Recovery targets and timescales for Lough Neagh and other lakes

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Recovery targets for Lough Neagh and other lakes

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Abstract

The framework, model and methods of Nürnberg were applied and evaluated in Lough Neagh and 19 other lakes in order to establish inflow phosphorus concentrations that support target lake values. Supporting concentrations, in the absence of an internal load, were derived and the effect of uncertainty in the model retention coefficient was relatively small, ±11-20 % in Lough Neagh and an average (n=17) of ±9.7 % in the other lakes. There was further support for the model and methods from an independent estimate of the net internal load in Lough Neagh (13 % difference) and from another model in the other lakes (Supporting concentrations, which should be lower, were by an average of 11 mg P m^{-3}). In the framework, steady state with the phosphorus load is assumed, but, based on a generic lake model, is not likely if the hydraulic residence time>0.5-0.8 yr and should lead to a decrease in phosphorus retention, which was found during three periods in Lough Neagh. Based on a compilation of internal load recovery times from 23 lakes in the literature, it could take between 8 and 20 years for lakes with an internal load to achieve their targets.

Key words

Lakes
Phosphorus
Targets
Good/Moderate boundary
Timescales
Internal load

1 Introduction

Lake nutrient models, especially for phosphorus, have been a major and sustained research topic in limnology. A lake phosphorus model was an important element in the structure that linked nutrient sources in the catchment to the biological quality of the lake proposed early in the field by Dillon & Rigler (1975), a framework that this still valid today. Useful water quality models also allow managers to assess how a lake should respond to actions in the catchment and help stakeholders recognize this relationship (Manno et al. 2008).

While research on this topic has generally focussed on model concepts, complexity and accuracy (Prairie 1989; Arhonditsis & Brett 2004; Brett & Benjamin 2008; Khorasani & Zhu 2021), the main practical application has been to estimate the nutrient load or concentration, usually of phosphorus, in the inflow(s) that supports a target lake concentration and biological condition. Directed management of catchment activities to reduce the export of phosphorus, nitrogen or both should, ideally, lead to a high quality lake.

Within the paradigm of the condensed box (Continuously Stirred Tank Reactor) lake model, which has a large literature, the publications of Prairie (1989), Brett & Benjamin (2008) and Khorasani & Zhu (2021) cite most of the models. An important issue that needs to be considered when applying one to a lake that has a high phosphorus concentration, where the target is to reduce it, is the internal phosphorus load. Generally, this load is high in such lakes but should decrease as the external load is reduced, albeit slowly (Jeppesen et al. 2005). Where the internal load is not explicitly incorporated into the model, its effect is assumed to contribute via the range of lakes used to calibrate the model (Nürnberg 2009). Lakes with a high phosphorus concentration often have considerable internal loads and *vice versa*, so the varying contribution of internal load to the lake concentration is incorporated through the range of lakes used to calibrate the model.

Nürnberg (2009) noted the uncertainty with the contribution of internal load when calibrating a lake phosphorus model, and the lack of control of it, and went on to formally separate the contributions of external and internal phosphorus load to the lake concentration (Nürnberg 1984; 1998; 2009). That model predicts the steady-state concentration from the external and internal loads and she suggested three methods to estimate the internal load, depending on the type of results available and whether the lake thermally stratifies. This approach can also be used to derive inflow phosphorus concentrations that support a target lake concentration, and our aim was to apply and evaluate the framework, model and methods in Lough Neagh and 19 other smaller lakes. The model, as with others used in the field, assumes steady-state and so, in addition, we assessed the conditions under which a typical CSTR model is at steady state. Knowing the limitations of a model helps when using it for lake management purposes.

As the model is a static one, the time it takes to reach steady-state with the inflow(s) depends only on the lake hydraulic residence time. However, if the lake has an internal load, then, while the model explicitly incorporates the internal load, how long it would take for that load to reduce needs to be derived separately. The time for reduction of the internal load has been estimated using lake models (e.g. Katsev et al. 2006), observations on lakes (e.g. Jeppesen et al. 2005) and through a model of the diagenesis and burial of labile phosphorus in sediment (e.g. Rippey et al. 2021). There is some consistency in these estimates, with an overall indication of one to three decades, but to provide some more direct evidence, we collated results from lakes that had their external loads reduced and for which sufficient monitoring results were available.

Therefore, the aim of the research was to apply and evaluate the framework, model and methods of Nürnberg (1984; 1998; 2009) in order to derive an inflow phosphorus concentration that supports a target lake concentration in Lough Neagh and 19 other smaller lakes, including establishing the uncertainties in estimating the lake concentration from the external and internal loads. We also estimated the time it should take to reach the target lake concentrations. There were two supporting objectives: to identify the conditions under which a typical CSTR model is at steady state and collate results provide direct evidence of the time it takes for the internal phosphorus load to reduce.

2. Material and methods

The symbols and definitions used here are given in Table 1. With Rpred, we use the original definition, net retention in oxic lakes that have no or a naturally low net internal load (Nürnberg 1998), before the change to gross sedimentation only (Nürnberg 2009).

Table 1. Symbols and definitions used.

Property	Definition
z, m	Mean depth
τ_w, yr	Annual mean hydraulic residence time. ρ, yr^{-1}, the hydraulic flushing coefficient is τ_w^{-1}.
qs, m yr^{-1}	Annual hydraulic load, qs = z/τ_w
Cext, mg P m^{-3}	Annual volume-weighted average total phosphorus concentration in the inflow(s). Cext = Lext/qs, where Lext, g P m^{-2} yr^{-1} is the annual average areal external total phosphorus load.
Obs C, mg P m^{-3}	Annual average or monthly average total phosphorus concentration in the lake. Predicted C is the concentration predicted by a lake phosphorus model.
Rmeas, dimensionless	Implicitly the total phosphorus retention coefficient for one year, is (Input total phosphorus load-Output total phosphorus load)/Input total phosphorus load or, equivalently, Retained load/Input load

Rpred, dimensionless	Implicitly the total phosphorus retention coefficient for one year, predicted by the R7 model of Nürnberg (1984)
Cint, mg P m^{-3}	The internal total phosphorus load expressed as a concentration, implicitly in one year. Cint = Lint/qs, where Lint, g P m^{-2} yr^{-1}, is the annual average areal internal total phosphorus load.

2.1. *Lough Neagh and its phosphorus budget*

Lough Neagh, a site in the UK's Environmental Change network, is a large (383 km^2) relatively shallow (z 8.9 m) lake, which only rarely stratifies, but has a long history of eutrophication (Wood & Smith 1993), up to the 1960s as a result of an increasing external phosphorus load (Foy et al. 2003), since then by phosphorus and nitrogen (Bunting et al. 2007). Since the mid-1990s, a reduction in external nitrogen load and lake concentration have resulted in a decrease in the chlorophyll *a* concentration (McElarney et al. 2021; Elliott et al. 2016).

The six main river catchments (Upper Bann, Blackwater, Ballinderry, Moyola, Main and Sixmilewater) and two smaller catchments (Crumlin and Glenavy) of Lough Neagh have been gauged and monitored since the 1970s, along with the outflow (Lower Bann). Discharge is measured continuously (15 min internals) and water samples taken weekly from the eight inflows and outflow. The annual mean Input and Output total phosphorus loads are calculated using Method 5 in Johnes (2007), i.e. sum of total loads over sampling days multiplied by the annual mean discharge as a proportion of the total discharge over the sampling days. As the monitored catchments comprise 86 % of the whole catchment, the whole catchment load was estimated as load from the monitored catchments divided by 0.86. If more than 4 % of flow results for a catchment were missing, the load was not estimated. There were no outflow results for 2007 and no results for the Upper Bann in 1995, Sixmilewater in 2010 and Moyola in 1983 and 2010-11, so no catchment phosphorus loads were estimated for 1983, 1995, 2007 and 2010-2011.

An integrated water sample was taken at a mid-lake station in 10 m depth, weekly up to 1992, fortnightly thereafter, and the mean total phosphorus concentration calculated; there were no lake results for 2009. The Limit of Quantitation for the total phosphorus determination is 10 mg P m^{-3}.

Rmeas was calculated as (Input-Output)/Input and Annual Obs C as the arithmetic mean of typically 30.3 results in each year, minimum 15 and maximum 52.

2.2. Other lakes

Samples were retrieved at least monthly from the shores of 19 other lakes from 1999, 2004 or 2008 onwards. The Limit of Quantitation of the total phosphorus determination is 10 mg P m^{-3}. The theoretical τ_w values were estimated using the measured catchment area, lake area and mean depth, along with rainfall and potential evapotranspiration estimates made by interpolation using long-term (1971-2000) data sets of annual mean rainfall and potential evapotranspiration for sites throughout Northern Ireland.

2.3. Lake phosphorus models

The main use of the models was to estimate the inflow phosphorus concentration (Cext) that supports a target lake concentration (Section 2.6) and the lake phosphorus framework, model and methods of Nürnberg (1984; 1998; 2009) was used. While there is choice of whether to use the gross internal load or the net, after any sedimentation, we used the net for Lough Neagh as it could be estimated using the phosphorus mass balance budget (Net Cint_2) method (Section 2.5) and, therefore, the model is (Nürnberg 2009):

Predicted C = Cext(1–Rpred) + Net Cint,_2 where Rpred = 15/(18+qs) and Net Cint_2 = Cext(Rpred-Rmeas) Eqn. 1

We assumed that a lake of high quality, at or better than the Good/Moderate (Quevauviller et al. 2008) boundary (Section 2.6), would have little or no net internal load, so Net Cint_2 in Eqn. 1 would be zero. Rpred, estimated using the R7 model of Nürnberg (1984), is therefore key in Eqn.1. That statistical model was developed and calibrated using oxic lakes (n=54) and so there is some uncertainty in the predicted value for a specific lake. Based on Fig. 1A in Nürnberg (1984), it applies over a qs range up to 80 m yr^{-1} with an uncertainty of ±0.05 up to a qs value of 20 m yr^{-1}, ±0.1 at higher values. An uncertainty in Rpred of ±0.05 was used when applying Eqn. 1 and when calculating Net Cint_2 (Section 2.5).

Even incorporating this uncertainty into the model predictions, some additional evidence to support the Rpred value or the accuracy of the lake concentrations based on Eqn. 1 with little or no internal load is desirable (Nürnberg 2009). For this, we used the predictions of another lake phosphorus model, Model 28 of Khorasani & Zhu (2021). It was selected after comparing the behaviour of three general lake models and R7 Nürnberg (1984) (Section 1 Supplementary materials) and establishing its accuracy in 14 Irish lakes (Section 2 Supplementary materials). Model 28 of Khorasani & Zhu and Eqn. 9 of Prairie performed best in these 14 lakes which have some and variable internal load. The mean and median errors (Observed-Predicted) are -6.2 and -2.3 mg P m^{-3} for Prairie and -2.3 and -0.8 mg P m^{-3}

for Khorasani & Zhu Model 28. The error is larger in some lakes but both models are most accurate at Predicted C<50 mg P m^{-3}.

Based on this assessment, we used Model 28 of Khorasani & Zhu (2021) to provide some support for the Cext value derived using Eqn. 1 in the other 19 lakes. As the data set (n=738) used to calibrate this model contains lakes with unknown and variable internal loads, the supporting Cext concentrations should be lower than those from Eqn. 1 with a Net Cint_2 of zero, which applies to lakes with no or naturally low internal phosphorus loads. Model 28 of Khursani & Zhu (2021);

$$\text{Predicted C} = \text{CF x } \frac{-1+\left(1+4\times0.095\times tw^{0.489}\times Cext^{(-0.333+1)}\times z^{0.288}\right)\text{^}0.5}{2\times tw^{0.489}\times Cext^{-0.333}\times z^{0.288}} \qquad \text{Eqn. 2}$$

Where CF, the Correction Factor (Sprugel 1983), is 1.159.

2.4. Steady-state of lake phosphorus models

We investigated the conditions under which a lake is in steady state with its inflow phosphorus and internal phosphorus cycling, mainly the internal load. In a CSTR model, loss through the outflow is described by ρ or τ_w and permanent loss to the sediment by the sedimentation coefficient (σ) (Chapra 1997, Lecture 3). A time to 90 % of the steady-state concentration (t_{90}) was used, as most of the change has occurred by then, with progressively slower change to 95 or 99 % of the steady-state value thereafter. t_{90} for loss only through the outflow is $2.303\tau_w$. As the residence time for sedimentation (t_s) is σ^{-1}, t_{90} for loss only through sedimentation is $2.303\tau_s$.

The t_{90} times, for τ_w values of 0.5, 1.0 and 1.5 yr and σ values between 0.3 and 1.0 yr^{-1} to represent smaller eutrophic lakes, were first calculated separately and then combined. The σ range was selected based on the following. For populations of lakes, Khorasani & Zhu (2021) derived a value of 0.786 yr^{-1}, Jones & Bachman (1976) 0.65 and Brett & Benjamin (2008) 0.45. In a hierarchical framework, Cheng et al. (2010) estimated values for all lakes and for categories of z and τ_w; 0.45 yr^{-1} for all lakes, but 0.73 for lakes with $z \leq 10.3$ m and 0.32 for >10.3 m and 1.01 for lakes with $\tau_w \leq 2.6$ yr and 0.33 for >2.6 yr. In summary, σ values for most lakes vary between 0.3 and 1.0 yr^{-1}.

The overall residence time for 90 % of the combined loss through the outflow and by sedimentation ($t_{90,\ combined}$) was calculated using the addition of residence times (Lerman 1979, pp.5);

$t_{90,\ combined} = 1/(\rho + \sigma)$, with the $t_{90} = 2.303t_{combined}$.

2.5. Internal phosphorus load

The annual internal phosphorus load for Lough Neagh was estimated using the phosphorus mass balance method of Nürnberg (2009; 1998) and expressed as a concentration: Net Cint_2 = Cext(Rpred-Rmeas). To provide some support for these values and to estimate the internal load in the other 19 lakes, the *in situ* P increase method of Nürnberg (2009; 1998) was used and the value expressed as a concentration (Cint_1). This method uses the increase of concentration during the summer and the load lies between the gross and net value.

2.6. Target lake total phosphorus concentration

The target lake total phosphorus concentrations were derived using the WFD-UKTAG (2016) methodology and was taken to be at the Good/Moderate boundary. With this approach, the site-specific reference concentration is estimated using statistical models, from which the boundary values for five quality classes, High/Good, Good/Moderate, Moderate/Poor and Poor/Bad, are calculated. The statistical models were derived by Cardoso et al. (2007) using results from 567 lakes distributed throughout Europe and considered to be at reference condition (only slightly impacted). The reference concentration is the annual geometric mean value and the statistical models use altitude, the Morphoedaphic Index (alkalinity and mean depth) and region. There are two regions and one additional model for humic lakes (Hazen>30 mg/L Pt) in Northern Ireland.

2.7. Time to reduce the internal phosphorus load

To provide additional information on how long it takes the internal load to reduce to a low or natural amount, we collated results from the literature from lakes that had their external loads reduced and had been monitored for at least 5 years. The following results were collated from tables or digitized from charts: τ_w, qs, the time period of monitoring after reduction in external load and Cext at the start and end of the monitoring. From this information, an estimate of the time for the internal load to decrease was made. Errors may have been introduced during digitizing the charts. In the valuable compilation of Jeppesen et al. (2005), no results for Cext were directly presented. However, Cext was estimated from the Predicted C values in their Fig. 1(a) by applying the lake model in their Eqn. 1.

3. Results

3.1. Steady state of lake phosphorus models

As the CSTR model used assumes steady state, the conditions under which this applies were assessed. The t_{90} times for loss only through the outflow represented by τ_w of 0.5, 1.0 and 1.5 yr are 1.15, 2.30 and 3.45 yr, respectively, loss only through sedimentation represented by σ of 0.3 and 1.0 yr^{-1} are 7.68 and 2.30 yr, respectively, and the variation of $t_{90, combined}$ for the combined losses is shown in Fig. 1.

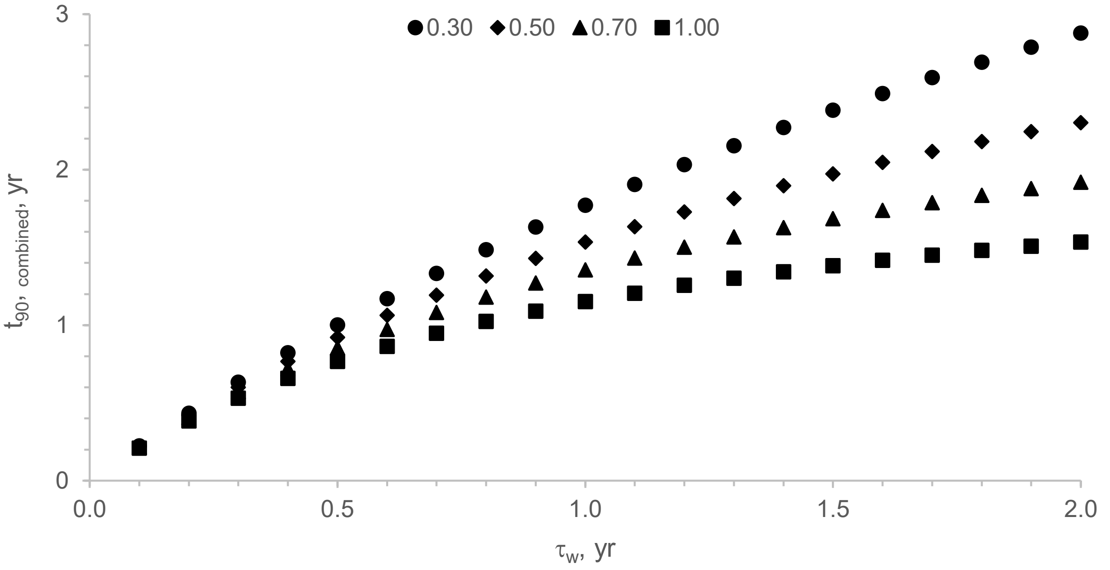


Fig. 1. The variation with τ_w of the time to 90 % steady state lake water total phosphorus concentration for combined loss through the outflow and by sedimentation ($t_{90, combined}$) for four values of the sedimentation coefficient (σ) in a Continuously Stirred Tank Reactor.

For $t_{90, combined}$ to be 1 yr or less, τ_w needs to be less than 0.5 to 0.8 yr for a lake to be at steady state with $\sigma<1$ yr^{-1}. This should apply to a relatively large change in Cext at the start of a year and it is possible this criterion could be relaxed for smaller changes in Cext. Changes in Cext later in the year may only produce steady state the following year.

This is a simple framework with generic τ_w and σ values, and phosphorus sedimentation in smaller rapidly flushed lakes is best described using the retention coefficient (Prairie 1989). However, it suggests that only relatively rapidly flushed lakes would be at steady state with a changing phosphorus load..

While there are implications for the estimation of σ in lakes that are not at steady state, the effect on the more empirically based Rmeas is relevant here. In a lake at steady state, loss through the outflow and to the sediment are at equilibrium with the input, therefore, as the Retained load is in equilibrium with the Input load, Rmeas is accurate (Retained load/Input load). In a lake not at steady state, if Input is increasing, then loss through the outflow or to the sediment or both would not be complete and so the Retained load would be smaller than that at steady state. While Rmeas is Retained/Input, a smaller Retained load should lead to a smaller Rmeas. Further, the phosphorus that is in excess of the steady state concentration would be carried over to the following year, contributing to a smaller Rmeas in that year as well. The same outcome, a depression in Rmeas, also applies to a decreasing Input load when a lake is not at steady state.

Based on this assessment, a lake is not likely to be in steady state if τ_w>0.5-0.8 yr and this may lead to a decrease in Rmeas for one or more years, compared to the steady state value.

3.2. Lough Neagh phosphorus budget

The Lough Neagh phosphorus model (Eqn. 1) uses annual values for Cext, τ_w/qs, Input and Output total phosphorus load, from which Rpred and Rmeas are calculated and then Net Cint_2 and Predicted C. The variation of τ_w, Input load, Output load and Retained load over 1984-2018 is shown in Section 3 Supplementary materials, with changes in the key properties, Rpred, Rmeas and Cext presented in Fig. 2 and Obs C, Cext(1–Rpred) and Net Cint_2 in Fig. 3.

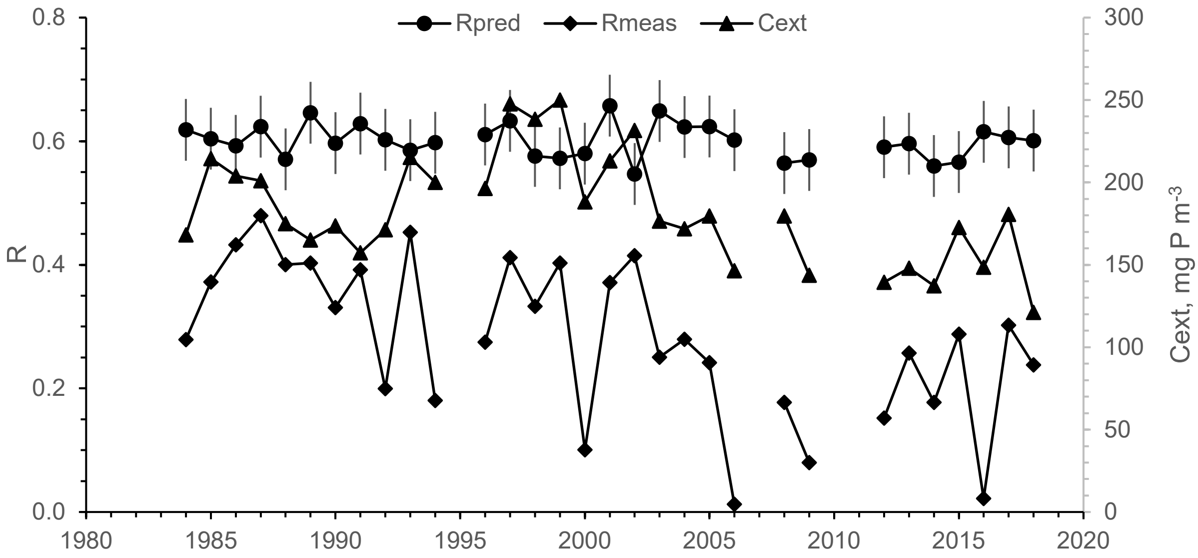


Fig. 2. The variation of Rpred, Rmeas and Cext in Lough Neagh, 1984-2018. The error bars represent an uncertainty in Rpred of ±0.05.

Rpred varied little, being influenced only by relatively small changes in qs/τ_w, while Rmeas was quite variable. It tended to be smaller from 2003 onwards, with an average of 0.357±0.0298 between 1984-1994, 0.330±0.0427 between 1995-2002 and 0.191±0.0274 between 2003-2018 (Table 1 Section 3 Supplementary materials). The reasons for this change are investigated in the Discussion.

In relation to the budget, described fully in Section 3 Supplementary materials, some features can be noted. First, the variations in Input load are mainly determined by changes in the annual inflow volume. Second, it follows that the Input and Output loads decrease as τ_w increases, although there is always substantial variability at a given τ_w value. Finally, even with the variability in Input, Output and Retained loads, there were three periods during which Input load, Cext, Obs C, Rpred, Rmeas, Net Cint_2 and τ_w were different but relatively constant, 1984-1994, 1995-2002 and 2003-2018 (Table 1 Section 3 Supplementary materials).

As the model is Predicted C = Cext(1-Rpred) + Net Cint_2 (Eqn. 1), Fig 3 shows how the relative contributions of the net external and net internal loads to the lake water concentration vary. Both contribute, with external load more important up to 1999, generally equal afterwards. There were rapid year to year variations in both contributions, particularly between 1991 and 1994, 1998-2003 and 2014-2017 and especially with internal load. The variations in internal load were mainly caused by changes in Rmeas (Fig. 2), as Net Cint_2 = Cext(Rpred-Rmeas), with Rpred relatively constant and Cext intermediate (Fig. 2).

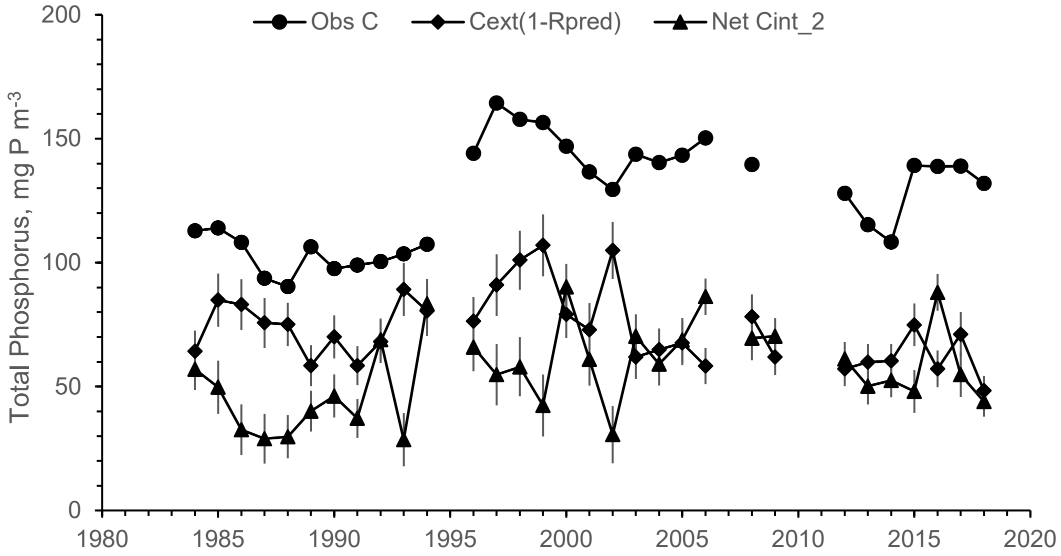


Fig. 3. The variation of Obs C, Cext(1-Rpred) and Net Cint_2 in Lough Neagh, 1984-2018. The error bars represent the effect of an uncertainty in Rpred of ±0.05.

The reason for these rapid changes in Net Cint_2 and Rmeas (1991-1994, 1998-2003, 2014-2017) is likely to the lake not being at steady state with changing Input phosphorus load. First, the overall average τ_W is 1.30 yr (Section 3 Supplementary materials), larger than the criterion of <0.6-0.8 yr suggested for steady state. Second, a detailed analysis of the changes in Rmeas and Input phosphorus load (Section 4 Supplementary materials) shows that the reductions in Rmeas coincide with a rapid change in the Input load eight out of ten times during these three periods.

3.3. Lough Neagh phosphorus model and supporting Cext

The relationship between Obs C and Predicted C, 1984-2018, is shown in Fig. 4. The correlation coefficient is 0.616 ($p<0.001$), with a mean and median error (Obs C-Predicted C) of -2.3 and 0.28 mg P m^{-3}. While there is almost no bias over the 30 years of predictions, the error is relatively large (>20 mg P m^{-3}) in 1992, 1994, 2000 and 2018. The first three years fall within two of the periods of rapid changes in Rmeas and Net Cint_2, 1991-1994, 1998-2003, and the fourth is close to the third period (2014-2017). In 2018, the Predicted C (92.2 mg P m^{-3}) and Cext(1-Rpred) (48.3 mg P m^{-3}) were the lowest in the monitoring period, while Obs C was not unusual (Fig. 3), leading to the large error. Omitting these four years, the correlation coefficient becomes 0.860 ($p<0.001$) and the mean and median errors 0.21 and 2.2 mg P m^{-3}.

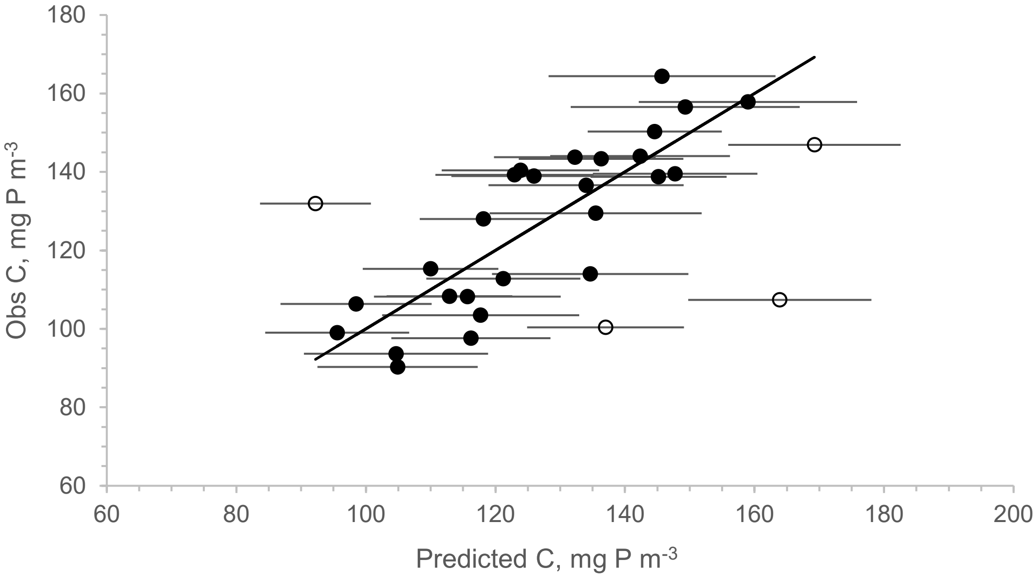


Fig.4. Relationship between Annual Obs C and Predicted C in Lough Neagh, 1984-2018, based on the lake phosphorus model in Eqn. 1. The error bars are the propagation of the errors for external load (Cext(1-Rpred)) and net internal load (Cext(Rpred-Rmeas)) based on the effect of an uncertainty in Rpred of ±0.05. The unity line is shown and the open circles are 1992, 1994, 2000 and 2018.

The main evidence available to support this model is another estimate of the internal load. The *in situ* P increase method (Cint_1) method was applied and the value compared to the results from the phosphorus mass balance method (Net Cint_2) (Fig. 3). Gibson et al. (2001), in a description and analysis of the internal phosphorus load in Lough Neagh 1974-1997, presented the variation of monthly mean Obs C values for 1995. During the summer, Obs C increased from 70 mg P m^{-3} in June to 200 in September, an increase of 130 mg P m^{-3}. This *in situ* P increase should lie between the gross and net concentration, but if it is taken to be gross, then Net Cint_1 = (1-Rpred)Gross Cint_1. The inflow was missing for one catchment in 1995, so no qs value is available, but the mean of 1994 and 1996 was used for Rpred (0.604), giving a Net Cint_1 of 51.5 mg P m^{-3}. A Net Cint_2 value is missing for 1995, and the values fluctuate between 28.6 (1993), 83.4 (1994), 65.9 (1996) and 54.8 (1997), but the mean (58.2 mg P m^{-3}) is close to the Net Cint_1 value of 51.5, a 13 % difference. This relatively small difference allows us to take the Cint_1 value in Lough Neagh to be an estimate of the gross internal load. Similar analysis of other years would provide additional evidence on the nature of the internal load derived by the *in situ* P increase method in Lough Neagh.

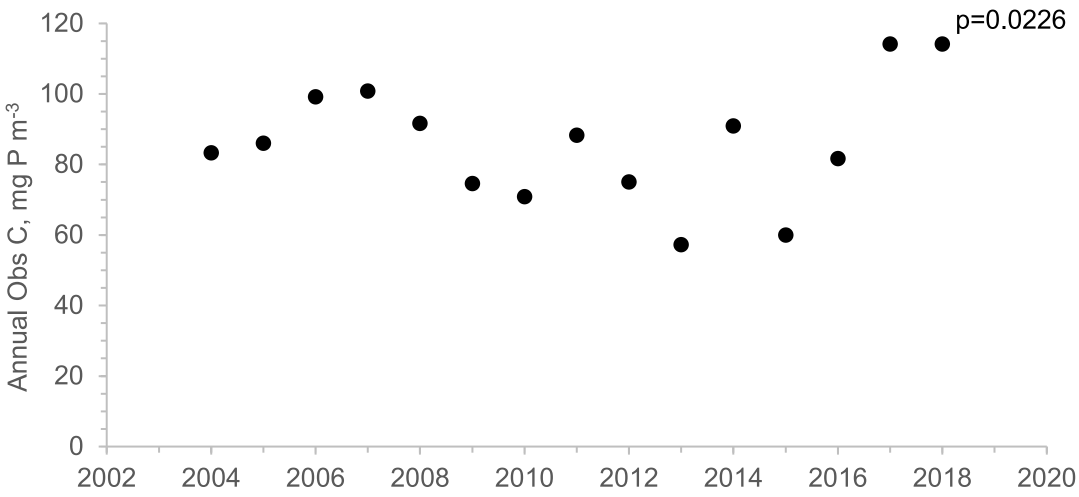
With this support for the phosphorus model for Lough Neagh, it can be used to derive the Cext value that supports the (geometric) mean total phosphorus concentration at the Good/Moderate (G/M) boundary with no or a naturally low net internal phosphorus load. Lough Neagh is on the boundary between a clear water and a coloured lake, so the G/M boundary could be 24 or 44 mg P m^{-3}, respectively. Based on Eqn. 1, with Net Cint_2 of zero and the mean Rpred for 2003-2018 of 0.597 (Table 1 Section 3 Supplementary materials), uncertainty ±0.05, the supporting Cext concentrations are 60±6.6 (±11 %) and 109±0.22.1 (±20 %) mg P m^{-3}. A lake at the boundary between two classes always needs further assessment, but Lough Neagh on the boundary between a clear and coloured water lake has a large effect on the targets for the lake and inflow.

As the value of Rpred is central to the model (Eqn. 1), we used an uncertainty in Rpred of ±0.05 (Fig. 2) to indicate its influence on the estimates of the net external and net internal loads (Fig. 3). The uncertainties are not large compared to the values of the properties and the magnitude of the changes. When the errors are combined in the model, as Lough Neagh has a substantial internal load in its current state, the uncertainty is larger (Fig. 4).

3.4. The other lakes

These 19 lakes do not have phosphorus budgets so the monitoring results were used to describe the long-term change in Annual Obs C and the long-term annual cycle of Monthly Obs C. The full results are presented in Section 5 Supplementary materials, with two representative examples shown in Fig. 5 and 6. For each lake, the G/M total phosphorous boundary was derived, depending on whether it is clear or coloured water, and the Cext value that supports it was calculated using two models, Eqn. 1, with a Net Cint of zero and an uncertainty in Rpred of ±0.05, and Eqn. 2.

There was little change in the Annual Obs C in Stoneyford, although a suggestion of an increases from 2017 (Fig. 5), but the long-term (2004-2018) average concentration (mean of the Annual Obs C) is 85.9 mg P m^{-3}. There is clear evidence of a summer increase in concentration, due to an internal load, from which a Cint_1 value of 95.0 mgP m^{-3} can be estimated. It is a coloured water lake with a G/M boundary of 21 mg P m^{-3} and the supporting Cext value is 42±4.3 mg m^{-3} with Eqn 1 and 29 mg P m^{-3} with Eqn. 2.



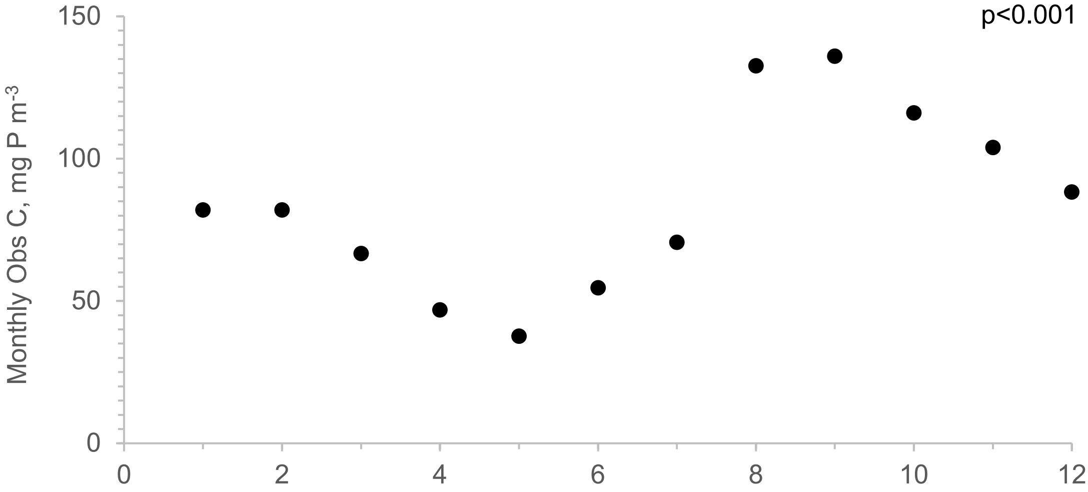


Fig. 5. The variation of annual mean total phosphorus concentration (Annual Obs C) in Stoneyford, 2004-2018, and of the long-term average monthly concentration (Monthly Obs C). The significance (p) of a one-way ANOVA is shown. τ_w is 0.44 yr and z 5.2 m.

The was no change in the Annual Obs C in Lough Ross, giving a long-term average concentration of 63.6 mg P m^{-3}, and there is no evidence for a summer increase in concentration (Fig. 6). It is a coloured water lake with a G/M boundary of 37 mg P m^{-3} and the supporting Cint is 45±2.7 mg m^{-3} with both Eqn, 1 and Eqn.2. Unlike Stoneyford, the two models give identical supporting Cext values, but this is may be due to the lake's short τ_w time (0.08 yr compared to 0.44 in Stoneyford) increasing the Predicted C in the Khorasani & Zhu model (Section 1 Supplementary materials), and consequently producing a larger Cext value.

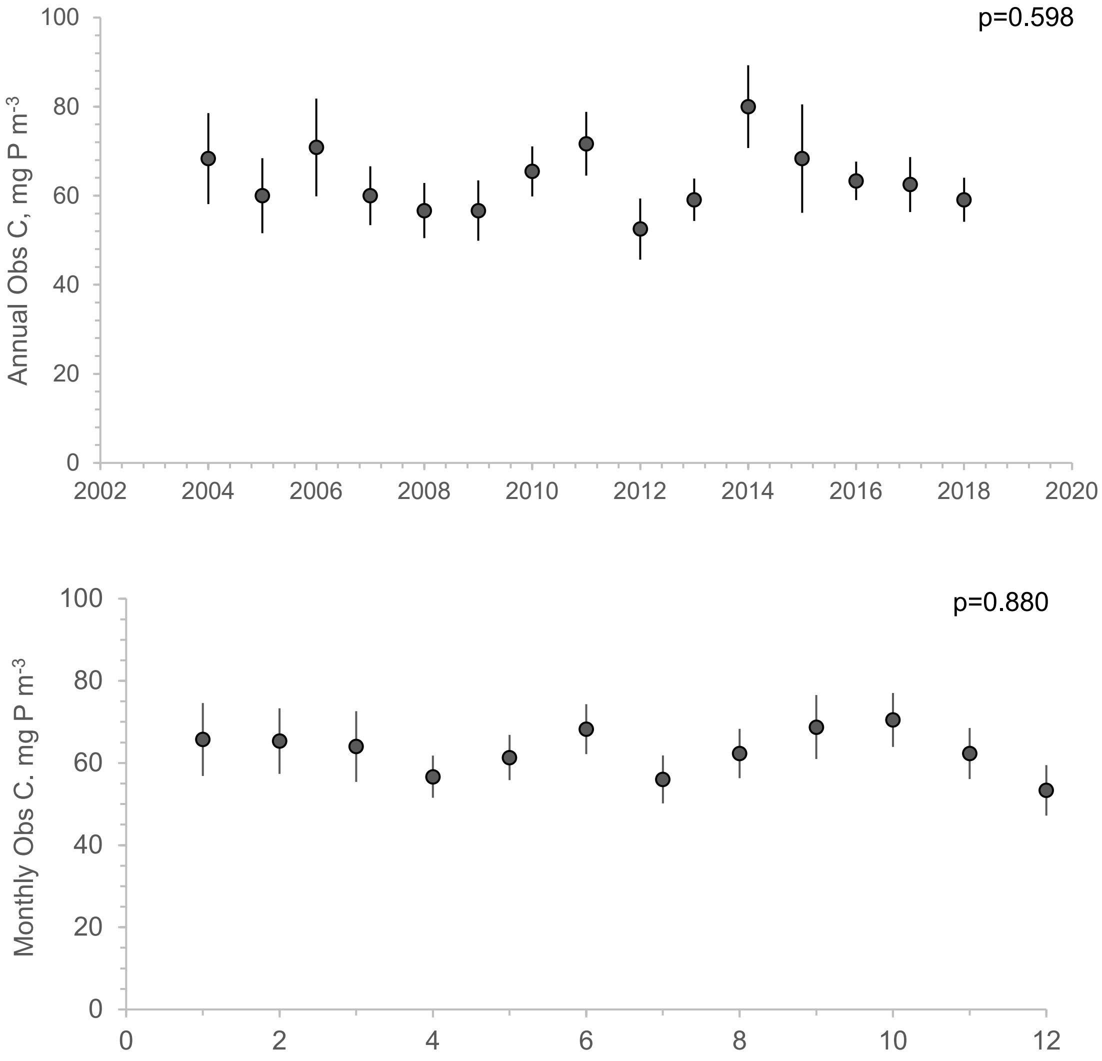


Fig. 6. The variation of annual mean total phosphorus concentration (Annual Obs C) in Lough Ross, 2004-2018, and of the long-term average monthly concentration (Monthly Obs C). The significance (p) of a one-way ANOVA is shown. τ_w is 0.08 yr and z 5.6 m.

Table 2 summarize the results for the 19 lakes; note two sites are used for Lower Lough Erne. Eleven lakes have no internal load (Cint_1), eight have, varying from 8.3 mg P m^{-3} in Lough Island Reavy to 327.5 in Portmore, but typically 20-60 mg P m^{-3}. The G/M boundary concentration varies from 15 mg P m^{-3} in Island Reavy to 65 in Gullion, with a mean of 37.3 mg P m^{-3}, median 36. Five lakes have G/M values greater than 50 mg P m^{-3}. They are coloured water, shallow ($z<2.4$ m) lakes with alkalinities greater than 1.2 meq L^{-1}, all of which increase the reference concentration (WFD-UKTAG 2016). Lough Beg is a widening of the Lower River Bann outlet of Lough Neagh and is omitted from further analysis. There are two other linked lake systems. Upper Lough MacNean (G/M boundary 37 mg P m^{-3}) flows into Lower Lough MacNean (G/M boundary 53 mg P m^{-3}) and so achieving the quality target in the Upper Lough should lead to that in the Lower Lough as well. Similarly, Upper Lough Erne (51 mg P m^{-3}) flows into Lower Lough Erne A and B (36 mg P m^{-3}), but, as the lower lake is deeper its G/M boundary concentration is lower.

The Cext values that support the G/M boundary concentrations, in the absence of an internal load, vary from 28±2.1 to 80±10.2 mg P m^{-3}, except for Clea Lakes (148±21.1), Gullion (336±93.2) and Portmore (134±14.5). They all have boundary values greater than 50 mg P m^{-3} and higher (0.536-0.807) than the average Rpred value (0.494), both of which increase the supporting Cext concentration. The effect of the uncertainty in the Rpred value is relatively small in most of the lakes, only over ±20 % in two, Gullion (±28 %, Rpred 0.807) and Island Reavy (±21 %, 0.748). Both have high Rpred values, which lead to low (1-Rpred) values, where that the influence of a fixed uncertainty on the Cext is greatest. Ignoring these two lakes, the mean (n=17) error is 9.7 %, median 9.3, minimum 6.0, maximum 14.

The only support for the model (Rpred value) in these lakes was the predictions of another model, Model 28 Khorasani & Zhu (2021). As it contains some and unknown contributions from internal load, the supporting Cext values should be lower. The difference (Eqn. 1, with Net Cint_2 of zero, minus Khorasani & Zhu) is over 50 mg P m^{-3} in three lakes (Clea lakes 65, Gullion 226, Portmore 64), which have high G/M boundary concentrations. Omitting these, the mean difference (n=16) is 12 mg P m^{-3}, median 14, minimum -9 (Lower Lough

Erne), maximum 35 (Fea). There is little basis to determine if these differences are sufficient to support the Rpred values, but, at least, they are not large for most of the lakes.

Table 2. The total phosphorus concentration at the Good/Moderate (G/M) boundary, theoretical hydraulic residence time (τ_w), measured mean depth, long-term (1999- or 2004-2018) or recent measured average total phosphorus concentration (Obs C), *in situ* P increase and the supporting inflow concentration (Cext) that supports the G/M boundary concentration according to two lake phosphorus models. An uncertainty in R of ±0.05 was used with the Nurnberg model and is shown in brackets. The timescale of recovery is selected using the criteria in Section 4.3.

Lake	G/M boundary, mg P m^{-3}	Theoretical τ_w, yr	Mean depth, m	Obs C, mg P m^{-3}	*In situ* P increase, mg P m^{-3}	Modelled supporting Cext, mg P m^{-3}		Timescale, yr
						Nurnberg (1984) R7	Model 28 Khorasani & Zhu (2021)	
Beg	63	Note 1	2.0	136.5	51.4	---	---	Rapid
Cam	18	0.76	5.4	59.6	20.5	45±5.6	26	8 to 18
Castlehume	28	0.24	3.1	33.3	None	55±5.	36	0.55
Clea Lakes	53	0.41	2.2	44.5	42.9	148±21.1	83	8 to 18
Lower Erne		0.33	11.9					0.76
Devenish	36			63.3	None	50±3.5	59	
Ross Harbour	36			45.8	None	50±3.5	59	
Upper Erne	51	0.08	2.3	65.1	None	75±5.6	76	0.18
Fea	32	0.40	2.8	23.6	None	80±10.2	36	0.92
Gullion	65	1.01	0.6	253.3	60.9	336±±93.2	74	8 to 18
Island Reavy	15	3.82	7.8	30.3	8.3	60±12.3	23	8.8
Upper MacNean	37	0.3	4.4	32.3/23.9 Note 2	None	68±6.3	54	0.69
Lower MacNean	53	0.04	1.4	59.9/31.9 Note 2	None	74±5.2	58	0.09

Melvin	40	1.05	8.3	17.0	None	95±11.4	83	2.42
Mourne	20	0.80	5.4	63.2	60.4	51±6.5	31	8 to 18
Portmore	62	0.07	0.7	433.0	327.5	134±14.5	70	8 to 18
Ross	37	0.08	5.6	63.6	None	45±2.7	45	0.18
Scolban	35	0.47	7.8	35.8	None	62±5.5	58	1.08
Silent Valley	19	0.26	7.4	24.2	None	28±2.1	25	0.63
Spelga	24	0.41	6.5	26.8	None	43±3.9	35	0.94
Stoneyford	21	0.44	5.2	85.9	95.0	42±4.3	29	8 to 18

Note 1. Lough Beg is a widening of the Lower River Bann River exit of Lough Neagh and so its total phosphorus concentration should be identical to Lough Neagh's.

Note 2. Where open lake samples were available, as well as shore samples, the average concentration of shore/open lake are given.

Note 3. With a small and uncertain internal load (8.3 mg P m^{-3}) and a long τ_w value (3.82 yr), a t_{90} of $2.303\tau_w$ was used.

3.5. Time to reduce the internal phosphorus load

The detailed results collated are provided in Section 6 Supplementary materials, with a summary in Table 3. It illustrates the uncertainty of the estimates, e.g. more than 5-8 years, over 10 years etc., and there was no relationship between the time and either Start Cext, End Cext or the change. The estimates are relatively imprecise, as factors such as how quickly and by how much the external load was reduced, the frequency and length of the monitoring, length of the initial eutrophication of the lake, size of the internal load, etc. could affect the time and will vary from lake to lake. However, there is a broad tendency to three values, approximately 8 (<6 to 10) yr, 14 yr (12 to 16) or 20 yr (Fig. 7); the average (n=21) is 12.2 yr, 7.6 yr for those lakes (n=11) with time <11 yr and 17.2 for those lakes (n=10) with a time 12 yr or more.

Table 3. Summary of the findings of the observed decrease in internal phosphorus load in lakes. The hydraulic residence time (τ_w), hydraulic load (qs), time period of results, annual average inflow concentration (Cext) at the start and end of the period and the time for the internal load to decrease are given. If a range of τ_w and qs values are available, the ranges are given.

Lake	τ_w, yr	qs, m yr^{-1}	Time period	Cext at start and end, mg P m^{-3}	Time for internal load to decrease	Reference
Shagawa Lake	0.52-1.2	4.5-10.9	1971-76	72 & 21	5-6 years	1
Oxundasjon	0.15	22.5	1979-75	844 & 93	More than 5-8 years	2
Edssjon	0.18	16.8	1970-75	655 & 131	More than 5-8 years	2
Norrviken	1.1	4.7	1969-78	321 & 74	5-8 years	2
Lake Washington	1.7-3.1	10.5-19.4	1962-78	162-48	7-13 years	3
Mondsee	1.7	21.2	1978-89	51 & 22	Small internal load reduced over 9 years	4
Lake Pyhajarvi	3.0	1.8	1980-92	78 & 78	No internal load	5
Grundsomagle	0.08	15.0	10 years	3079 & 180	15 or more years	6
Albufera	0.1	12.0	10 years	1843 & 421	15 or more years	6
Eemmeer	0.05	34.0	15 years	1224 & 281	15 to 20 years	6
Gooimeer	0.16	21.9	15 years	1008 & 336	Over 10 years	6
Arreso	2.2	1.4	10 years	1167 & 236	13-14 years	6
Vesterborg	0.05	26	5 years	245 & 116	More than 5 years	6
Barton Broad	0.045	33.3	15 years	364 & 97	15 years	6
Sogard	0.05	32.0	10 years	318 & 196	Internal load increased over 10 years	6
Okeechobee	2.7	1.0	20 years	581 & 238	Internal load increased from year 10-20	6
Ornso	0.05	80.0	10 years	208 & 110	Small internal load recovering in 20 years	6
Vortsjarv	1.0	2.8	10 years	240 & 48	Internal load developed in last 5 years	6
Galten	0.05	68.0	20 years	67 & 29	Internal load maintained for 20 years	6

Bryrup	0.15	30.7	10 years	132 & 101	Internal load only at the start, so rapid (5 yr) reduction	6
Loch Leven	0.42	9.3	1975-2005	135 & 154	Internal load began after 1985, maintained and reduced up to 2008. Responds rapidly (few years). Little reduction in Cext	7
Muggelsee	0.12-0.23	21.2-42.6	1979-2016	149 & 67	Internal load between 1982 and 2015 changes rapidly (few years) to changes in lake concentration	8
Lake Apopka	2.5	0.64	1989-2002	1563 & 344	Increasing, small internal load from 1992 to 2002, so more than 10 years	9

Baddeggersee (τ_w 4.2 yr), Sempachersee (16), Hallwillersee (3.9) and Pfaffikersee (2.2) are all calcareous lakes and had reductions in Cext of 40, 30, 66 and 75 %, while Obs C decreased by 95, 80, 90 and 90 %, respectively (Muller et al 2014). The models used the sedimentation coefficient and it was variations in σ that mainly determined Obs C. As Obs C changed over a 30 year period, it is difficult to establish how quickly s changed. However, the rate of change of s with Obs C increases as Obs C falls below 60-80 mg L^{-1}. 1 Larsen et al. (1979). 2 Ahlgren (1980). 3 Edmondson & Lehman (1981). 4 Dokulil & Jagsch (1992). 5 Ekholm et al. (1997). 6 Jeppesen et al. (2005). 7 Spears et al. (2012), May et al. (2012) and Bailey-Watts & Kirika (1999). 8 Shatwell & Kohler (2019) and Kohler et al. (2005). 9 Coveney et al. (2005)

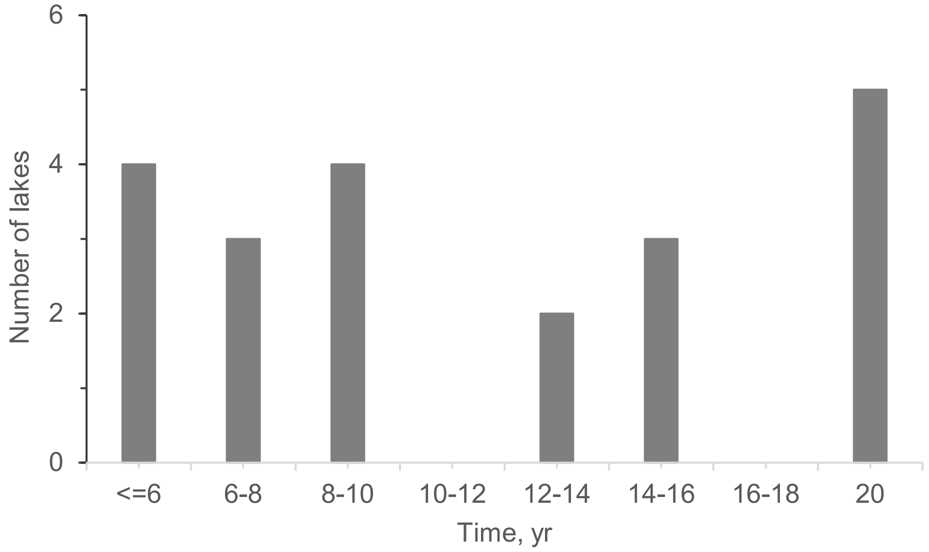


Fig. 7. Frequency distribution of the observed time for the internal load to reduce in 21 lakes (Table 3).

4. Discussion

The main aim of the research was to apply and evaluate the framework, model and methods of Nürnberg in order to derive an inflow phosphorus concentrations that support target lake concentrations, using Lough Neagh and 19 other smaller lake as examples. In the evaluation, the uncertainties in estimating the lake concentration from the external and internal loads were estimated and we also identified the conditions under which a typical CSTR model is at steady state and collated results to provide direct evidence of the time it takes for the internal phosphorus load to reduce.

4.1. Nürnberg's framework, model and methods

The framework to separate the contributions of the external and internal loads to the lake phosphorus concentration was clear to understand, the CSTR lake model is well established and the methods used to estimate the internal load were easy to apply. Generally, steady state conditions are assumed, but we identified using a generic CSTR lake model that it is not likely if τ_w>0.5-0.8 yr and should lead to a decrease in Rmeas for one or more years, compared to the steady state value (Section 3.1). We found this behaviour in Lough Neagh, where there were rapid changes in Rmeas during 1991-1994, 1998-2003 and 2014-2017 when the lake was not at steady state with a changing Input phosphorus load (Section 3.2). Averaging results is recommended when applying these models (Nürnberg 2009).

The value of Rpred is key in the lake model (Eqn. 1) and so we included a fixed uncertainty (Fig. 2) in estimating the net external and net internal loads (Fig. 3). The uncertainty is small compared to the load values and their variation, but a little larger when the external and internal loads are combined in the model (Fig. 4). However, as there are also uncertainties in estimating Cext and Rmeas when calculating the loads, its influence may not be the most important. We also provided some additional support for the model in Lough Neagh (4.1.1) and the other lakes (4.1.2).

4.1.1. Lough Neagh

The Lough Neagh phosphorus model reproduced the variation of annual mean Obs C over 1984-2018 period well, with mean and median errors of -2.3 and 0.28 mg P m^{-3}, respectively (Section 3.3). While this is not an independent assessment of the model, it does provides some evidence that it can be used to derive a Cext that supports a target lake concentration.

There was evidence to support the lake model, in the agreement between two estimates of the internal load, 51.5 and 58.2 mg P m^{-3} (Section 3.3). The difference, 13 %, is relatively small and provides support for the lake model. Foy et al. (2003) reconstructed the phosphorus budget for Lough Neagh, 1840-2000, using the diatom and chironomid record in sediment cores and a contemporary budget, identified that sediment release began in the 1960s and estimated it to be at least 36 mg P m^{-3}. If this is taken to be net release and that it would increase as eutrophication of the lake developed, then this is some further support for the Net Cint_2 values in Fig. 3.

4.1.2. The other lakes

The water column monitoring results were used to establish long-term trends and if there was an internal load, which was estimated using the *in situ* P increase method (Cint_1). Cext values that support the target concentrations were able to be derived (Table 2).

The only support for the model was to use another lake model (Model 28 of Khorasani & Zhu 2021) to derive supporting Cext values; these should be lower, as that model includes variable contributions from internal load. For most of the lakes (16 out of 19), the values were an average of 12 mg P m^{-3} lower (Section 3.4), which lends some general support to the Rpred values used in Eqn. 1 for these lakes.

4.2. Time to reduce the internal load and reach steady-state concentration

The model is a steady state one and only indicates the time it would take the lake adjust to it external load based on the hydraulic residence time. If there is an internal load, which is common in lakes needing remediation, the time it takes for it to reduce is also involved. Based on observational evidence, there is a general tendency for it to be either approximately

8 (<6 to 10) yr, 14 yr (12 to 16) or 20 yr (Fig. 7). These values are similar to the one to three decades summarized by Rippey et al. (2021) from a compilation of evidence from models and observations. A better basis to choose a time for internal load reduction in a lake is desirable, but, in the absence of a direct estimate of 8 to 20 yr can be suggested. If there is no or little internal load, then the time to the new steady-state concentration would be determined by τ_w, with $t_{90} = 2.303\tau_w$. These two rules were used to select the time to steady state in the 19 lakes (Table 2).

4.2.1. Lough Neagh

The t_{90} value for the internal phosphorus load to reduce in Lough Neagh has been estimated by applying the Lewis/Penn model to five sediment cores (Rippey et al. 2021), varing from 15 to 23 yr, mean 20.6. As the mean τ_w is 1.30 yr, the time to reach the target lake concentration of 24 or 44 mg P m^{-3} should be determined mainly by the reduction in internal load, so around 21 years. Fig. 8 shows the modelled change in lake phosphorus concentration to reductions in the inflow concentration for three values of net internal load, as the current value reduces to a half and one tenth over 21 years. As advised (Nürnberg 2009), average values were used to apply the model (Eqn. 1); the 2003-2018 mean Rpred is 0.597, Net Cint_2 63.3 mg P m^{-3} and Cext 159 mg P m^{-3} (Table 1 Section 3 Supplementary materials). An uncertainty in Rpred of ±0.05 was applied.

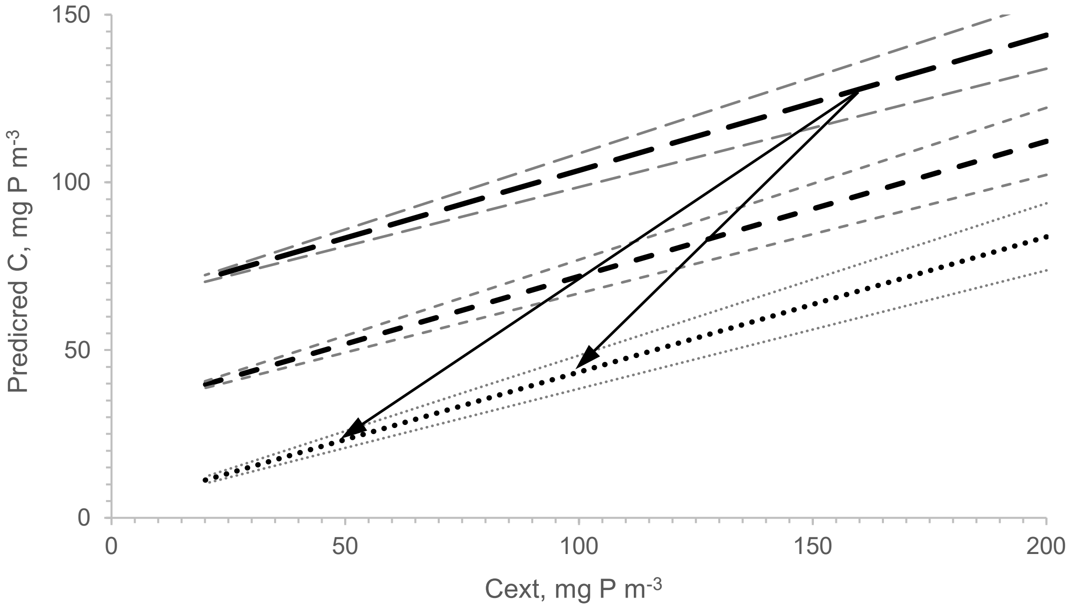


Fig. 8. The variation of steady-state lake total phosphorus concentration predicted by Eqn. 1 (Predicted C) with inflow concentration (Cext) for three values of net internal load, full Net Cint_2 (2003-2018 average of 63.3 mg P m^{-3}) (long dash), half (intermediate dash) and a tenth (short dash). The error due to an uncertainty in Rpred of ±0.05 is shown and the 2003-2018 average Rpred value (0.597±0.05) was used. The arrows indicate the change in Predicted C as Cext is reduced and Net Cint_2 reduces to one tenth of the current value over 21 yr.

The model indicates that the internal load needs to be reduced considerably, approaching one tenth of the current value, to be able to achieve either G/M boundary concentration. The main uncertainty is how the internal load reduces as Cext/Obs C (or net phosphorus sedimentation) decreases as a result of reductions in Cext. Katsev et al. (2006) found unstable predictions of the long-term efflux of phosphorus from sediment in their diagenetic model when return of phosphorus from the water was included. More understanding of this link is desirable, but we can note that there is some consistency in the time for the internal load to reduce in the 21 lakes in Fig. 7, even though there is great variety in their eutrophication history, size, depth, how much and how quickly the external load was reduced, etc.

4.2.2. Other lakes

The t_{90} times for the lakes given in Table 2 were selected using the two criteria established in Section 4.2. Eight of the lakes have internal loads (Beg, Cam, Clea Lakes, Gullion, Island Reavy, Mourne, Portmore, Stoneyford) and without direct information on the rate of reduction of internal load in them, there is uncertainty in their response time. At present, this is given as 8 to 20 years, except for Lough Island Reavy. That lake has a small internal load of 8.3 mg P m^{-3} and a long τ_w value (3.82 yr), so the 2.303τ_w criterion was applied. The remaining lakes should respond according to the 2.303τ_w values.

4.3. Recovery of Lough Neagh

The modelled recovery of Lough Neagh (Fig. 8) indicates the response of the lake concentration to reductions in the inflow concentration and net internal load. In addition to the uncertainty about how the internal load responds to reduction in inflow/lake concentration, there are two further considerations for the recovery of the lake; change in the lake phosphorus cycle from 2003 and the influence of phosphorus and nitrogen on chlorophyll *a*.

4.3.1 Change in the lake phosphorus cycle

The reduction in Rmeas from 0.330 during 1995-2002 to 0.191 in 2003-2018 (Section 3.2) represents a considerable change in the lake phosphorus cycle, and the evidence suggests that it was a consequence of the earlier depletion of total oxidized nitrogen (TON, nitrate/nitrite) in the water column (McElarney et al. 2021). Once the sequence of mineralization of organic matter in the sediment moved from TON, after its depletion in the water column, to Mn(IV), then Fe(III), etc. (Froelich et al. 1979; Wersin et al. 1991), the release of phosphorus sorbed to iron oxyhydroxide from the sediment began earlier. There is no direct evidence for this sequence in the Lough Neagh sediment but there is for other lakes (Wersin et al. 1991; Park & Jaffe 1999; Hemond & Lin 2010; Smith et al. 2011). Further, movement of high soluble reactive phosphorus concentrations towards the sediment surface has been observed in Lake Okeechobee (Moore et al. 1998) and increases of soluble reactive phosphorus concentration along with soluble iron and especially manganese have been observed in the upper sediment layers of Lake Vallentunasjon (Lofgren & Bostrom 1989).

There is, however, indirect evidence to support this release mechanism in Lough Neagh. First, the redox potential at four sediment depths, from March to October, 1979, shows a sudden decrease in mid-July even at 10 mm, indicating that release of phosphorus was likely (Rippey & Jewson 1982); Gibson et al. (2001) measured a release of 80 tonnes P in July 1979. The results for 1983 show similar behaviour, with a decrease in July, even temporarily at the sediment surface (Section 9 Supplementary materials); the release was 140 tonnes P in July 1983 (Gibson et al. 2001). Second, the seasonal cycle of iron, manganese and soluble reactive phosphorus in the water column of Lough Neagh, 1983 (Section 7 Supplementary materials), is similar to that described by Mayer et al. (1982) in the hypolimnion of hypereutrophic Lake Sebasticook. As mineralization proceeds to produce first soluble Mn and then Fe, the concentration of soluble reactive phosphorus increases, more closely associated with Mn than Fe. The increase of Fe in Lough Neagh is not as great as that observed in Sebasticook, probably as there is still a thin oxic layer in the sediment, compared to full anoxia in the hypolimnion of Sebasticook.

4.3.2 Influence of phosphorus and nitrogen on chlorophyll *a*

Whether achieving the target inflow and lake phosphorus concentrations alone will lead to a desired chlorophyll *a* concentration needs consideration of the relative influence of nitrogen and phosphorus on biological productivity (Lewis Jr et al. 2011; Schindler et al. 2016; Paerl et al. 2016). The chlorophyll concentration has been reducing Lough Neagh since the mid-1990s, as a result of a lower nitrogen input load and lake concentration (McElarney et al. 2021; Elliott et al. 2015). This is a result of catchment based nutrient management measures under the Northern Ireland Nitrates Action Plan; this outlines seasonal and mass controls on fertilisers in addition to restrictions on land types that can receive fertilisers and failure to comply with such measures can result in financial penalties. If the trend continues, further decreases in chlorophyll would be expected.

Action to reduce nitrogen inputs has been successful, whereas it is more difficult to reduce phosphorus inputs from the large catchment and there is also the influence of the internal phosphorus load on the lake concentration. Whether further action to reduce nitrogen or phosphorus inputs or both depends on the reduction in chlorophyll expected and the relative ease of reducing the inputs. A reduction in lake phosphorus concentration is, however, needed to reduce the internal load.

Some indication of the response of chlorophyll to combinations of lake total phosphorus and TON concentrations can be provided by using chlorophyll-nutrient models (Table 4). As no Correction Factors are available for the models, a typical value of 1.15 was used, or the untransformed values could be considered geometric means. Table 4 was generated using the following values: observed 2003-2018 mean total phosphorus concentration of 135 mg P m^{-3}, 72 in the absence of an internal load, 44 and 24 the target values for a colored and clear water lake; observed 2003-2018 mean TON concentration of 294 mg N m^{-3} and 100 which could be produced if the current reductions continue. The observed 2003-2018 mean chlorophyll *a* concentration is 43.4 mg m^{-3}.

Table 4. The chlorophyll *a* concentration in Lough Neagh predicted by four models, for combinations of total phosphorus and total oxidized nitrogen values. Model 1 is Prairie et al. (1989) Eqn 3, based on N and P; Model 2 Prairie et al. (1989) Table 2, based on P and N/P ratio; Model 3 Phillips et al. (2008) Eqn. 3, based on N and P; Model 4 Phillips et al. (2008) Eqn. 6, based on P for high alkalinity shallow lakes. The predicted values could be considered geometric means and the values in brackets are adjusted for bias. The TP/TON (mass) ratio is given.

TP, mg P m^{-3}	TON, mg N m^{-3}	TP/TON (mass)	Model 1	Model 2	Model 3	Model 4
135	294	2.18	9.1 (10)	25.0 (29)	28.8 (33)	34.9 (40)
72	294	4.08	6.5 (8)	16.7 (19)	17.5 (20)	20.2 (23)
44	294	6.68	5.1 (6)	12.2 (14)	11.8 (14)	13.2 (15)
24	294	12.3	3.7 (4)	6.9 (8)	7.3 (8)	7.8 (9)
135	100	0.74	3.7 (4)	25.0 (29)	20.3 (23)	34.9 (40)
100	100	1.00	3.1 (4)	20.6 (24)	16.0 (18)	26.9 (31)
80	100	1.25	2.8 (3)	17.9 (21)	13.4 (15)	22.2 (26)

Model 1 does not reproduce the chlorophyll concentration, the other models are better predictors, with values of 29-40 mg m^{-3}, compared to the observed 43.4, and Model 4 the closest. A decrease of chlorophyll to 14-15 and 8-9 mg m^{-3} as phosphorus is reduced to 44 and 24 mg P m^{-3} is predicted. Reducing TON to 100 mg N m^{-3} is predicted to not affect the chlorophyll at the current total phosphorus concentration and only reduce it a little even if it decreases (18-31 and 15-26 mg m^{-3} for total phosphorus of 100 and 80 mg P m^{-3}). For all of the nitrogen and phosphorus combinations, except total phosphorus of 24 mg P m^{-3}, the N/P (mass) ratio still indicates nitrogen deficiency, based on phosphorus deficiency above 23 and nitrogen deficiency below 9 (Guildford & Hecky 2000). Even at the lowest phosphorus concentration, there is still no phosphorus deficiency, with both nutrients influencing the chlorophyll concentration. Further assessment is required to determine the influence of nitrogen and phosphorus on chlorophyll and other biological properties and the catchment actions needed to reduce the nutrient input loads.

The predictions of these empirical models are most accurate for lakes with typical relative concentrations of nitrogen and phosphorus. Lough Neagh, however, has an unusual relationship, as the 2003-2018 averages, 135 mg P m^{-3} for total phosphorus, 294 mg N m^{-3} for total oxidized nitrogen and 43.4 mg m^{-3} for chlorophyll *a*, place it well outside the scatter plot of European lakes (Poikane et al. 2022).

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ahlgren, I. 1980. A dilution model applied to a system of shallow eutrophic lakes after diversion of sewage effluents. Archiv fur Hydrobiologie 80, 17-32.

Arhonditsis, G.B. and Brett, M.T. 2004. Evaluation of the current state of mechanistic aquatic biogeochemical modeling. Marine Ecology Progress Series 271, 13-26.

Bailey-Watts, A.E. and Kirika, A. 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.

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

Bunting, L., Leavitt, P.R., Gibson, C.E., McGee, E.J. and Hall, V.A. 2007. Degradation of water quality in Lough Neagh, Northern Ireland, by diffuse nitrogen flux from a phosphorus-rich catchment. Limnology & Oceanography 52, 354-369.

Cardoso, A.C., Solimini, A., Premazzi, G., Carvalaho, L., Lyche, A. and Rekolainen, S. 2007. Phosphorus reference concentrations in European lakes. Hydrobiologia 584, 3-12.

Chapra, S.C. (1997) Surface Water-Quality Modeling, McGraw-Hill, New York.

Cheng, V., Arhonditsis, G. and Brett, M.T. 2010. A revalulation of lake-phosphorus loading models using a Bayesian hierarchical framework. Ecological Research 25, 59-76.

Coveney, M.F., Lowe, E.F., Battoe, L.E., Marzolf, E.R. and Conrow, R. 2005. Response of a eutrophic, shallow subtropical lake to reduced nutrient loading. Freshwater Biology 50, 1718-1730.

Dillon, P.J. and Rigler, F.H. 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. Journal of the Fisheries Research Board of Canada 32, 1519-1531.

Dokuill, M.T. and Jagsch, A. 1992. The effects of reduced phosphorus and nitrogen loading on phytoplankton in Mondsee, Austria. Hydrobiologia 243/244, 389-394.

Edmondson, W.T. and Lehman, J.T. 1981. The effect of changes in the nutrient income on the condition of Lake Washington. Limnology and Oceanography 26, 1-29.

Ekholm, P., Malve, O. and Kirkkala, T. 1997. Internal and external loading as regulators of nutrient concentrations in the agriculturally loaded Lake Pyhajarvi (southwest Finland). Hydrobiologia 345, 3-14.

Elliott, J.A., McElarney, Y.R. and Allen, M. 2016. The past and future of phytoplankton in the UK's largest lake, Lough Neagh. Ecological Indicators 68, 142-149.

Foy, R.H., Lennox, S.D. and Gibson, C.E. 2003. Changing perspectives on the importance of urban phosphorus inputs as the cause of nutrient enrichment in Lough Neagh. The Science of the Total Environment 310, 87-99.

Froelich, P.N., Klinkhammer, G.P., Bender, M.L., Luedtke, N.A., Heath, G.R., Cullen, D., Dauphin, P., Hammond, D., Hartman, B. and Maynard, V. 1979. Early oxidation of organic matter in pleagic sediments of the eastern equatorial Atlantic: suboxic diagenesis. Geochimica et Cosmochimica Acta 43, 1075-1090.

Gibson, C.E., Wang, G., Foy, R.H. and Lennox, S.D. 2001. The importance of catchment and lake processes in the phosphorus budget of a large lake. Chemosphere 42, 215-220.

Guildford, S.J. and Hecky, R.E. 2000. Total nitrogen, total phosphorus, and nutrient limitation in lakes and oceans: Is there a common relationship? Limnology & Oceanography 45, 1213-1223.

Hemond, H.F. and Lin, K. 2010. Nitrate supresses internal phosphorus loading in an eutrophic lake. Water Research 44, 3645-3650.

Jeppesen, E., M., Sondergaard, M., Jensen, J.P., Havens, K.E., Anneville, O., Carvalaho, L., Conveny, M.F., Deneke, R., Dokulil, M.T., Foy, B., Gerdeauz, D., Hampton, S.E., Hilt, S., Llikangur, K., Kohler, J., Lammens, E.H.H.R., lauridsen, T.L., Manica, M., Miracle, M.R., Moss, B., Noges, P., Persson, G., Phillips, G., Portielje, R., Romo, S., Schelske, C.L., Straile, D., Tatrai, I., Willen, E. and Winder, M. 2005. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. Freshwater Biology 50, 1747-1771.

Johnes, P.J. 2007. Uncertainties in annual riverine phosphorus load estimation: Impact of load estimation methodology, sampling frequency, baseflow index and catchment population density. Journal of Hydrology 332, 241-258.

Jones, J.R. and Bachmann, R.W. 1976. Prediction of phosphorus and chlorophyll levels in lakes. Journal of Water Pollution Control Federation 48, 2176-2182.

Katsev, S.I., Tsandev, I., L'Heureux, I.L. and Rancourt, D.G. 2006. Factors controlling long-term phosphorus efflux from lake sediments: Exploratory reactive-transport modeling. Chemical Geology 234, 127-147.

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

Khorasani, H. and Zhu, Z. 2021. Phosphorus retention in lakes: A critical reassessment of hypotheses and static models. Journal of Hydrology 603, 126886.

Larsen, D.P., van Sickle, J., Malueg, K.W. and Smith, P.D. 1979. The effect of wastewater phosphorus removal on Shagawa Lake, Minnesota: phosphorus supplies, lake phosphorus and chlorophyll a. Water Research 13, 1259-1272.

Lerman, A. (1979) Geochemical Processes Water and Sediment Environments, Wiley-Interscience, New York.

Lewis Jr, W.M., Wurtsbaugh, W.A. and Paerl, H.W. 2011. Rationale for control of anthropogenic nitrogen and phosphorus to reduce eutrophication of inland waters. Environment Science & Technology 45, 10300-10305.

Lofgren, S. and Bostrom, B. 1989. Interstitial water concentrations of phosphorus, irn and manganese in a shallow eutrophic Swedish lake-implications for phosphorus cycling. Water Research 23, 1115-1125.

Manno, J., Smardon, R., DePinto, J.V., Cloyd, E.T. and Del Granado, S. 2008 The Use of Models on Great Lakes Decision Making. An Interdisciplinary Synthesis, p. 95, Randolph G. Pack Environmental Institute, Syracuse, NY.

May, L., Defew, L.H., Bennion, H. and Kirika, A. 2012. Historical changes (1905-2005) in external phosphorus loads to Loch Leven, Scotland, UK. Hydrobiologia 681, 11-21.

Mayer, L.M., Liotta, F.P. and Norton, S.A. 1982. Hypolimnetic redox and phosphorus cycling in hypereutrophic Lake Sebasticook, Maine. Water Research 16, 1189-1196.

McElarney, E., Rippey, B., Miller, C., Allen, M. and Unwin, A. 2021. The long-term response of lake nutrient and chlorophyll concentrations to changes in nutrient loading in Ireland's largest lake, Lough Neagh. Biology and Environment: Proceedings of the Royal Irish Academy 121, 47-60.

Moore Jr, P.A., Reddy, K., R. and Fisher, M.M. 1998. Phosphorus flux between sediment and overlying water in Lake Okeechobee, Florida: spatial and temporal variations. Journal of Environmental Quality 27, 1428-1439.

Nürnberg, G.K. 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. Limnology and Oceanography 29, 111-124.

Nürnberg, G.K. 1998. Prediction of annual and seasonal phosphorus concentrations in stratified and polymictic lakes. Limnology and Oceanography 43, 1544-1552.

Nürnberg, G.K. 2009. Assessing internal phosphorus load - Problems to be solved. Lake and Reservoir Management 25, 419-432.

Paerl, H.W., Scott, J.T., McCarthy, M.J., Newell, S.E., Gardner, W.S., Havens, K.E., Hoffman, D.K., Wilhelm, S.W. and Wurtsbaugh, W.A. 2016. It takes two to tango: when and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environment Science & Technology 50, 10805-10813.

Park, S.S. and Jaffe, P.R. 1999. A numerical model to estimate sediment oxygen levels and demand. Journal of Environmental Quality 28, 1218-1226.

Phillips, G., Pietilainen, O.-P., Carvalaho, L., Solimini, A., Solheim, A.L. and Cardoso, A.C. 2008. Chlorophyll-nutrient relationships of different lake types using a large European dataset. Aquatic Ecology 42, 213-226.

Poikane, S., Kelly, M.G., Varbiro, G., Borics, G., Eros, T., Hellsten, S., Kolada, A., Lukacs, B.A., Solheim, A.L., Lopez, J.P., Willby, N.J., Wolfram, G. and Phillips, G. 2022. Estimating nutrient thresholds for eutrophication management: Novel insights from understudied lake types. Science of the Total Environment 827, 154242.

Prairie, Y.T. 1989. Statistical models for the estimation of net phosphorus sedimentation in lakes. Aquatic Sciences 51, 192-210.

Prairie, Y.T., Duarte, C.M. and Kalff, J. 1989. Unifying nutrient-chlorophyll relationships in lakes. Canadian Journal of Fisheries and Aquatic Sciences 46, 1176-1182.

Quevauviller, P., Borchers, U., Thompson, C. and Simonart, T. (2008) The Water Framework Directive. Ecological and Chemical Status Monitoring, John Wiley & Sons Ltd., Chichester.

Rippey, B. and Jewson, D.H. 1982. The rates of sediment-water exchange of oxygen and sediment bioturbation in Lough Neagh, Northern Ireland. Hydrobiologia 92, 377-382.

Rippey, B., Campbell, J., McElarney, E., Thompson, J. and Gallagher, M. 2021. Timescale of reduction on long-term phosphorus release from sediment in lakes. Water Research 2000, 117283.

Schindler, D.E., Carpenter, S.R., Chapra, S.C., Hecky, R.E. and Orihel, D.M. 2016. Reducing phosphorus to curb lake eutrophication is a success. Environment Science & Technology 50, 8923-8929.

Shatwell, T. and Kohler, J. 2018. Decreased nitrogen loading controls summer cyanobacterial blooms without promoting nitrogen-fixing taxa: Long-term response of a shallow lake. Limnology & Oceanography 64, 5166-5178.

Smith, L., Watzin, M.C. and Druschel, G. 2011. Relating sediment phosphorus mobility to seasonal and diel redox fluctuations at the sediment-water interface in a eutrophic freshwater lake. Limnology & Oceanography 56, 2251-2264.

Spears, B.M., Carvalho, L., Perkins, R., Kirika, A. and Paterson, D.M. 2012. Long-term variation and regulation of internal phosphorus loading in Loch Leven. Hydrobiologia 681, 23-33.

Sprugel, D.G. 1983. Correcting for bias in log-transformed allometric equations. Ecology 64, 209-210.

Wersin, P., Hohener, P., Gioanoli, R. and Stumm, W. 1991. Early diagenetic influences on iron transformations in a freshwater lake sediment. Chemical Geology 90, 233-252.

WFD-UKTAG 2016 UKTAG Lake Assessment Method, Phosphorus, Lake Phosphorus Standards, p. 8.

Wood, R.W. and Smith, R.V. (eds) (1993) Lough Neagh. The Ecology of a Multipurpose Water Resource, Kluwer Academic Publishers, Dordrecht.