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# Long-term homeostasis of filterable un-reactive phosphorus in a shallow eutrophic lake following a significant reduction in catchment load

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ABSTRACT

We demonstrate the use of long-term (1985–2008) filterable un-reactive phosphorus (FURP) concentration data from Loch Leven, Scotland, UK, to explore responses of in-lake FURP concentrations following a significant reduction of catchment P loading (i.e., from 25.5 t TP $yr^{-1}$ in 1985 to 7.0 t TP $yr^{-1}$ and 11.6 t TP $yr^{-1}$ in 1995 and 2005, respectively), including FURP load reduction (i.e., from 10.2 t FURP $yr^{-1}$ in 1985 to <1.6 t FURP $yr^{-1}$ in 1995 and 2005). The reduction in FURP loading was achieved mainly through the control of an industrial point source. The concentration of FURP in Loch Leven did not decrease following the reduction in catchment loading, remaining at around 10–40 μg FURP $L^{-1}$ during the monitoring period. In addition, the contribution of FURP to TP in the water column increased after 2000 from <40% to <80% up to 2008. Loch Leven switched from being a sink of FURP in 1985 (retention of 8.7 t FURP $yr^{-1}$) to being a source of FURP to downstream ecosystems in 1995 (relinquishment of 0.3 t FURP $yr^{-1}$) and 2005 (relinquishment of 0.02 t FURP $yr^{-1}$). These results indicate a complex series of processes resulting in conditions of homeostasis of FURP in Loch Leven, regardless of the catchment load.



## 1. Introduction

Understanding the drivers of phosphorus (P) accumulation and its transport through aquatic ecosystems is critical for the effective management of cultural eutrophication (Bennett et al., 2001; Withers and Haygarth, 2007; Sharpley et al., 2013). In most cases, the reduction of P inputs to lakes is targeted as a first step towards improving water quality in eutrophic lakes. However, even if this is effective, recovery of these impacted lakes can take decades to occur whilst legacy P stores in lake bed sediments are slowly released to the overlying water; a process known as 'internal P loading' (Jeppesen et al., 2005; Spears et al., 2007). Although many studies have quantified the effects of catchment, and in some cases in-lake, management measures on total phosphorus (TP) loads and seasonality, relatively few have reported changes in TP composition.

Traditionally, TP composition has been characterised into operationally defined pools that include particulate P, filterable reactive P (FRP, assumed to represent orthophosphate) and filterable un-reactive P (FURP, assumed to represent inorganic and organic polymeric compounds and hydrolysable dissolved organic P compounds) (Jarvie et al., 2002; Haygarth and Sharpley, 2000). Evidence from many eutrophication management case studies assessing responses in TP and FRP in the water column of lakes have allowed key ecosystem scale processes to be identified. For example, in lakes where catchment TP loading has been reduced, strong seasonal patterns in TP and FRP concentrations are commonly observed; in temperate lakes these are higher in summer and autumn compared to winter and spring as a result of 'internal loading' from legacy P stores in bed sediments (Farmer et al., 1994; Gibson et al, 1996; Søndergaard et al., 2005). These observations have been based on long-term records, with more targeted experimental studies being conducted in recent years to underpin more comprehensive mechanistic understanding (Spears et al., 2008). This is in contrast to FURP, the P pool that can contain organic P compounds, which has received little attention even though dissolved organic P compounds are expected to play a key intermediary role in the cycling of P in lakes (Hupfer et al., 2004; Rietzel et al., 2007). As such, there is a need for a better understanding of cycling patterns of FURP in lakes as indicators of longer-term ecosystem scale processes and responses to perturbations, in a manner similar to TP and FRP responses (i.e., response times of years to decades; Jarvie et al., 2013).

The use of FURP as an indicator of organic P in aquatic ecosystems is contentious, because the ascorbic acid–molybdenum blue assay used in its determination has been shown to hydrolyse certain dissolved organic P compounds to FRP, thus potentially underestimating the FURP pool and overestimating the FRP pool (for further discussion; Baldwin, 2013). However, although other techniques are now available with which to characterise and quantify dissolved organic P compounds within the FURP pool, any available long-term historical data will not have been produced to this level of analytical resolution.

We utilise long-term (1985–2008) data from Loch Leven, Scotland, UK, to test the following hypotheses: (1) that the lake will switch

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from a net sink to a net source of FURP following catchment management to reduce a significant source of FURP, indicating internal loading of FURP; (2) the contribution of FURP to TP in the water-column will decrease following reduction of catchment FURP loading, indicating the reduction in FURP load relative to TP load from the catchment to the lake; and (3) that FURP concentrations will be higher in summer than winter following the control of the point source (i.e., similar to TP and FRP in this lake), indicating an increase in the dominance of internal loading processes.

## 2. Methods

### 2.1. Study site description

Loch Leven is a large (13.7 $km^2$), shallow (mean depth 3.9 m) lake in east central Scotland with an annual retention time of between 140 and 180 days (Bailey-Watts and Kirika, 1999). The lake has a long and well-documented history of elevated catchment P loading and subsequent management to address water quality issues (May et al., 2012). The surface water catchment of the lake covers an area of 145 $km^2$, about two-thirds of which is drained by the four main inflows (North Queich, South Queich, Gairney Water and Pow Burn). The remainder is drained by several minor inflows, with some small areas of land delivering direct runoff along the shoreline (Fig. 1).

P inputs from the catchment have reduced significantly over the past 30 years (Defew, 2008). These reductions have targeted point sources, mainly, including a woollen mill (estimated reduction of 6.3 tonnes P per year; controlled in 1987) and various wastewater treatment works (Bailey-Watts et al., 1987; Bailey-Watts and Kirika, 1987, 1996, 1999; May et al., 2012). The woollen mill was discharging effluent that was especially rich in FURP (Bailey-Watts, 1983). Anecdotal evidence from early surveys documented the use of sodium hexametaphosphate ($(Na\ PO_3)_6$) and tetrasodium pyro-phosphate ($Na_4P_2O_7$) in the manufacturing process of the woollen mill (Bailey-Watts, 1983).

In recent years, it has become evident that diffuse P inputs are now the dominant source of P to the loch (May and Carvalho, 2010). Around 80% of the catchment is under intense agricultural use and large quantities of P laden sediments are delivered into feeder streams during periods of heavy rainfall and surface runoff (Defew, 2008). In addition, private on-site sewerage systems are estimated to account for about 10% of the catchment P load to the lake (Brownlie et al., 2014). Overall reductions of around 9.6 tonnes (t) per year of TP were targeted between 1987 and 1997, 94% of this being targeted between 1985 and 1995 (May et al., 2012).

### 2.2. Assessing catchment P loading in 1985, 1995 and 2005

Data from catchment P loading surveys conducted in 1985, 1995 and 2005 were extracted from the Loch Leven long-term monitoring database for inflow streams draining 5 sub-catchments and for the lake outflow (L). The inflow streams were the Ury Burn (Ua), the South Queich (Sa), the Pow Burn (Pb), the North Queich (Na), and the Gairney Water (Ga) (Fig. 1). Methods for collection of water samples and P analyses are described in detail by Defew (2008) and May et al. (2012). Water samples were collected at 8-day intervals in all years.

Flow gauging stations were equipped with a continuous recording device and/or a stage board. Recording devices on the Pow Burn (Pb), South Queich (Sc) and North Queich (Ne) provided stream flow ($m^3\ s^{-1}$) at 30 minute intervals in 1985 and 1995, and 15 minute intervals in 2005. These stations were operated and maintained by the Scottish Environment Protection Agency. At the remaining sites, stage board measurements of water level were noted on each sampling occasion and ratings curves, constructed from a number of direct measures of stream flow at known gauge heights, were used to convert stage height to stream discharge (Bailey-Watts and Kirika, 1987, 1999; Defew, 2008).

Collectively, the inflows sampled drain about 84% of the surface water catchment. However, during 1985, 1995 and 2005, the volume of water entering the lake through these inflows accounted for, on average, about 93% of the volume of water leaving the lake via the outflow. Although rainfall and groundwater sources were not included in this study, it is assumed that these represented only a minor source of water to the lake (Bailey-Watts and Kirika, 1999).

For each year, estimates of the daily, monthly and annual inputs of TP, FRP and FURP from the monitored streams were calculated using the linear interpolation methods of Stevens and Smith (1978) and

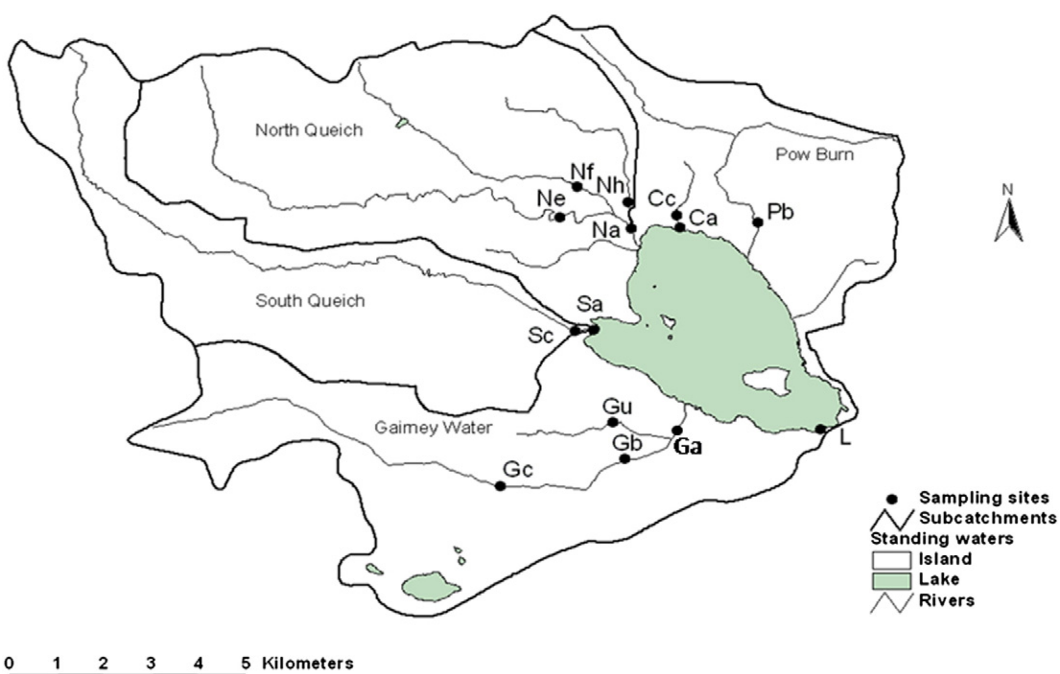


**Fig. 1.** Location and site codes of sample points in the Loch Leven catchment.