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Title

Historical changes (1905-2005) in external phosphorus loads to Loch Leven, Scotland, UK

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This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to Hydrobiologia.

Abstract

This paper reviews historical changes in the total phosphorus (TP) inputs to Loch Leven, Scotland, UK. Data derived from palaeolimnological records suggest that inputs in the early 1900s were about 6 t TP y^{-1} (0.45 g TP m^{-2} y^{-1}). By 1985, this had risen to about 20 t TP y^{-1} (1.5 g TP m^{-2} y^{-1}) due to increases in runoff from agricultural land and discharges from point sources. By the late 1970s, increased TP inputs were causing serious degradation of lake water quality. Most noticeably, there had been an increase in cyanobacterial blooms. A catchment management plan was implemented in the early 1990s. This resulted in a 60% reduction in the annual TP input between 1985 (20 t TP y^{-1}/1.5 g TP m^{-2} y^{-1}) and 1995 (8 t TP y^{-1}/0.6 g TP m^{-2} y^{-1}). The main reduction was associated with better control of point source discharges, but attempts were also made to reduce inputs from diffuse sources. The reduction in external TP loading to the lake led to a marked decline in TP retention by the lake each year.

Introduction

External nutrient loading has long been recognised as one the most important factors controlling the productivity or trophic state of a lake (Vollenweider, 1968; Dillon & Rigler, 1974; Jeppesen et al., 2005). Under natural conditions, nutrient inputs to lakes are generally low and cause few water quality problems. However, anthropogenic activity within the catchment can increase nutrient inputs to waterbodies to a level that degrades water quality (Gulati & Van Donk, 2002) and promotes troublesome, and sometimes toxic, cyanobacterial blooms (Codd, 1995; Schindler, 2006; Leigh et al., 2010). This process is known as eutrophication. Such activities include fertiliser applications to farmland, animal husbandry, population increases and industrial development (Harper, 1992; Jeppesen et al., 2007).

Eutrophication is the most widespread water-quality problem in many parts of the world (Carpenter et al., 1998) and dealing with it can be costly. For example, Pretty et al. (2003) estimated that responding to eutrophication problems in England and Wales, alone, cost *c*. USD 89M y^{-1}, with associated social and ecological damage estimated to be a further USD 121M - 232M y^{-1}. In addition to these short-term costs, there are also enormous additional costs associated with the restoration of lakes that have undergone cultural eutrophication to achieve the "good" or "high" ecological status required by the EU Water Framework Directive (European Parliament, 2000). For this reason, it is important that the most cost effective solutions to lake eutrophication problems are used and these need to be derived from the results of well-documented, previous, restoration projects (Sondergaard & Jepessen, 2007).

Loch Leven (Scotland, UK) is a good example of a large, shallow lake with a long, and well documented, history of water quality problems caused by anthropogenic eutrophication. The most noticeable symptom of these problems was an increase in the frequency of cyanobacterial blooms from 1963 onwards (Morgan, 1974; Holden & Caines, 1974). By the mid 1980s, these blooms had become so serious that they threatened the high conservation, recreational and economic value of the lake (May & Spears, this volume a). As early as the 1970s, it was broadly recognised that this degradation in water quality was closely related to increases in nutrient-laden agricultural runoff and elevated levels of discharges from waste water treatment works (WWTWs) and industrial sources (Holden & Caines, 1974).

By the 1980s, it was generally believed that phosphorus (P) was the main nutrient limiting phytoplankton production and biomass accumulation in most shallow lakes (e.g. Schindler, 1977). Long term water quality records from Loch Leven were examined and these showed a close, positive relationship between algal abundance (expressed as chlorophyll *a* concentration) and total P (TP) availability (Figure 1). It was, therefore, concluded that reducing TP inputs to the lake would improve water quality and this became the focus of a range of catchment management activities undertaken in the late 1980s and early 1990s (LLCMP, 1999).

Increased TP input associated with anthropogenic development within the catchment seemed to be the main cause of the eutrophication problems at Loch Leven. Initial estimates suggested that, between 1967 and 1976, the external TP input to the lake ranged between 7 and 17 t y^{-1} (0.53 – 1.28 g m^{-2} y^{-1}), with up to 70% of that input coming from a single industrial source (Holden & Caines, 1974; Holden et al., 1975;

Caines & Harriman, 1976). By 1985, the overall TP input had risen to about 20 t y^{-1} (1.5 g m^{-2} y^{-1}), 57% of which could be attributed to point source discharges from WWTWs and industry (Bailey-Watts & Kirika, 1987; Bailey-Watts et al., 1987).

Between 1985 and 1995, controls imposed on industrial discharges from a local woollen mill (D'Arcy, 1991) and improvements in local sewage treatment facilities (Bailey-Watts & Kirika, 1996, 1999) reduced the TP input to the lake from point sources by about 70% (Bailey-Watts & Kirika, 1996, 1999). However, a 53% fall in TP transported by runoff between 1985 and 1995 also reduced the overall TP load (Bailey-Watts & Kirika, 1999). At the end of this period, the external TP load to the lake was estimated to be about 8 t y^{-1} (0.6 g m^{-2} y^{-1}). It should be noted, however, that the reduction in runoff may have been caused by inter-annual variation in rainfall, which was about 30% lower in 1995 than in 1985, rather than changes in catchment management activities (Bailey-Watts & Kirika, 1996, 1999).

Management activities aimed at reducing the TP input to the lake continued beyond 1995 as a part of a long term strategy for its restoration (LLCMP, 1999). Although at a much lower level than before, and focusing on reducing TP losses from diffuse sources rather than point sources, these activities aimed to provide a sustainable future for the lake. Most activities were focused on one particular feeder stream, the Pow Burn, and its catchment (Figure 2). Although only accounting for about 10% of the lake's catchment, this stream had been shown to be the source of about 30% of the total river-borne P entering the lake during 1985 (Bailey-Watts & Kirika, 1987). Fields within this sub-catchment had also been identified as being at high risk of soil erosion (Frost, 1994).

In-field land management techniques were introduced to reduce the risk of soil erosion at source within the Pow Burn catchment and a series of grass or grass/tree buffer strips up to 20 m wide were installed along the banks of this inflow and its feeder streams to intercept eroded material and prevent it from entering the watercourses (Castle et al., 1999). Although there is little evidence that these buffer strips significantly reduced P runoff from this area under 'normal' conditions, Vinten et al. (2004) concluded that they may have been at least partially effective during high runoff events. In addition to these specific management activities, local farmers were encouraged to control livestock grazing, fertiliser usage, and slurry/manure spreading across the whole of the catchment (Castle et al., 1999).

The main aim of this paper is to review recent historical changes in the external TP input to Loch Leven, using data compiled from published records for the period 1965 to 1995 and new data from 2005, and compare them to 'baseline' data derived from palaeolimnological records. Changes in the annual TP balance of the lake between 1975 and 2005 are explored and the effectiveness of catchment management measures at reducing the TP input to the lake is considered. This paper also provides background information and context for the series of papers that follow, which describe the ecological response of the lake to these historical changes in nutrient conditions (Carss et al., this volume; Carvalho et al., this volume; Dudley et al., this volume; Elliott & Defew, this volume; Gunn et al., this volume; May & Spears, this volume b; Spears et al., this volume; Winfield et al., this volume;).

Site description

Loch Leven is a shallow lake situated in the lowlands of Scotland, UK. The structure and physical environment of the lake are described in detail by Smith (1974). In summary, the lake lies at a latitude of 56°10'N, a longitude of 3°30'W and an altitude of 107 m.a.o.d. It has a surface area of 13.3 km^2, and mean and maximum depths of 3.9 m and 25.5 m, respectively (Kirby, 1971).

The catchment of the lake (Figure 2) covers an area of about 145 km^2, which rises to an altitude of 482 m.a.o.d. About two-thirds of the catchment is drained by four main rivers (North Queich, South Queich, Gairney Water and Pow Burn), and the remainder is drained by several minor inflows and some small areas of land along the shoreline that drain directly into the lake (Figure 2). The catchment is mainly rural and intensively farmed, with about 80% being used for agricultural production (LLCMP, 1999). Currently, the land use in this area is dominated by mixed farmland with the best land being used for high-value potato and vegetable crops, cereals and oilseed rape (Castle et al., 1999). There is some livestock rearing, but this is mainly restricted to the more upland areas, which tend to be further away from the lake (LLCMP, 1999). A further 11% of the catchment is woodland and about 2% is used for habitation. High levels of P-laden runoff enter the lake from areas of intensive agriculture within the catchment.

Population density in this area is low, with only about 11,000 people living within the catchment (Frost, 1996). About 60% of these live in the towns of Kinross, Milnathort and Kinnesswood (Perth & Kinross Council, 2004), which are served by mains sewerage networks that are connected to WWTWs. However, it is estimated that about 650 households in the more remote parts of the catchment rely upon private sewage treatment systems, such as septic tank systems, for managing their domestic waste (Dudley & May, 2007). In the past, high levels of P have entered the lake in the form of WWTW effluent (Bailey-Watts & Kirika, 1999) and septic tanks discharges (Frost, 1996).

Although there is little industry within the catchment, there have been one or more woollen mills on the banks of one of the South Queich since 1840 (Munro, 1994). These mills have discharged large quantities of P-laden effluent into the lake in the past, but the introduction and enforcement of strict discharge limits in the late 1980s reduced TP discharges from the one remaining mill from about 6 t TP y^{-1} (0.45 g TP m^{-2} y^{-1}) in 1985 to about 0.4 t TP y^{-1} (0.03 g TP m^{-2} y^{-1}) by 1988 (D'Arcy, 1991; D'Arcy et al., 2006). More recently, processing methods at the mill have changed and there is no longer any discharge of TP to the lake from this source (D'Arcy, 1991).

Methods

Historical TP loads, 1905 – 1965

Inputs of TP to the lake for the period 1905 to 1965 were derived from palaeolimnological records, because no measured values were available for this period. This was achieved by, first, inferring in-lake TP concentrations from the diatom assemblages in a 90 cm sediment core (LEVE11) that was taken with a mini-Mackereth corer (Mackereth, 1969) on 5-5-1999. The core was collected at a water depth of 4 m near to the Reed Bower site and extruded at 1 cm intervals.

The core was radiometrically dated using standard gamma assay procedures (Appleby et al., 1986; Appleby et al., 1992) and the chronology was calculated based on ^{210}Pb using the constant rate of supply model (Appleby & Oldfield, 1978). Sediment accumulation rates of 0.12-0.15 cm yr^{-1} were estimated for this core for the period ~1930-1970, and a rate of 0.12 cm yr^{-1} was assumed for the period prior to 1930. The errors associated with the dating were relatively small, with errors of ±5-10 years for the period 1950-1970, and ±10-14 years for the period 1930-1950. Sixteen sub-samples were prepared and analysed for diatoms using standard procedures (Battarbee et al., 2001).

The reconstruction of diatom-inferred TP (DI-TP) was produced using a northwest European training set of 152 relatively small, shallow lakes (< 10 m maximum depth) with a median value for the data of 104 µg TP l[-1] and a root mean squared error of prediction (RMSEP) of 0·22 $\log_{10}$ µg TP l[-1] for the weighted averaging model (Bennion et al., 1996; Bennion et al., 2004). The reconstructions were implemented in C2 (Juggins, 2003), following taxonomic harmonization between the training set and the fossil data.

The DI-TP values were used to back-calculate the corresponding TP load to the lake using the equation of Dillon & Rigler (1974) and annual flushing rates calculated from daily outflow records (Sargent & Ledger, 1992; Loch Leven Trustees, *pers. comm.*). The resultant annual TP loading values were averaged over five 10-year periods, i.e. 1900-1909, 1910-1919, 1930-1939, 1950-1959 and 1960-1969, to take account of uncertainties in the core chronology. Each derived value was assigned to the 5th year of each decade, i.e. 1905, 1915, 1935, 1955 and 1965.

TP load for 2005

The TP load to Loch Leven in 2005 was estimated from measured in-stream nutrient concentrations and measured or derived flows determined for each of the 12 major inflows and the outflow at 8-day intervals between 18 January 2005 and 17 January 2006 (Figure 2). Water samples were collected with 250 ml plastic sample bottles that had been pre-washed in Decon 90®, rinsed with distilled water and then rinsed again with stream water prior to sample collection.

Duplicate stream water samples were collected at each site by submerging the sample bottles to about 20 cm below the water surface. Samples were analysed for TP content using the methods of Murphy & Riley (1962), as modified by Eisenreich et al. (1975), on samples that had been subjected to an acid hydrolysis reaction prior to colorimetric analysis. This was achieved by mixing the sample with a solution of sulphuric acid (H_2SO_4) and potassium persulfate ($K_2S_2O_8$) and then autoclaving at 121°C for 30 minutes. The intensity of colour formed was quantified by measuring absorbance with a Philips PU8620 Series UV/VIS/NIR single beam spectrophotometer, using a 4 cm flow cell and a wavelength of 882 nm. The concentration of TP within each sample was determined from this value using a linear calibration equation generated from the measured absorbance values of known TP standards. All analyses were performed in triplicate to ensure accuracy and quality of the results. The TP detection limit was estimated to be 2 µg l^{-1}.

Flow data from continuous recording devices located on the Pow Burn (Pb), South Queich (Sc) and North Queich (Ne) were provided by the Scottish Environment Protection Agency (SEPA). This information was supplemented by water height measurements recorded from gauging boards on the smaller streams, i.e. Camel Burn (Cc), Gairney Water (Gb) and the Hatton Burn (Nh), on each sampling date. Stream flows were estimated from these water height measurements using ratings curves that had been constructed from a range of measured in-stream flows across known gauge heights (Defew, 2008).

Two small streams flowing into the lake, i.e. Ury Burn and Kinnesswood Burn, were not included in the field survey. Phosphorus concentrations at these sites were assumed to be similar to those of the nearest sampled sub-catchment, i.e. the North Queich and the Pow Burn, respectively. Stream flow at these un-gauged sites was assumed to be directly proportional to the measured stream flows at the nearby North Queich and the Pow Burn in terms of relative catchment area, because Bailey-Watts and Kirika (1987a,b) had previously found strong correlations (r = 0.97, TP < 0.05) between mean discharge and drainage area at these sites. This proportional method was also used to account for additional stream flow downstream of sampling sites that were not close to the confluence of the stream with the lake, and for water draining directly into the lake from areas outside the sampled sub-catchments.

The annual TP load to the lake from each inflow or area of direct runoff was calculated using the method of Stevens & Smith (1978), as follows:

$$TotalLoad = K\left(\sum_{i=1}^{n}(C_cQ_c)\right)$$

Where:

K = conversion factor to convert from time period of record to annual value

n = number of samples.

C_c = estimate of TP concentration from continuous stream flow value

Q_c = measured or estimated flow ($m^3\,s^{-1}$)

The estimated TP loads were corrected statistically following the method of Ferguson (1986) and the final values were summed to give an overall annual TP load to the lake from its catchment. Further details of these methods are given by Defew (2008).

As P loads to the lake also include inputs from non-catchment sources such as excreta from over-wintering geese and rain falling directly onto the surface of the lake, these were also estimated. Phosphorus inputs from geese were calculated from data provided by Scottish Natural Heritage which suggested that, on average, 12,656 pink-footed geese *per* day roosted on the lake from January to March and between September and December, 2005. Assuming that these geese were feeding, primarily, on grass, the input *per* goose was estimated to be *c.* 172 mg TP d[-1] (Hancock, 1982). Direct inputs from rainfall were calculated from the total amount of rain falling onto the lake surface each year (data provided by Kinross Estates) and the estimated TP content of rain in this area, i.e. *c.* 25 mg TP m[-3] y[-1] (Bailey-Watts et al., 1987).

Phosphorus retention rates

Annual TP retention rates for Loch Leven were calculated at ten-yearly intervals for the years for which detailed TP loading data were available, i.e. 1975, 1985, 1995 and 2005, using a mass balance approach. This involved calculating the annual discharge of TP from the lake for each year from the TP concentrations measured at or near the outflow at roughly weekly intervals (Caines & Harriman, 1976; Bailey-Watts & Kirika, 1987, 1996, 1999; Bailey-Watts et al., 1987; this study) and the corresponding rates of hydraulic discharge (data provided by the Loch Leven Trustees). In outline, discharges of TP from the outflow on each sampling occasion (kg day^{-1}) were estimated as the product of the corresponding concentration and flow values outlined above. The average of these daily values was then multiplied by 365 to estimate the annual discharge of TP from the lake in each year. The TP retention coefficient for the lake was then calculated by subtracting the annual TP discharge value from the corresponding annual TP loading value for each year, dividing the result by the annual TP loading and then expressing the result as a percentage.

Results

The diatom inferred TP concentration (DI-TP) in Loch Leven was relatively stable for the period 1905-1965 at ~65-75 μg TP l^{-1}. The DI-TP values for the uppermost part of the core were in very good agreement with the measured 3-year mean TP concentration of the lake for 1997-1999 suggesting that the reconstructions are likely to be reliable. Furthermore, comparison of DI-TP values from a more recent core with measured annual mean TP concentrations for the period 1969-2005 shows that the DI-TP reconstruction agrees well with the time series of measured values in terms of both the overall trend and the actual TP values (Bennion et al., unpublished).

The annual TP inputs to Loch Leven between 1905 and 1965, as estimated from the palaeolimnological record, are shown in Figure 3. Although the data suggest that the TP load was relatively stable over this period, i.e. about 6 t y^{-1} (0.45 g m^{-2}), it should be noted that this apparent stability may be an artefact generated by the decadal averaging method applied to the palaeolimnological data.

Measured data for the period between 1965 and 1995 showed that the annual TP load to the lake varied significantly over that period (Figure 3), ranging from about 7.5 t y^{-1} (0.56 g m^{-2} y^{-1}) in the 1970s to about 20.5 t y^{-1} (1.54 g m^{-2} y^{-1}) by 1985, then falling to about 8 t y^{-1} (0.6 g m^{-2} y^{-1}) by 1995.

The most recent loading survey suggested that the TP load to the lake in 2005 was about 8.2 t y^{-1} (0.62 g m^{-2} y^{-1}) (Figure 3), with less than 6% of the external load being attributable to inputs from over-wintering geese and less than 5% being accounted for by rain falling directly onto the surface of the lake. This overall value was only about 2 t y^{-1} (0.15 g m^{-2} y^{-1}) greater than the average historical load that had been estimated for 1905 to 1965 and was, essentially, the same as that measured in 1995.

Changes in the calculated annual TP balance of the lake at 10-yearly intervals between 1975 and 2005 are shown in Figure 4. Varying proportions of the TP entering the lake were retained in all of the years examined. In 1975, 44% of the external TP input (3 t y^{-1}/0.23 g m^{-2} y^{-1}) was retained. By 1985, this had risen to 61% (12.5 t y^{-}

^{1}/0.94 g m^{-2} y^{-1}) of the TP input. Once external inputs from the catchment had been reduced by about 60%, TP retention rates fell dramatically to 12% (1 t y^{-1}/0.08 g m^{-2} y^{-1}) in 1995 and 15% (1.25 t y^{-1}/0.09 g m^{-2} y^{-1}) in 2005. In contrast, however, the actual amount of TP discharged *via* the outflow was relatively constant each year, i.e. 1975: 4 t y^{-1} (0.3 g m^{-2} y^{-1}); 1985: 8 t y^{-1} (0.6 g m^{-2} y^{-1}); 1995: 7 t y^{-1} (0.53 g m^{-2} y^{-1}); 2005: 7 t y^{-1} (0.53 g m^{-2} y^{-1}).

Discussion

The survey data from the studies reviewed above, and the additional data presented from this study, show that the TP load to Loch Leven increased from about 6 t y^{-1} (0.45 g m^{-2} y^{-1}) to about 20 t y^{-1} (1.5 g m^{-2} y^{-1}) over the main period of enrichment. When catchment management measures were introduced in the late 1980s and early 1990s, this external load fell by about 12 t P y^{-1} (0.9 g P m^{-2} y^{-1}), or 60%. This reduction comprised about 8.5 t P y^{-1} (0.64 g P m^{-2} y^{-1}) from point sources and about 3.5 t P y^{-1} (0.26 g P m^{-2} y^{-1}) from diffuse sources, although the latter is believed to be better explained by the lower rainfall in 1995 compared to 1985 (Bailey-Watts & Kirika, 1999) than by any improvements in catchment management. Since 1995, strict controls have continued to be enforced within this P sensitive catchment and, in 2005, P inputs to the lake were still low (i.e. 8 t y^{-1}/0.6 g m^{-2} y^{-1}). This value is lower than the target value of 10 t y^{-1} (0.75 g m^{-2} y^{-1}) set by the catchment management group (LLCMP, 1999) and seems to be approaching that estimated for the early 1900s (i.e. 6 t y^{-1}/0.45 g m^{-2} y^{-1}). The level of reduction of P input to Loch Leven is similar to that of other lakes that have undergone nutrient input reductions as part of lake restoration strategies. These include a 50% reduction in P load to Muggelsee, Germany (Kohler et al., 2005) and a 55% reduction in P load to Lake Apopka, USA (Coveney et al., 2005). An improvement in water quality followed in many of these lakes, albeit often following a significant time lag (i.e. 10-15 years: Jeppesen et al., 2005; Jeppesen et al., 2007). However, this is not always the case. Gulati & van Donk (2002), in their review of the eutrophication of Dutch lakes and the restoration techniques applied, found that decreasing P inputs did not always result in an improvement in water quality.

When reducing the P input to a lake, it is important to identify the main sources of those inputs. At Loch Leven, when inputs were high, 56% of those inputs came from point source discharges with less than 44% coming from diffuse sources (Bailey-Watts & Kirika, 1987). Of the diffuse sources, P entering from rain falling directly onto the surface of the lake was generally low, i.e. about 0.3 – 0.4 t y^{-1}, which equated to about 2% of the external TP load in 1985 and 5% in 1995 and 2005. Inputs from geese over-wintering at the lake were also low, i.e. 0.5 t P y^{-1}, or about 3% of the external TP load in 1985 and about 6% of that load in 1995 and 2005. This is in contrast to the situation in many other shallow lakes where P inputs from wildfowl are relatively high (e.g. 70%: Manny et al., 1994; 88-92%: Ronicke et al., 2008; 73%: Chaichana et al., 2010). It is also likely that P inputs from geese to Loch Leven have changed very little in recent years because, although the proportion of greylag and pink footed has changed over time, the total number of geese has remained fairly stable (Carss et al., this volume).

There have been varying levels of TP retention within the lake over the period of available data, 1975 to 2005. However, on an annual timescale, P retention has

remained positive, suggesting that TP continues to accumulate in the lake sediments. Such accumulations are important in terms of lake recovery because, when external TP loads are reduced, these internal sources tend to release P into the water column causing a considerable delay in recovery (Sas, 1989; Gulati & van Donk, 2002; Søndergaard et al., 2003; Nürnberg & LaZerte, 2004; Jeppesen et al., 2005; Søndergaard et al., 2007; Spears et al., this volume). That said, in most lakes, P release from the sediments also promotes recovery because it increases the rate at which TP from internal sources can be exported from the system, especially during the summer months (Sondergaard et al., 2001). In Loch Leven, however, hydrological discharge from the outflow is restricted during the summer months by the use of sluice gates that are employed to maintain a constant water supply for downstream users (May & Spears, this volume b). So, it is likely that P leaves this system more slowly than in naturally flushed lakes, thus slowing down the recovery process.

Data from Loch Leven for 1975 and 1985 show that, prior to the 60% reduction in external TP load, the TP retention rate was about 50%. After the reduction in external input, the TP retention rate fell to about 15%. Given that TP retention in lakes tends to be negatively correlated with hydraulic retention time (Brett & Benjamin, 2008), and that the latter two years were much drier than the earlier years, this suggests that that the lake is now retaining significantly less TP from external sources than it was in the 1970s and 1980s. However, total (rather than relative) export of TP from the lake has changed very little from year to year. This is probably because the rate of flow in the outflow, which is managed to ensure a constant flow of water to downstream industry over the summer period (May & Carvalho, 2010; May & Spears, this volume b), and in-lake annual average TP concentrations have remained fairly constant over this period (Carvalho et al, this volume). Although similar in terms of values, however, it should be noted that in-lake TP concentrations in the earlier years were driven by external TP loads, while those from 1995 onwards were increasingly driven by internal TP loads (Spears et al., this volume).

Although some relatively minor point source upgrades were implemented between 1995 and 2005, improvements in catchment management over that period were mainly focused on reducing TP inputs from agricultural (diffuse) sources through the better management of farm nutrient budgets and the installation of buffer strips along the banks of some of the inflows to reduce stream contamination by nutrient laden runoff. Although a comparison of the TP inputs to the lake in 1995 and 2005 seems to suggest that these activities had little effect, the real impact of these measures cannot be determined by simply comparing these values directly. Source apportionment needs to be taken into account before conclusions are reached. This is not possible with the existing data, because the less detailed survey that was carried out in 2005 did not include sampling up- and down-stream of point source discharges. Nevertheless, it seems likely that the implementation of buffer strips, lower fertiliser application rates and other agricultural initiatives implemented across the catchment to reduce P losses from agriculture were probably more effective than the data suggest. This is because any resultant reduction in TP delivery to the lake from diffuse sources was probably masked by parallel increases in P-laden sewage effluent associated with recent population growth in this area. Government census statistics suggest that the resident population in the area around Loch Leven has grown rapidly in recent years, with an increase of about 22% occurring between 1981 and 1991 and 16% between 1991 and 2001 (Perth & Kinross Council, *pers. comm.*).

Conclusion

This study shows that the implementation of a catchment management plan in the late 1980s and early 1990s reduced the external TP load to Loch Leven by about 60%. Most of this reduction was due to better control of point source discharges rather than reductions in nutrient laden runoff from the surrounding farmland. Very little of the observed reduction could be attributed directly to the implementation of best management practices on agricultural land or the installation of buffer strips next to drainage channels. However, this does not necessarily mean that these measures were ineffective. It is possible that any decreases in P-laden runoff from agricultural activities may have been masked by concurrent increases in population density and, consequently, higher TP discharges from WWTWs. This highlights the importance of obtaining good source apportionment data when assessing the effectiveness of catchment management activities in reducing nutrient loads to waterbodies.

When the input of TP to the lake from external sources was reduced by 60%, the overall TP retention rate fell from about 50% to about 15%. This was because the rate of hydraulic discharge rate was unchanged and in-lake P concentrations remained high (Carvalho et al., this volume) as a result of increased P release from the sediments. This seemed to be 'compensating' for the reduction in TP load from the catchment (Spears et al., this volume) as has been observed in other lakes (Søndergaard et al., 2003; Nürnberg & LaZerte, 2004). This suggests that, while internal recycling appears to delay recovery in terms of in-lake water quality parameters, it also promotes recovery in terms of increasing the rate at which TP from internal sources is exported from the system. This should be taken into account when assessing the success of reductions in external load on the long term recovery of eutrophic lakes.

Acknowledgements

References

Appleby P. G. & F. Oldfield, 1978. The calculation of 210Pb dates assuming a constant rate of supply of unsupported 210Pb to the sediment. Catena 5: 1-8.

Appleby P. G., P.J. Nolan, D. W. Gifford, M. J. Godfrey, F. Oldfield, N. J. Anderson & R. W. Battarbee, 1986. 210Pb dating by low background gamma counting. Hydrobiologia 141: 21-27.

Appleby P. G., N. Richardson & P. J. Nolan, 1992. Self-absorption corrections for well-type germanium detectors. Nuclear Instruments and Methods in Physics Research B, 71: 228-233.

Bailey-Watts, A. E. & A. Kirika, 1987. A re-assessment of the phosphorus inputs to Loch Leven (Kinross, Scotland): rationale and an overview of results on instantaneous loadings with special reference to runoff. Transactions of the Royal Society of Edinburgh, Earth Sciences 78: 351 367.

Bailey-Watts, A. E. & A. Kirika, 1996. A re-assessment of the phosphorus loading to Loch Leven (Kinross, Tayside) - 1995. Report to Scottish Natural Heritage and Scottish Environment Protection Agency, 30 pp.

Bailey-Watts, A. E. & A. Kirika, 1999. Poor water quality in Loch Leven (Scotland) in 1995, in spite of reduced phosphorus loadings since 1985: the influences of catchment management and inter-annual weather variation. Hydrobiologia 403: 135-151.

Bailey-Watts, A. E., R. Sargent, A. Kirika & M. Smith, 1987b. Loch Leven phosphorus loading. Report to Department of Agriculture and Fisheries for Scotland, Nature Conservancy Council, Scottish Development Department and Tayside Regional Council, 46 pp.

Battarbee R. W., V. J. Jones, R. J. Flower, N. G. Cameron, H. Bennion, L. Carvalho & S. Juggins, 2001. Diatoms. In Smol, J. P., H. J. B. Birks & W. M. Last (eds) Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands: 155-202.

Bennion, H., J. Fluin, & G. L. Simpson, 2004. Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. Journal of Applied Ecology 41: 124-138.

Bennion H., S. Juggins & N. J. Anderson, 1996. Predicting epilimnetic phosphorus concentrations using an improved diatom-based transfer function and its application to lake eutrophication management. Environmental Science and Technology 30: 2004-2007.

Brett, M. T. & M. M. Benjamin, 2008. A review and reassessment of lake phosphorus retention and the nutrient loading concept. Freshwater Biology 53: 194-211.

Caines, L. A. & R. Harriman, 1976. Chemical investigations. In Loch Leven Annual Report, 1976: 1 – 6.

Carpenter, S. R., N. E. Caraco, D. L. Correll, W. Howarth, A. N. Sharpley & V. H. Smith, 1998. Non-point pollution of surface waters with phophourus and nitrogen. Ecological Applications 8: 559-568.

Carvalho, L., C. Ferguson, I. Gunn, H. Bennion, B. Spears, A. Kirika & L. May, this volume. Water quality of Loch Leven: responses to enrichment, restoration and climate change. Hydrobiologia 00: 000 – 000.

Carss, D., B. M. Spears, L. Quinn & R. Cooper, this volume. Long-term variations in waterfowl populations in Loch Leven: identifying discontinuities between local and national trends. Hydrobiologia 00: 000-000.

Castle, K., C. A. Frost, & D. F. Flint, 1999. The Loch Leven Project – Buffer strips in practice on a catchment scale. Aspects of Applied Biology 54: 71.78.

Chaichana R., R. Leah & B. Moss, 2010. Birds as eutrophicating agents: a nutrient budget for a small lake in a protected area. Hydrobiologia 646: 111-121.

Codd, G. A., 1995. Cyanobacterial toxins: occurrence, properties and biological significance. Water Science Technology 32: 149–156.

Coveney, M. F., E. F. Lowe, L. E. Battoe, E. R. Marzolf & R. Conrow, 2005. Freshwater Biology 50: 1718-1730.

D'Arcy, B. J., 1991. Legislation and control of dye-house pollution. Journal of the Society of Dyers and Colourists 107: 387 – 389.

D'Arcy, B. J., L. May, J. Long, I. R. Fozzard, S. Greig & A. Brachet, 2006. The restoration of Loch Leven, Scotland, UK. Water Science Technology 53: 183-91.

Defew, L. H., 2008. The influence of high-flow events on phosphorus delivery to Loch Leven, Scotland, UK. PhD Thesis, University of Edinburgh, 275 pp.

Dillon, P. J. & F. H. Rigler, 1974. A test of a simple nutrient budget model predicting phosphorus concentration in lake water. Journal of the Fisheries Research Board of Canada 31: 1771 – 1778.

Dudley, B., I. D. M. Gunn, L. Carvalho, I. Proctor, M. T. O'Hare, K. J. Murphy & A. Milligan, this volume. Changes in aquatic macrophyte communities in Loch Leven – evidence of recovery from eutrophication? Hydrobiologia 00: 000-000.

Dudley, B. & L. May, 2007. Estimating the phosphorus load to waterbodies from septic tanks. Report to the Scottish Environment Protection Agency and Scottish Natural Heritage, 45 pp.

Eisenreich, S. J., R. T. Bannermann & D. E. Armstrong, 1975. A simplified phosphorus analytical technique. Environmental Letters 9: 45-53.

Elliott, J. A. & L. Defew, this volume. Modelling the response of phytoplankton in a shallow lake (Loch Leven, UK) to changes in lake retention time and water temperature. Hydrobiologia 00: 000-000

European Parliament, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000, establishing a framework for community action in the field of water policy. Official Journal of the European Communities, L327/1: 1-72.

Ferguson, R. I., 1986. River loads underestimated by ratings curves. Water Research 22: 74-76.

Frost, C. A., 1994. Soil erosion: Loch Leven. Report to Scottish Natural Heritage, 16 pp.

Frost, A., 1996. Loch Leven and diffuse pollution. In Petchey, A. M., D'Arcy, B. J. & Frost, C. A. (eds), Diffuse pollution and agriculture. Scottish Agricultural College, Aberdeen: 174-182.

Gulati, R. D. & E. van Donk (2002) Lakes in the Netherlands, their origin, eutrophication and restoration: state-of-the-art review. Hydrobiologia 478: 73-106.

Gunn, I. D. M., M. T. O'Hare, P. S. Maitland & L. May, this volume. Long-term trends in Loch Leven invertebrate communities. Hydrobiologia 00: 000-000

Hancock, C.G., 1982. Sources and utilisation of nutrients in the Loch of Strathbeg, Aberdeenshire. PhD Thesis, University of Aberdeen, 308 pp.

Harper, D., 1992. Eutrophication of freshwaters: principles, problems and restoration. Chapman & Hall, London, 327 pp.

Holden, A. V. & L. A. Caines, 1974. Nutrient chemistry of Loch Leven. Proceedings of the Royal Society Edinburgh B, 74: 101 - 122.

Holden, A., L. A. Caines & R. Harriman, 1975. Chemical investigations. In Loch Leven Annual Report, 1975: 3 – 8.

Jeppesen E, M. Søndergaard, J. P. Jensen, K. Havens, O. Anneville, L. Carvalho, M. F. Coveney, R. Deneke, M. Dokulil, B. Foy, D. Gerdeaux, S. E. Hampton, K. Kangur, J. Köhler, S. Körner, E. Lammens, T. L. Lauridsen, M. Manca, M. Miracle, B. Moss, P. Nõges, G. Persson, G. Phillips, R. Portielje, S. Romo, C. L. Achelske, D. Straile, I. Tatrai, E. Willén & M. Winder, 2005. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. Freshwater Biology 50: 1747-1771.

Jeppesen, E., M. Sondergaard, T. L. Lauridsen, B. Kronvang, M. Bekiloglu, E. Lammens, H. S. Jensen, J. Kohler, A. M. Ventela, M. Tarvainen & I. Tatrai, 2007. Danish and other European experiences in managing shallow lakes. Lake and Reservoir Management 23: 439-45.

Juggins, S. 2003. C2 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne, UK, 69 pp.

Kirby, R. P. (1971). The bathymetrical resurvey of Loch Leven, Kinross. Geography Journal 137, 372–378.

Kohler, J., S. Hilt, R. Adrian, A. Nicklisch, H. P. Kozerski & N. Walz, 2005. Long-term response of a shallow, moderately flushed lake to reduced external phosphorus and nitrogen loading. Freshwater Biology 50: 1639-1650.

Leigh, C., M. A. Burford, D. T. Roberts & J. W. Udy, 2010. Predicting the vulnerability of reservoirs to poor water quality and cyanobacterial blooms. Water Research 44: 4487-4496

LLCMP, 1999. Loch Leven Catchment Management Plan: The Report of the Loch Leven Area Management Advisory Group, 93 pp.

Mackereth, F. J. H., 1969. A short core sampler for sub-aqueous deposits. Limnology and Oceanography 14: 145-151.

Manny, B. A.; Johnson, W. C.; Wetzel, R. G., 1994. Nutrient additions by waterfowl to lakes and reservoirs: Predicting their effects on productivity and water quality Hydrobiologia 279-280: 121-132.

May, L. & L. Carvalho, 2010. Maximum growing depth of macrophytes in Loch Leven, Scotland, United Kingdom, in relation to historical changes in estimated phosphorus loading. Hydrobiologia 646: 123-131.

May, L. & B. M. Spears, this volume, a. A history of scientific research at Loch Leven, Kinross, Scotland. Hydrobiologia 00: 000-000.

May, L. & B. M. Spears, this volume, b. Managing ecosystem services at Loch Leven, Scotland, UK: actions, impacts and unintended consequences. Hydrobiologia 00: 000-000

Morgan, N. C., 1974. Historical background to International Biological Program Project at Loch Leven, Kinross. Proceedings of the Royal Society of Edinburgh Section, B, 74: 45-55.

Munro, D., 1994. Loch Leven and the River Leven – A landscape transformed. The River Leven Trust, Markinch, 196 pp.

Murphy, J. & Riley, J. P., 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27: 31-36.

Nürnberg, G. & B. D. LaZerte, 2004. Modeling the effect of development on internal phosphorus load in nutrient poor lakes. Water Resources Research 40: 1-9.

Perth & Kinross Council, 2004. Kinross Area Local Plan 2004, 106 pp.

Pretty, J. N., C. Mason, D. Nedwell, R. Hine, S. Leaf & R. Dils, 2003. Environmental costs of freshwater eutrophication in England and Wales. Environmental Science and Technology 37: 201-208.

Ronicke, H., R. Doerffer, H. Siewers, O. Buttner, K. E. Lindenschmidt, P. Herzsprung, M. Beyer & H. Rupp, 2008. Phosphorus input by nordic geese to the eutrophic Lake Arendsee, Germany. Fundamental and Applied Limnology 172: 111-119.

Sargent, R. J. & D. C. Ledger, 1992. Derivation of a 130 year runoff record for the Loch Leven catchment, south-east Scotland. Proceedings of the Institute of Civil Engineers Water, Maritime and Energy 96: 71–80.

Sas, H., 1989. Lake Restoration by Reduction of Nutrient Loading: Expectations, Experiences, Extrapolations. Acad Verlag Richarz, Berlin, Germany.

Schindler, D. W., 1977. Evolution of phosphorus limitation in lakes. Science 195: 260-262.

Schindler, D. W., 2006. Recent advances in the understanding and management of eutrophication. Limnology and Oceanography 51: 356-363.

Smith, I. R., 1974. The structure and physical environment of Loch Leven, Scotland. Proceedings of the Royal Society Edinburgh, B, 74: 82-99.

Sondergaard, M., P. J. Jensen, E. Jeppesen, 2001. Retention and internal loading of phosphorus in shallow, eutrophic lakes. The Scientific World Journal 1: 427-442.

Søndergaard M., J.P. Jensen & E. Jeppesen, 2003. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506/509: 135–145.

Sondergaard, M. & Jeppesen, E., 2007. Anthropogenic impacts on lake and stream ecosystems, and approaches to restoration. Journal of Applied Ecology 44: 1089-1094.

Søndergaard, M., E. Jeppesen, T. Lauridsen, S. C. H. Van Nes, R. Roijackers, E. Lammens & R. Portielje, 2007. Lake restoration: successes, failures and long-term effects. Journal of Applied Ecology 44: 1095–1105.

Spears, B., L. Carvalho, R. Perkins A. Kirika & D. Paterson, this volume. Long-term variation and regulation of internal loading in Loch Leven. Hydrobiologia 00: 000 – 000.

Stevens, R.J. & R.V. Smith, 1978. A comparison of discrete and intensive sampling for measuring river loads of nitrogen and phosphorus in the Lough Neagh system. Water Research 11: 631-636.

Vinten, A. J. A., C. Crawford, L. Cole, D. I. McCracken, G. Sym, A. Duncan, & M. N. Aitken, 2004. Evaluating the impact of buffer strips and rural BMPs on water quality and terrestrial biodiversity. In Lewis, D. & L. Gairns (eds) Agriculture and the

Environment: Water Framework Directive and Agriculture. Proceedings of the SAC and SEPA Biennial Conference, Edinburgh, 24-25 March 2004: 42-50.

Vollenweider, R. A., 1968. The scientific basis of lake eutrophication, with particular reference to phosphorus and nitrogen as eutrophication factors. Technical Report, Organisation of Economic Cooperation and Development, Paris, 159 pp.

Winfield, I. J., C. E. Adams, J. D. Armstrong, R. Gardiner, A. Kirika, J. Montgomery, B. M. Spears, D. C. Stewart, J. E. Thorpe & W. Wilson, this volume. Changes in the fish community of Loch Leven: untangling anthropogenic pressures. Hydrobiologia 00: 000-000.

Tables

Table 1 Point sources of total phosphorus (TP), and the size and timing of significant reductions in their respective output, within the catchment of Loch Leven between 1985 and 2005 (after LLCMP, 1999). WWTW = waste water treatment works.

Point source	Anticipated reduction in TP output ($t\ y^{-1}$ / $g\ m^{-2}$)	Date achieved by
Woollen mill	6.3 / 0.47	1987
Kinross WWTW	1.7 / 0.13	1993
Kinross WWTW	0.4 / 0.03	1997
Milnathort WWTW	0.6 / 0.05	1995
Kinnesswood WWTW	0.6 / 0.05	1997
Total reduction	**9.6/0.72**	**1997**

Figure captions

Fig. 1 The relationship between annual mean in-lake total phosphorus (TP) concentration and annual mean algal abundance (expressed as chlorophyll*a* concentration) in Loch Leven, 1964 to 1985 (p<0.001)

Fig. 2 Map of the Loch Leven catchment showing sampling sites on the main inflows (Pow Burn [P], North Queich [N], South Queich [S], Gairney Water [G]) and at the outflow [L] in 2005 and corresponding catchments for each stream; the position of point source discharges in 1985 are indicated (waste water treatment works: triangles; industry: inverted triangle)

Fig. 3 Historical changes in the external input of total phosphorus (TP) to Loch Leven between 1905 and 2005. Open squares are values calculated from palaeolimnological data (see text for details); filled triangles are measured values

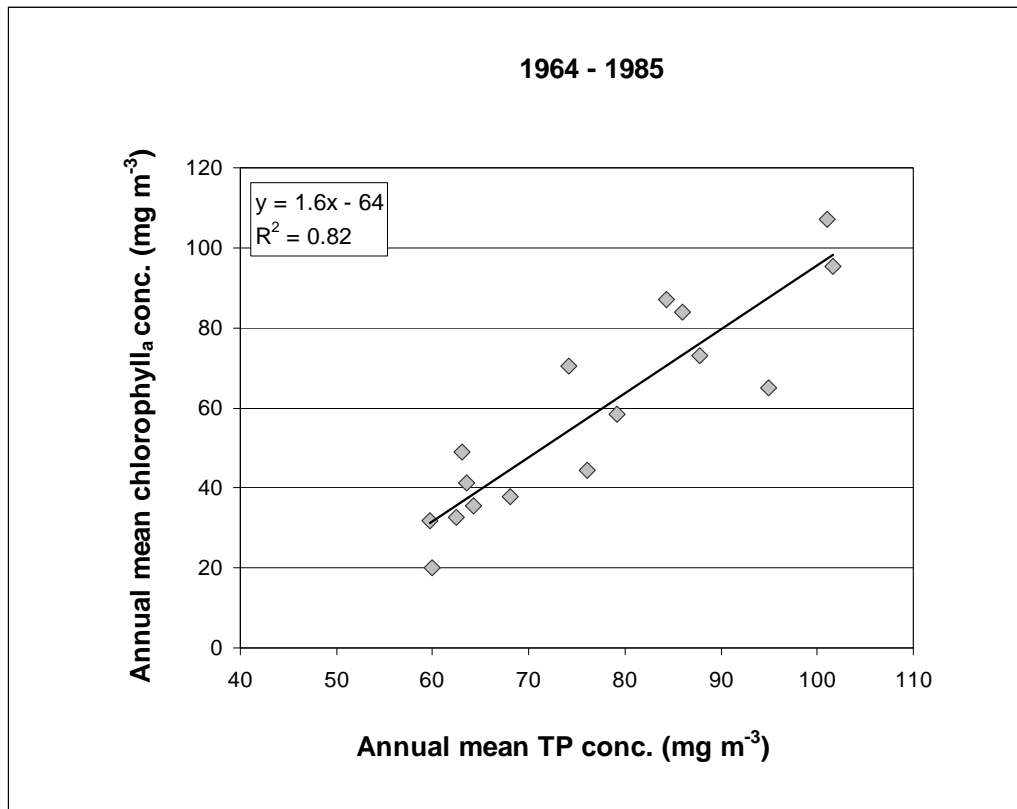**Fig. 4** Total phosphorus (TP) input and retention at Loch Leven estimated at decadal intervals from 1975 to 2005
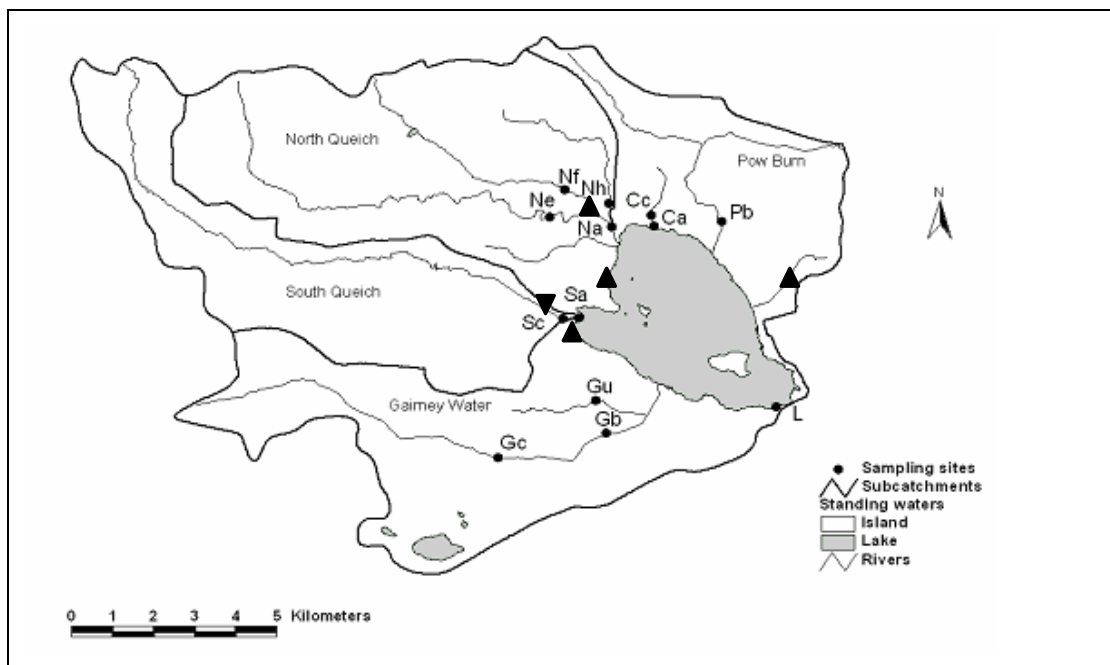
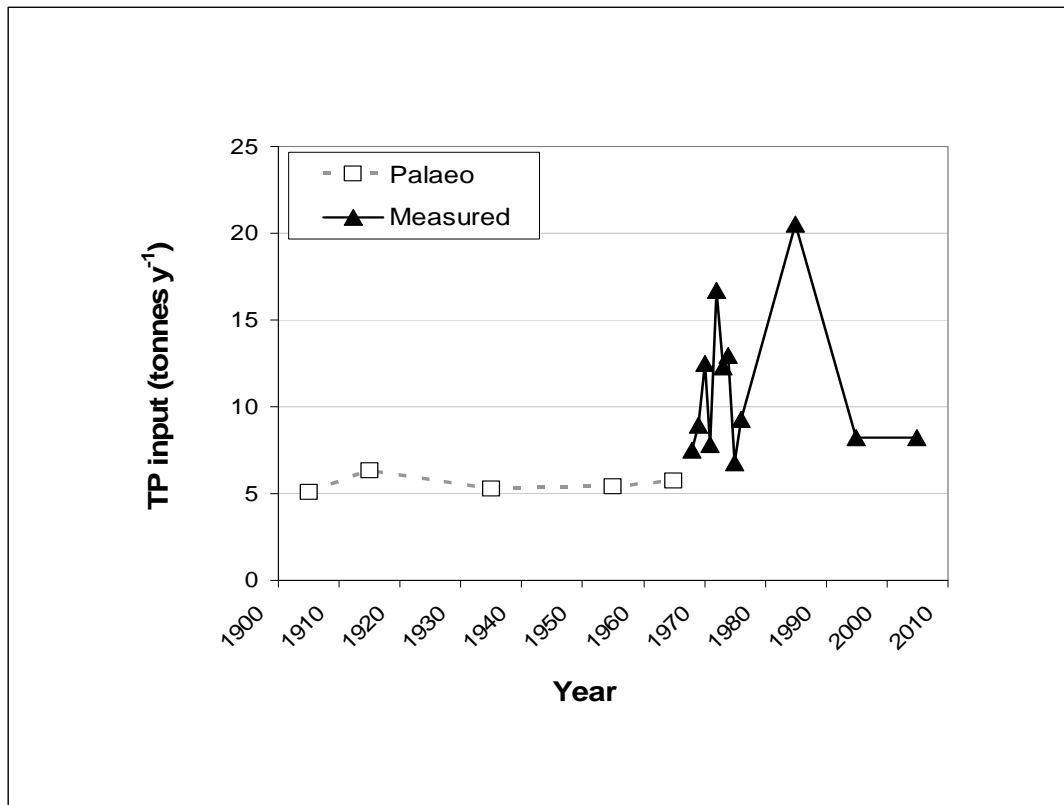Figure 1

Figure 2

Figure 3

Figure 4