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Drivers of long-term trends and seasonal changes in total phosphorus loads to a mesotrophic lake in the west of Ireland

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Abstract. Excess phosphorus (P) loading is a major cause of deterioration in surface water quality. In Ireland, regulation has focussed on control of P losses from agriculture and wastewater treatment plants (WWTPs): the two main sources of excess P. Hindcast modelling for Lough Leane, south-west Ireland, indicated that, while the only municipal (point) source contributed up to 41% of the annual TP loading until the mid 1980s, over 90% of the TP load was from diffuse sources following upgrading of the WWTP. Field data from 2000–2006 confirmed that most of the TP load came from agriculture, with 73% being exported between September and February, generally the wettest months in the region. However, the WWTP contributed up to 60% of daily loads during summer. Short lake residence times (two to four months) between October and February indicated that external loadings during these months were unlikely to make a significant contribution to summer phytoplankton growth in the lake. In contrast, the potential effects of point sources during low flows were maximised by longer residence times between April and September. The results highlight the importance to aquatic pollution impacts of, and therefore the need for regulatory responses to respect, seasonal variations in loading and residence time.

Additional keywords: diffuse sources, eutrophication, GWLF, lake residence time, phosphorus, point sources.

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Introduction

Phosphorus (P) loading steadily increased in many regions of the world over the twentieth century (Jeppesen *et al.* 2005; Schindler 2006; Søndergaard *et al.* 2007; Vaccari 2009). Increases were related to P inputs from both point sources, such as municipal wastewater treatment plants (WWTPs), and diffuse sources, the latter driven by a progressive intensification in agricultural practices in catchments. However, while reductions in P inputs from point sources have been achieved in many locations through upgrading of WWTPs, these decreases have not always been associated with an improvement in lake trophic status. Concurrent increases in diffuse losses from agricultural sources have often been considered the cause (Foy and Lennox 2006; Bowes *et al.* 2008; Jennings *et al.* 2008; Withers *et al.* 2009).

The increase in P losses from agriculture has been driven by intensification during the latter decades of the twentieth century. Intensification in the sector in Ireland began in the 1960s. For example, national cattle numbers rose from just under 4 million in the 1930s to 7.6 million in 1998 (CSO 2000). In addition to this increase, changes in farming practice, in particular a shift from over-wintering on pasture to the use of slatted floor winter housing together with the increased nutrient content of concentrated feed, resulted in an escalation in the quantity of stored organic P requiring disposal (Hyde and Carton 2005; Maguire *et al.* 2009). Sheep numbers also increased dramatically in the 1990s, driven by subsidies provided by the European Union (O'Connor 2000), although they declined again in more recent years when these payments ceased. Additional sources of P in rural areas of Ireland include small on-site wastewater treatment

Table 1. Area (km^2) and % of total for each land cover for the four main subcatchments in the Lough Leane catchment

Subcatchment (*km^2*)	Pasture	Other agriculture	Peat/natural grass %	Coniferous forest	Urban	Other
Flesk (*325*)	30	6	49	7	1	7
Deenagh (*31*)	70	8	10	3	2	7
Upper (*125*)	<1	1	85	<1	0	14
Folly (*0.9*)	0	0	0	0	100	0

units such as septic tanks, which serve 40% of the Irish population of over 4 million people (CSO 2000). Studies have shown that many of these systems are poorly maintained or sited in unsuitable locations (Kirk McClure Morton 2003; Arnscheidt *et al.* 2007; Macintosh *et al.* 2011), increasing the risk of nutrient losses to both surface and ground waters. Current regulations in Ireland to control exports of P include a regionally specific closed period for spreading of inorganic and organic fertilisers, limits on livestock intensity and soil P status (Humphreys 2008), and a discharge limit of 2 mg total P (TP) L^{-1} for WWTPs.

The classic statistical relationship between TP loading to a lake and both in-lake TP concentrations and chlorophyll *a* levels was detailed in studies by Vollenweider (1968; OECD 1982). The model described a strong log-log relationship between mean chlorophyll *a* concentration and inflowing TP load. However, as pointed out by Lewis and Wurtsbaugh (2008), the use of both TP and chlorophyll *a* values averaged over the same time span to describe this relationship can result in a confounding error, as the P contained in phytoplankton biomass will also contribute to water column TP concentrations. Many lakes in Ireland, even those that are relatively deep, have residence times of less than one year (Foy 1992; Irvine *et al.* 2001). Much of the research on the relationship between TP loading and lake phytoplankton biomass in lakes with short residence times has focussed on shallow lakes. These differ from deeper lakes in high rainfall areas as internal loading in shallow lakes can make a substantial contribution to P availability for phytoplankton (Jeppesen *et al.* 2005; Søndergaard *et al.* 2007). Deeper lakes in Ireland are known to stratify during the summer (Allott 1986; Irvine *et al.* 2001; Jennings *et al.* 2012), thereby preventing thorough mixing of P from depth during the phytoplankton growing season. In addition, locally high rainfall may then flush this P from the system in the autumn and winter mixing periods, before the following growing season commences.

The success of initiatives to restore lakes to previous reference conditions, as required by the EU Water Framework Directive (Directive 2000/60/EC) (WFD), will be compromised without data that provide an insight into the seasonal patterns and historical drivers of nutrient loading in all lake types. Jeppesen *et al.* (2005) assessed data from 35 lakes covering a range of depths, and concluded that it took a period of 10 to 15 years following nutrient load reduction for a new equilibrium in lake TP levels to be reached. They attributed this delayed response to the release of sediment P. However, all the lakes in that study with residence times of less than one year were shallow lakes (defined as mean depth <5 m) and therefore would have had relatively high rates of sediment P release during the growing season. All the deeper lakes had residence times of greater than one year: P released from sediment during the summer in those lakes would be recirculated through the water column following mixing, and would still be available in the next growing season.

The WFD states that where long-term data do not exist, hindcast modelling techniques may be used to assess if proposed management plans will be successfully achieved (European Commission 2000). Semi-empirical models, which mechanistically describe the hydrologic and sediment components and estimate nutrient loads based on simple relationships between flow and nutrient loading, offer a compromise between simple and more complex approaches. A version of one such model, the Generalised Watershed Loading Functions model (GWLF) (Haith and Shoemaker 1987; Schneiderman *et al.* 2002), has been widely used in the USA to simulate nutrient loading for management purposes and has been applied across European sites to assess projected climate change impacts on nutrient loading (Jennings *et al.* 2009; Pierson *et al.* 2010).

The research that underpins the current study is focussed on Lough Leane, a moderately deep, mesotrophic lake in a high rainfall area in south-west Ireland. Lakes in such high rainfall areas can have short residence times, and may, therefore, be particularly sensitive to changes in external P loading. The main objective of this current study was to investigate the relative importance of both point and diffuse sources of P on both long-term and seasonal timescales, and the relationship between in-lake TP and lake phytoplankton levels. Although monitoring of TP inputs to Leane is now well established, long-term data on external loading to the lake are lacking. This problem has been circumvented in this research through hindcast modelling using GWLF. Hindcast simulations of the TP loadings to Leane for the period 1941–2006 are discussed in the context of regulatory attempts to control pollution by nutrients from both diffuse and point sources. More recent, high-frequency monitoring data from the inflows to the lake are then used to assess seasonal differences in the relative contributions, while the effects of lake residence time on the relationship between P loading and trophic status in this lake are also explored.

Material and methods

Site description

The Leane catchment (52°05′N 9°36′W) covers 553 km^2 (Table 1) and consists of two contrasting components: an area of upland mountain peat and forest to the south and west that drains through two smaller lakes into Lough Leane, and an area to the east that is mainly agricultural grassland (Fig. 1). Lough Leane has an area of 19.9 km^2, a mean depth of 13.4 m and a maximum depth of 65 m. It has soft water and is moderately coloured. The

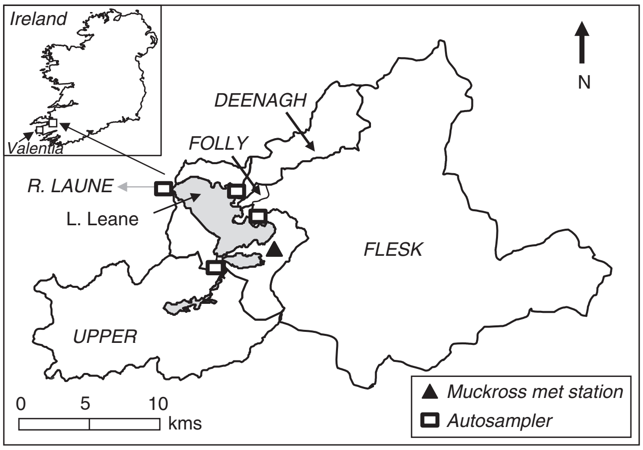

Fig. 1. Map of the Lough Leane catchment showing the four subcatchments (Upper, Flesk, Deenagh and Folly) and the location of the two meteorological stations Muckross (main map) and Valentia (inset map).

lake volume is 2.67×10^8 m^3 and the average annual hydraulic residence time, based on the years 2000 to 2006, is 0.37 years. The lake is generally monomictic, although stratification can break down during periods of high wind speed in some summers. Ice-cover is rare. There are three main inputs to the lake: the River Flesk; the River Deenagh; and the Long Range (which drains the Upper subcatchment). Land use in the Deenagh subcatchment and in the northern and eastern sections of the largest subcatchment, the Flesk, is almost entirely pasture for cattle, with one-third of all cattle being dairy cows. The Upper catchment and the southern section of the Flesk are dominated by upland peat and natural grassland vegetation, which is used for sheep grazing (Table 1). The town of Killarney, an important tourist site with a resident population of 13 497 (CSO 2006) that is increased greatly during summer by tourists, lies on the eastern shores of Leane. A fourth input, the Folly Stream, drains a small area of 0.9 km^2 surrounding Killarney. The main WWTP for the town discharges into this stream and is the only major point source in the Leane catchment. The River Laune is the only outflow from the lake.

The catchment is in receipt of Atlantic air masses and associated precipitation originating from the south-west and experiences a cool temperate and oceanic climate. Meteorological data are available from Muckross, on the eastern shores of the lake, from 1970. Data are also available from Valentia, situated outside of the catchment ~40 km south-west of Killarney, from 1941 (Fig. 1). The average annual air temperature at Muckross from 1970 to 2005 was 10.5°C. Average annual rainfall for the same period for the Muckross station was 1691 mm year^{-1}, with seasonal averages of 598, 344, 261 and 578 mm season^{-1} for winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November) respectively. Rainfall, however, varies considerably across the catchment, from ~1000 mm year^{-1} in the north-east to 2700–3200 mm year^{-1} in the south-west (Allott *et al.* 2008). There was a slight but significant increase in annual rainfall at Muckross from 1970 to 2006 ($r^2 = 0.20$, $P < 0.01$).

The lake has undergone several changes in trophic status in recent decades (Twomey *et al.* 2000; Jennings *et al.* 2008). Leane was classed as mesotrophic for most of the period to the early 1980s and as moderately eutrophic in 1983 and 1984. Following the implementation of phosphorus removal at Killarney WWTP in the mid-1980s, the status improved to oligotrophic in 1990 and 1991 but was again mesotrophic for most of the 1990s. In August 1997, hypereutrophic conditions were recorded, with chlorophyll *a* levels greater than 65 mg m^3 at all three sites used for assessment (Twomey *et al.* 2000). Eutrophic conditions were again recorded in 1998. This decline in water quality was linked to increased external inputs of P, with diffuse sources estimated to contribute the bulk of the increased loading (Jennings *et al.* 2008). The lake returned to mesotrophic status in the 2000s. Although this change has not been linked to any specific change in management, it followed the implementation of an intensive monitoring program on catchment nutrient export to the lake, and was also coincident with changes in both national regulation of P export from agriculture, and a slight decline in the cattle-farming population in the catchment.

Hindcast modelling

Daily and annual TP loads (1941–2006) were hindcast for each subcatchment using the GWLF model. The model is driven by measured air temperature and precipitation data. Water balances are calculated on a daily interval. The version of the model used in the current research was created by New York City Department of Environmental Protection in the Vensim visual modelling software package (Ventana Systems Inc., Harvard (USA)) (Schneiderman *et al.* 2002). Further developments have included incorporation of European CORINE (Coordination of Information on the Environment) (Commission of the European Communities 1994) land cover classifications, and an improved optimisation procedure for the hydrology routine (Schneiderman *et al.* 2010). Modelled streamflow consists of surface runoff, and fast and slow subsurface flow components. Additional input data requirements are land-use areas for the catchment, land-use-specific dissolved nutrient concentrations, soil total nutrient concentrations, and catchment human and livestock populations.

Dissolved P loads from each land use are simulated in the model by multiplying modelled runoff by a land-use-specific nutrient concentration, derived from either literature or catchment studies (Haith and Shoemaker 1987; Haith *et al.* 1992; Schneiderman *et al.* 2002). Soil erosion is calculated using the Universal Soil Loss Equation, and particulate P loads are then calculated according to streamflow on that day, and sediment yield and soil P concentration for each land use. The contribution of nutrients from septic systems is based on population, a per capita P export coefficient, and estimates of system performance. Septic tanks are assigned to one of four categories: normal, short-circuited, ponded and direct (Schneiderman *et al.* 2002). In order to simulate historical changes in agricultural practice, the hindcast simulations also included losses from livestock using an export coefficient approach. The input time series are grazing and winter-housed livestock numbers, and a P output per head for livestock type. A portion of this load is lost by grazers based on the loss rates for cattle and sheep used for export coefficient calculations of 2.8% and 3% respectively (Johnes 1996; Johnes and Heathwaite 1997). The P load from winter-housed cattle is added to a slurry load that accumulates over the housing period. This is output as an equally divided additional P load on all dry days during a defined slurry spreading period. Losses from spread slurry are proportional to runoff on the two days immediately following spreading. The loss rate on other dry days is zero. The dates for the start and end of the winter-housing period, and for the slurry spreading season, are defined by the user.

Land-use specific runoff and soil nutrient concentrations for the present study were based on data from small area studies carried out in the Leane catchment between 1999 and 2002 (Kirk McClure Morton 2003) and literature values (see Jennings *et al.* 2009). Human and livestock population data were obtained from the Irish Central Statistics Office. CORINE land cover data were available for 1990 and 2000. Additional data were available for years in which agricultural censuses were undertaken (five- to 10-year intervals) from 1939 to present. Population, land-use data and livestock numbers were interpolated in the model between census years, assuming a linear trend. Results from a study on septic tanks in the Leane catchment concluded that no nutrients were retained by soils in areas with <3 m of overburden (Kirk McClure Morton 2003). All persons in areas with <3 m soil depth were assigned to the short-circuited class. The P load per capita for the population using septic tanks of 2.5 g P person^{-1} day^{-1} was based on the results of a study carried out in the Leane catchment (Kirk McClure Morton 2003). This load was adjusted to account for the addition of P to detergents from the mid-1950s (Carvalho *et al.* 2004), and their subsequent removal in Ireland after 2000. The dates for the start and end of the slurry spreading period, and P output per head for livestock (12 kg TP head^{-1} year^{-1} for cattle and 0.85 kg TP head^{-1} year^{-1} for sheep) were based on values in the Irish Good Agricultural Practice Regulations (S.I. 378 of 2006). The seasonal pattern for slurry management was assumed to have followed a similar timing throughout the simulation period for the purposes of this modelling exercise. No historical data were available for P output for livestock, therefore, the load per head for cattle was set at 65% of the S.I. 378 regulations value for the period from 1941 to 1965, and then increased to that maximum value by 1975. This was implemented to reflect changes in P content of cattle feed over time, and based on studies of P output for differing cattle dietary regimes (O'Rourke *et al.* 2010). Winter housing of cattle was introduced in the model simulations in 1965. Annual loads in tonne TP year^{-1} were output from the model for land use, livestock and septic systems (rural population).

Mean daily discharge data were available for the three inflows to Leane for 1982 to 2008 from gauging sites. The daily stream flow data from 1996 to 2000 were used to calibrate the hydrology model, while those from 2001 to 2004 were used for model validation. The Nash-Sutcliffe coefficient of model efficiency, NS (Nash and Sutcliffe 1970), was used to measure model performance. NS values range from 1, a perfect fit between modelled and observed data, to $-\infty$ (Moriasi *et al.* 2007). Validation values of the NS coefficient for daily stream flow were 0.65, 0.79 and 0.85 for the Deenagh, Flesk and the Long Range sites, respectively, and indicated a good model fit for catchment hydrology. These are similar to values from other studies (Moriasi *et al.* 2007; Schneiderman *et al.* 2010). The precipitation correction factor in the model was recalibrated to account for any differences between the two meteorological station sites in historical simulations. Air temperature data were also compared and adjusted as required.

Annual TP loads for the WWTP plant were available from 1990 to 2006. WWTP load estimates from 1941 to 1989 were based on population numbers and tourist estimates using a per capita loading for Killarney WWTP of 1.12 kg TP population equivilant^{-1} year^{-1} (Casey *et al.* 1978). This figure was reduced to 0.42 kg TP population equivilant^{-1} year^{-1} before 1955 and post 2000 to account for the use of P in detergents during that period (Carvalho *et al.* 2004). Before 1971, untreated sewage was discharged directly into the lake. From 1971, sewage received preliminary and primary treatment, while secondary treatment commenced in 1977. Preliminary treatment consisted of removal of gross solids in sewage and grit, while primary treatment consisted of removal of settleable solids (Casey *et al.* 1978; EPA 1995). This treatment would not have reduced P concentrations. Phosphorus removal using ferric chloride was fully implemented in 1985. Estimated loads up to 1989 were amended for treatment type following recommendations in Carvalho *et al.* (2004).

Water quality model calibration and validation

Water quality data, available from locations on the three main inflows to Leane, have been collected using autosamplers, set to take six samples in each 48 h period that are then pooled, since 1999. These samples were analysed for TP following persulfate digestion on a Lachat autoanalyser (Lachet Instruments, Loveland, Colorado, USA). Weekly and bi-weekly data were also available for the same locations for suspended sediment and soluble reactive P (SRP). In general, SRP represented between 50% and 60% of TP concentrations at the three inflow sites. Monitoring data from 2000 to 2004 were used for model calibration and validation. Estimates of sediment yield and sediment P concentration were optimised as described in Schneiderman *et al.* (2002). Occasional high daily TP loads in measured data were not replicated by the model. These were probably due to incidental losses of P that could not be simulated. NS values for monthly TP loads for the validation period (1999–2001) were 0.79, 0.65 and 0.68 for the Flesk, Deenagh and Upper subcatchments respectively.

Inflow loads

Daily TP loads were calculated or modelled for the period 1 January 2000 to 31 December 2006. Calculated loads were the product of mean daily flow and mean daily TP concentration using the data from the autosamplers or from grab samples when no autosampler data were available. Where there were gaps in data, daily GWLF-modelled TP daily loads were used. For each year, there were 66 days on average when there were no measured TP data. For the year 2003, data were only available for 125 days for the Deenagh catchment and this year was therefore omitted from the 2000–2006 monthly averages. Daily composite data were also available from an autosampler situated just

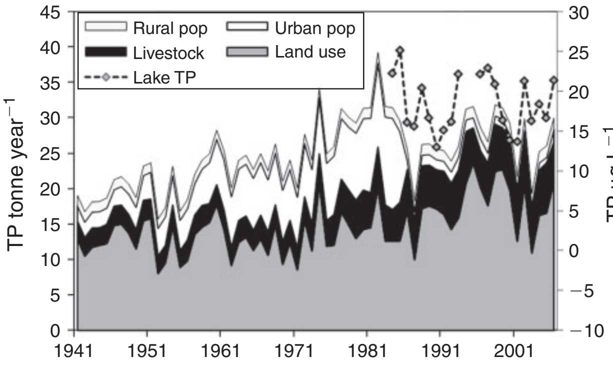

Fig. 2. Source of the TP load to Lough Leane from 1941 to 2006 based on output from simulations using the GWLF model (tonne TP $year^{-1}$) (rural population, livestock and land use), together with data from Killarney WWTP (1990–2006) and estimates based on the town population and treatment method (1941–1989) (urban population). Also shown are mean annual TP concentrations (µg TP L^{-1}) at an open lake site in Lough Leane (1984–2006).

downstream of the WWTP for 2000. These data would have included TP from the small upstream Folly catchment and the WWTP.

In-lake parameters

Although flow data were available for the lake outflow site, there were gaps in these data. Missing data in the inflow data from all sites were estimated using modelled output from GWLF. The combined measured inflow data was within −2% to +6% of the measured outflow where both datasets were available, indicating that the combined inflow could be used as a proxy for outflow volumes. The residence time for Lough Leane was therefore calculated (in months) as the mean depth (m) multiplied by the lake area (m^2)/total inflow (m^3) in that month. Water samples (2–4 per month) were collected from the deepest point of the lake. A grab sample was taken from just below the surface for TP analysis; for chlorophyll *a* samples a composite sample was taken over the top 1.5 m. TP was measured colourimetrically based on Eisenreich *et al.* (1975) using a 10-cm spectrophotometer cell from 1984 to 1992, based on the stannous chloride method from 1992 to 1997 (APHA, 1994), and using the Lachet system (as above) from 1998 to 2006. Chlorophyll *a* was measured by the cold methanol method (Talling and Driver 1961) from 1984 to 1992, and by the hot methanol method from 1993 to 2006. Where concentrations were less than detection limits, they were estimated using the methods outlined in Helsel (2008).

Results

Trends in hindcast nutrient export

The combined hindcast TP load, from the four Leane subcatchments and Killarney Town WWTP, ranged from an average of 20 tonne TP $year^{-1}$ (0.36 kg TP ha^{-1} $year^{-1}$) in the 1940s to 29 tonne TP $year^{-1}$ (0.54 kg TP ha^{-1} $year^{-1}$) in the 1980s and 1990s (Fig. 2 and Table 2). There was a slight decrease for years after 2000 to 26 tonne TP $year^{-1}$ (0.46 kg TP ha^{-1} $year^{-1}$). The load was dominated by export from land use, which contributed, on average, 13 tonne TP $year^{-1}$ (0.23 kg TP ha^{-1} $year^{-1}$) from the 1940s to the 1970s. Both the load, and percentage contribution from land use, increased to a maximum of 19 tonne TP $year^{-1}$ (0.36 kg TP ha^{-1} $year^{-1}$: 68%) in the 1990s. This reflected an increase in rainfall in more recent years, which drove losses of P from land use in the model. There was also an increasing trend in the livestock contribution, which rose from 3 tonne TP $year^{-1}$ (0.06 kg TP ha^{-1} $year^{-1}$) in the 1940s to 6 tonne TP $year^{-1}$ (0.12 kg TP ha^{-1} $year^{-1}$) in the 1990s and 2000s. Although sheep numbers increased dramatically from 12 506 in 1980 to 33 231 in 2000, the contribution from livestock was largely due to higher cattle numbers, which rose from 15 739 in 1961 to a maximum of 22 994 in 2000, and due to the higher per capita TP output for cattle. The contribution from the rural population remained below 9% throughout the full time period but did increase from 1 to 2 tonne TP $year^{-1}$ from 1990, due to an increase in the rural population. In contrast, there was a steady increase in the load from the urban population until the mid 1980s, which is served by the WWTP at Killarney. The population of Killarney increased from ~6000 in the 1940s and 1950s to just under 9000 in 1981. The WWTP contributed on average 13% of the overall TP load in the 1940s but this increased to 30% in the 1970s and 1980s, with a maximum estimated load of 13 tonne TP $year^{-1}$ (41% of the total load) in 1984, just before upgrading of treatment facilities. The load then fell and, based on the data supplied by the plant managers, the measured TP load from the WWTP has been <2 tonne TP $year^{-1}$ in most years since 1990. Measured in-lake mean annual TP concentrations fell from 25 µg L^{-1} in 1985 to 15 µg L^{-1} in 1987 and were at their lowest level of 12 µg L^{-1} in 1990. However, they subsequently rose again in the late 1990s. There was a significant but low coefficient of determination between these values and estimated annual P loading to the lake ($r^2 = 0.26$; $P = 0.018$, $n = 19$), indicating that other factors were also contributing strongly to in-lake concentrations.

Seasonal trends in TP loads

Daily TP loads to the lake during 2000 (Fig. 3), and in other years for which data were available, were dominated by export from the two subcatchments where intensive cattle agriculture is practiced (the Flesk and the Deenagh). These contributed, on average, 65% of the daily load over the year and over 90% for most days in months between October and March. However, during summer months, the contribution from the Folly Stream and WWTP, which remained more constant than the loading from the general catchment, contributed between 50% and 60% of the total loading on many dates (Fig. 3*b*).

Between 2000 and 2006, on average, 73% of the loading from the catchment to the lake was exported during the months between September and February, with highest values of 22%, 12% and 13% in during December, January and February respectively (Fig. 4*a*). Loading during the remaining six months of the year (March to August) represented only 27% of the annual load. In contrast, the estimated residence time for the lake was less than 4 months during November, December, January and February (Fig. 4*b*). The average residence time, however, increased to 4.7 and 5.7 months in March and April, respectively, and to greater than 10 months during the time of peak algal growth in the lake (June, July and August).

Table 2. Catchment livestock and human population (data for first census in each decade), hindcast modelled TP load (kg TP ha^{-1} year^{-1}) and percentage contribution to the overall load (in brackets) for livestock, general land use, rural population and urban population (Killarney Town WWPT): decadal means 1941–1949, 1950–1999, 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2008

Decade	Cattle *number*	Sheep	Rural human	Urban human	Livestock	Rural *Septics* *tonne TP year^{-1}*	Land use	Urban *WWTP*	Total
1940s	15 666	13 831	7379	6237	3 (14%)	1 (7%)	13 (66%)	3 (13%)	20
1950s	15 489	17 051	6610	6463	3 (13%)	1 (6%)	12 (59%)	5 (22%)	21
1960s	15 739	20 497	6143	6828	3 (12%)	1 (5%)	13 (52%)	7 (30%)	24
1970s	18 590	12 179	6158	7536	4 (15%)	1 (5%)	14 (50%)	8 (30%)	28
1980s	21 950	12 506	6819	8800	5 (19%)	2 (5%)	15 (53%)	7 (23%)	29
1990s	22 295	31 564	6949	9950	6 (22%)	2 (5%)	19 (68%)	2 (5%)	29
2000s	22 994	33 231	7421	13 212	7 (25%)	2 (6%)	16 (63%)	2 (6%)	26

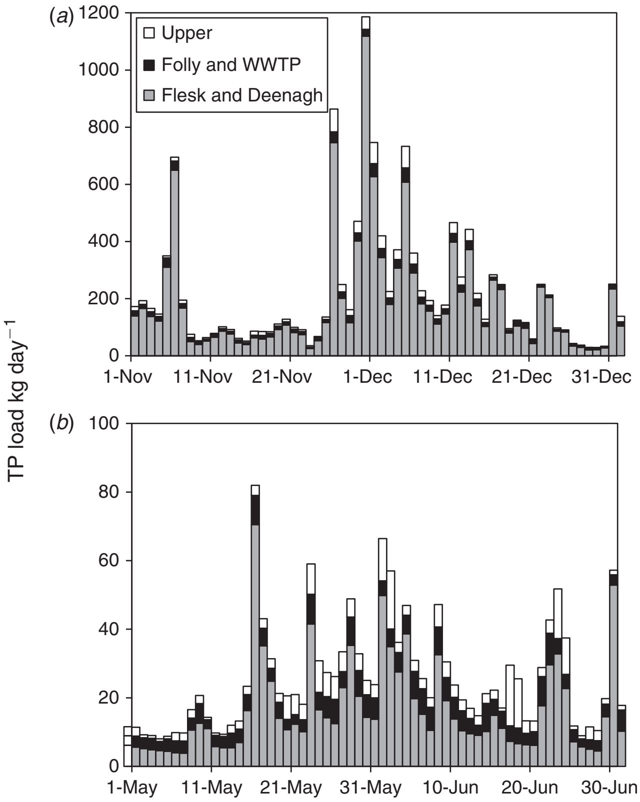

Fig. 3. Measured daily TP loads (kg TP day^{-1}) to Lough Leane for two periods in 2000: (*a*) 1st November 2000 to 31st December 2000 and (*b*) 1st May 2000 to 30th June 2000. Note difference in scales.

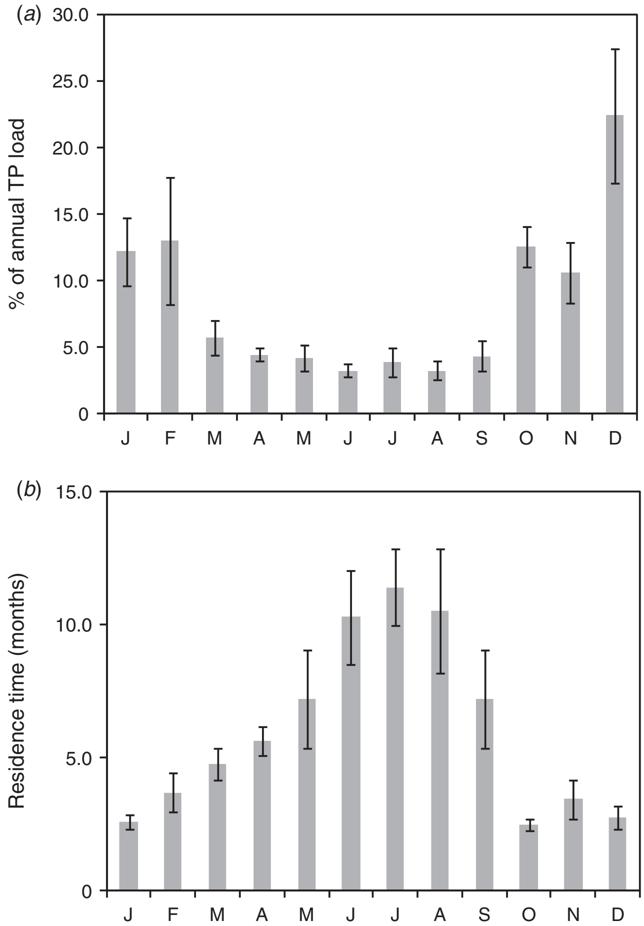

Fig. 4. (*a*) percentage of annual TP load exported to the lake in each month and (*b*) average residence time in months for Lough Leane (2000–2006: mean +/− s.e.).

Assessment of the relationship between the mean summer (June, July, August) chlorophyll *a* concentration for the lake from 1984 to 2006, and the mean TP concentration for each of the previous months between January and May showed a significant but weak relationship only with data from May ($r^2 = 0.21$; $P = 0.031$, $n = 22$) (Fig. 5*a*, *b*). Note that the 1997 value, when hypertrophic levels of chlorophyll *a* were recorded in the lake in August, was an outlier in the dataset (Fig. 5*b*) and was omitted from the regression. The relationship between the mean summer TP concentration and mean summer chlorophyll *a* concentration (not shown) had a coefficient of determination of r^2 of 0.28 ($P = 0.01$, $n = 22$).

Discussion

As is the case generally for temperate, freshwater lakes (Vollenweider 1968), most lakes in Ireland are considered to be P-limited and the deterioration in the water quality of many of these lakes in recent decades has been attributed to increases in the availability of P, particularly P from agricultural sources

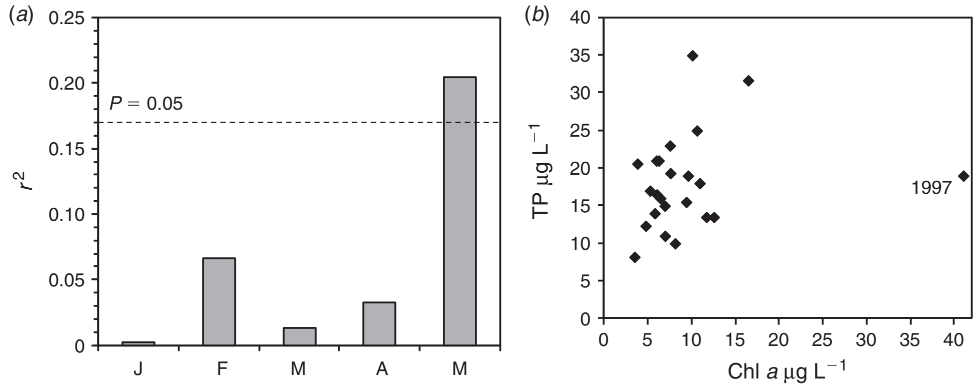

Fig. 5. (*a*) Coefficient of determination (r^2) between mean chlorophyll *a* in summer (June, July and August) and mean monthly surface water TP concentration for each of the previous months from January to May (1984–2006); (*b*) mean chlorophyll *a* in summer (June, July and August) plotted against mean monthly surface water TP concentration for the previous May (note the 1997 outlier was omitted from the regression analysis).

(Foy *et al.* 1995; Irvine *et al.* 2001; Taylor *et al.* 2006). Although the most recent report on water quality in Ireland concluded that 81% of lakes were of satisfactory quality (McGarrigle *et al.* 2010), the report also noted a decline of more than 4% in lakes in this category since the previous reporting period and reported that almost 42% of lakes surveyed were not compliant with the national target of a mean annual TP concentration of $<20\ \mu g$ TP L^{-1}. The concentration of P in a lake at a given time is the result of a complex equilibrium between not only external loading from the catchment, but also internal loading from sediments, together with the physical and biological processes occurring in the water column and the sediment (Schindler *et al.* 1987; Schindler 2006). Increases in external TP loading from both point and diffuse sources have been reported for lakes in many regions over the twentieth century, based on both monitoring data (e.g. Jeppesen *et al.* 2005) and on palaeolimnological studies (e.g. May *et al.* 2012). However, while the loading from point sources has decreased in many catchments owing to tighter controls on effluent P levels, lake trophic status has not always shown a concurrent improvement, often attributed to loading from diffuse sources.

The hindcast modelling simulations presented in the present study indicated that variation in the TP load from the catchment accounted for only 26% of the total variability in in-lake TP concentrations in Leane on an annual basis. They also highlighted the dominance of diffuse sources of P in the annual TP load to the lake. All modelling exercises include varying levels of uncertainty associated with, for example, model structure and with input and calibration data. In calculating these hindcast TP loads, for example, the P load per capita for the population using septic tanks was based on the results of a study carried out in the Leane catchment (Kirk McClure Morton 2003). While this estimate was almost identical to that suggested in the GWLF manual (Haith *et al.* 1992), literature values can be up to ~40% higher or lower (Carvalho *et al.* 2004). Similarly, the nutrient outputs per head of livestock, which were based on values in Irish regulations, were lower than values quoted for the UK (Carvalho *et al.* 2004). In addition to these potential uncertainties, uncertainty will have been included through the assumption of a linear trend in human and livestock populations between census years. There is, therefore, a margin of error in these TP load estimates, but one that is comparable to export coefficient models (e.g. Bennion *et al.* 2005). Nevertheless, the hindcast modelling exercise did enable identification of the main potential drivers of changes in loading to the lake, and an estimation of the load attributable to each driver. These results suggest that diffuse losses from both land use and livestock, particularly cattle, were the dominant contributor to the overall P load in the last two decades. Similar relative changes in loading, with similar time lines, have been reported from other catchments in Ireland (Foy and Lennox 2006) and Europe (Jeppesen *et al.* 2005; May *et al.* 2012). These coincidental patterns most likely reflect regional scale drivers of policy and management, particularly a reduction in P loads from WWTPs due to implementation of EU directives on wastewater treatment, together with intensification of agriculture due to implementation of the EU Common Agriculture Policy in the 1980s and 1990s.

However, the more recent data from the WWTP at Killarney indicated that, even in years when this plant contributed a relatively small percentage (5–6%) of the annual TP load, it contributed a relatively large proportion of the overall load during periods of low flow and had, therefore, a high potential to contribute to P availability in lake waters at those times. The importance of TP loads from point sources during low flow periods in rivers has been highlighted in several studies, including those using Load Apportionment Models (LAMs) (Bowes *et al.* 2008; Greene *et al.* 2011), but not in previous studies from lakes. Greene *et al.* (2011) used the LAM approach to investigate point and diffuse sources in an intensively farmed and populated drumlin region in central Ireland. They concluded that, despite an overall prominence of diffuse loads, point sources dominated during some summer flows and were the most influential sources (up to 64%) in one rural subcatchment river in a hydrological year. Bowes *et al.* (2008) followed a similar modelling exercise in the UK, and concluded that, even where ~75% of the annual load came from diffuse sources, reductions in point inputs were the most effective measure to reduce eutrophication in rivers because of the dominance of these TP sources during the algal growing season. Lakes with short residence times will be particularly sensitive to changes in external loading, especially during the main phytoplankton growing season. The Lough Leane catchment was designated as a sensitive area under the EU Urban Waste Water Treatment Regulations (91/271/EC). Although the TP concentrations in effluent from the plant meet current regulations, the bulk of this load will be in dissolved form and therefore available to primary producers, as will the load from small single-house treatment systems (Greene *et al.* 2011). Our results indicate that despite the high loading from diffuse sources, continued, and even more stringent, regulation of point sources at sites that are sensitive to increases in TP loads during summer months are needed if the requirements of the WFD are to be met.

The more recent data presented for Leane for 2000–2006 also showed that 73% of the catchment TP load was exported to the lake during autumn and winter months when the residence time of the lake was short due to seasonally high flow rates. The bulk of this loading came from the two agricultural subcatchments. Some of the particulate component of this TP load would sediment out (Dalton *et al.* 2010) but a large proportion would be flushed downstream from the lake to the coast before the algal growing season. Although internal loading from sediment P can contribute to phytoplankton P requirements in shallow lakes (Jeppesen *et al.* 2005), studies have shown that this is not an issue in the relatively deep Lough Leane (Kirk McClure Morton 2003).

In contrast to TP exported to the lake in the months before February, TP exported to the lake during March and April, when the residence time of the lake increased to 5 to 6 months, would have been available to primary producers during the spring and summer, as would any additional P exported during the summer growing season. The modelling exercise indicated that 20% to 30% of the TP load was from livestock sources during the 2000s, particularly from cattle. Land spreading of slurry is the main method of disposing of organic waste that has accumulated during the winter-housing period for cattle in Ireland (Carton and Hyde 2005). Nationwide regulations were implemented in 2006 to prohibit spreading between mid-October and mid-January (S.I. 378 of 2006). Prior to 2006, and during the period covered by the present study, spreading followed a Code of Practice with similar recommendations. A survey in 2003 of actual practice indicated that 26% of slurry was spread in spring (defined as February to April), 46% in summer (May to July) with only 3% between November and January (Carton and Hyde, 2005). The seasonal pattern in spreading in the Leane catchment would, therefore, have been similar to current practice, with the bulk of organic slurry and manure being spread during the months when the lake is most sensitive to increased TP loading, and when the hydrological connection is lowest.

The weak but significant relationship between summer chlorophyll *a* concentrations in Leane and TP concentrations in the previous May, and the lack of any relationship to TP concentrations in the months before that, would support the hypothesis that summer phytoplankton biomass in this lake is particularly responsive to changes in external loading in the months immediately preceding the growing period. Although Jeppesen *et al.* (2005) concluded that a 10- to 15-year recovery time would be needed before a new equilibrium is established in a lake following P-load reduction, there was no lake similar to Leane in that study; that is, relatively deep but with a short hydraulic residence time. Our results indicate that, despite their larger volume, such lakes can be highly sensitive to point sources during low flow periods. They also indicate that a relatively rapid response in trophic status to a reduction in external P loading would be the likely scenario, as evidenced by the reduction in in-lake TP concentrations in Leane following reduced loading in the 1980s. In fact, based on the average water residence time in recent years, the three residence times required to flush the lake and allow recovery would occur in one to two years.

Conclusions

The results presented in the present study are from a combination of modelling studies, long-term monitoring and intensive monitoring of catchment loads and, taken together, provide a comprehensive insight into the causes of the changes in trophic status that have been recorded in Lough Leane over the last forty years. They illustrate the linkages between changes in loading, in-lake P levels and in-lake phytoplankton response, but in particular highlight the importance of flushing rate in similar deeper lakes in high rainfall areas. This responsiveness of in-lake TP availability to changes in loading indicates that nutrient reduction measures can lead to a relatively rapid response in the lake. However, the results also highlight the effect of seasonal variations in discharge and residence time on in-lake phytoplankton biomass and the need for regulatory responses to consider such site-specific characteristics in management strategies.

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