35a							3·8
18·8·86	36		0·51	1·17	0·8	1·8	2·48	0·68	
		36a							2·5
1·9·86	37		4·25	1·00	0·8	5·7	6·05	0·35	
		37a							7·9
15·9·86	38		0·73	0·09	0·8	2·6	1·62	−0·98	
		38a							−11·7
29·9·86	39		1·10	0·59	0·8	1·5	2·49	0·99	
		39a							7·6
13·10·86	40		1·59	1·17	0·8	1·8	3·56	1·76	
		40a							−14·6
27·10·86	41		5·58	2·86	0·8	9·4	9·24	−0·16	

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰−⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		41a							−4·8
10·11·86	42		11·17	1·55	0·3	5·6	13·02	7·42	
		42a							−6·4
24·11·86	43		4·85	2·19	0·3	7·7	7·33	−0·37	
		43a							6·4
8·12·86	44		25·24	2·97	0·3	8·7	28·51	19·81	
		44a							−0·6
22·12·86	45		16·88	2·96	0·3	10·6	20·14	9·54	
		45a							0·9
5·1·87	46		12·69	1·43	0·3	8·6	14·42	5·82	
		46a							3·5
(19)·1·87			5·95	0·12	0·3	8·8	6·37	−2·47	
									4·0
2·2·87	47		0·41	1·74	0·3	2·4	2·45	0·05	
		47a							−7·2
16·2·87	48		1·26	0·13	0·3	1·9	1·69	−0·21	
		48a							−8·3
2·3·87	49		7·47	1·19	0·8	14·4	9·46	−4·94	
		49a							5·1
16·3·87	50		0·98	0·56	0·8	2·9	2·34	−0·56	
		50a							
kg P									
Σ year 1			97·60	33·72	16·3	96·3	147·62	51·32	−1·46
Σ yr 2			114·74	34·05	18·4	117·1	167·19	50·09	0
mean			106·17	33·89	17·3	106·7	157·41	50·71	−0·73
						plus	half fertiliser area 4·2		
							gulls 0·8		
						total mean	163		

Table 5. Component fluxes of the inorganic $(NO_3 + NH_4)$-N budget of Malham Tarn, assessed in kg (2 weeks)$^{-1}$ as input, output, storage and water-stock increase quantities for successive 2-week periods during March 1985 - March 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Use is made of columns 3, 8 and 11 of the water budget in Table 1.

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	kg (2wks)$^{-1}$ INFLOW × CONC'N ⑪ × conc^n ÷ 100	kg (2wks)$^{-1}$ RAINFALL ON TARN × MEAN CONC'N ⑧ × conc^n ÷ 100	kg (2wks)$^{-1}$ HOUSE SEEPAGE [person - days] × FACTOR units: 2·3 rest 2·8	kg (2wks)$^{-1}$ OUTFLOW ③ × conc^n ÷ 100	kg (2wks)$^{-1}$ INPUT ⑬ + ⑭ + ⑮	kg (2wks)$^{-1}$ TARN RETENTION ⑰ − ⑯	kg (2wks)$^{-1}$ TARN STOCK INCREASE $(\bar{c}_2-\bar{c}_1)\times 1.46$
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
11.3.85	1		108·25	8·64	1·6	78·2	118·49	40·29	
		1a							−81·76
25.3.85	2		122·19	26·91	1·6	80·9	150·70	69·80	
		2a							56·94
9.4.85	3		66·42	73·88	1·6	80·0	141·90	61·90	
		3a							−284·70
22.4.85	4		86·41	8·64	1·6	65·3	96·65	31·35	
		4a							−112·42
6.5.85	5		59·95	6·55	1·6	25·1	68·10	43·00	
		5a							−232·14
20.5.85	6		88·64	49·35	1·6	39·3	139·59	100·29	
		6a							−262·80
3.6.85	7		66·83	17·98	1·6	9·8	86·41	76·61	
		7a							−146·00
17.6.85	8		85·84	36·84	1·6	2·0	124·28	122·28	
		8a							27·74
1.7.85	9		76·39	9·24	1·6	3·7	87·23	83·53	
		9a							−64·24
15.7.85	10		68·47	39·72	1·6	1·8	109·79	107·99	
		10a							105·12
29.7.85	11		436·76	86·29	1·6	71·6	524·65	453·05	
		11a							74·46
12.8.85	12		247·61	61·26	1·6	12·6	310·47	297·87	
		12a							162·06
26.8.85	13		293·32	71·69	1·6	117·6	366·61	249·01	
		13a							−39·42
9.9.85	14		342·95	48·96	1·6	148·4	393·51	245·11	
		14a							−48·18
22.9.85	15		408·05	30·78	1·6	91·9	440·43	348·53	

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰−⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		15a							124·10
7·10·85	16		341·80	53·03	1·6	177·9	396·43	218·53	
		16a							109·50
21·10·85	17		53·70	0·20	1·6	25·6	55·5	29·90	
		17a							83·22
(4·11·85)			175·05	44·78	0·6	102·5	220·43	117·93	
11·11·85	18								87·60
(18·11·85)		18a	143·45	16·18	0·6	99·7	160·23	60·53	
25·11·85	19								131·40
(2·12·85)		19a	158·00	38·94	0·6	97·0	197·54	100·54	
9·12·85	20	20a							287·62
16·12·85	21		510·92	92·55	0·6	396·1	604·07	207·97	
									48·18
(30·12·85)		21a	741·37	19·36	0·6	567·9	762·33	194·43	
									36·50
(13·1·86)			737·53	115·78	0·6	697·8	853·91	156·11	
20·1·86	22								0
(27·1·86)		22a	557·39	28·01	0·6	541·5	586·00	44·50	
									−43·80
10·2·86	23		77·15	3·78	0·6	26·8	81·53	54·73	
		23a							−36·50
(24·2·86)			28·33	4·57	0·6	25·5	33·50	8·00	
2·3·86	24		29·12	22·35	1·6	25·6	53·07	27·47	
		24a							470·12
17·3·86	25		275·59	43·30	1·6	172·6	320·49	147·89	
		25a							−160·60
1·4·86	26		840·17	34·56	1·6	634·1	876·33	242·23	
		26a							−143·08

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
14·4·86	27		69·04	55·90	1·6	99·6	126·54	26·94	
		27a							-93·44
28·4·86	28		102·68	36·44	1·6	81·1	140·72	59·62	
		28a							-208·78
12·5·86	29		210·01	38·73	1·6	164·9	250·34	85·44	
		29a							-131·4
27·5·86	30		417·53	28·80	1·6	249·0	447·93	198·93	
		30a							-395·66
9·6·86	31		7·55	28·60	1·6	8·6	37·75	29·15	
		31a							-369·33
23·6·86	32		41·35	8·15	1·6	2·0	51·10	49·10	
		32a							-27·74
7·7·86	33		50·35	10·03	1·6	0·6	61·98	61·38	
		33a							-5·84
21·7·86	34		23·26	25·52	1·6	0·3	50·38	50·08	
		34a							-2·92
4·8·86	35		138·09	38·73	1·6	3·4	178·42	175·02	
		35a							-1·46
18·8·86	36		78·29	35·05	1·6	2·2	114·94	112·74	
		36a							81·76
1·9·86	37		187·69	30·19	1·6	5·6	219·48	213·88	
		37a							-74·46
15·9·86	38		56·08	2·59	1·6	1·2	60·27	59·07	
		38a							23·36
29·9·86	39		70·03	17·88	1·6	5·2	89·51	84·31	
		39a							-1·46
13·10·86	40		87·28	35·15	1·6	3·4	124·03	120·63	
		40a							414·64
27 [illegible]	41		569·06	86·19	1·6	168·7	656·85	488·15	

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		41a							200.02
10.11.86	42		403.06	46.57	0.6	302.0	450.23	148.23	
		42a							167.90
24.11.86	43		521.83	65.44	0.6	499.4	587.87	88.47	
		43a							93.44
8.12.86	44		344.54	89.47	0.6	581.8	434.61	-147.19	
		44a							137.24
22.12.86	45		316.01	88.97	0.6	586.9	405.58	-181.32	
		45a							-263.97
5.1.87	46		360.00	43.00	0.6	517.3	403.60	-113.7	
									-28.03
(19.1.87)		46a	259.2	3.68	0.6	41.6	263.48	221.88	
									-30.66
2.2.87	47		24.79	52.44	0.6	47.4	77.83	30.43	
		47a							39.42
16.2.87	48		179.81	3.97	0.6	112.6	184.38	71.78	
		48a							-43.80
2.3.87	49		519.77	35.85	1.6	353.7	557.22	203.52	
		49a							90.52
16.3.87	50		184.18	16.88	1.6	106.9	202.66	95.76	
kg N									
Σyr1			6083.27	994.41	32.6	3586.5	7110.28	3523.78	-17.52
Σyr2			6366.06	1024.43	36.8	4777.7	7427.29	2649.59	-264.08
mean			6224.67	1009.42	34.7	4182.1	7268.79	3086.69	-140.8

Table 6. Component fluxes of the SiO_2 budget of Malham Tarn, assessed in kg (2 weeks)$^{-1}$ as input, output, storage and water-stock increase quantities for successive 2-week periods during (a) March 1985 - March 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Use is made of columns 3, 8 and 11 of the water budget in Table 1.

SAMPLE DATE	SAMPLE NO. ①	PERIOD NO. ②	kg (2wks)$^{-1}$ INFLOW × CONC'N ⑪ × conc^n × 10 ⑬	kg (2wks)$^{-1}$ RAINFALL ON TARN × MEAN CONC'N ⑧ × conc^n × 10 ⑭	HOUSE SEEPAGE [person - days × FACTOR] ⑮	kg (2wks)$^{-1}$ OUTFLOW ③ × conc^n × 10 ⑯	kg (2wks)$^{-1}$ INPUT ⑬ + ⑭ ⑰	kg (2wks)$^{-1}$ TARN RETENTION ⑰ − ⑯ ⑱	kg (2wks)$^{-1}$ TARN STOCK INCREASE $(\bar{c}_2-\bar{c}_1)\times 1460$ ⑲
11.3.85	1		152.86	0.87		53.04	153.73	100.69	
		1a							−511.00
25.3.85	2		158.20	2.71		24.20	160.91	136.71	
		2a							146.00
9.4.85	3		73.26	7.44		22.99	80.70	57.71	
		3a							−350.40
22.4.85	4		144.77	0.87		58.00	145.64	87.64	
		4a							−43.80
6.5.85	5		98.81	0.66		31.20	99.47	68.27	
		5a							87.60
20.5.85	6		119.78	4.97		10.16	124.75	114.59	
		6a							102.20
3.6.85	7		90.24	1.31		15.75	92.05	76.30	
		7a							73.00
17.6.85	8		117.73	3.71		2.16	121.44	119.28	
		8a							262.80
1.7.85	9		128.02	0.93		36.19	128.95	92.76	
		9a							540.20
15.7.85	10		177.62	4.00		73.60	181.62	108.02	
		10a							−219.00
29.7.85	11		1302.64	8.69		563.85	1311.33	747.48	
		11a							−58.40
12.8.85	12		871.08	6.17		206.15	877.25	671.10	
		12a							−29.20
26.8.85	13		991.37	7.22		319.44	998.59	679.15	
		13a							−175.20
9.9.85	14		1217.71	4.93		327.18	1222.64	895.46	
		14a							292.00
23.9.85	15		1839.26	3.10		350.70	1842.36	1491.66	

SAMPLE DATE	SAMPLE No.	PERIOD No.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭	TARN RETENTION ⑰-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		15a							87.50
7.10.85	16		1127.15	5.34		430.92	1132.49	701.57	
		16a							-131.40
21.10.85	17		167.28	0.02		55.08	167.30	112.22	
									138.70
(4.11.85)		17a	459.36	4.51		199.50	463.87	264.37	
11.11.85	18								73.00
(18.11.85)		18a	355.30	1.63		156.80	356.93	200.13	
25.11.85	19								36.50
(2.12.85)		19a	340.20	3.92		135.80	344.12	208.32	
9.12.85	20	20a							379.60
16.12.85	21		807.62	9.32		567.64	816.94	249.30	
									-58.40
(30.12.85)		21a	1112.81	2.00		864.15	1114.81	250.66	
									109.50
(13.1.86)			1059.63	11.66		1131.60	1071.29	-60.31	
20.1.86	22								73.00
(27.1.86)		22a	883.61	2.32		975.00	886.43	-88.57	
									109.50
10.2.86	23		34.88	0.38		49.72	35.26	-14.46	
									109.50
(24.2.86)		23a	73.98	0.46		40.95	74.44	33.49	
3.3.87	24		85.31	2.25		39.14	87.56	48.42	
		24a							-1241.0
17.3.86	25		245.10	4.36		80.84	249.46	168.62	
		25a							-540.20
1.4.86	26		714.00	3.48		99.96	717.48	617.52	
		26a							-131.40

SAMPLE DATE	SAMPLE NO. ①	PERIOD NO. ②	INFLOW × CONC'N ⑬	RAINFALL ON TARN × MEAN CONC'N ⑭	HOUSE SEEPAGE [person - days × FACTOR] ⑮	OUTFLOW ⑯	INPUT ⑬+⑭ ⑰	TARN RETENTION ⑰−⑯ ⑱	TARN STOCK INCREASE ⑲
14.4.86	27		69.23	5.63		10.89	74.86	63.97	
		27a							102.20
29.4.86	28		100.17	3.67		15.12	103.84	88.72	
		28a							204.40
15.5.86	29		296.32	3.90		72.28	300.72	228.44	
		29a							−189.80
27.5.86	30		480.36	2.90		59.52	483.76	424.24	
		30a							−73.00
9.6.86	31		9.33	2.88		4.03	12.26	8.23	
		31a							131.40
23.6.86	32		81.66	0.82		8.36	82.48	74.12	
		32a							394.20
7.7.86	33		86.40	1.01		12.90	87.41	74.51	
		33a							29.20
21.7.86	34		43.30	2.57		7.20	45.87	38.67	
		34a							277.40
4.8.86	35		270.69	3.90		133.94	274.59	140.65	
		35a							−292.00
18.8.86	36		186.88	3.53		63.27	190.41	127.14	
		36a							29.20
1.9.86	37		412.38	3.04		130.66	415.42	284.76	
		37a							−408.80
15.9.86	38		121.44	0.26		14.07	121.70	107.63	
		38a							−87.60
29.9.86	39		182.95	1.80		15.98	184.75	168.77	
		39a							189.80
13.10.86	40		202.83	3.54		35.52	206.37	170.85	
		40a							569.40
27.10.86	41		1294.75	8.68		502.03	1303.43	801.40	

Sample Date	Sample No.	Period No.	Inflow × conc'n	Rainfall on tarn × mean conc'n	House seepage [person-days × factor]	Outflow	Input ⑬ + ⑭	Tarn retention ⑰ - ⑯	Tarn stock increase
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		41a							292.00
10.1/36	42		1029.47	4.69		625.48	1034.16	408.68	
		42a							-29.20
24.11.36	43		1181.00	6.59		735.68	1187.59	451.91	
		43a							43.80
8.12.36	44		962.92	9.01		817.91	971.93	154.02	
		44a							131.40
22.12.36	45		882.17	8.96		847.00	891.13	44.13	-
		45a							87.60
5.1.87	46		999.00	4.33		1000.64	1003.33	2.69	
		46a							109.50
(19.1.87)			792.80	0.37		598.00	793.17	195.17	
									124.10
2.2.87	47		82.78	5.28		115.00	88.06	-26.94	
		47a							-467.20
16.2.87	48		361.61	0.40		144.16	362.01	217.85	
		48a							-598.60
2.3.87	49		897.74	3.61		340.56	901.35	560.79	
		49a							-277.4
16.3.37	50		297.46	1.70		49.44	299.16	249.72	
kg SiO									
Σ yr1			13905.17	100.14		6701.77	14005.31	7303.54	1043.9
Σ yr2			12371.10	103.16		6579.58	12474.26	5894.68	-1620.6
mean			13138.14	101.65		6640.68	13239.79	6599.11	-288.3

Table 7. Component fluxes of the K budget of Malham Tarn, assessed in kg (2 weeks)$^{-1}$ as input, output, storage and water-stock increase quantities for successive 2-week periods during (a) March 1985 - March 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Use is made of columns 3, 8 and 11 of the water budget in Table 1.

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	Kg (2wks)$^{-1}$ INFLOW × CONC'N ⑪ × conc^n × 10	Kg (2wks)$^{-1}$ RAINFALL ON TARN × MEAN CONC'N ③ × conc^n × 10	HOUSE SEEPAGE [perscr. - days × FACTOR]	Kg (2wks)$^{-1}$ OUTFLOW ③ × conc^n × 10	Kg (2wks)$^{-1}$ INPUT ⑬ + ⑭	Kg (2wks)$^{-1}$ TARN RETENTION ⑰ - ⑯	Kg (2wks)$^{-1}$ TARN STOCK INCREASE $(\bar{C}_2-\bar{C}_1)\times 1460$
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
11-3-85	1								
		1a							
25-3-85	2								
		2a							
9-4-85	3								
		3a							
22-4-85	4		55.32	2.78		59.16	58.10	-1.06	
		4a							73.00
6-5-85	5		35.80	2.11		31.20	37.91	6.71	
		5a							-87.60
20-5-85	6		57.24	15.90		58.42	73.14	14.72	
		6a							-73.00
3-6-85	7		40.65	5.79		33.00	46.44	13.44	
		7a							-262.80
17-6-85	8		43.43	11.87		23.76	55.30	31.54	
		8a							-204.40
1-7-85	9		47.89	2.98		10.78	50.87	40.09	
		9a							-14.60
15-7-85	10		56.75	12.80		5.52	69.55	64.03	
		10a							29.20
29-7-85	11		33.20	27.81		71.60	61.01	-10.59	
		11a							73.00
12-8-85	12		21.78	19.74		33.25	41.52	8.27	
		12a							73.00
26-8-85	13		23.93	23.10		79.86	4703	-32.83	
		13a							-146.0
9-9-85	14		315.99	15.78		79.80	331.77	251.97	
		14a							58.4
23-9-85	15		344.86	9.92		91.85	354.78	262.93	

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SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬ + ⑭	TARN RETENTION ⑰ – ⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		15a							146·00
7·10·85	16		368·35	17·09		143·64	385·44	241·80	
		16a							-73·00
21·10·85	17		42·64	0·06		16·20	42·70	26·50	
		17a							0
(4·11·85)			115·46	14·43		53·20	129·89	76·69	
11·11·85	18								7·30
(18·11·85)		18a	87·40	5·22		50·40	92·62	42·22	
25·11·85	19								80·30
(2·12·85)		19a	86·44	12·54		50·44	98·98	86·44	
9·12·85	20	20a							116·80
16·12·85	21		214·27	29·82		222·12	244·09	21·97	
–									80·30
(30·12·85)		21a	329·72	6·40		370·35	336·12	-34·23	
									80·30
(13·1·86)			347·56	37·31		528·08	384·87	-143·21	
20·1·86	22								102·2
(27·1·86)		22a	305·87	9·02		438·75	314·89	-123·86	
									102·2
10·2·86	23		11·48	1·22		24·20	12·70	-11·50	
–		23a							116·80
(24·2·86)			23·84	1·47		23·01	25·31	2·30	
3·3·86	24		27·40	7·20		23·18	34·60	11·42	
		24a							-204·40
17·3·86	25		93·55	13·95		120·32	107·50	-12·82	
		25a							-102·20
1·4·86	26		263·42	11·14		442·68	274·56	-168·12	
		26a							146·00

SAMPLE DATE	SAMPLE NO. ①	PERIOD NO. ②	INFLOW × CONC'N ⑬	RAINFALL ON TARN × MEAN CONC'N ⑭	HOUSE SEEPAGE [person - days × FACTOR] ⑮	OUTFLOW ⑯	INPUT ⑬ + ⑭ ⑰	TARN RETENTION ⑰ - ⑯ ⑱	TARN STOCK INCREASE ⑲
14.4.86	27		23.72	18.02		75.02	41.74	-33.23	
		27a							0
28.4.86	28		43.47	11.74		65.38	55.21	-10.67	
		28a							-102.2
12.5.86	29		91.54	12.48		161.24	104.02	-57.22	
		29a							-160.6
27.5.86	30		166.64	9.28		238.08	175.92	-62.16	
		30a							-175.
9.6.86	31		3.74	9.22		12.09	12.96	0.87	
		31a							-58.4
23.6.86	32		28.36	2.62		13.20	31.48	18.28	
		32a							-262.
7.7.86	33		27.54	3.23		3.00	30.77	27.77	
		33a							-71.5
21.7.86	34		16.13	8.22		0.65	24.35	23.70	
		34a							-14.6
4.8.86	35		67.67	12.48		6.15	80.15	74.00	
		35a							7.30
18.8.86	36		39.67	11.30		4.44	50.97	46.53	
		36a							91.98
1.9.86	37		114.84	9.73		22.52	124.57	102.05	
		37a							7.30
15.9.86	38		39.01	0.83		7.37	39.84	32.47	
		38a							-49.6
29.9.86	39		65.34	5.76		11.84	71.10	59.26	
		39a							87.60
13.10.86	40		53.08	11.33		15.32	64.41	49.09	
		40a							70.08
27.10.86	41		207.78	27.78		154.72	235.56	80.84	

SAMPLE DATE	SAMPLE NO. ①	PERIOD NO. ②	INFLOW × CONC'N ⑬	RAINFALL ON TARN × MEAN CONC'N ⑭	HOUSE SEEPAGE [person - days] × FACTOR ⑮	OUTFLOW ⑯	INPUT ⑬+⑭ ⑰	TARN RETENTION ⑰-⑯ ⑱	TARN STOCK INCREASE ⑲
		41a							308·06
10·11·86	42		296·96	15.01		334·96	311·97	-22·99	
		42a							59·86
24·11·86	43		320·43	21·09		454·96	341·52	-113·44	
		43a							43·80
8·12·86	44		265·63	28·83		468·69	294·46	-174·23	
		44a							14·60
22·12·86	45		272·32	28·67		398·09	300·99	-97·10	
		45a							-131·4
5·1·87	46		351·00	13·86		396·48	364·86	-31·62	
									116·80
(19·1·87)		46a	247·75	1·18		239·20	248·93	9·73	
									131·4
2·2·87	47		24·68	16·90		46·00	41·58	-4·42	
		47a							-43·8
16·2·87	48		118·95	1·28		106·00	120·23	14·23	
		48a							-58·4
2·3·87	49		264·04	11·55		410·22	275·59	-134·63	
		49a							-43·5
16·3·87	50		68·48	5·44		88·58	73·92	-14·66	
Kg K									
Σyr1	from 22·9·85		3009·87	285·16		2498·59	3295·03	796·44	277
Σyr2			3603·64	330·12		4320·88	3933·76	-387·12	-394
mean			3306·76	307·64		3409·74	3614·40	204·66	-58·

Table 8. Component fluxes of the Ca budget of Malham Tarn, assessed in kg (2 weeks)$^{-1}$ as input, output, storage and water-stock increase quantities for successive 2-week periods during (a) March 1985 - March 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Use is made of columns 3, 8 and 11 of the water budget in Table 1.

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	kg(2wks)$^{-1}$ INFLOW × CONC'N ⑪ × conc^n × 10	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days] × FACTOR	kg (2wks)$^{-1}$ OUTFLOW ③ × conc^n × 10	INPUT ⑬ + ⑭ + ⑮	kg(2wks)$^{-1}$ TARN RETENTION ⑬ - ⑯	kg(2wks)$^{-1}$ TARN STOCK INCREASE $(\bar{c}_2-\bar{c}_1)\times 1460$
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
11·3·85	1		7227·32			–		–	
		1a						–	-2482·0
25·3·85	2		6204·66			5977·4		227·26	
		2a							-584·0
7·4·85	3		3490·76			5989·5		-2498·74	
		3a							292·0
22·4·85	4		7932·98			5695·6		2237·38	
		4a							-1752·0
6·5·85	5		4482·16			2511·6		1970·56	
		5a							-1336·0
20·5·85	6		6667·40			5765·8		901·60	
		6a							-5256·0
3·6·85	7		5780·43			3187·5		2592·93	
		7a							-6132·0
17·6·85	8		6735·70			4082·4		2653·30	
		8a							-876·0
1·7·85	9		6769·35			2779·7		3989·65	
		9a							-6716·0
15·7·85	10		6200·9			2944·0		3256·90	
		10a							3942·0
29·7·85	11		59002·02			34457·5		24544·53	
		11a							17082·0
12·8·85	12		37954·2			27664·0		10290·2	
		12a							4526·0
26·8·85	13		48064·11			33759·0		14305·11	
		13a							-1314·0
9·9·85	14		59960·46			38383·8		21576·66	
		14a							5548·0
23·9·85	15		60186·63			41666·5		18520·13	

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SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑬-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		15a							438.0
7.10.85	16		50390.28		–	42214.2		8176.08	
		16a							0
21.10.85	17		6961.8			4195.8		2766.0	
		17a							-3066.0
(4.11.85)			19367.4			13300.0		6067.4	
11.11.85	18								-730.0
(18.11.85)		18a	13680.0			11312.0		2368.0	
25.11.85	19								0.0
(2.12.85)		19a	13198.90			9700.0		3498.9	
9.12.85	20	20a							1168.0
16.12.85	21		34172.68			32269.1		1903.58	
									1022.0
(30.12.85)		21a	45633.7			41191.15		7442.55	
									-2920.0
(13.1.86)			48318.9			46207.0		2111.9	
20.1.86	22								-730.0
(27.1.86)		22a	39422.6			36375.0		3047.6	
									2190.0
10.2.86	23		1102.5			2156.0		-1053.5	
		23a							2190.0
(24.2.86)			2959.2			2008.5		950.7	
3.3.86	24		3376.88			2033.0		1343.88	
		24a							-9344.0
17.3.86	25		9616.94			8723.2		893.74	
		25a							-2336.0
1.4.86	26		38680.56			33058.2		5622.36	
		26a							5694.0

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days] × FACTOR	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑬−⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
14.4.86	27		3910.1			5916.9		−2006.8	
		27a	–						−2628
28.4.86	28		6199.2			5032.8		1166.4	
		28a							730.0
12.5.86	29		15534.4			13010.4		2524.0	
		29a							−4818.0
27.5.86	30		28375.56			22419.2		5956.36	
		30a							−5986.0
9.6.86	31		571.87			1289.6		−717.73	
		31a							−4234.0
23.6.86	32		4795.34			1707.2		3088.14	
		32a							−876.0
7.7.86	33		4293.0			903.0		3390.0	
		33a							−1752.0
21.7.86	34		2258.34			382.5		1875.84	
		34a							−438.0
4.8.86	35		11193.48			4706.0		6487.48	
		35a							1314.0
18.8.86	36		7527.24			2874.9		4652.34	
		36a							7154.0
1.9.86	37		15973.2			7839.6		8133.6	
		37a							1314.0
15.9.86	38		6020.48			2251.2		3769.28	
		38a							−1606.0
29.9.86	39		7656.88			2914.0		4742.88	
		39a							1606.0
13.10.86	40		7753.71			3574.2		4179.51	
		40a							1883.0
27.10.86	41		56751.96			33989.9		22762.06	

SAMPLE DATE	SAMPLE NO. ①	PERIOD NO. ②	INFLOW × CONC'N ⑬	RAINFALL ON TARN × MEAN CONC'N ⑭	HOUSE SEEPAGE [person - days × FACTOR] ⑮	OUTFLOW ⑯	INPUT ⑬+⑭+⑮ ⑰	TARN RETENTION ⑬−⑯ ⑱	TARN STOCK INCREASE ⑲
		41a							6716·0
10·11·86	42		41416·37			38681·0		2735·37	
		42a							9052·0
24·11·86	43		60056·8			52272·0		7784·8	
		43a							−7650·4
8·12·86	44		42235·49			47089·56		−4854·07	
		44a							−2029·4
22·12·86	45		38715·54			42748·09		−4032·55	
		45a							919·8
5·1·87	46		49320·0			45028·8		4291·2	
									2190·0
(19·1·87)		46a	27004·75			26520·0		484·75	
									2920·0
2·2·87	47		2153·18			48760		−2722·82	
		47a							−4964·0
16·2·87	48		16629·21			10472·8		6156·41	
		48a							−2336·0
2·3·87	49		36965·6			36610·2		355·4	
		49a							−3796
16·3·87	50		12133·8			10032·2		2101·6	
kg Ca									
Σ yr 1			604867·04			455793·05		133670·59	3504
Σ yr 2			557119·88			466956·45		90163·43	−12118
mean			580993·46			461374·75		111917·01	−4307

Table 9. Component fluxes of the alkalinity (largely HCO_3^-) budget of Malham Tarn, assessed in kg (2 weeks)$^{-1}$ as input, output, storage and water-stock increase quantities for successive 2-week periods during (a) March 1985 - March 1986 (b) March 1986 - March 1987, with annual summations for the two years involved. Use is made of columns 3, 8 and 11 of the water budget in Table 1.

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	Keq (2wks)$^{-1}$ INFLOW × CONC'N ⑪ xconc'n x10	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days] × FACTOR	Keq (2wks)$^{-1}$ OUTFLOW ③ xconc'n x10	INPUT ≏ ⑬ ⑬ + ⑭ + ⑮	Keq (2wks)$^{-1}$ TARN RETENTION ⑬ - ⑯	Keq (2wks)$^{-1}$ TARN STOCK INCREASE $(C_2-C_1)\times 1460$
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
11.3.85	1		312.25			225.06		87.19	
		1a							-33.6
25.3.85	2		271.08			259.06		12.01	
		2a							-30.7
9.4.85	3		155.30			256.52		-101.22	
		3a							-18.9
22.4.85	4		364.05			244.41		119.63	
		4a							-58.4
6.5.85	5		202.56			107.48		95.07	
		5a							-163.5
20.5.85	6		300.40			248.29		52.12	
		6a							-205.9
3.6.85	7		261.62			136.05		125.57	
		7a							-306.6
17.6.85	8		298.86			173.23		125.63	
		8a							-125.6
1.7.85	9		314.89			116.89		198.00	
		9a							-267.2
15.7.85	10		280.20			122.82		157.38	
		10a							185.4
29.7.85	11		2629.98			1308.49		1321.48	
		11a							512.5
12.8.85	12		1907.67			1205.65		702.02	
		12a							439.5
26.8.85	13		2366.97			1534.76		832.21	
		13a							233.6
9.9.85	14		2990.32			1814.65		1175.66	
		14a							178.1
23.9.85	15		2959.25			2000.66		958.58	

2

SAMPLE DATE	SAMPLE No.	PERIOD No.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days] × FACTOR	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰-⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
		15a							−65.7
7.10.85	16		2347.13			1876.09		471.03	
		16a							93.44
21.10.85	17		357.93			195.62		162.32	
		17a							−21.9
(4.11.85)			968.37			638.4		329.97	
11.11.85	18								0
(18.11.85)		18a	684.00			537.6		146.4	
25.11.85	19								0
(2.12.85)		19a	650.65			465.6		185.05	
9.12.35	20	20a							112.42
16.12.35	21		1502.61			1528.31		−25.7	
									−221.92
(30.12.85)			2143.18			1913.48		229.71	
		21a							−182.5
(13.1.86)			2119.25			2074.6		44.65	
20.1.86	22								−73.0
(27.1.86)		22a	1767.22			1612.5		154.72	
									8.76
10.2.86	23		67.50			94.86		−27.36	
									210.24
(24.2.86)		23a	137.69			89.7		47.99	
3.3.86	24		158.06			91.01		67.05	
		24a							−525.6
17.3.86	25		403.76			382.58		21.18	
		25a							−144.54
1.4.86	26		1663.68			1382.30		281.38	
		26a							179.58

SAMPLE DATE	SAMPLE NO.	PERIOD NO.	INFLOW × CONC'N	RAINFALL ON TARN × MEAN CONC'N	HOUSE SEEPAGE [person - days × FACTOR]	OUTFLOW	INPUT ⑬+⑭+⑮	TARN RETENTION ⑰−⑯	TARN STOCK INCREASE
	①	②	⑬	⑭	⑮	⑯	⑰	⑱	⑲
14·4·86	27		161·02			249·14		− 88·12	
		27a							− 86·14
28·4·86	28		274·99			216·0		58·99	
		28a							108·04
12·5·86	29		719·30			576·57		142·73	
		29a							− 64·24
27·5·86	30		1395·45			1006·88		388·57	
		30a							−175·2
9·6·86	31		28·32			59·21		− 30·89	
		31a							−407·34
23·6·86	32		214·23			71·76		142·46	
		32a							− 547·5
7·7·86	33		197·21			37·68		159·53	
		33a							− 283·24
21·7·86	34		103·44			15·93		87·51	
		34a							− 5·84
4·8·86	35		502·98			191·50		311·48	
		35a							75·92
18·8·86	36		354·23			123·21		231·02	
		36a							347·48
1·9·86	37		806·23			374·74		431·49	
		37a							306·6
15·9·86	38		292·49			104·39		188·10	
		38a							−309·52
29·9·86	39		379·07			126·52		252·55	
		39a							109·5
13·10·86	40		378·41			156·73		221·68	
		40a							556·26
27·10·86	41		2603·46			1483·05		1120·41	

SAMPLE DATE	SAMPLE NO. ①	PERIOD NO. ②	INFLOW × CONC'N ⑬	RAINFALL ON TARN × MEAN CONC'N ⑭	HOUSE SEEPAGE [person-days × FACTOR] ⑮	OUTFLOW ⑯	INPUT ⑬+⑭+⑮ ⑰	TARN RETENTION ⑰−⑯ ⑱	TARN STOCK INCREASE ⑲
		41a							354.78
10.11.86	42		1898.98			1683.04		215.94	
		42a							118.26
24.11.86	43		2508.47			2057.97		450.50	
		43a							237.98
8.12.86	44		1867.73			2103.59		−235.87	
		44a							−75.92
22.12.86	45		1725.98			1894.74		−171.47	
		45a							−331.42
5.1.86	46		2059.2			1897.44		161.76	
									204.4
(19.1.87)		46a	1325.46			1105.0		220.46	
									220.46
2.2.87	47		121.27			211.69		−90.42	
		47a							−211.7
16.2.87	48		743.68			457.07		286.60	
		48a							−7.3
2.3.87	49		1585.75			1664.87		−79.13	
		49a							67.16
16.3.87	50		529.86			452.58		77.28	
Key Alk									
Σ yr 1			28360.93			20780.78		7580.11	198.54
Σ yr 2			25002.68			20177.20		4825.48	289.08
mean			26681.80			20478.99		6202.79	243.81

Table 10. Summary of main features in the chemical budgets of the Tarn, based on mean annual estimates for March 1985 - March 1987. Small and probably negligible terms are indicated by -. Note 1 t = 10^3 kg.

			C		P	N*	K	Ca	SiO_2
		units	inorg.	partic. org.					
1.	total input	t yr^{-1}	320		0.165	7.3	3.6	581	13.2
2.	fertiliser input	t yr^{-1}	-	-	0.008	0.038	0.016	-	-
3.	sewage input	t yr^{-1}	-	-	0.027	c.0.3	-	-	-
4.	catchment-rain input	t yr^{-1}	-	-	0.34	10.1	3.1	-	1.0
5.	outflow	t yr^{-1}	246		0.10	4.2	3.4	461	6.6
6.	annual Tarn retention	t yr^{-1}	74		0.06	3.1	0.2	120	6.6
7.	retention as fraction of total input		0.23	-	0.36	0.42		0.21	0.50
8.	solute depletion, seasonality		summer		year-round	summer	summer	summer	spring
	, fractional fall		0.57		-	0.97	0.85	0.40	0.92
	, absolute fall	t	12		-	1.3	0.7	29	1.8
9.	<u>Chara</u> stock, summer max.	t	66	112	1.40	12.8	7.1	185	
10.	phytoplankton stock, summer max.	t	-	2	0.03	0.2	-	-	-
11.	total sediment stock, 0-4 cm	t	146	329	3.09	34.4	9.5	403	
12.	exchangeable sediment stock, 0-4 cm	t			0.90	0.16	0.52		

* excluding dissolved organic N