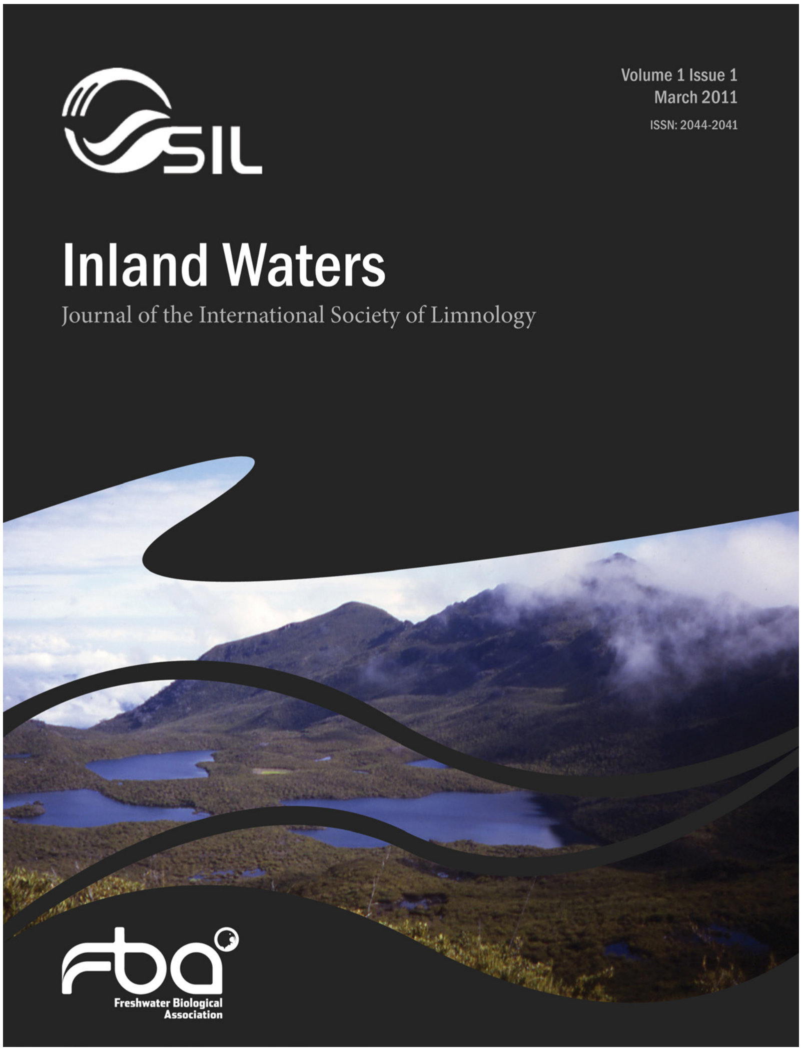
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Article

Storm-triggered, increased supply of sediment-derived phosphorus to the epilimnion in a small freshwater lake

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Abstract

This study investigated internal loading of sediment-derived phosphorus (P) in a small, meso-eutrophic lake (surface area 0.2 km^2, catchment area 2.7 km^2, mean depth 6 m, maximum depth 14 m) on the Atlantic seaboard of western Europe. High resolution data collected over 2.5 years (1 Mar 2011 to 30 Sep 2013) revealed inconsistent patterns in (1) the timing and magnitude of lake turnover and (2) the relative importance of the transfer of hypolimnetic sediment-derived P to the epilimnion when compared with external catchment loading. Lake turnover events during spring and summer had the effect of increasing the internal loading of epilimnetic P during the main growing season, thus adding to eutrophication pressure and contributing to algal blooms in the lake. Abrupt pre-fall (autumnal) turnover events and associated increases in eutrophication pressure such as those reported here may become more frequent occurrences in western Europe because of warming-induced increases in Atlantic summer storm frequency and magnitude, and they could counter the apparent effectiveness of measures aimed at reducing eutrophication impacts through limiting external loadings of nutrients from the catchment.

Key words: agriculture, climate change, geochemistry, monitoring, pollution, stratification, water quality

Introduction

Freshwater eutrophication effects may persist long after implementation of measures aimed at improving water quality (Schauser and Chorus 2007, Kagalou et al. 2008, Mehner et al. 2008, Jones and Schmitz 2009, Lathrop and Carpenter 2013). One potential and often overlooked cause is continued and possibly increased internal loading of bioavailable phosphorus (P) released by lake sediments (Brett and Benjamin 2008, Gulati et al. 2008). Such sediment-derived loading can be considered a delayed effect of decades of deposition of P transported to the lake from sources in the catchment (O'Dwyer et al. 2013).

Phosphorus is released from iron-rich sediments as a result of changes in oxygen conditions at the sediment–water interface (Nürnberg 1984, Jeppesen et al. 2005, Kagalou et al. 2008, Nürnberg 2009, Özkundakci et al. 2011, Loh et al. 2013, Penning et al. 2013). In lakes that stratify for prolonged periods during summer under generally stable meteorological conditions, sediment-derived P may be effectively trapped in the hypolimnion and thus have little or no impact on the epilimnion (Nürnberg 2009). Nevertheless, turnover during late summer–early autumn may introduce hypolimnetic P to the epilimnion by entrainment and deliver a boost to algal growth toward the end of a year (Rippey et al. 1997). Furthermore, partial or complete breakdown of the thermocline may occur during late spring and summer storms, potentially enriching the euphotic zone with high P concentration hypolimnetic waters (Jennings et al. 2012). Depending on antecedent conditions in a lake (Dokulil and Herzig 2009, Laugaste et al. 2010), levels of

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predation by zooplankton (Reynolds 2008), and the composition of the algal community (Tonno et al. 2003), the resulting algal bloom from these turnover events may persist throughout the remaining summer season (Soranno et al. 1997).

Identification of lake-turnover events has previously been largely dependent on chance recording through low frequency manual monitoring of dissolved oxygen profiles and thermoprofiles in a lake (e.g., Larsen et al. 1981). However, the use of automatic high temporal frequency (e.g., up to sub-hourly) monitoring equipment in lakes and associated computer software (e.g., Lake Analyser; Read et al. 2011) has enabled the detection of short-lived and often sub-daily changes in lake conditions and processes (Brookes et al. 2013, Jennings et al. 2013). In this study, data from a combination of manual sampling and high frequency automated monitoring of lake water quality parameters over 2.5 years (1 Mar 2011–30 Sep 2013) were used to investigate the proportions of P load derived from internal (sediment) and external (catchment) sources and their impact on chlorophyll *a* (Chl-*a*) concentrations, used as a proxy for algal growth. More specifically, the research was guided by 2 hypotheses; first, that abrupt lake-turnover events can deliver sediment-derived bioavailable P (soluble reactive phosphorus, or SRP) to the epilimnion in quantities that may exceed those from catchment sources. Second, that bioavailable P delivered in this way can be a source of substantial eutrophication pressure. These are currently important considerations when efforts aimed at reducing external P loads from catchment sources to waterbodies are being widely legislated and their effectiveness evaluated (Cherry et al. 2008, Meals et al. 2010, Melland et al. 2012).

Study site

This research focused on a small (0.2 km^2) freshwater lake, Lough Namachree (54°1′59″N; 6°51′59″E), located in a drumlinised, agricultural (improved grassland) catchment (2.7 km^2) in north-central Ireland (Fig. 1). Mean and maximum depths for the lake were 6 m and 14 m, respectively (O'Dwyer et al. 2013). Lough Namachree is also the primary source of water for a group water scheme, a community-owned enterprise providing piped potable water to a rural area without a mains supply (Brady and Gray 2010).

The landscape locally carries an imprint of past glaciation in the form of drumlins, drumlinised rib moraines (Dunlop and Clark 2006), poorly drained till deposits, and inter-drumlin lakes. Similar lakes to Lough Namachree in the region are known to stratify in summer and to overturn in autumn and have thus been defined as monomictic (Lewis 1983, Anderson 1990). North-central Ireland experiences a temperate climate and 4 distinct seasons (Garcia-Suarez et al. 2009). The Atlantic Ocean also has a strong influence on the weather (Hanna et al. 2008) and is a source of frontal systems associated with abrupt variations in air temperature, wind speed and direction, and precipitation (Jennings et al. 2013).

Phosphorus entering the lake from diffuse sources, such as soils in the catchment, is commonly regarded as the major cause of eutrophication in lakes in drumlinised, intensively farmed parts of Ireland (Douglas et al. 2007). Lough Namachree has been classed as mesotrophic to eutrophic (Tierney 2008; B. O'Flaherty, Monaghan County Council, Jan 2011, pers. comm.). Recent palaeolimnological research suggested that water quality in Lough Namachree has improved over the last decade and is moving toward a more stable mesotrophic state (O'Dwyer et al. 2013). The risk posed by internal loading of P jeopardises this recent improvement, however.

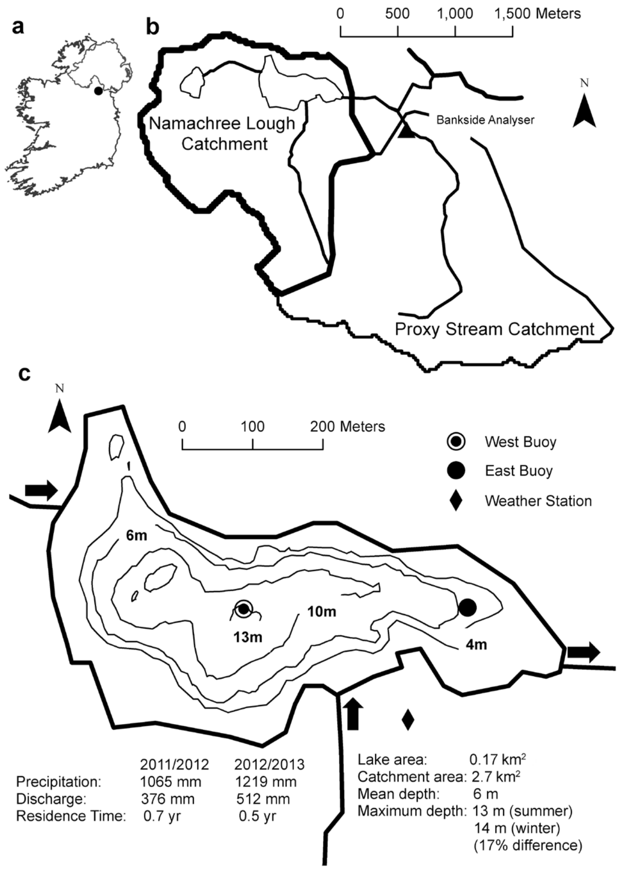

Fig. 1. (a) Location of study site in north-central Ireland; (b) Lough Namachree catchment and proxy stream catchment boundaries with location of stream bankside analyser; and (c) location of lake monitoring stations (west and east buoys) and bathymetry of lake with inflows and outflow identified. Figure produced using ArcGIS 10.1.

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Methods

Instrumentation and sampling

Two water quality datasondes (Hydrolab 5SX, OTT, Germany) were suspended at 1 m and 9 m depths from a buoy located in the deepest part of the lake. A second buoy located in the shallower eastern part of the lake supported a third datasonde, suspended at 1 m depth. Each datasonde supported sensors for measuring Chl-*a* (µg L^{-1}), temperature (°C), conductivity (µS cm^{-1}), turbidity (NTU), pH, dissolved oxygen (DO, % saturation) and redox (mV) at a frequency of once per hour (Supplementary Fig. A1–A4, available in supporting information Appendix A). Sensors for chemical parameters were calibrated and corrected for drift in the field on a 4–6 week rotation with industrial calibration standards and data subjected to quality control measures. Chl-*a* sensors were laboratory calibrated in August 2011, August 2012, and March 2014 using a prepared standard from an algal culture of *Chorella vulgaris* Beyerinck [Beijerinck]. The calibration outcomes and extracted Chl-*a* values (from manual sampling) were used to correct drift in 2011 and 2013. Chl-*a* sensor data were presented as night-time maxima between 22:00 and 04:00 h. Redox potential data were converted to standard redox potential (Eh) using:

$$\mathrm{Eh} = \mathrm{EM} + 223 + (0.76 \times t), \qquad (1)$$

where EM is the measured electrode potential and t the corresponding temperature (°C; West and Skoog 1976).

A thermistor chain (custom made, RSHydro, USA) was installed in January 2012 in the deepest part of the lake to record temperature at 1 m depth intervals every 15 min. Before this method, the lake temperature depth profile was obtained manually on a monthly basis using a temperature–DO sensor (LDO101, HACH, Germany) at 1 m sampling intervals.

Manual sampling of lake water quality over the 2.5 years was on a monthly basis during the periods March 2011–December 2011 and October 2012–September 2013, and on a fortnightly basis January 2012–September 2012. Samples were collected in 1 L polyethylene bottles at 2 surface locations and at a depth of 9 m to correspond with the datasonde monitoring and were kept cool prior to laboratory analysis. During periods of prolonged stratification, additional samples were taken between 9 and 13 m depths to investigate a possible chemocline in the hypolimnion. Filtered (Whatman GF/C 1.2 µm pore size) samples were analysed for Chl-*a* hot methanol extraction (DOE 1980), silicate (Wolters 2002), nitrate (Smith and Borgren 2003), and total dissolved phosphorus (TDP; Murphy and Riley 1962, Koroleff 1983) and SRP (Murphy and Riley 1962). Unfiltered samples were analysed for total phosphorus (TP; Murphy and Riley 1962, Koroleff 1983) and total reactive phosphorus (TRP; Murphy and Riley 1962). Samples collected during spring and summer 2012 for phytoplankton identification were preserved with Lugol's iodine in 250 mL glass bottles. Phytoplankton taxa were identified under an inverted microscope (Type 090-131.001, Leica Microsystems, Germany) using the US Environmental Protection Agency standardised method (EPA 1994).

External P loads (TP and TRP) were monitored at high resolution in an immediately adjacent catchment (3.5 km^2) using a bankside analyser (Phosphax-Sigma, HACH-LANGE, Germany; Jordan et al. 2007) at a rated stream gauging station, similar to other research catchments in Ireland (Melland et al. 2012, Mellander et al. 2012; Supplementary Fig. A5–A6). Data were collected on a sub-hourly basis; quality controlled, hourly mean P concentrations and hourly total stream discharges were factored to hourly total loads (kg) using the WISKI-7 (Kisters 2011) data management system (see Mellander et al. 2012). The timing and normalised (kg ha^{-1}) P loads leaving the adjacent catchment were assumed to equate to external P loads in the lake catchment because of proximity, similar environmental conditions, and land uses (Ó Dochartaigh 2003, Jordan et al. 2005, Douglas et al. 2007). Using the high-resolution stream dataset, the effects of individual heavy rainfall events on TP loading were identified and used to estimate the total rainfall-driven (external) catchment loading to the lake. In addition, monthly grab samples were collected for TDP and SRP laboratory analyses.

A weather station (BWS200, Campbell Scientific, USA) located next to the lake provided high frequency, locally relevant meteorological data, including wind speed (m s^{-1}) and direction (degrees from north), air temperature (°C), solar radiation (W m^{-2}), and precipitation (mm), based on hourly collations of 10 min sampling intervals throughout the period of monitoring lake water conditions. Hourly total precipitation was subsequently summed to total daily precipitation.

Estimation of P loading

Calculated internal loadings of P for all fractions were based on estimates of the total amount of P in the hypolimnion just before lake-turnover events. Because manually sampling at the precise point of lake turnover was not possible, estimates used an extrapolation based on previous measured concentrations at 9 m and the volume of hypolimnetic waters (Lake et al. 2007). The upper boundary of the hypolimnion before lake turnover was established from temperature profiles, recorded by the thermistor chain and manually, using Lake Analyzer software (Read et al. 2011), while the distance to the lower boundary (the lake bed) was established using bathymetric data (EPA 2010). For estimates of external loads of P, regression coefficients were used along with stream discharge data to convert high frequency TP load data to a TDP equivalent. The P loads were then scaled to the Lough Namachree catchment area for comparison with estimates of sediment-derived P loading. The process was repeated using SRP and TRP data.

Effects on algal growth rates

Chl-*a* concentration data collected at high temporal resolution were segregated into periods of algal growth during spring and summer and converted to daily rate of change (µg L^{-1} d^{-1}). The growth periods were differentiated according to characteristic profiles of P source: (1) predominantly catchment-derived P (i.e., following major rainfall events); (2) a combination of sediment- and catchment-derived P (i.e., after lake turnover has occurred); (3) predominantly sediment-derived P (i.e., following lake turnover); and (4) at, or close to, baseflow. The t-test ($p < 0.05$) was used to compare estimated growth rates between and within all 4 types of growth periods.

Results

Variations in meteorological conditions and thermocline depth

Winds over the study site were primarily west to southeast (Supplementary Fig. B1, Appendix B) and <4 m s^{-1} 80% of the time, although far higher wind speeds above the annual 90th percentile of 5 m s^{-1} occurred occasionally (Table 1). Spring and summer air temperatures were marginally higher in 2011 than in 2012. Spring air temperatures in 2013 were comparable with 2012, while summer temperatures were higher (Supplementary Fig. B2 and Table B1).

Lough Namachree experienced a turnover event in early May 2011 following a short period of weak stratification and before full stratification set in and persisted until early September (Fig. 2). A maximum thermocline depth of 7.5 m in July had declined to 5.6 m in August. By comparison, the lake stratified at the end of May 2012, with little evidence of preceding spring stratification. Full lake turnover in late summer–early fall occurred at a similar time to 2011; however, partial lake-turnover events, during which incomplete mixing occurred, disrupted stratification during June 2012 (Fig. 2 and 3), leading to the penetration of oxygenated waters at 9 m depth. Therefore, while Eh in the hypolimnion reached similar minimum values for the first 2 summers (−133 and −109 mV), the period of standard redox potential with the capacity to induce iron reduction was significantly shorter in 2012 (19 days <200 mV with ~pH 7) compared with 2011 (38 days <200 mV; Fig. 3). The thermocline before lake turnover in early September 2012 extended much deeper than 2011, reaching a depth of 8.5 m and reducing the volume of the hypolimnion. Thermal stratification did not occur during spring 2013 due to a much lower average air temperature. Lake surface temperatures increased at the beginning of June, leading to stratification that persisted throughout summer 2013 until the lake mixed in mid-September, 2 weeks later than the 2 previous years. Standard redox potential values reached a minimum of −195 mV and remained below 200 mV at ~pH 7 for a period of 56 days. The thermocline extended to a similar depth (8.5 m) to 2012.

The temporary breakdown of the thermocline in June 2012 occurred due to a combination of increased wind strength and cooling temperatures; however, other strong wind events recorded (16 Jul 2011 and 14 Aug 2012; Table 1) failed to disrupt stratification, irrespective of wind direction, and were associated with a large (>4.5 °C) temperature differential between the hypolimnia and epilimnia.

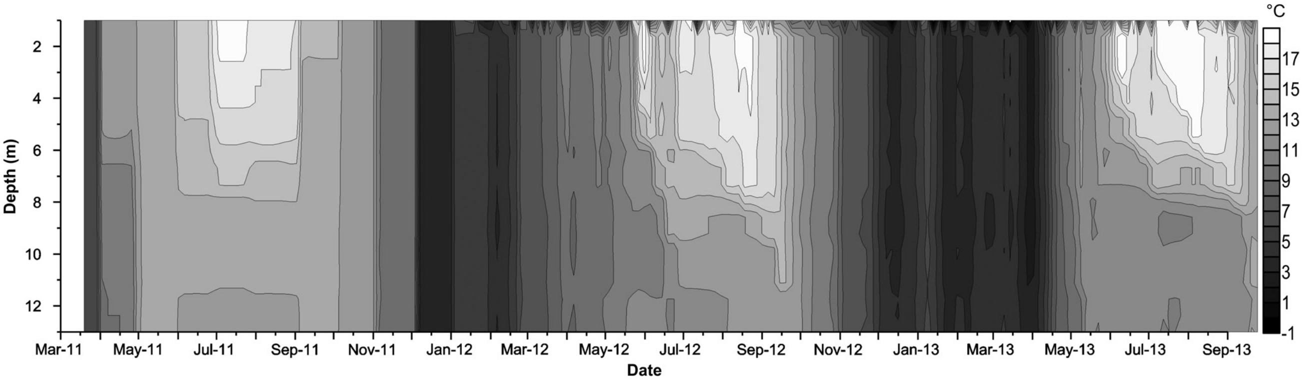

Fig. 2. Thermoprofile for Lough Namachree, data from Mar 2011 to Sep 2013 collected at the west buoy (Fig. 1) located in the deepest part of the lake. Figure produced using Grapher 9.0.

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Table 1. Physical attributes of strong wind events observed at Lough Namachree over years 2011, 2012, and 2013 during spring–summer periods (Apr–Sept). Figures provided show lake condition before a wind event and immediately after. Wind speed is maximum value observed between 2 dates quoted with corresponding wind direction.

Date	Max Wind Speed (m s^{-1})	Wind Direction (degrees from N)	Air Temperature (°C)		Lake Temperature (°C)		Lake Turnover?
			Max	Min	Surface	Deep	
30 Apr 2011	8.5	117	16.0	0.2	15.0	10.5	Yes
2 May 2011			15.5	7.3	13.2	13.8	
16 Jul 2011	7.2	299	16.4	11.2	19.2	13.8	No
17 Jul 2011			14.4	11	17.2	13.6	
3 Sept 2011	7.0	211	13.2	3.8	16.2	15.0	Yes
6 Sept 2011			15.2	11.2	15.2	15.0	
8 Jun 2012	6.9	289	12.0	8.5	17.2	11.0	No
9 Jun 2012			15.6	8.3	14.5	11.0	
14 Jun 2012	7.7	109	13.2	9.8	15.4	11.0	Yes
16 Jun 2012			13.8	11.0	14.3	13.6	
21 Jun 2012	8.9	286	12.8	9.8	16.0	12.6	Yes
22 Jun 2012			13.2	9.6	14.3	13.7	
14 Aug 2012	7.4	116	21.0	14.0	19.5	13.4	No
15 Aug 2012			17.5	14.0	17.6	13.2	
31 Aug 2012	5.8	244	16.2	6.0	16.5	14.4	Yes
1 Sept 2012			17.2	12.5	16.2	15.4	
22 Jun 2013	6.5	297	14.1	10.1	17.8	11.4	No
23 Jun 2013			12.0	8.6	16.8	11.4	
09 Aug 2013	5.8	323	14.8	4.4	15.6	11.9	No
10 Aug 2013			14.7	8.3	15.4	11.8	
14 Sept 2013	9.2	291	15.4	2.0	15.3	12.4	Yes
16 Sept 2013			10.7	5.0	14.1	14.0	

Estimated P loading

Based on linear extrapolation, internal loadings of biologically available P (SRP) were estimated to be 47, 21, and 24 µg L^{-1} at the point of late summer (Aug–Sep) lake turnover for, respectively, 2011, 2012, and 2013 (equivalent TP and TRP values were, respectively, 74, 38, 36 µg L^{-1} and; 52, 23, and 26 µg L^{-1}).

Sediment-derived P load was much lower in 2012 (Fig. 4; Supplementary Table B2), than 2011 due to the lower concentration of hypolimnetic P before late summer lake turnover (Fig. 3) and the reduced volume of hypolimnetic water (due to a deeper thermocline), and was lower again in 2013. Extra P was also added to the epilimnion in summer 2012 following lake turnover in June (TP, TRP, and SRP hypolimnetic concentrations linearly extrapolated to, respectively, 22, 21, and 19 µg L^{-1} at the point of lake turnover), which was lower than the estimated loading of P from the hypolimnion in late spring in 2011 (Fig. 4; TP, TRP, and SRP hypolimnetic concentrations linearly extrapolated to, respectively, 33, 33, and 31 µg L^{-1} at the point of lake turnover).

Strong relationships were found between high frequency TP and grab sample TDP concentrations and between high frequency TRP and grab sample SRP concentrations when analysed on a seasonal basis (Supplementary Table B3). The spring TP–TDP relationship ($R^2 = 0.7$) was affected strongly by high levels of particulate matter, while the other 3 seasons showed similar relationships to each other ($R^2 > 0.8$; Supplementary Table B3).

Spring 2011 was relatively settled meteorologically, with one rainfall event recorded in March (Fig. 3). By comparison, spring 2012 was associated with 3 large rainfall events yielding an estimated 1.0 kg SRP and a total catchment-derived SRP load of 2.8 kg (Fig. 4). This rainfall event was the only source of P to the lake in the absence of lake turnover. Catchment loading in spring 2013 was much higher, owing to several heavy rainfall events, although lake turnover once again did not occur.

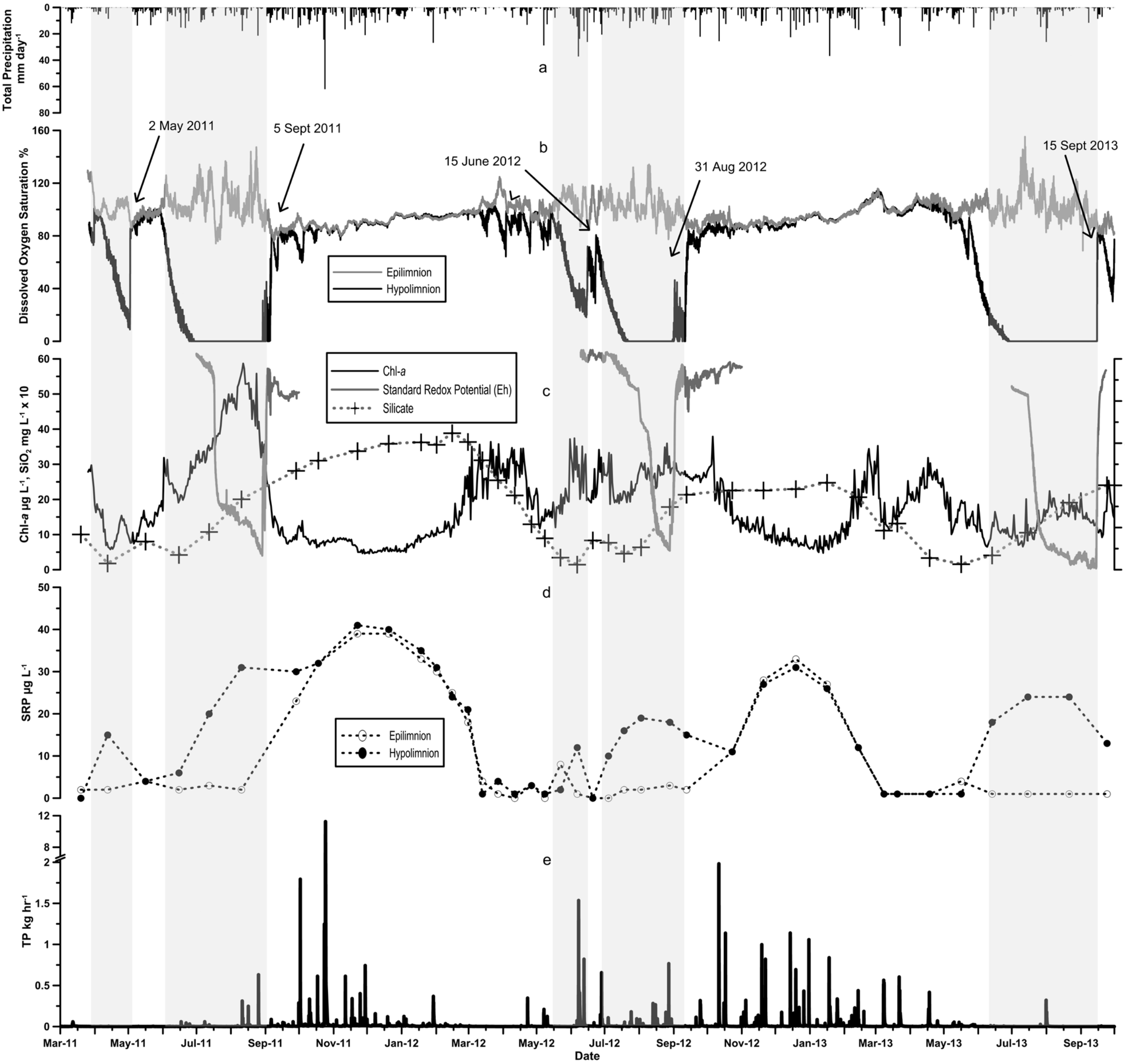

Fig. 3. (a) Total daily precipitation for Lough Namachree catchment; (b) epilimnetic/hypolimnetic dissolved oxygen saturation readings (dates of lake turnover cited; Table 1); (c) night-time (22:00–04:00 h) maximum surface-water Chl-*a* concentrations, hypolimnetic standard redox potential during anoxia (grey shading denotes dissolved oxygen levels <45% saturation in hypolimnion), and manually sampled epilimnetic silicate concentrations; (d) manually sampled epilimnetic and hypolimnetic SRP concentrations; and (e) hourly external TP load, measured in neighbouring catchment scaled to lake catchment size. Figure produced using Grapher 9.0.

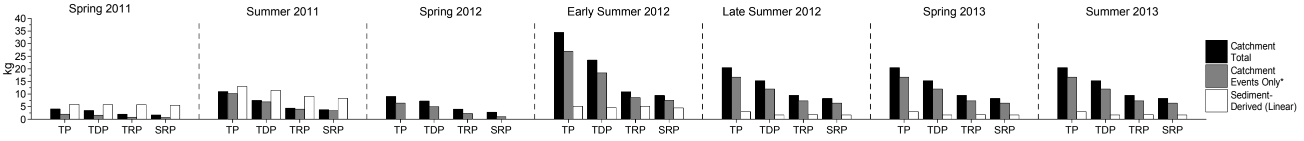

Fig. 4. Bar charts of catchment and sediment-derived P loads for Spring (Mar, Apr, May) and Summer (Jun, Jul, Aug) 2011; Spring (Mar, Apr, May), Early Summer (Jun only), and Late Summer 2012 (Jul, Aug); and Spring and Summer 2013. Summer sediment-derived loading calculated by end of summer–early fall lake turnover on 5 September 2011, 31 Aug 2012, and 15 Sept 2013. *contains storm and baseflow.

Relatively low rainfall during the 2011 growing season resulted in internal (sediment-derived) loading being a major source of P for primary producers in the lake following spring turnover. While external loadings were much higher the following year, lake turnover in early summer ensured additional SRP was made available to photosynthesising organisms in surface waters at a crucial time for growth. Relatively high levels of external loading in spring and summer and an absence of internal loading until late summer–fall lake turnover characterised 2013.

Algal growth rates

High frequency measurements of epilimnetic Chl-*a* indicated 2 maxima in algal blooms per year (Fig. 3); however, the algal blooms in 2013 occurred at different times and for different periods from 2011 and 2012. Cyanobacteria were the dominant group (by number) in the phytoplankton community throughout the growing season in 2012, whereas diatoms were prevalent during the spring bloom, indicated by epilimnetic silicate consumption (Fig. 3) and supported by count numbers in spring 2012. In addition, concentrations of nitrate were high (~300 µg L^{-1}) during spring and became limiting throughout each summer, suggesting the presence of a nitrogen-fixing algal species such as cyanobacteria. A marked reduction in Chl-*a* concentration characterised 2012 compared with the previous year, but measured values ~30 µg L^{-1} indicated the maintenance of eutrophic conditions (Tierney 2008, SI 2009). Despite lower catchment TP loads, 2011 had a sustained algal bloom throughout the summer, possibly due to P diffusion across the thermocline (Özkundakci et al. 2011) or motile algae accessing the nutrient-rich upper hypolimnion boundary (Camacho 2006).

An influx of sediment-derived P in late spring 2011 would have aided primary productivity, with cyanobacteria favoured by relatively warm temperatures overall (Kanoshina et al. 2003). Lake turnover in September 2011 led to the introduction of hypolimnetic SRP to the surface waters, but poor weather conditions initially prevented a response in algal growth until an episode of settled weather at the end of September produced a spike in Chl-*a* concentration (~15 µg L^{-1}). Variability in epilimnetic Chl-*a* concentration characterised summer 2012 with a breakdown in the algal bloom in June; however, an abrupt return to high Chl-*a* concentration was observed, followed by a period of hypolimnetic anoxia. A strong wind event on 15 August 2012 was associated with a temporary dip in Chl-*a* concentration in surface waters. An early spring bloom in February 2013 was followed by a crash in mid-March coinciding with a strong wind event (>5 m s^{-1}). A recovery of a similar spring bloom followed until the beginning of May (Fig. 3). There was no persistent summer bloom until early August 2013, although some peaks in Chl-*a* concentration were observed in early July (Fig. 3).

Accelerated algal growth was segregated into 12 periods (Table 2). Overall, there is no simple relationship between algal growth rate and sources of P loading evident (Table 3). In both cases of abrupt lake turnover during the growing season, however, the growth rate increased above the rates observed during periods of catchment-derived P loading (May 2011 vs. Jun 2011) and baseflow (May–Jun 2012 vs. Jun–Jul 2012).

Table 2. Results of linear regression on Chl-*a* values during periods of accelerated growth. Growth periods in bold are associated with sediment-derived and baseflow P loading (May 2011) or periods with a combination of catchment and sediment-derived P loading (Jun–Jul 2012); periods in italics are associated with flow at, or close to, baseflow; and all remaining periods are associated with catchment-derived P loading.

Growth Period	Growth rate (slope of line) µg L^{-1} d^{-1}	Standard Error	95% Confidence Intervals	Growth rate, linear regression R^2
Apr 2011	1.22	0.081	1.03–1.41	0.97
May 2011	1.19	0.111	0.92–1.46	0.95
Late May 2011	0.61	0.085	0.41–0.79	0.83
Jun 2011	0.96	0.105	0.73–1.19	0.88
Jul 2011	0.65	0.035	0.58–0.72	0.90
May-Jun 2012	0.51	0.066	0.38–0.65	0.62
Jun-Jul 2012	0.60	0.143	0.30–0.91	0.51
Jul 2012	0.22	0.048	0.12–0.32	0.51
Jan-Feb 2013	0.39	0.043	0.30–0.48	0.69
Mar-Apr 2013	0.39	0.038	0.32–0.47	0.76
Jun 2013	1.03	0.158	0.66–1.39	0.84
Jul 2013	0.66	0.170	0.27–1.05	0.65

Discussion

Internal loading versus external loading

High resolution data collected over 2.5 years revealed inconsistencies in the timing, duration, magnitude, and likely cause of lake-turnover events. In 2011, lake turnover early in the growing season provided a mechanism for transferring SRP released from sediments to photosynthesising algae in the epilimnion. Sediment sources provided 300% more SRP to the euphotic zone via lake turnover in comparison with catchment-derived SRP loading during the spring and summer periods. In 2012, the converse occurred when catchment-derived sources during summer were nearly 3 times larger than sediment-derived SRP loading, most likely due to relatively high levels of precipitation at the time (Preedy et al. 2001). An absence of significant P entrainment during spring–early summer in 2013 resulted in a reduced contribution of SRP from sediments and, coincidently, was associated with a much reduced catchment loading, the latter owing to the occurrence of settled weather. Internal loading of P is likely to continue at Lough Namachree until the sedimentary reservoir is depleted and/or all P becomes permanently lost to sediments (Søndergaard et al. 2001). The results thus tend to support the first hypothesis, that the amount of P derived from sediments and delivered to the epilimnion during turnover events can be substantial relative to levels from catchment sources.

Impact of sediment-derived P loading on primary productivity

Efforts to mitigate eutrophication are often based on estimates of the most likely contributors to an overall TP budget and their relative weightings (Dahl and Pers 2004, Brett and Benjamin 2008, Canale 2010, Hargan et al. 2011, Jennings et al. 2013). However, the use of annual budgets of TP may:

- miss the timing of variations in P loads, which can be critical if changes occur during nutrient sensitive times, such as late spring–early summer;
- fail to account for the proportion of P allocated to the biologically available SRP fraction; and
- potentially lead to an inaccurate identification of the primary cause of eutrophication.

The Chl-*a* growth rate immediately after lake turnover in May 2011 was higher than that observed at the study site during June 2011. When lake turnover recurred in the autumn, the resultant elevated epilimnetic concentration of P also led to an increase in Chl-*a* concentration. Water quality was also impacted a year later, even though internal P loads were reduced because of a shorter overall duration of stratified conditions. The immediate reestablishment of the algal bloom after mixing in June 2012 may not have occurred without a large influx of bioavailable P from sediment-derived sources. The rate of increase in Chl-*a* concentration similarly reflected a boost in algal growth, with a daily increase nearly 3 times higher in June–July 2012 than a month later. Thus, the second hypothesis also seems valid: sediment-derived P can add to eutrophication pressures by boosting algal growth at a time when ambient weather conditions are most suitable for phytoplankton growth, particularly nitrogen-fixing cyanobacteria (Kanoshina et al. 2003, Nürnberg et al. 2013), and when the availability of nutrients, notably P, would otherwise be limiting.

In cases when sediment-derived sources do not play a large part in SRP loading to the euphotic zone (due to an absence of lake turnover), increased hypolimnetic SRP concentration may provide a source of nutrients to any motile algae. Establishment of an algal bloom may be dependent on other factors, however, such as temperature, as observed in Lough Namachree in 2013. Furthermore, the duration and composition of the algal bloom may be subject to other factors such as availability of nitrogen and grazing pressure.

Implications for lake water quality

Water quality at the study site remained relatively poor throughout the 2.5 monitoring years, with algal blooms present in varying degrees of severity, despite recognition that the lake was moving toward a more mesotrophic state (O’Dwyer et al. 2013). Recommended measures to mitigate eutrophication effects in lakes are generally targeted at catchment (i.e., external) sources and therefore do not consider the contribution by sediments within a lake, particularly at nutrient-sensitive times in spring and summer. The focus on reducing catchment loading is prevalent internationally, with transfers from agricultural sources commonly targeted (Henriksson and Miljökonsulter 2007, Kronvang et al. 2008, SI 2014); however, sediment-derived P can be viewed as a legacy of decades of accumulation in a lake and is likely to remain a risk to water quality for many years to come. Mitigating the risk requires a clear understanding of the mechanisms and conditions that drive P release from sediments and its transfer to the epilimnion and how they are likely to vary in future. This requirement is particularly pertinent to the process of recovery in lakes such as Lough Namachree, where water quality is at the sensitive mesotrophic to eutrophic status.

Lake turnover events described in the current research occurred under varying weather conditions, and therefore describing the precise meteorological conditions needed for lake turnover to occur is difficult. Air temperature is important because of its effect on lake surface temperature and therefore the strength of the thermocline (Danis et al.

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Table 3. P values obtained by t-tests ($p < 0.05$ is significant) between slope of linear regression for each growth period.

			Catchment	Sediment	Base	Catchment	Base	Base	Combination	Base	Catchment	Catchment	Base	Base
			Apr	May	Late May	Jun	Jul	May–Jun	Jun–Jul	Jul	Jan–Feb	Mar–Apr	Jun	Jul
			2011					**2012**			**2013**			
Catchment	**2011**	Apr		0.08	**<0.001**	0.016	0.07	0.20	0.14	**<0.001**	<0.05	**<0.01**	0.34	**<0.02**
Sediment		May	0.83		**<0.005**	0.29	0.15	0.30	0.24	**<0.001**	0.101	**<0.05**	0.50	**<0.05**
Base		Late May	**<0.001**	**<0.005**		<0.02	0.82	0.80	0.99	**<0.005**	0.40	0.26	**<0.05**	0.76
Catchment		Jun	0.16	0.29	<0.02		0.08	0.15	0.15	**<0.001**	**<0.02**	**<0.005**	0.73	0.14
Base		Jul	0.07	0.15	0.82	0.08		0.07	0.73	**<0.001**	**<0.05**	**<0.001**	0.16	0.97
Base	**2012**	May-Jun	0.20	0.30	0.80	0.15	0.07		0.63	**<0.05**	0.12	0.13	0.27	0.76
Combination		Jun-Jul	0.14	0.24	0.99	0.15	0.73	0.63		**<0.01**	0.15	0.09	0.24	0.88
Base		Jul	**<0.001**	**<0.001**	**<0.005**	**<0.001**	**<0.001**	**<0.05**	**<0.01**		0.08	<0.05	**<0.001**	**<0.02**
Catchment	**2013**	Jan-Feb	<0.05	0.101	0.40	**<0.02**	**<0.05**	0.12	0.15	0.08		0.97	0.07	0.44
Catchment		Mar-Apr	**<0.01**	**<0.05**	0.26	**<0.005**	**<0.001**	0.13	0.09	**<0.05**	0.97		**<0.02**	0.29
Base		Jun	0.34	0.50	**<0.05**	0.73	0.16	0.27	0.24	**<0.001**	0.07	**<0.02**		0.13
Base		Jul	**<0.02**	**<0.05**	0.76	0.14	0.97	0.76	0.88	**<0.02**	0.44	0.29	0.13	

2004). Wind speed was also found to be important in promoting the likelihood of lake turnover, particularly when strong winds coincided with low air temperatures and weak stratification. Recent studies suggest that the frequency of high intensity storms that provide cooling air temperatures and high wind speeds in the North Atlantic region will increase (Lozano et al. 2004, Emanuel et al. 2008, Knutson et al. 2010). The main hurricane season in the North Atlantic is during summer and autumn, and hurricanes (leading to strong storms at this latitude) seem to have increased in frequency during summer, particularly since 1995 (Holland and Webster 2007). Moreover, the frequency of hurricanes, including the most severe, is predicted to continue to increase in coming years as a result of increases in sea surface temperatures driven by climate change (Holland and Webster 2007, Bender et al. 2010). These changes in storm frequency and strength in the North Atlantic will increase the likelihood of water column instability in lakes on adjoining land masses in summer, potentially increasing eutrophication pressures during an ecologically critical period when nutrients would otherwise be limiting.

An increased risk of lake turnover, and with it increased loading of sediment-derived P, will require the implementation of targeted new measures if eutrophication effects are to be mitigated. These measures may include the prevention of thermal stratification (Toffolon et al. 2013) or the prevention of P release from sediments (Hansen et al. 2003, Cooke et al. 2005) where appropriate and/or possible. Moreover, in cases with a significant accumulation of P in sediment over many decades, there is likely to be a considerable lag before the true effectiveness of measures aimed at mitigating eutrophication impacts through reducing external loading is evident (Søndergaard et al. 2007).

Conclusions

Phosphorus loads from internal and external sources have varying degrees of importance in terms of algal growth. Aided by high-resolution monitoring, the current research showed that temporary breakdown of stratification in the water column of a small lake preceded heightened rates of algal growth, particularly when entrainment of hypolimnetic P-charged waters coincided with depleted epilimnetic levels. External loads from catchment sources also delivered nutrients to the epilimnion during periods of heavy rainfall. Lake-turnover events and resulting epilimnetic and hypolimnetic mixing were attributed to changing air temperature, wind direction and speed, and strength of thermal stratification, but the precise combination of circumstances and the relative weight of their contributions were less clear. A possible increase in summer storms in areas under the climatic influence of the North Atlantic could increase the influence of sediment-derived P loading by reducing lake water quality and put at risk the effectiveness of catchment management measures aimed at limiting P transfer from land to water.

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Supplementary Material

Supplementary Material is available for download via the Inland Waters website, https://www.fba.org.uk/journals/index.php/IW:

Supplementary figures A1-A6, B1-B2, supplementary tables B1-B3.

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