DRAFT: Internal loading in the lakes of the Bay of Plenty

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Authors/Contributors:
Verburg, P.
Semadeni-Davies, A.

For any information regarding this report please contact:

Dr Piet Verburg
Limnologist
Freshwater
+64-7-856 1787
piet.verburg@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 1787
Fax +64-7-856 0151

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Cover photos: The 12 main lakes in the Bay of Plenty, in order of mean chlorophyll *a* concentration increasing from top to bottom and from left to right [Piet Verburg, NIWA].

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Executive summary

We estimate net internal loading of nitrogen and phosphorus by the sediment in 12 lakes in the Bay of Plenty region using both previously reported and new estimates for external loading, lake morphometry, outflow rates, and lake nutrient concentrations. The net internal nutrient loading is estimated from the difference between observed and predicted nutrient retention. The net internal load, as opposed to the gross release rates by the sediment, is in particular of interest in respect to decision making concerning the reduction of external loading and of proposals to inactivate nutrients contained in the sediment, for instance by locking P in the sediment by a P absorbing capping agent.

To estimate nutrient retention in the lakes both models from literature and new models were used. New models were developed which were more suitable for the conditions in the Bay of Plenty lakes than those from literature.

The release rates of P from the sediment were lower than the sedimentation rates of P in all 12 Bay of Plenty lakes. This follows from the fact that the losses of P through the outlet were less than the external inputs in all 12 lakes.

Our results agree with internal loads given in the action plans for lakes Rotoehu and Okaro but are far lower for lakes Rotorua and Rotoiti. In particular, the internal loads given in the action plan for Lake Rotorua (360 t TN y^{-1} and 36 t TP y^{-1}) are substantially higher than our estimates for the net internal loading in Lake Rotorua, 8-63 t TN y^{-1} and 4-11 t TP y^{-1}.

For an internal load to occur in Lake Rotorua of 36 t TP y^{-1}, while the external load is 39 t TP y^{-1} (both as reported in the action plan), the loss of TP through the outlet would need to be 118-138% of the total external load. Instead, the observed loss of TP through the outlet is only 55% of the total external load. To have a net internal load that is similar to the external load while the loss through the outlet is about half of the external load is a mathematical impossibility.

In lakes Okaro and Rotoehu, internal loads were proportionally larger than in the other lakes. In these lakes, the amount of TP lost through the outflow was 93% and 100% of the external load, respectively, and the internal TP load was 42-60% and 49-69% of the external load, respectively. The amounts of TN lost from lakes Okaro and Rotoehu through their outflows were 159% and 52% of the external load, respectively, and the internal TN loads were 115-123% and 21-23% of the external load, respectively. However, even when internal loads are substantial it is important to realize that much of the total load, the sum of the external and internal loads, is permanently retained by the lake by burial in the sediment, or, in the case of TN, by denitrification. The percentage retained of the total TP load ranged from 33-41% for Lake Rotoehu to 92.5-93.1% for Lake Rotoma, and the percentage retained of the total TN load ranged from 26-29% for Lake Okaro to 90-91% for Lake Rotoma.

The observed fractional retention ranged between lakes from 0.00 to 0.93 for P, and from -0.59 (negative, i.e., more N was lost via the outlet than entered the lake from the catchment) to 0.90 for N.

The relatively low nutrient retention in lakes where internal loading occurs means that estimation of the external nutrient loading by back-calculating from lake nutrient concentrations with an assumed nutrient retention will generally result in overestimation of the external nutrient load.

For Lake Rerewhakaaitu no realistic estimate could be achieved for the net internal P loading, probably because of errors in the available data used to estimate the loading.

1 Introduction

Management of the lakes in the Bay of Plenty region receives much attention. For most of the larger lakes, action plans have been prepared by the Bay of Plenty Regional Council (BOPRC 2012a). Action Plans have been completed for Lakes Okareka, Okaro, Rotoehu, Rotorua, Rotoiti and Rotoma (BOPRC 2012a). Lakes Tarawera, Rerewhakaaitu, and Okataina have action plan processes underway (Scholes 2010). For several of these lakes, in which water quality has deteriorated in recent decades, a goal central to the Bay of Plenty Regional Council's management strategy is to reduce the external nutrient loading of nutrients from the catchments to achieve an improvement in water quality. It is acknowledged in the action plans that internal loading of nutrients is important as well in determining the water quality, especially in the lakes where external loading has increased markedly in the past century. In these lakes, nutrients have built up in the sediments and under conditions such as anoxia (low oxygen concentrations) in bottom waters, these nutrients are released back to the water column in the lake. Such conditions have become gradually more prevalent in some of the lakes in recent years.

The concentration of phosphorus in the hypolimnion often increases in lakes during stratified periods, in particular in the more eutrophic lakes (Nurnberg 1984; Søndergaard et al. 2003; Hamilton et al. 2004; Ozkundakci et al. 2011), as nutrients are released from the sediment. Fluxes of internal loads increase with frequency of anoxia occurring in bottom water and with the bottom area covered by anoxic water (Nurnberg 1984). Most attention has been focused on internal loading of phosphorus because of its relative importance in causing eutrophication. In addition, nitrogen can be permanently removed from lakes by denitrification while no such pathway exists for loss of phosphorus. However, internal loading of nitrogen can be substantial as well.

The estimation of internal nutrient loads from nutrient budgets is the main focus of this report. In addition, available metadata sets that are relevant for constructing the nutrient budgets of lakes such as for lake surface areas, lake volumes, mean depths, and outflow rates are reviewed. Furthermore, external loading estimated with the Catchment Land Use Environmental Sustainability model (CLUES), which uses information on land cover and mean rainfall in the catchment to derive mean total nitrogen (TN) and total phosphorus (TP) loads, is compared with previously reported results.

2 Methods

2.1 Theory

The predicted mean TP concentration in the lake is estimated from lake volume, the outflow rate (which combined give residence time), lake area and total P loading, using the Vollenweider (1976) equation:

$$[\mathrm{P}]_{\mathrm{lakepred}} = (1 - R_{pred})\frac{L_p}{q_s} = \frac{L_p / q_s}{(1+\sqrt{T_w})} \qquad \text{Eq. 1}$$

where L_p is the annual external loading rate of phosphorus per area of the lake surface (mg m^{-2} y^{-1}), q_s = *O*/*A* is the annual hydraulic load (m y^{-1}), *A* is the lake surface area (m^2), *O* is the annual outflow rate (m^3 y^{-1}), R_{pred} is the predicted lake retention coefficient (Ahlgren et al. 1988) and T_w is the hydraulic residence time (y) given by $V/O = z/q_s$, where *V* is the lake volume (m^3) and *z* the mean depth (m). Vollenweider (1975) derived

$$R_{pred} = \frac{\sigma}{T_w^{-1} + \sigma} \qquad \text{Eq. 2}$$

where σ is the sedimentation rate of TP (y^{-1}), and Vollenweider (1976) found empirically that

$$R_{pred} = \frac{\sqrt{T_w}}{(1+\sqrt{T_w})} \qquad \text{Eq. 3}$$

With σ defined as *v*/*z*, where *v* (m y^{-1}) is the settling velocity of TP containing particles (Dillon and Kirchner 1975), the expression (Eq. 2) for the predicted retention can be rearranged as

$$R_{pred} = \frac{T_w \dfrac{v}{z}}{1+T_w \dfrac{v}{z}} = \frac{\dfrac{v}{q_s}}{1+\dfrac{v}{q_s}} = \frac{v}{v+q_S} \qquad \text{Eq. 4}$$

Several authors derived R_{pred} from q_s using an equation of the form R_{pred} = a/(a+q_s), which assumes *v* to be a constant, *v* = a, with the value of 'a' found by fitting the equation to data from a set of lakes (Dillon and Kirchner 1975; Chapra 1975; Vollenweider 1975). However, Dillon and Molot (1996) showed from empirical results that *v* can vary substantially between lakes and with time. Also Ahlgren et al. (1988) pointed out that *v* should not be treated as a constant.

Nurnberg (1984) adapted Eq. 4 into the following expression for predicted P retention

$$R_{pred} = \frac{15}{18+q_S} \qquad \text{Eq. 5}$$

This model for P retention (Eq. 5) of Nurnberg (1984) suggests that *v* is a function of q_s:

$$v = \frac{(v+q_S)15}{18+q_S} = \frac{15 q_S}{3+q_S} \qquad \text{Eq. 5b}$$

Eq. 5 of Nurnberg (1984) turns *v* into a monotonically increasing function of q_s with an asymptotic maximum of *v* = 15 m y^{-1}. However, in the empirical results of Dillon and Molot

(1996) v varied from 3 to 27 m y^{-1} in their set of 8 lakes, and from Eq. 2 and Eq. 4 it follows that v is controlled by z and T_w as:

$$v = \frac{z}{\sqrt{T_w}} \qquad \text{Eq. 6}$$

Eq. 6 allows for more variability in the relationships between v and T_w and v and q_s, than compared with Eq. 5b. In our data set, Eq. 6 allows for a range in v more than twice that allowed by Eq. 5b. In the Bay of Plenty lakes discussed in this report v as estimated using Eq. 6 varies from 6 to 25 m y^{-1}, consistent with the results of Dillon and Molot (1996) which found a range of 3 to 27 m y^{-1} in 8 lakes. Using Eq. 5b v varies only from 4 to 13 m y^{-1}. In addition, the theoretical maximum value of R_{pred} with Eq. 3 is 1.00, while with Eq. 5 R_{pred} can be no higher than 0.83. However, in the 12 lakes examined here observed R_{pred} was > 0.83 in four lakes (average 0.91, maximum 0.95). As a result of unrealistic bounds set for R_{pred} and v by Eq. 5, the accuracy of the estimation of R_{pred} suffers by applying Eq. 5.

The method of Nurnberg (1984) to estimate P retention (Eq. 5) has been popular in New Zealand (Rutherford and Cooper 2002) since it was described in the Lake Managers Hand Book by Vant (1987). However, it has not caught on in the international literature (Brett and Benjamin 2008; Prairie 1989). For instance, the two most influential limnology textbooks of the past decade (Kalff 2003; Wetzel 2001) do not mention the method of Nurnberg (1984) but instead advocate Vollenweider's equations (Eq. 1 and Eq. 3) to estimate retention and predict lake P concentrations from catchment loading. Brett and Benjamin (2008) carried out an assessment of lake P retention and lake P concentration models using data of 305 lakes, the largest data base examined in such comparative studies thus far. Brett and Benjamin (2008) showed that expressions for retention which describe retention based on residence time, such as the Vollenweider expression (Eq. 3), give better results than expressions that effectively assume a constant particle settling velocity (i.e., when the two constants in Eq. 5 are identical; Vollenweider 1975; Dillon and Kirchner 1975) or a limited range in particle settling velocity, such as is inherent to the method (Eq. 5) which Nurnberg (1984) found most successful in a smaller lake data base (54 lakes). Here we apply Eq. 3 for the prediction of P retention but we do compare our results with those derived from Eq. 5.

Empirical P loading models have been developed for lakes with 'normal' sediment P retention (Ahlgren et al. 1988), which are in general oxic lakes (lakes with high dissolved oxygen in bottom water). In these lakes observed retention of P usually agrees well with retention predicted by Eq. 3. However, Eq. 1 does not apply to lakes where internal loading is present. In lakes where substantial internal loading occurs, generally in lakes where anoxia occurs in bottom water, the retention predicted by Eq. 3 does not reflect observed retention well (Nurnberg 1984). In such lakes, internal loading results in a lower observed proportional retention and a higher than expected lake P concentration given the external load and given the retention expected from the lake's volume, area and outflow rate. We estimated the net internal loading as the difference between observed retention and predicted retention (Eq. 7d). This estimate of the net internal load is equal to the sum of the predicted mass of TP that would have been retained by the lake if it remained oxic (with retention calculated using Eq. 3), and the difference between what is lost through the outlet and the external P load:

$$\Sigma \mathrm{P}_{\mathrm{internal}} = O[\mathrm{P}]_{\mathrm{lake}} - \Sigma \mathrm{P}_{\mathrm{ext}} + R_{pred}\Sigma \mathrm{P}_{\mathrm{ext}} \qquad \text{Eq. 7a}$$

where $[P]_{lake}$ is the observed average TP concentration in the lake and ΣP_{ext} is the external TP load (t y^{-1}). Rearranging shows it to be identical to the difference between the observed and predicted mass of TP lost through the outlet:

$$= \quad \Sigma P_{internal} = O([P]_{lake} - [P]_{lakepred}) \qquad \text{Eq. 7b}$$

$$= \quad \Sigma P_{internal} = O[P]_{lake} - (1 - R_{pred})\Sigma P_{ext} \qquad \text{Eq. 7c}$$

$$= \quad \Sigma P_{internal} = \Sigma P_{Rpred} - \Sigma P_{Robs} \qquad \text{Eq. 7d}$$

with ΣP_{Rpred} = the predicted mass of P (t y^{-1}) retained in the lake given by

$$\Sigma P_{Rpred} = R_{pred} \Sigma P_{ext} \qquad \text{Eq. 8}$$

and the observed retained mass of P (t y^{-1}) is given by

$$\Sigma P_{Robs} = R_{obs} \Sigma P_{ext} = \Sigma P_{ext} - O[P]_{lake} \qquad \text{Eq. 9}$$

and the observed retention is

$$R_{obs} = 1 - \frac{O[P]_{lake}}{\Sigma P_{ext}} \qquad \text{Eq. 10}$$

The predicted lake P concentration, taking both external (L_{pext}) and internal loads (L_{pint}, in mg m^{-2} y^{-1}) into account, is

$$[P]_{lakepred} = (1 - R_{pred})\frac{L_{pext}}{q_s} + \frac{L_{pint}}{q_s} \qquad \text{Eq. 11}$$

The TP concentration used to estimate the mean $[P]_{lake}$ is the mean concentration in the epilimnion, and not the average whole lake concentration or the spring overturn concentration, because $[P]_{lake}$ is used in Eq. 7-11 to estimate the loss through the outlet and the concentration in the outflow is expected to be similar to the surface water or epilimnion concentration.

The observed retention can be negative when more P leaves a lake than enters. Our method to estimate the net internal load is essentially the same as the method used by Nurnberg (1984). Our method to estimate internal load differs from the non-steady state mass balance model used by Rutherford (1988) by being a steady state model using long-term mean data inputs, with the nutrient concentrations in the lake assumed equal to that in the outflow and trends in the nutrient concentrations in the lake not considered. Rutherford's (1988) model allowed for retention of part of the internal load, whereas our method does not as it estimates the net internal load.

Our method to estimate net internal loading has an advantage over measuring release rates *in situ* because release rates can be highly variable in time and space and are in addition balanced by sedimentation rates. It is important to realize that $\Sigma P_{internal}$ (Eq. 7) is the net internal load and not the gross internal load, meaning it is what remains of the internal load after sedimentation is taken into account. Gross internal loads, as determined *in situ* by measuring release rates from the sediment, can be comparatively huge (in the order of hundreds of times the external load; Ekholm et al. 1997), but most of the gross internal load cycles back into the sediment (Burger et al. 2007).

Our equation for the net internal load considers retention to occur only for the external load and not for the net internal load. This is most clearly shown by the form of Eq. 7a, and by Eq. 11. The predicted retention for the external load should not be applied to the internal load, which can be demonstrated by taking the P load in Eq. 1 as the sum of the external and internal loads, and rewriting Eq. 1 as

$$[\mathrm{P}]_{\mathrm{lakepred}} = (1-R_{pred})\frac{\Sigma\mathrm{P}_{\mathrm{ext}} + \Sigma\mathrm{P}_{\mathrm{internal}}}{O} \qquad \text{Eq. 12}$$

Rearranging results in

$$\Sigma\mathrm{P}_{\mathrm{internal}} = \frac{O[\mathrm{P}]_{\mathrm{lake}}}{1-R_{pred}} - \Sigma\mathrm{P}_{\mathrm{ext}} \qquad \text{Eq. 13a}$$

$$= \Sigma\mathrm{P}_{\mathrm{ext}}\sum_{n}[(R_{pred}-R_{obs})R_{pred}{}^{n}] \quad \text{for } n \text{ is } 0, 1, 2, \ldots, \infty-1, \infty \qquad \text{Eq. 13b}$$

Equations 12 and 13 consider predicted retention to be the same for the external and internal load and Eq. 13 differs from the net internal P load estimate given by Eq. 7a by a factor equal to $(1-R_{pred})^{-1}$. In other words, for an R_{pred} = 0.5, Eq. 13 would result in a doubling of the estimate of the internal load, and for R_{pred} = 0.75 the estimate of the internal load increases fourfold.

The method of Eq. 12 and Eq. 13 assumes that part of the P released as the internal load would be retained by precipitation in the sediment. Therefore Eq. 13 does not give the real net internal load because it would count the same P atom multiple times (as is clear from Eq. 13b), upon its first release from the sediment, and again upon subsequent release from the sediment after subsequent precipitation, and so on. Eq. 13 represents a cycling loop between P sedimentation and release from the sediment. Assuming retention to be the same for the internal load as for the external load would result in overestimation of the net internal load while not being equal to the gross internal load either.

That Eq. 13 is incorrect is most easily understood by considering the hypothetical example of a lake where no observed retention occurs at all, because of the chemical conditions of its water and sediment. In such a lake the same amount leaves the lake through the outlet as entered it from the catchment and atmosphere, which means that $O[\mathrm{P}]_{\mathrm{lake}} = \Sigma\mathrm{P}_{\mathrm{ext}}$. Because no retention occurs in such a lake no P accumulates in the sediment. The estimated internal load in this lake amounts to $R_{pred}\Sigma\mathrm{P}_{\mathrm{ext}}$ according to Eq. 7, while the estimate for the internal load suggested by Eq. 13 is in this special case equal to:

$$\Sigma\mathrm{P}_{\mathrm{internal}} = \Sigma\mathrm{P}_{\mathrm{ext}}\frac{R_{pred}}{1-R_{pred}} = \Sigma\mathrm{P}_{\mathrm{ext}}\sum_{n}R_{pred}{}^{n} \qquad \text{Eq. 14}$$

with n in this case being all integers from 1 to infinity. In other words, if R_{pred} = 0.75, then the estimate for the internal load using Eq. 13 would be three times higher than the external load. It is clear that this is not possible, as there is no P in the sediment to result in an internal load higher than the external load. Note that this hypothetical example differs from that of a lake which ‘flips’ between alternative stable states, a clear water state in which P accumulates in the sediment and builds a P legacy potentially available for later release, and a turbid water state in which the P in the sediment is depleted by high internal loading (Verburg et al. 2012). Nevertheless, in any case in the long run net internal loads cannot on average exceed external loads because the phosphorus must come from somewhere.

The overestimation of actual retention occurring in lakes where internal loading occurs means that the estimation of the external nutrient loading by backcalculating from lake nutrient concentrations using Eq. 1, such as has been done for Lake Okareka (Rutherford and Cooper 2002), will result in overestimating external nutrient loading. Instead, where the net internal load can be estimated confidently by other means (Dillon and Molot 1996), the external load can be estimated by rearranging Eq. 7c.

Equations 1 and 7-10 can be applied for TN as well. However, the estimation of predicted retention of TN requires a different expression than used for TP because the retention of TN in the sediment is affected differently from TP by constituents in the sediment and because nitrogen is lost from the lake water column not only by sedimentation but also by denitrification. In deep and fully oxic lakes, retention of nitrogen is usually less efficient than retention of phosphorus (Wetzel 2001). The average retention of nitrogen found in lakes is 34% (Saunders & Kalff 2001). The predicted retention, using an equation of Harrison et al. (2009) for total nitrogen removal in lakes, is

$$R_{pred} = 1 - \exp\frac{-aT_w}{z} \qquad \text{Eq. 15}$$

with the value of the parameter a = 9.92. Nitrogen retention increases with water residence time (Windolf et al. 1996) as does phosphorus retention. In lakes, on average about two thirds of nitrogen retention is accounted for by denitrification and the remainder by uptake by aquatic plants and sedimentation resulting in permanent burial (Saunders & Kalff 2001).

The predicted retention for N under oxic conditions is certainly not expected to be similar to that of P because binding properties which affect the sedimentation rates are different for P and for N and because N is in addition lost from the lake by denitrification which accounts for part of the retention value. Therefore Eq. 3 cannot be used for N. Instead we used Eq. 15 to predict retention of N.

2.2 Input data required for the nutrient budgets

Lake outflow rates were determined using the model of Woods et al. (2006a). This model uses the mean annual rainfall and potential evapotranspiration to determine the mean annual runoff. This was done for each sub-catchment of the overall lake catchment (including the lake surface) and the flows from the sub-catchments were summed to determine the total lake outflow. The estimated outflow is the total loss of water from the lake after accounting for rainfall and potential evapotranspiration, and therefore includes losses to groundwater systems (Woods pers. comm.). In addition, measured outflow rate data were obtained for Lake Okaro (data kindly provided by D. Ozkundakci based on 21 flow measurements in 2007-2008 which were used in Ozkundakci et al. [2010]), and for lakes Rotoiti, Rotorua and Tarawera (monitored by NIWA). BOPRC does not monitor lake outlet flows (pers. comm. Heather MacKenzie). Furthermore, for lakes Rotorua, Rotoiti, Rotoehu, and Rotoma outflows were compared with those estimated by Pittams (1968) which accounted for groundwater flows from springs, and the outflow rate of Lake Tarawera was obtained from Hamilton et al. (2006).

Lake surface areas were estimated from digitized topographic maps. Lake surface areas were also obtained from the LERNZ website (LERNZ 2012), Hamilton et al. (2006) and Viner (1987). Lake volumes were obtained from LERNZ (2012), Ellery (2004; using the most recent years of the data time series) and compared with volumes calculated from the product of lake areas and mean depths in Viner (1987). Mean depths were obtained from Viner (1987) and were in addition estimated as the ratio of volume to surface area using data provided by LERNZ (2012), Ellery (2004) and the surface areas estimated for this study from digitized topographic maps.

External loading estimates were obtained from the BOPRC (2012a) action plans for lakes Rotorua, Okaro, Rotoehu, Rotoiti, Okareka, Rotoma and Tikitapu. External loads comprise both catchment and atmospheric sources. Catchment loads were derived from land use coefficients (BOPRC 2012a). The external TN load for Lake Rotorua is from BOPRC (2012b), reporting results of ROTAN analysis (Rutherford et al. 2011). External loading estimates were obtained from Hamilton (2006) for lakes for which no data are available in action plans. In addition, external loads, including atmospheric inputs, were estimated with the modelling package CLUES (Woods et al. 2006b; Semadeni-Davies et al. 2011; Semadeni-Davies et al. 2012) based on land cover (Land Cover Data Base 2) and regional climate by estimating loads in the outflows and disabling the default in-lake attenuation routinely applied by CLUES. The methodology used is summarised in Appendix A.

Internal loads are given in the BOPRC (2012a) action plans for lakes Rotorua, Okaro, Rotoehu and Rotoiti.

Dissolved oxygen profiles were measured by BOPRC (received from Paul Scholes). Nutrient concentrations in the epilimnion of the lakes are averages for 1992-2010 from Scholes (2010), except for Lake Rotokakahi (average of 1990-2009) which was taken from Scholes (2009).

3 Results

For the following sections, tables are presented in Appendix B and figures in Appendix C.

Available metadata for lake surface areas, volumes, mean depths, hypolimnion oxygen concentrations and outflow rates are compared in Tables B-1 to B-5. Previously reported external loads of TP and TN are compared with results obtained with CLUES in Tables B-6 and B-7. Internal loads given in the action plans (BOPRC 2012a and 2012b) are given as well in Tables B-6 and B-7.

The input data used to derive the nutrient budgets are given in Tables B-8 and B-9. The data used for the nutrient budget analysis were: mean epilimnetic TN and TP concentrations from Scholes (2010), outflow rates modelled following Woods et al. (2006a; this report), lake volumes from LERNZ (2012), lake surface areas from this report, mean depth estimated as the ratio of the volumes from LERNZ (2012) and the lake surface areas from this report, external TN and TP loads from action plans (BOPRC 2012a; BOPRC 2012b for TN in Lake Rotorua), and from Hamilton (2006) when not available in action plans. The results of the nutrient budgets of TP and TN are in Tables B-10 and B-11. All data plots in the figures are based on these data (except where otherwise indicated), however, the nutrient budgets were also constructed using external load estimates obtained with CLUES (Tables B-12 and B-13). The Vollenweider (1976) method was used to predict P retention (Eq. 3), unless otherwise indicated.

Mean and minimum dissolved oxygen concentrations (DO concentrations provided by Paul Scholes) were determined at the deepest depth for which good time series were available in each lake, well below the mean depth in each case except Lake Rotoehu (Table B-1). The minimum DO concentration was the mean of the lowest three measurements at the monitoring depth on different sampling days. In lakes Rotorua, Okareka, Okataina, Okaro, Rotoiti, Tikitapu and Rotoehu bottom water becomes anoxic (DO <1 g m^{-3}) during part of the summer (Table B-1). Among these lakes, the dissolved oxygen measurements below 1 g m^{-3} varied from 4% of all data in Lake Rotorua to 53% in Lake Okaro (and 2% in Lake Rotoehu but in this lake the monitoring depth was similar to the mean depth and low oxygen concentrations may have been more frequent in deeper water). In lakes Tarawera, Rotokakahi, Rotomahana, and Rotoma bottom water never became anoxic and only occasionally hypoxic in Lake Rerewhakaaitu. No oxygen profiles are available for Lake Rotokakahi. There were, as expected, strong relationships between mean DO concentrations and the % of anoxic (R^2 = 0.81) or the % hypoxic (DO <3 g m^{-3}; R^2 = 0.86) measurements (R^2 = 0.91 and R^2 = 0.99, respectively, for mean DO concentrations <6.7 g m^{-3}, above which bottom water was never anoxic or hypoxic). Mean summer (January – March) DO was anoxic only in lakes Okaro and Rotoiti and hypoxic in lakes Okareka and Tikitapu (Table B-1).

Lake Rerewhakaaitu is excluded from much of the analysis below for P, because the results (in particular the misfit between expected and observed lake P concentrations; Fig. C-5 and others) suggested error in the input data. It appears that the reported external P load may be a large overestimate of the real external P load. The average lake P concentration was over-predicted by a factor of ten (Fig. C-5a) although the predicted lake N concentration was reasonable (Fig. C-13). As a result the estimated internal P loading was unrealistic, a negative number 44% of the external load. Even when using the volume of Ellery (2006), which is about 58% larger compared with that of LERNZ (2012), and thereby increasing the estimates of T_w and retention, the average lake P was still nine fold overpredicted. It appears the external load in the action plan of 5.7 t P y^{-1} is overestimated. An estimate of 3.4 t P y^{-1} was obtained with CLUES, which still results in a predicted lake P concentration five times the observed concentration and a negative internal load of -1.2 t P y^{-1}. An additional manipulation of input data by using an outflow of 9 m^3 s^{-1} instead of the modelled 1 m^3 s^{-1} would bring the observed and predicted values in agreement and result in zero internal P load.

While the correlation was good between the TN and TP loads in the action plans and the CLUES estimates (Fig. C-1; Tables B-6 and B-7) there were large differences for individual lakes. Ozkundakci et al. (2010) reported an external TP load for Lake Okaro ranging from 575.2 mg m^{-2} yr^{-1} in 2005–2006 to 306 mg m^{-2} yr^{-1} in 2007–2008. These loads would amount to total external loads of 173 kg TP y^{-1} and 92 kg TP y^{-1} respectively. Ozkundakci et al. (2010) must have underestimated the external TP loads for Lake Okaro because the external TP loads are 396 kg TP y^{-1} in the action plan (BOPRC 2012a), 414 kg TP y^{-1} in Hamilton et al. (2006), and we obtained an estimate of 470 kg TP y^{-1} with CLUES (Table B-7).

Our lake surface areas (Table B-1) in some cases differ substantially from Viner (1987) but agree within 1 or 2% from values of LERNZ (2012), except for Lake Rerewhakaaitu. The lake surface area of Lake Rerewhakaaitu in our results is 30% smaller than reported by Viner (1987) and 10% smaller than reported by LERNZ (2012), and is identical to that reported by Hamilton et al. (2006). On the other hand, Hamilton et al. (2006) lists a 9% larger surface area estimate for Lake Okataina while our number agrees with Viner (1987) and LERNZ (2012).

The correlation between modelled outflows (Woods et al. 2006a) and flows for four of the Bay of Plenty lakes estimated from water balances (Pittams 1968) and observed mean annual flows was very good (R^2 = 0.997 for combined data; Fig. C-2) although there were some large proportional discrepancies for the lakes with the smallest outflows (Lakes Okaro and Rotoma; Table B-5). The flows estimated by Pittams (1968) accounts for ground water flows, as do our modelled flows. No observed flows are available for Lake Tikitapu, but because its modelled outflow is relatively small as well (in the order of that of Lake Okaro; Table B-5) it is possible that this estimate has a large proportional error as well.

The observed mean outflow of Lake Okaro (Ozkundakci's pers. comm.) was only 22% of the modelled flow (Table B-5). Using the observed outflow for Lake Okaro, instead of the much larger modelled outflow (Table B-8), would decrease the estimated nutrient load leaving the lake and therefore decrease the estimated internal TN load by 71% and the internal P load would be zero (Eq. 7d), instead of 42% of the external load (Table B-10). Clearly the observed outflow data of Ozkundakci are too low.

For the 12 lakes in the Bay of Plenty the Vollenweider method (Eq. 3) tends to predict higher P retention values than the Nurnberg method (Eq. 5; Fig. C-3). Predicted R increased with T_w and decreased with q_s, irrespective of the method used to predict R (Figs. C-3B and C-3C).

In six of the lakes (not including Lake Rerewhakaaitu) the estimate for the internal P loading was negative (Table B-10), suggesting that P retention may have been underestimated and/or the external P load overestimated in these lakes. Using the P retention method (Eq. 5) proposed by Nurnberg (1984) made matters worse as in 3 lakes internal P loading estimates became even more negative. In addition, using the equation of Nurnberg (1984) for P retention resulted in a negative internal loading of -0.46 t P y^{-1} in Lake Rotoiti, instead of +4.26 t P y^{-1}.

In the six lakes with negative estimates for the internal P load observed P retention was higher than predicted with the Vollenweider method and in seven lakes with the Nurnberg method (Fig. C-4). Clearly, either both methods underestimate retention in these lakes or the external P load is overestimated. The six lakes with negative estimates for the internal P load are the lakes with the lowest lake P concentrations (Fig. C-5). In none of these six lakes have internal loads been reported previously. However, in two of these six lakes, lakes Okareka and Tikitapu, the oxygen concentration in the bottom water is >20% of the time anoxic (Table B-1) and internal loading is therefore expected to occur (if conditions such as P present in the sediment are met). The average predicted retention of P using Eq. 3 in these six lakes with negative estimates for the internal P load was 0.74 (Table B-10) and the average observed retention of P in the same lakes was 0.83 (Table B-10).

The average predicted retention of P in all lakes (Table B-10; not including Lake Rerewhakaaitu) was 0.66 using Eq. 3 (and slightly lower, 0.61, with Eq. 5 of Nurnberg 1984). The average observed retention of P in the same lakes (Table B-10) was lower (0.59), as expected. Predicted and observed retention are not expected to correlate when internal loading occurs in some of the lakes which have anoxic bottom water. Therefore comparing these values of predicted and observed retention in all 12 lakes does not help to determine which method (Vollenweider 1976, versus Nurnberg 1984) performs better to predict R in oxic lakes. Four of the lakes can be considered to be entirely oxic lakes as minimum oxygen concentration in the hypolimnion never drops below about 4 to 5 g m^{-3}: Lakes Tarawera, Rotomahana, Rerewhakaaitu and Rotoma. In these lakes, predicted P retention is expected to best resemble the observed P retention, because the expressions for P retention were based on observations of P retention in oxic lakes. Excluding Lake Rerewhakaaitu (because of likely error in the P loading estimate, see above), in the three lakes with permanently oxygenated bottom water the average predicted retention of P (Table B-10) was 0.78 (and lower, 0.66, with Eq. 5 of Nurnberg 1984). The average observed retention of P in these three oxic lakes (Table B-10) was 0.76, as expected greater than in the remaining eight lakes (R_{obs} = 0.53 and R_{pred} = 0.61) where bottom water oxygen concentrations are frequently below 2 mg L^{-1}, because of internal loads. The Vollenweider method overestimated R for TP on average by a factor +0.02 (= predicted R – observed R) in the three oxic lakes and the Nurnberg method underpredicted R by a factor -0.10. It seems that the Vollenweider (1976) method performs best, while the Nurnberg method may under-estimate the retention expected in oxic lakes. However, with only 3 lakes no definite conclusions can be made about relative performance. Moreover, the apparent fit between predicted and observed P retention with Eq. 3 is mainly the result of the low observed retention in Lake Rotomahana (R_{obs} = 0.54) compared with the predicted P retention (R_{pred} = 0.71). It is not clear why P retention is so overpredicted in Lake Rotomahana. Using only Lakes Tarawera and Rotoma, the average observed retention (R_{obs} = 0.87) was underestimated by -0.06 compared with the average predicted P retention (R_{pred} = 0.81), using Eq. 3. The largest underestimate of P retention (predicted R – observed R = -0.18) occurred in Lake Rotokakahi (Table B-10; not including Lake Rerewhakaaitu), which was not expected, as low oxygen conditions sometimes may occur in this lake (pers. comm. David Hamilton). It is possible that either the external load is overestimated or the P concentrations measured in the lake were not representative.

In lakes with low mean P concentrations the predicted lake P concentrations were slightly too high (Figs. C-5 and C-6) and the ratio observed:predicted lake P concentrations increased with increasing observed lake P concentrations (Fig. C-7). The more eutrophic a lake is the more the lake P concentrations were underestimated by the predictions (Fig. C-7) presumably because of internal loads. In the five lakes with an observed lake P concentration higher than the predicted lake P concentration (Figs. C-5 and C-6) internal loading occurs. The pattern was broadly similar when using retention predicted following Nurnberg (1984), except that the latter method results in a lower observed than predicted lake P concentration in Lake Rotoiti, suggesting no internal P loading occurs in that lake (Fig. C-5b), which considering the known increase of P in the hypolimnion during summer cannot be correct (Burns and Rutherford 1998). Chlorophyll *a* in each of the lakes was equally well predicted by observed lake P and N concentrations (Fig. C-8) and slightly better than by predicted lake P concentrations (after excluding the anomalous value for Lake Rerewhakaaitu from the latter). The internal loading of TP and TN per unit area correlated strongly with observed mean concentrations in the lakes (Fig. C-9; $r^2 = 0.92$ and $r^2 = 0.87$, respectively). The proportion of the variance in chlorophyll *a* explained by internal loading per unit area was $r^2 = 0.50$ for TP and $r^2 = 0.75$ for TN.

In none of the lakes is the P export through the outlet greater than the external P inputs (Table B-10). Lake Rotoehu is the lake where least P is retained as 99.6% of the external P inputs are flushed through the outlet. Lake Okaro is the only lake where the N export through the outlet is greater than the external N inputs (Table B-11), as 59% more than the external N inputs are flushed through the outlet, assuming that this observation is not the result of an underestimated external N load, overestimated outflow rate and/or overestimated lake concentration.

While the predicted retention of TN (Eq. 15) was larger than the predicted retention of TP in 10 of the 12 lakes (all but lakes Rotomahana and Rotoiti), the observed retention of TN was larger than the observed retention of TP only in lakes Rotoiti, Rotoehu, and Rotorua (Tables B-10 and B-11). These three lakes had short residence times (1 to 1.5 y, Table B-8) and were among those with lowest minimum hypolimnetic oxygen concentrations.

The relationships between mean or minimum dissolved oxygen concentrations in near-bottom water (Table B-1) and the internal load of TP (per unit area), or the ratio of observed to predicted lake TP concentrations, were all negative, as expected, but they were not strong (Fig. C-10). For instance, in lakes Okareka and Okataina hypolimnion concentrations at 28 m and 58 m depth, respectively, drop to below 1 mg L^{-1} during summer but the results suggest no internal loading occurs (Table B-10). Low minimum oxygen concentrations in Rotorua, Okaro, Rotoehu and Rotoiti, are consistent with our results which suggest internal loading occurs, but average hypolimnion concentrations in several of these lakes can be relatively high, for instance 8.4 mg L^{-1} at 20 m depth in Lake Rotorua, and 9.1 mg L^{-1} at 8 m depth in Lake Rotoehu (Table B-1). However, oxygen concentrations depend on the depth as even within the hypolimnion lower concentrations are found with increasing depth and the depths of the dissolved oxygen measurements were not at the same height above the maximum depth in each lake (Table B-1). In addition, internal loading will also depend on the extent of anoxia across the full area of the lake bottom (i.e., number of days with anoxia and the proportion of the lake bottom that is anoxic) and on sediment P content (Nurnberg 1984), two factors which we are not accounting for.

In a plot of internal load (per unit area) against the ratio of observed to predicted lake P concentrations, Lake Okaro is an obvious outlier (Fig. C-11). In Lake Okaro, the internal P load per unit area is substantially higher than in any of the other lakes. The maximum internal P load as a percentage of external load was found in Lake Rotoehu, with 49% (42% in Lake Okaro). There was a strong relationship (r^2 = 0.94) between the ratio of internal P load to external P load and the ratio of observed to predicted P concentrations (Fig. C-11). For TN the internal load ranged from 0% of the external load for Lake Rotoiti (the estimate was actually negative) to 115% of the external load for Lake Okaro. The weight ratio of internal loading ranged from 5 to 18 in the four lakes where the internal loading of both TN and TP was positive (Tables B-10 and B-11).

In six of the 12 lakes (not including Lake Rerewhakaaitu) P retention was underestimated (Fig. C-4). In lakes where observed P retention was greater than the predicted P retention the average difference in predicted *R* from the observed *R* was 0.09 (excluding Lake Rerewhakaaitu where the results suggested errors in the input data, see Fig. C-5), using Eq. 3, and 0.15 using Eq. 5 (Nurnberg 1984) to predict retention, suggesting Eq. 3 (Vollenweider 1976) is the better method for predicting *R*. The lakes where P retention was underestimated were the lakes with the higher T_w (those where T_w >4 y, except Lake Rotomahana, T_w = 5.8, where P retention was not underestimated). In 8 of the 12 lakes P retention predicted by Eq. 3 was larger than P retention predicted by Eq. 5 (Table B-10). That means that in each of these 8 lakes the estimate for the internal P load would have been smaller if we had used the Nurnberg (1984) equation (Eq. 5) to predict P retention. For instance, the estimated internal P load for Lake Rotoiti would have been negative, -0.5 t y^{-1} instead of 4.2 t y^{-1}. This suggests the Vollenweider equation for *R* (Eq. 3) provides a better fit for predicted P retention for Lake Rotoiti than the Nurnberg equation (Eq. 5) because in Lake Rotoiti an internal P load is expected (BOPRC 2012a). However, it seems likely that also the Vollenweider equation for *R* (Eq. 3) results in an underestimate of R_{pred} and therefore of the internal load.

Retention of N predicted by Eq. 15 was unrealistically high for lakes with high values of T_w/z (in particular lakes Rotoma and Tikitapu) (Fig. C-12A), while retention of N was underestimated in lakes with low values of T_w/z (Lake Rotoiti in particular). In all but one (Lake Rotoiti) of the lakes observed N retention was lower than the predicted retention, partly explained by internal loading, most markedly in Lake Okaro (Fig. C-12B). As a result, observed TN concentrations were much higher than predicted in lakes Rotoma and Tikitapu while Lake Rotoiti was the only lake where it was less than predicted (Fig. C-13). The underestimate of N retention in Lake Rotoiti resulted in a substantial negative estimate for internal N loading, which is clearly unrealistic. The equation for prediction of N retention (Eq. 15) has been less tested than the equation for P loading (Eq. 3). It is probably less reliable and N retention may be affected by factors not taken into account in the equation. Therefore, our results for internal N loading should be regarded with more caution than our results for internal P loading.

Using external P loads obtained from CLUES resulted in worse predicted lake P concentrations and internal P loads for lakes Okareka and Rotorua and produced better results for other lakes (Fig. C-14; Table B-12). With CLUES external loads, lake P concentrations are overestimated and internal loads are large negative numbers in lakes Okareka and Rotorua, suggesting that the CLUES estimates for external P loads are too high in these two lakes. On the other hand, as can be seen from improved estimates for internal P loading, the CLUES external P loads for lakes Tarawera, Rotoma and Rotokakahi are more realistic, although still too high for the latter (compare with Fig. C-5 and Table B-10). With the external P loads from CLUES Lake Rotoiti is the only lake where more P leaves the lake than enters. The CLUES external P load results in an internal P load in Lake Rotoiti (10 t P y^{-1}) more than twice that which results from the action plan external load (BOPRC 2012a). This internal load is closer to that given by the action plan for Lake Rotoiti (20 t P y^{-1}). The highest relative internal P load resulting from CLUES external P loads was found in Lake Rotoiti where the internal P load was 67% of the external P load. In Lake Rotoehu, where the ratio of internal to external P load was highest using the external P loads in the action plans and Hamilton et al. (2006), the proportion of the internal load relative to the external P load was reduced to 24%, down from 49% with the external P inputs from the action plan.

With the external N loads obtained with CLUES, internal N loads were higher in all lakes than with the external N loads reported in the action plans and Hamilton et al. (2006), except for lakes Rotomahana and Okaro (Table B-13, compare with Table B-11). With the external N loads obtained with CLUES the lake N concentration was not overestimated in any of the lakes (Fig. C-14, compare with Fig. C-13). As mentioned, underestimation of lake nutrient concentrations results from internal loading and is expected in some of the lakes, while overestimation likely results from too high estimates of external N loads and/or underestimated retention. Therefore the CLUES external N load provided a better fit for Lake Rotoiti, where the lake N concentration was overestimated by the external load reported by BOPRC (2012a). As a result, Lake Rotoiti had a sizeable internal N load, 26 t N y^{-1} (Table B-13), while it was large and negative using the external N loads in the action plan (Table B-11). Therefore, for Lake Rotoiti both the P and N external loads obtained with CLUES are probably improvements relative to those reported in the action plan. However, the estimate for the internal load using the CLUES external N loads was still only half of the estimate for the internal load in the action plan (50 t N y^{-1}, Table B-6) which is probably an overestimate.

With the external N loads obtained with CLUES the internal N load in Lake Rotorua was almost twice as high, 118 t P y^{-1}, compared with the result obtained with the external N load in the action plan, 63 t P y^{-1}, but still far less than the internal load given by the action plan for Lake Rotorua (360 t P y^{-1}, Table B-6) which is probably an overestimate.

With the external N loads obtained with CLUES, only in Lake Tikitapu did the N load lost through the outlet slightly exceed the external load, contrary to the results with the external N loads reported in the action plans and Hamilton et al. (2006) which resulted in a large net loss only for Lake Okaro. This was due to a CLUES estimate for the external N load in Lake Tikitapu that was only 21% of that given in the action plan, while that for Lake Okaro was 68% larger than in the action plan. Observed N retention in lakes Rotoehu, Tarawera, Rotokakahi, Rotoma and Tikitapu was much less with the CLUES estimates for the external N load because these were much lower than the respective external N loads for these lakes in the action plans and Hamilton et al. (2006). The estimates for the internal loads in lakes Rotoma and Tikitapu are relatively unresponsive to changes in the estimated external load because of their very small outflows. As a result there is hardly any difference in the estimate for the internal N load in either lake, in spite of very large differences in external N load estimates between the CLUES results and those reported in the action plans for lakes Rotoma and Tikitapu (Tables B-11 and B-13).

4 Discussion

Lake Rerewhakaaitu is an outlier in the TP plots, probably because of an error in the input data. Overestimates of both external loading and of the outflow rate, and an underestimate of the lake's volume could cause the predicted lake TP concentration to be far greater than the observed mean TP concentration. However, the predicted and observed lake TN concentrations are in fair agreement, with observed concentration only slightly higher than predicted (Fig. C-13), therefore it seems likely that the error is primarily the result of too high an estimate for TP external loading given by BOPRC (2012a), and not of an error in the outflow rate or the volume. Increasing the estimate of the lake's volume by adopting the value from Ellery (2004; Table B-3) instead of that of LERNZ (2012) reduced the negative estimate of the internal P load only slightly.

Unexpectedly, observed P retention was greater than predicted in seven of the lakes (Fig. C-4; Table B-10; including Lake Rerewhakaaitu). While the method to estimate retention under oxic conditions where no internal loading occurs may be inaccurate, it is equally likely that errors in the external loading data are the cause of the disagreement between predicted and observed retention in the oxic lakes, resulting in negative estimates of internal loading. Apparently underestimated retention may be an artefact of overestimated external P loads or underestimated outflow rates resulting in overestimates of observed retention, although underestimated outflow rates seems a less likely explanation. For instance, with the external loads obtained with CLUES for lakes Tarawera and Rotoma, which both are most certainly permanently oxic lakes, P retention was not underestimated (Fig. C-14A) and their internal P load estimates were positive (Table B-12). In addition, most negative estimates of internal P loading were small (in P m^{-2} y^{-1}), close to zero, in contrast to the positive estimates of internal P loading (Fig. C-9). Underestimated P retention and a negative estimate for the internal load may also be caused by mismatching of the time period used for the average lake P concentrations and the other data on which the loading estimates are based (in particular external loads). In several lakes the P concentration has increased in recent years which suggests that using long term mean lake nutrient concentrations (in Eq. 7, 9 and 10) has resulted in lower estimates of internal P loads than is likely to occur at present. On the other hand, where lake water quality has improved recently the use of long term mean lake nutrient concentrations results in higher estimates for the internal load. For instance, water quality has improved in Lake Rotorua (Scholes 2010). The observed mean P concentration in Lake Rotorua in 1992-2010 was 23% higher than the predicted P concentration (33 mg m^{-3}; Fig. C-5). However, the mean of 2005-2010 was only 1% higher than predicted (Scholes 2010). Therefore, the use of the 1992-2010 mean P concentration in Lake Rotorua results in a higher internal load estimate than what would be the internal load at present (Eq. 7d). Where the actual internal loading is expected to be exactly zero, statistically some results would be expected to be below zero and others above zero by random error contained in the input data. In fully oxic lakes this should result in some of the internal load estimates being negative. Also Nurnberg (1984), using the same technique (Eq. 7), found negative estimates of internal P loading, in about half of the oxic lakes (in 29 out of 54 lakes) as expected from randomness, with the same method given by Eq. 7d. Therefore, it is not too surprising to find internal load estimates that are slightly negative in fully oxic lakes such as lakes Tarawera and Rotoma (using BOPRC 2012a and Hamilton et al. 2006 for the external loads, but not when using the CLUES estimates, Fig. C-14A), where the difference between observed and predicted retention is expected to be around zero. However, using Eq. 3 to predict P retention also lakes Okataina, Okareka and Tikitapu appear to retain P as if they are fully oxic lakes, in spite of summer time DO dropping below 1 mg L^{-1} in these lakes. The lakes where P retention was underestimated were distinguished by high T_w (>4 y) and low lake P concentrations (<15 mg m^{-3}). The Vollenweider method to estimate retention is expected to be most accurate for lakes with residence times >1 y (Vollenweider 1976), therefore the residence times of the lakes would probably not have contributed to any underestimation of P retention.

The equation of Vollenweider (1976) for P retention is widely used in literature and produced better results for the Bay of Plenty lakes than that of Nurnberg (1984). The OECD (1982; in Ahlgren et al. 1988) study modified Eq. 1-3 (Vollenweider 1976). The derived OECD equation produces even lower predicted P concentrations for lakes where P concentrations are above about 15 mg m^{-3} (increasingly lower with increasing predicted P concentrations) and slightly higher predicted P concentrations for lakes where P concentrations are below about 15 mg m^{-3}, resulting in a worse fit of predicted and observed lake concentrations, both for high P and for low P lakes, compared with Eq. 1-3. However, in view of the fact that the seven lakes where observed lake P concentrations were less than predicted (and therefore retention underestimated and the internal load estimate negative) were the lakes with lowest lake P concentrations (Fig. C-5), it seems reasonable to conclude that also Eq. 3 for retention may underestimate actual retention under oxic conditions. Eq. 3 was based on empirical work in temperate European lakes. Temperate lakes generally freeze over during winter. Dillon and Molot (1996) realized that annual mean P retention must be higher on average in lakes in warmer climatic zones than those lakes on which the empirical relationships were based when they found that P retention was much lower in winter, during ice cover, than during the rest of the year. The lakes in the Bay of Plenty are relatively warm and never freeze over. Therefore it may be that the empirical relationships found in temperate European lakes are not valid in most New Zealand lakes and result in underestimated P retention. If Eq. 3 underestimates expected retention (R_{pred}) in the oxic lakes then this would mean that in the anoxic lakes the expected R is also being underestimated and internal loading would be underestimated in all lakes. It was therefore decided to adapt Eq. 3 by fitting predicted retention to observed retention in five of the seven lakes with lowest P concentrations (Fig. C-5), in each of which observed retention was underestimated (but note that with CLUES external P loads retention was underestimated in only three of these five lakes, lakes Tikitapu, Okareka and Okataina, Fig. C-14A). Of the seven lakes with lowest P concentrations Lakes Rotokakahi and Rerewhakaaitu were not included because of doubts about their input data (see above). In these five lakes retention was on average underestimated by 0.08 (ranging from 0.03 for Lake Tarawera to 0.13 for Lake Tikitapu), i.e., mean observed retention was 0.83 while mean predicted retention was 0.75. In order to achieve near zero or positive values for the difference R_{pred}-R_{obs} for each of the five lakes, the equation for predicted P retention was adjusted by fitting the predicted P retention to observed retention in Eq. 16:

$$R_{pred} = \frac{\mathrm{a}\sqrt{T_w}}{(1+\mathrm{a}\sqrt{T_w})} \qquad \text{Eq. 16}$$

with a = 2.3 (Fig. C-15A). With a < 2.3 R_{pred}-R_{obs} for Lake Rotoma would still be negative (in other words R_{pred} would be underestimated) and as a result the internal load as well. With this method to adjust Eq. 3 to reflect the higher expected retention the minimum and maximum possible values of R_{pred} are zero and 1.00, respectively, as they should be. This would not be the case if R_{pred} would simply be raised by a constant value. Using Eq.16 predicted R in the five lakes was on average 0.12 greater than using Eq. 3. The average increase in R_{pred} was 0.15 for all 12 lakes. It should be noted that the five lakes used to fit R_{pred} under oxic conditions to R_{obs} actually includes three lakes (Okataina, Okareka and Tikitapu) where bottom water does become anoxic (7 to 28% of the time DO <1 g m^{-3}). Nevertheless, the average increase in R_{pred} provided by Eq. 16 is larger (0.15) than the average difference R_{obs} - R_{pred} for the two reliably oxic lakes without issues with their input data (0.05 for lakes Tarawera and Rotoma), suggesting that Eq. 16 provides an upper limit for R_{pred}. In addition, as mentioned above, with the external loads obtained with CLUES for lakes Tarawera and Rotoma P retention was not underestimated using Eq. 3, corroborating the supposition that Eq. 16 provides an upper limit for R_{pred}. However, for lakes Tikitapu, Rerewhakaaitu and Rotokakahi R_{pred} is still less than R_{obs}, suggesting that the external P loading may be overestimated in these three lakes. Therefore, in these three lakes the new method to estimate R_{pred} results in negative estimates of the internal load. As in particular in lakes Rerewhakaaitu and Rotokakahi this is probably the result of error in the external load data no positive R_{pred}-R_{obs} can be expected in these lakes. However, the differences R_{pred}-R_{obs} have dropped to less than half their value for each of these three lakes compared with using Eq. 3 (down to 17% and 1% of the original value for lakes Rotokakahi and Tikitapu, respectively), the negative estimate for internal P loading in Lake Tikitapu has become very small, and estimates of internal loads in lakes Rotoma, Okataina, Okareka and Tarawera are no longer negative. The change in R_{pred} between Eq. 3 and Eq. 16 decreased from 0.20 to 0.08 with T_w increasing from 0.9 y (Lake Okaro) to 36 y (Lake Rotoma). This is consistent with Vollenweider's (1976) statement that his method tended to underestimate retention for lakes with low T_w.

Using Eq.16 for P retention, the lake TP concentration predicted by Eq. 1 was on average 6.6 mg m^{-3} lower (range 5.2-9.1 mg m^{-3}) than that given by the modified Vollenweider equation given by OECD (1982). The difference was not related to lake TP concentration. The combination of Eq. 16 and Eq. 1 resulted in predicted lake TP concentrations that were on average 9.0 mg m^{-3} lower than predicted using retention following Eq. 3, with the difference increasing from 4.0 to 21.6 mg m^{-3} with increasing lake TP concentrations (not including the outlier Rerewhakaaitu).

In contrast to the retention of P, the retention of N appears in general overpredicted by Eq. 15. In oligotrophic and oxic lakes we would expect the net internal N load to be about zero and the predicted N concentrations to agree with observed N concentrations, instead of the 10 to 20% of the external loads in Table B-11 and the disagreement between concentrations in Fig. C-13. The average predicted nitrogen retention was 77%. Saunders & Kalff (2001) found a much lower average retention of nitrogen in lakes of 34%, although this may be in part explained by more lakes with short residence times in their data set. Retention of N in the Bay of Plenty lakes was especially overpredicted for lakes with high values of T_w/z. With the equation of Harrison et al. (2009; Eq. 15) the predicted retention of N becomes equal to 1 in lakes where T_w/z> 0.5, as in lakes Tikitapu and Rotoma. On the other hand retention of N is underpredicted by Eq. 15 in Lake Rotoiti, the lake where T_w/z is lowest (0.05; Fig. 12). We have, therefore, adjusted R_{pred} for N by a logarithmic fit (Fig. C- 15B) of observed retention against T_w/z (= q_s^{-1}) in the oxic lakes Tarawera, Rotoma and Rerewhakaaitu (not including Rotomahana because its observed retention was unexpectedly low relative to T_w/z):

$$R_{pred} = 0.107 LN(q_s)^{-1} + 0.909 \qquad \text{Eq. 17}$$

This is a better method than simply reducing R_{pred} following Eq. 15 by a constant amount equal to the mean amount by which R_{pred} of Eq. 15 overestimates N retention in the oxic lakes, because that would result in an even greater underestimate of internal N loading in Lake Rotoiti (it would become more negative than suggested in Table B-11). Also no adequate relationship could be found by adjusting the parameter in Eq. 15, because this approach could not satisfy the requirement of agreement with observed retention in the oxic lakes, nor the requirement of a non-negative internal load for Lake Rotoiti. The average predicted N retention was 72% using Eq. 17 (Table B-17), while the observed retention was 56%. As a result of the adjustment of predicted retention of N given by Eq. 17, and the smaller difference between predicted and observed retention, the estimates for internal loads of N are generally lower than when using Eq. 15 (Tables B-16 to B-21).

The new results produced by using Eq. 16 for predicted P retention and Eq. 17 for predicted N retention are given in Tables B-16 to B-23 and Figures C-16 to C-20. As expected, the estimated internal P loads are higher for all lakes in Tables B-16 and B-18 than in the corresponding Tables B-10 and B-12, while the estimated internal N loads are lower for most lakes in Tables B-17 and B-19 than in the corresponding Tables B-11 and B-13. In the case of lakes Rotomahana, Okaro and Rotoiti the estimated internal N load increased using Eq. 17, for both sets of external load data. In lake Rotoiti the internal N load becomes positive using Eq. 17 (Table B-17) while it was negative using Eq. 15 (Table B-11). In lakes Tikitapu, Rerewhakaaitu and Rotokakahi the estimated internal P load is still negative (Table B-16), suggesting that the external P loading may be overestimated in these three lakes by BOPRC (2012a) and Hamilton et al. (2006; see also Table B-18). The differences between observed and predicted lake N concentrations were in general greater with external loads obtained with CLUES (Fig. C-17B) compared with external loads from BOPRC (2912a) and Hamilton et al. (2006) (Fig. C-16B). The internal N and P loads in oxic lakes Rotoma and Tarawera estimated with external loads obtained from CLUES (Tables B-18 and B-19) are higher than with external loads from BOPRC (2912a) and Hamilton et al. (2006), which is a result of the fact that the adjustment of the retention equations was carried out using observed retention based on external loads from BOPRC (2912a) and Hamilton et al. (2006).

Ozkundakci et al. (2011) modelled the effect of reductions of both external and internal nutrient loads in Lake Okaro but did not specify the magnitude of the internal loads. In Lake Okaro the TN load leaving the lake was 59% greater than the external TN load entering the lake (Table B-11). Clearly internal loading of nitrogen is significant in this lake.

In lakes Okaro and Rotoehu internal loads were proportionally larger than in the other lakes. In these lakes the amount of TN lost through the outflow was 159% and 52% of the external load, respectively, and the internal TN load was 115-123% and 21-23% of the external load, respectively (Tables B-11 and B-17). The amount of TP lost through the outflow in lakes Okaro and Rotoehu was 93% and 100% of the external load, respectively, and the internal TP load was 42-60% and 49-69% of the external load, respectively (Tables B-10 and B-16).

It is important to note that we determined the net internal load and not the gross internal load, in other words sedimentation is taken into account. Gross internal loads as determined *in situ* by measuring release rates from the sediment can be comparatively huge. For instance, Ekholm et al. (1997) report a gross internal load of TP 356 times the external load and of TN 57 times the external load. In a literature review of 49 shallow lakes Van der Molen (1994) found a median internal load of 3000 mg m^{-2} y^{-1}. White et al. (1978) reported an internal load in Lake Rotorua of 20-40 mg P m^{-2} d^{-1} in 1975-1976, similar to the estimate of Burger et al. (2007) which varied from 8 to 44 mg P m^{-2} d^{-1}, depending on the bottom depth. Rutherford et al. (1996) found the lower bound of White et al.'s (1978) estimate to agree with their dynamic model which included separate terms for sediment P release and for the net P sedimentation rate. The internal load in Lake Rotorua reported by White et al. (1978) amounts to 7000 to 15,000 mg P m^{-2} y^{-1}, which is 50 to 300 times higher than the net internal load reported here (Tables B-10 and B-16), and 14 to 30 times higher than the external load (BOPRC 2012a). The high internal release rates found by White et al. (1997) occurred only part of the time and in part of the lake, when and where the bottom water was anoxic, explaining the large difference with our net internal load. The difference is further explained by the fact that most of the gross internal load cycles back into the sediment (Burger et al. 2007). While at any point in time and space within lakes fluxes of internal loading may be much larger and may outstrip the rates of sedimentation, on average sedimentation is usually larger than the release of N and P from the sediment. The mean sedimentation rates of P were higher than the release rates of P from the sediment in all 12 Bay of Plenty lakes. This follows from the fact that the losses of P through the outlet were less than the external inputs in all 12 lakes (except in Lake Rotoiti when using the CLUES external inputs; Table B-18). Also in none of the Bay of Plenty lakes does the export of N through the outlet exceed the external inputs, except in Lake Okaro. Therefore, there is a net retention of TP in all 12 lakes, and a net retention of TN in all lakes except Lake Okaro, indicating that the average fluxes of sedimentation and permanent burial of P and N in the sediment (and denitrification in the case of TN) are greater than the average fluxes of P and N release from the sediment.

In lakes where observed net sedimentation or retention was less than expected, based on relationships predicting retention in oxic lakes, the difference is explained by the net internal load. However, even in these lakes with a net internal load the sedimentation rates are actually higher than the rates of internal release of P and N. Even when net internal loads substantially increase the total nutrient loads (the sum of the external and net internal loads), such as in Lake Okaro (Tables B-10 to B-15 and B-16 to B-23), much of the total load is permanently retained by the lake. The percentage retained of the total TP load ranges from 33-41% for Lake Rotoehu to 92.5-93.1% for Lake Rotoma (Tables B-14 and B-20), and the percentage retained of the total TN load ranges from 26-29% for Lake Okaro to 90-91% for Lake Rotoma (Tables B-15 and B-21).

Several studies have estimated internal loading from the accumulation of TP in the hypolimnion in stratified lakes during the summer. Nurnberg (1984) found thus estimated internal P loading to be not significantly different from results obtained from the mass balance (Eq. 7). In Lake Okaro, the concentration of TP at 14 m depth increases by about 600 mg m^{-3} during summer (Ozkundakci et al. 2010; before the alum application). If we assume the same average annual increase in TP throughout an average hypolimnion height of 3 m (Ozkundakci et al. 2010; the lake has an average depth of 11 m and the thermocline is around 8 m depth) it follows that 1800 mg TP m^{-2} y^{-1} accumulates, about two to three times our estimate of the net internal load (Tables B-10 and B-16). This amounts to a flux of 0.54 t y^{-1}, more than the annual external TP load (0.40 t y^{-1}) in spite of the loss of TP through the outlet being less than the external load (Table B-10). Because the net internal load cannot exceed the loss though the outlet (Eq. 7) this can be explained if part of the accumulated TP in the hypolimnion stems directly from the external source, and therefore the hypolimnetic accumulation rate may not be a good estimator for the net internal load in Lake Okaro. A better alternative may be to examine accumulation rates at different depths in the hypolimnion because the rate at 14 m depth may not be representative. Another way to estimate internal P loads is to compare surface layer TP concentrations between the winter mixing period and the end of the stratified season, and multiplying the difference by mean depth (Dillon and Molot 1996).

It should be noted that, although a literature review carried out by Nurnberg (1984) found on average zero P release in oxic sediment core tubes, P and N may be released to the water column in lakes with an oxic sediment-water interface (White et al. 1980; Vincent et al. 1981; Sondergaard et al. 2001), which in the case of P release may be controlled by iron and sulfur concentrations in the sediment (Sondergaard et al. 2001; Gächter and Müller 2003). For instance, in oligotrophic Lake Taupo (Gibbs 2012), where dissolved oxygen in bottom water rarely drops below 7 mg L^{-1}, DRP near the maximum depth at 150 m increases by about 10 mg m^{-3} over summer. In shallow lakes P release can also be controlled by wind mixing (Sondergaard et al. 2001) as is probably the case in Lake Omapere (Verburg et al. 2012).

For Lake Rotoehu our results for the internal loads (11-12 t TN y^{-1} and 1.2-1.7 t TP y^{-1}) are similar to those in the action plans (6 t TN y^{-1} and 1.4 t TP y^{-1}). Also for Lake Okaro our results for the internal loads (3.0-3.2 t TN y^{-1} and 0.17-0.24 t TP y^{-1}) are close to those in the action plans (2.4 t TN y^{-1} and 0.38 t TP y^{-1}). On the other hand, for Lake Rotoroa our results for the internal loads (8-63 t TN y^{-1} and 4.0 -11.3 t TP y^{-1}) were much lower than those in the action plans (360 t TN y^{-1} and 36 t TP y^{-1}). Also for Lake Rotoiti our result for the internal load of TP (4.2-9.6 t y^{-1}) was much lower than that in the action plan (20 t TP y^{-1}). Our estimate for Lake Rotoiti for the internal load of TN was ~0 to 44 t TN y^{-1} (Tables B-10, B-11, B-16 and B-17), while it is 50 t TN y^{-1} in the action plan.

A predicted TN retention in Lake Rotoiti expected under oxic conditions of 0.60 instead of the predicted 0.59 (with Eq. 17) would result in an internal load of 50 t N y^{-1}, consistent with the estimate in the action plan (BOPRC 2012a). However, even a predicted TN retention of 1 (naturally the maximum possible in theory) instead of the predicted 0.71 in Lake Rotorua (Table B-17) could not result in an internal load more than 227 t N y^{-1}, much lower than the estimate for internal loading for that lake (360 t N y^{-1}, Table B-6) in the action plan (BOPRC 2012a). This number of 227 t N y^{-1} is naturally unrealistically high for a net internal load as retention of TN would not be 1 in this lake under conditions without anoxia (i.e., without net internal loading), in view of its low residence time to mean depth ratio. Similarly, a predicted TP retention of 1 instead of the predicted 0.74 in Lake Rotorua (Table B-16) could not result in an internal load more than 21 t P y^{-1}, much lower than the estimate for internal loading for that lake (36 t y^{-1}, Table B-6) in the action plan (BOPRC 2012a). And a predicted TP retention of 1 instead of the predicted 0.74 in Lake Rotoiti (Table B-16) could not result in an internal load more than 17 t P y^{-1}, lower than the estimate for internal loading for that lake (20 t y^{-1}, Table B-6) in the action plan (BOPRC 2012a).

The lakes in the Bay of Plenty, where sedimentation rates on average are greater than release rates and which have a net retention of TP and a net retention of TN (the latter in all lakes except Lake Okaro), contrast strongly with more eutrophic and unbalanced lakes such as Lake Omapere where internal loading is much more pronounced. In Lake Omapere, internal loading results in average losses through the outlet of TN and TP of 151% and 213% of the external load, respectively (Verburg 2012, which applied the same methods to estimate internal loading). In comparison, internal loading in the Bay of Plenty lakes is relatively minor. Naturally, a situation where the loss of nutrients through the outlet exceeds the external load can only be maintained temporarily, until the nutrients in the sediment are depleted. It is typical for lakes with alternative stable states, where phytoplankton dominated phases of high internal loading and low water quality alternate with macrophyte dominated phases of net sedimentation, sequestering of nutrients and higher water quality. Lake Omapere is a good example of such a lake (Verburg et al. 2012).

That the average fluxes of sedimentation of P and permanent burial in the sediment are greater than the average fluxes of P release from the sediment is also supported by the literature for Lake Rotorua (Burger et al. 2007). From the data presented by Burger et al. (2007; their Figure 6, reproduced here as Fig. C-21), it is clear that no more than about half of the TP and TN entering the lake from external sources leaves the lake through the outlet. This means there is net retention in the lake for both TN and TP, and therefore the average sedimentation flux must be higher than the release of P and N from the sediment. An even greater proportion of TN (56%) compared with TP (50%) remains in the lake or is lost by denitrification (Fig. C-21). From the data as provided by Burger et al. (2007) for external inputs and outputs through the outlet of TN and TP (Fig. C-21) an estimated internal loading follows of 83-123 t TN y^{-1} and 1.9-8.5 t TP y^{-1} if the retention under oxic conditions is estimated with Eq. 15 and Eq. 17 for TN and Eq. 3 and Eq. 17 for TP. These estimates are fairly close to our estimates in this report of 8-63 t TN y^{-1} and 4.0-11.3 t TP y^{-1} (Tables B-10, B-11, B-16 and B-17). Both our internal load estimates and those following from the data of Burger et al. (2007) are much lower than those reported in the Rotorua action plan (360 t TN y^{-1} and 36 t TP y^{-1}). The difference is especially large for TP. Net internal loading cannot be higher than the loads observed in the outflows (see Eq. 7c; Tables B-10 and B-11) and can only be equal to the loads in the outflows if 100% retention could be expected to occur under oxic conditions which is unrealistic in Lake Rotorua. The principle is explained by a schematic diagram which shows the partitioning of the total nutrient load, the sum of external and internal loads, according to its source and fate (Fig. C-22).

The internal TP load in the action plan for Lake Rotorua (BOPRC 2012a) is almost the same as the external load, 36 t TP y^{-1} and 39.1 t TP y^{-1} respectively. For an internal load to occur in Lake Rotorua of 36 t TP y^{-1} the loss of TP through the outlet should be 118 to 138% of the total external load (using Eq.16 and Eq.3, respectively, for predicted P retention). Instead, the observed loss of TP through the outlet is only 55% of the total external load (50% in the diagram of Burger et al. 2007; Fig. C-21). To have similar internal and external loadings while the loss through the outlet is half of the external load (as shown by our results and by data in Burger et al. 2007) is a mathematical impossibility. Clearly on a net basis internal loading in Lake Rotorua is less substantial than the internal load reported by BOPRC (2012a).

Burger et al. (2008) found internal N and P loads in Lake Rotorua calculated by the DYRESM–CAEDYM model that were even far higher than given in the action plan, amounting to 71% and 91%, respectively, of the total nutrient load to the lake during the summer months (December–March), and 62 and 88%, respectively, on annual average. Burger's et al. (2008) results suggest that the internal P load in Lake Rotorua is on average seven times higher than the external P load. This internal load probably represents the gross internal load. Our results suggest that the net internal N and P loads are far lower, 1-8% and 9-22%, respectively (Tables B-14, B15, B20 and B21), of the total nutrient loads in Lake Rotorua.

The internal load is especially of interest when deciding how much P loading must be reduced or how much stored P must be removed from the lake or inactivated, for instance by sediment capping, to reach an acceptable target for water quality. Gross internal loads are of interest because of the effect of nutrients on algal productivity. Bio-available P released from the sediment can contribute to algal growth even when it subsequently ends up in the sediment again. Phosphorous drives a continuous cycle of algal uptake and productivity, sedimentation, decomposition and remineralization. One P atom can be released from the sediment as part of the internal load, and eventually it is returned to the sediment. This can happen many times with the same P atom until it is permanently buried and locked in the sediment. Naturally, also a P atom entering the lake as part of the external load can be temporarily buried in the sediment, followed by release to become part of the gross internal load. However, one particular P atom needs to be locked in the sediment by P absorbing capping agents only once to be removed permanently from the productivity cycle in the lake. Once locked in the sediment it will no longer contribute to P cycling between internal release and sedimentation. Therefore the gross internal load is of no interest when deciding how much total P loading reduction is required in a lake. Using the gross internal load, i.e., the P release rate from the sediments, or any load larger than the net internal load, would lead to false accounting because one particular P atom would be counted many times.

The action plan for Lake Rotorua states that the total nutrient reduction target needed to reach sustainable phosphorus inputs at equilibrium when internal and external inputs are combined is 38 t P y^{-1} (36 internal +39.1 external – 37 sustainable load = 38 t P y^{-1}). BOPRC is considering achieving the total nutrient reduction target in part by sediment capping to neutralize the P in the lake bed. As we have shown for the net internal load, an estimate of 36 t P y^{-1} is not realistic. If, however, the internal loading estimates in the Rotorua action plan (and action plans for other lakes) are assumed to represent some measure of gross internal loads (the action plans do not describe data sources or methods) instead of net internal loads, then there is no need for such high nutrient reduction targets, because most of the gross internal load gets permanently buried in the sediment, even without sediment capping.

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Appendix A CLUES calculations

The method used to calculate annual TN and TP loads into the lakes using CLUES is outlined in this section. CLUES is a modelling system for assessing the effects of land use change on water quality and socio-economic factors at a minimum scale of sub-catchments (~10 km^2 and above). CLUES was developed for the Ministry of Agriculture and Forestry (MAF) in association with the Ministry for the Environment (MfE) by NIWA, in collaboration with Lincoln Ventures, Harris Consulting, AgResearch, HortResearch, Crop and Food Research, and Landcare Research. CLUES couples a number of existing models within a GIS-platform and is provided to users as a front-end interface for ArcGIS which queries a geo-spatial database.

The base areal unit of CLUES is the sub-catchment which comes from the NIWA River Environment Classification (REC) of the national stream and sub-catchment network[1]. Geo-spatial data needed to run CLUES are provided at national, regional, catchment and sub-catchment levels. Terrain data is at 30 m resolution. In addition to REC, data provided are land use, runoff (derived from rainfall less evapotranspiration), slope, soil data (from the NZ Land Resources Inventory, NZLRI, Fundamental Soils Layer[2] – Wilde et al. 2004), contaminant point sources and lakes. The land use layer provided with CLUES was developed with extensive reference to the LCDB2 (Land Cover Database)[3], AgriBase (AsureQuality Ltd)[4], and LENZ (Land Environments of New Zealand)[5] land use geo-databases and refers to land use in 2002. Considerable effort was expended, with Landcare Research, to ensure that the spatial data coverage was as accurate as possible.

Further details on the modelling framework can be found in Woods et al. (2006) and information on setting up and running CLUES scenarios can be found in Semadeni-Davies et al. (2011 and 2012).

CLUES returns annual loads for each REC river reach in the country. Lakes are represented as river reaches (Figure A-1). Lake outlets are identified as such within the REC geo-database. Inlet reaches are not identified. For this reason, this study back calculated the total load in the lake inflows from the loads in outflows using the following method:

1. CLUES was run with default land use settings for all river reaches in Bay of Plenty. The results for reaches identified as lake outlets were exported to EXCEL along with REC data (e.g., annual rainfall) needed for the calculations.

2. Where CLUES identifies more than one outlet reach in a lake, the annual loads for each were combined to give a lake total (Figure A-2).

3. Calculate the total loads entering the lake for each nutrient (N and P) as:
   external load = outflow load*(1+KRES/RESLOAD)
   where KRES is a settling parameter (see Table A1) and RESLOAD is the lake hydraulic overflow rate, that is, the discharge rate divided by the lake area (m y^{-1}).

[1] http://www.niwa.co.nz/our-science/freshwater/tools/rec (date of last access 5 April 2012)
[2] http://soils.landcareresearch.co.nz/contents/index.aspx (date of last access 5 April 2012)
[3] http://www.mfe.govt.nz/issues/land/land-cover-dbase/classes.html (date of last access 5 April 2012)
[4] http://www.asurequality.com/capturing-information-technology-across-the-supply-chain/agribase-database-for-nz-rural-properties.cfm (date of last access 5 April 2012)
[5] http://www.landcareresearch.co.nz/services/informatics/LENZ/about.asp (date of last access 5 April 2012)

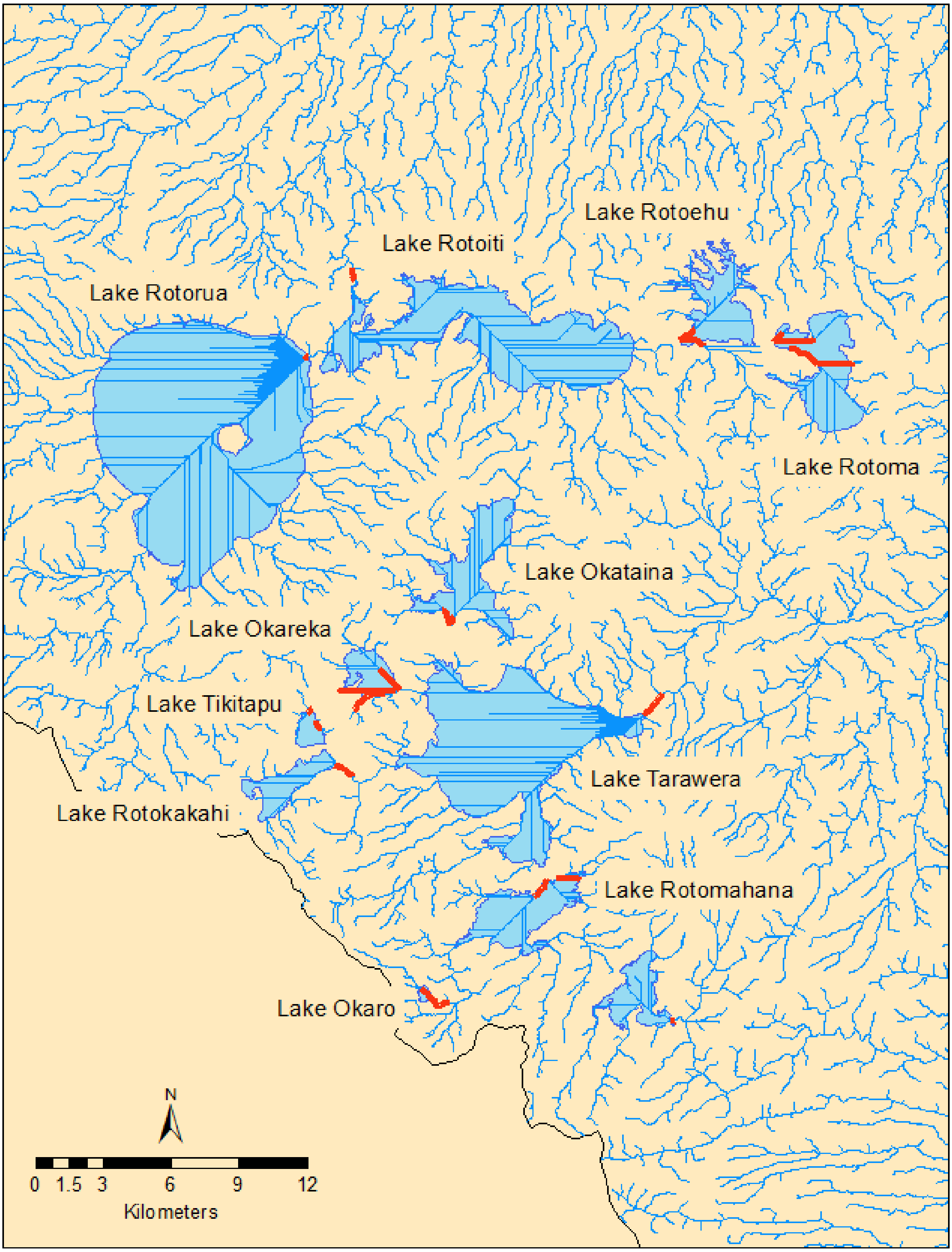

Figure A-1: CLUES representation of Bay of Plenty Lakes as river reaches in the REC database. Reaches identified as lake outlets are marked in red.

4. Calculate the direct (atmospheric) input to the lake surface as:
Annual deposition rate (t ha^{-1}) = Area*C1*e^((Rain-1.85)*C2)*e^(0.82*C3)

Where Rain = rainfall (mm y^{-1}), Area = lake area (ha).The coefficients C1, C2 and C3 differ for nitrogen and phosphorus (Table A1).

Table A-1: CLUES coeffiecients for lake load calculation.

	KRES	C1	C2	C3
Nitrogen	7.46	0.0004	0.2918	-0.4969
Phosphorus	36.1	0.000263	0	0

5. Calculate loads into the lakes from inlets as the total load less the atmospheric input.

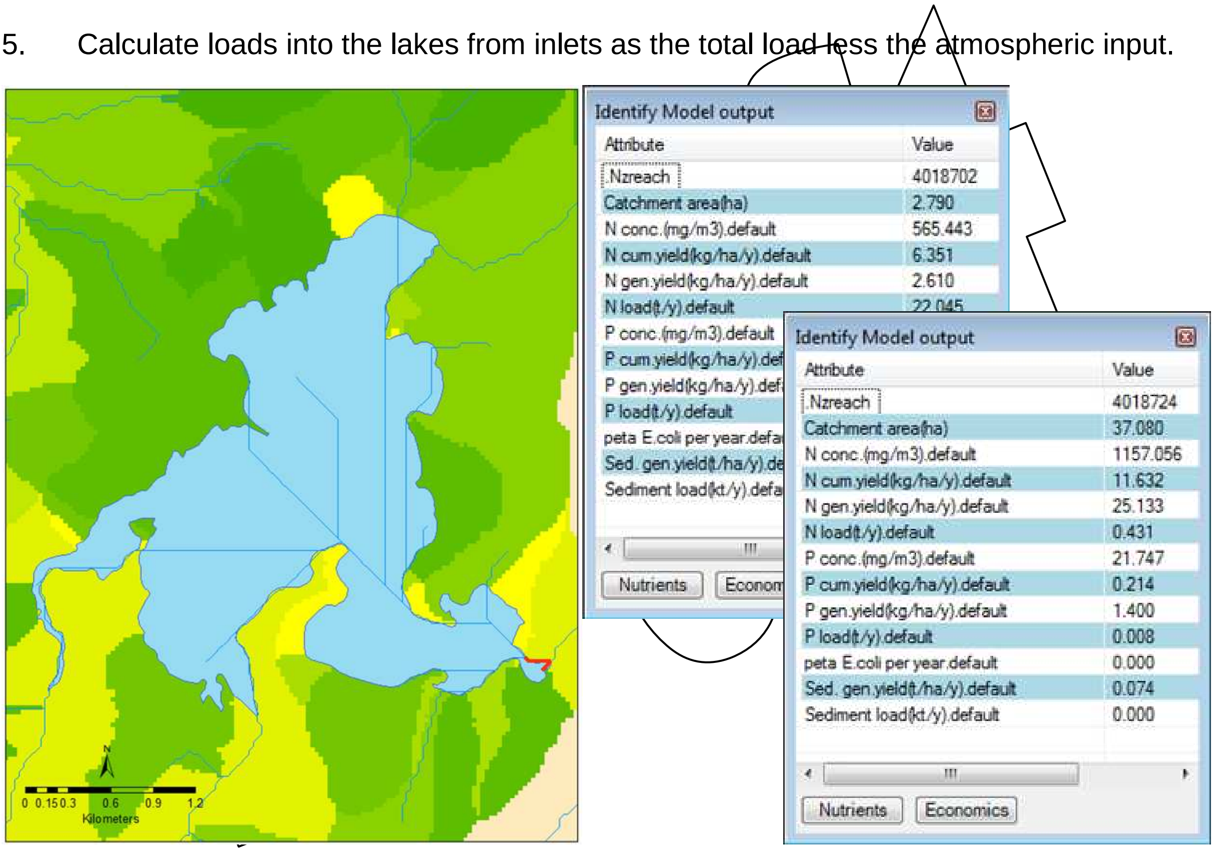

Figure A-2: CLUES results for Lake Rerewhakaaitu. Note there are two apparent outlet reaches from the lake identified in the REC database which are in fact one. The total load in the outflow is the sum of the load in both apparent reaches.

Appendix B Results tables

Table B-1: Oxygen concentrations.

Maximum and mean lake depths (LERNZ 2012) and the minimum, mean annual, and mean summer (January-March) oxygen (DO) near the bottom at the deepest point of each lake, with depths of the measurements, the monitoring period (years run from July to June) and % of the time dissolved oxygen was below 1 g m^{-3} or below 3 g m^{-3}. The minimum DO concentration was the mean of the lowest three measurements at the monitoring depth on different sampling days. For Lake Rotomahana data are given for two depths. * Indicates lakes where internal loads have been reported (BOPRC 2012a).

Lake	Maximum lake depth (m)	Mean lake depth (m)	Minimum DO (g m^{-3})	Mean annual DO (g m^{-3})	Mean summer DO (g m^{-3})	Monitoring depth (m)	<1 g m^{-3} (%)	<3 g m^{-3} (%)	n	Monitoring period
Rotorua*	44.8	10.1	0.2	8.4	5.2	20	4	6	140	1996-2009
Okataina	78.5	43.7	0.5	6.0	3.8	58	7	24	127	1990-2009
Okareka	33.5	19.1	0.1	5.4	2.2	28	23	36	179	1987-2009
Tarawera	87.5	55.5	6.3	8.8	8.4	70	0	0	92	2001-2009
Rotokakahi	32	17.5	na	na	na	na	na	na	na	na
Rotomahana	125	53.1	4.0	6.7	5.6	114	0	0	70	2003-2009
			4.3	7.3	6.2	108	0	0	36	2005-2009
Okaro*	18	11	0.1	3.1	0.5	14	53	65	119	1991-2009
Rerewhakaaitu	30	6.2	2.7	9.4	7.3	10	0	1	136	1990-2009
Rotoehu*	13.5	8	1.0	9.1	6.7	8	2	3	129	1996-2009
Rotoiti*	93.5	32.8	0.1	4.7	0.4	102	38	44	66	2003-2009
Rotoma	83	39	4.1	7.8	7.1	60	0	0	127	1990-2009
Tikitapu	27.5	18.4	0.2	5.5	1.6	24	28	35	69	2002-2009

Table B-2: Lake surface area estimates (km^2). The largest discrepancy between estimates is for Lake Rerewhakaaitu.

Lake	Data sources			
	Viner 1987	LERNZ 2012	Hamilton et al. 2006	This report
Rotorua	79.8	79.0		80.5
Okataina	10.8	10.7	11.7	10.7
Okareka	3.5	3.33	3.34	3.34
Tarawera	41	41.0	41.4	41.2
Rotokakahi	4.5	4.40	4.33	4.33
Rotomahana	8	9.02	9.02	9.02
Okaro	0.28	0.30	0.30	0.30
Rerewhakaaitu	7.4	5.92	5.17	5.17
Rotoehu	8.1	7.61		7.90
Rotoiti	34.3	31.8		33.7
Rotoma	11.2	11.0		11.1
Tikitapu	1.4	1.43	1.44	1.44

Table B-3: Lake volume estimates (10^3 m^3). In the 2nd column volume was estimated as the product of lake area and mean depth given by Viner (1987). Data from Ellery (2004) were recent data read from graphs of time series of volume. The largest discrepancies between estimates are for lakes Rerewhakaaitu and Rotoehu.

Lake	Data sources		
	Viner 1987	LERNZ 2012	Ellery 2004
Rotorua	798000	802000	765000
Okataina	475000	466000	440000
Okareka	64400	63600	59500
Tarawera	2340000	2270000	2270000
Rotokakahi	79700	76800	75000
Rotomahana	408000	479000	465000
Okaro	3220	3300	3400
Rerewhakaaitu	44400	36600	58000
Rotoehu	67200	61000	55000
Rotoiti	1130000	1040000	1060000
Rotoma	432000	429000	410000
Tikitapu	26700	26300	26000

Table B-4: Lake mean depth estimates (m). Mean depth in the 2nd column was given by Viner (1987) and is estimated as the ratio of volume to surface area in the remaining columns. The 4th column presents the ratio of volumes of Ellery (2004) and surface areas estimated for this study from digitized topographic maps. The largest discrepancy between estimates is for Lake Rerewhakaaitu.

	Data sources		
Lake	**Viner 1987**	**LERNZ 2012**	**Ellery 2004 / this report**
Rotorua	10.0	10.1	9.5
Okataina	44.0	43.7	41.0
Okareka	18.4	19.1	17.8
Tarawera	57.0	55.5	55.1
Rotokakahi	17.7	17.5	17.3
Rotomahana	51.0	53.1	51.5
Okaro	11.5	11.0	11.3
Rerewhakaaitu	6.0	6.2	11.2
Rotoehu	8.3	8.0	7.0
Rotoiti	33.0	32.8	31.5
Rotoma	38.6	39.0	36.9
Tikitapu	19.1	18.4	18.0

Table B-5: Lake mean outflow rate estimates ($m^3 s^{-1}$). This report used methods of Woods et al. (2006). In the last column are means of available data in 2000-2011 of flows monitored by NIWA. The largest proportional discrepancies between estimates are for the two lakes with the smallest outflows, Lakes Rotoma and Okaro.

	Data sources				
Lake	**This report**	**Ozkundakci (pers comm)**	**Pittams 1968**	**Hamilton et al. 2006**	**NIWA 2000–2011**
Rotorua	16.6		16.2		17.5
Okataina	2.58				
Okareka	0.494				
Tarawera	6.67			7.23	6.67
Rotokakahi	0.50				
Rotomahana	2.62				
Okaro	0.115	0.026			
Rerewhakaaitu	1.06				
Rotoehu	2.032		1.74		
Rotoiti	21.6		23.9		22.1
Rotoma	0.380		1.31		
Tikitapu	0.083				

Table B-6: Estimates of external loads of TN (t y^{-1}). Internal loads when given in the BOPRC (2012a) action plans are shown as well. External loads comprise both catchment and atmospheric sources. Catchment loads were derived from land use coefficients. The external load for Lake Rotorua is from BOPRC (2012b), reporting results of ROTAN analysis (Rutherford et al. 2011). Data of Hamilton (2006) are only given when no data are available in action plans.

Lake	External loads			Internal loads
	Action plans BOPRC 2012a	Hamilton et al. 2006	CLUES	Action plans BOPRC 2012a
Rotorua	755		500	360
Okataina		22.3	12.9	
Okareka	11.0		6.76	
Tarawera		84.6	36.9	
Rotokakahi		15.4	4.98	
Rotomahana		39.9	45.2	
Okaro	2.59		4.36	2.41
Rerewhakaaitu		47.5	47.3	
Rotoehu	53.3		27.7	5.60
Rotoiti	364		275.9	50.0
Rotoma	18.1		1.98	
Tikitapu	2.50		0.524	

Table B-7: Estimates of external loads of TP (t y^{-1}). Internal loads when given in the BOPRC (2012a) action plans are shown as well. External loads comprise both catchment and atmospheric sources. Catchment loads were derived from land use coefficients. Data of Hamilton et al. (2006) are only given when no data are available in action plans.

Lake	External loads			Internal loads
	Action plans BOPRC 2012a	Hamilton et al. 2006	CLUES	Action plans BOPRC 2012a
Rotorua	39.1		64.9	36.0
Okataina		2.93	2.52	
Okareka	0.408		1.39	
Tarawera		10.4	7.07	
Rotokakahi		1.44	0.800	
Rotomahana		5.53	4.13	
Okaro	0.396		0.47	0.380
Rerewhakaaitu		5.69	3.42	
Rotoehu	2.45		3.28	1.40
Rotoiti	29.0		15.3	20.0
Rotoma	0.736		0.193	
Tikitapu	0.125		0.114	

Table B-8: Input data on which the estimation of retention and internal loads of TN are based. $[TN]_{lake}$ = the mean epilimnetic TN concentration (Scholes 2010). Q = Outflow rate, T_w = hydraulic residence time, q_s = hydraulic load, TN_{ext} = external TN load. Lake surface areas are from this report, lake volumes from LERNZ (2012), mean depth is the ratio of columns 4 and 3, Q from this report, TN_{ext} from action plans (BOPRC 2012a), and from Hamilton (2006) when not available in action plans.

Lake	$[TN]_{lake}$ (mg m^{-3})	Area (km^2)	Volume (10^3 m^3)	Mean depth (m)	Q (m^3 s^{-1})	T_w (y)	q_s (m y^{-1})	TN_{ext} (t y^{-1})
Rotorua	434.3	80.479	801690	10.0	16.565	1.5	6.5	755.0
Okataina	129.7	10.728	466010	43.4	2.578	5.7	7.6	22.3
Okareka	219.2	3.341	63594	19.0	0.494	4.1	4.7	11.0
Tarawera	114.2	41.154	2273700	55.2	6.667	10.8	5.1	84.6
Rotokakahi	221.9	4.333	76832	17.7	0.502	4.9	3.7	15.4
Rotomahana	220.1	9.023	479050	53.1	2.624	5.8	9.2	39.9
Okaro	1130.2	0.301	3303	11.0	0.115	0.9	12.1	2.6
Rerewhakaaitu	389.6	5.170	36647	7.1	1.059	1.1	6.5	47.5
Rotoehu	432.3	7.901	61001	7.7	2.032	1.0	8.1	53.3
Rotoiti	285.0	33.691	1042300	30.9	21.641	1.5	20.3	364.0
Rotoma	145.2	11.116	428540	38.6	0.380	35.8	1.1	18.1
Tikitapu	207.8	1.442	26320	18.2	0.083	10.1	1.8	2.5

Table B-9: Input data on which the estimation of retention and internal loads of TP are based. $[TP]_{lake}$ = the mean epilimnetic TP concentration (Scholes 2010). TP_{ext} = external TP load. The remaining input data are as in Table 8. TP_{ext} from action plans (BOPRC 2012a), and from Hamilton (2006) when not available in action plans.

Lake	$[TP]_{lake}$ (mg m^{-3})	TP_{ext} (t y^{-1})
Rotorua	41.1	39.1
Okataina	7.7	2.9
Okareka	7.0	0.4
Tarawera	9.9	10.4
Rotokakahi	12.3	1.4
Rotomahana	30.6	5.5
Okaro	101.3	0.4
Rerewhakaaitu	8.3	5.7
Rotoehu	38.0	2.4
Rotoiti	25.1	29.0
Rotoma	4.3	0.7
Tikitapu	5.2	0.1

Table B-10: The budget for TP. TP_{ext} = external TP load (includes atmospheric deposition), TP_{out} = the load flushed from the lake through the outlet (mean flow x mean lake concentration), $TP_{retained}$ = TP_{ext} - TP_{out}, R_{pred} = predicted retention (Eq. 3), R_{obs} = observed retention, net TP_{int} = the net internal TP load = predicted $TP_{retained}$ – observed $TP_{retained}$ (presented in 3 different units). See Table B-16 for comparison.

Lake	TP_{ext} ($t\ y^{-1}$)	TP_{out} ($t\ y^{-1}$)	$TP_{retained}$ observed ($t\ y^{-1}$)	R_{pred}	R_{obs}	Net TP_{int} ($t\ y^{-1}$)	Net TP_{int} ($mg\ m^{-2}\ y^{-1}$)	Net TP_{int} (% of TP_{ext})
Rotorua	39.10	21.48	17.62	0.55	0.45	4.02	50	10
Okataina	2.93	0.63	2.31	0.71	0.79	-0.24	-22	-8
Okareka	0.41	0.11	0.30	0.67	0.73	-0.03	-8	-7
Tarawera	10.41	2.08	8.33	0.77	0.80	-0.35	-8	-3
Rotokakahi	1.44	0.19	1.25	0.69	0.87	-0.26	-59	-18
Rotomahana	5.53	2.53	3.00	0.71	0.54	0.91	101	16
Okaro	0.40	0.37	0.03	0.49	0.07	0.17	550	42
Rerewhakaaitu	5.69	0.28	5.41	0.51	0.95	-2.50	-484	-44
Rotoehu	2.45	2.43	0.01	0.49	0.00	1.20	151	49
Rotoiti	29.00	17.17	11.83	0.55	0.41	4.20	125	14
Rotoma	0.74	0.05	0.68	0.86	0.93	-0.05	-5	-7
Tikitapu	0.13	0.01	0.11	0.76	0.89	-0.02	-11	-13

Table B-11: The budget for TN. TN_{ext} = external TN load (includes atmospheric deposition), TN_{out} = the load flushed from the lake through the outlet (mean flow x mean lake concentration), $TN_{retained}$ = TN_{ext} - TN_{out}, R_{pred} = predicted retention (Eq. 15), R_{obs} = observed retention, net TN_{int} = the net internal TN load = predicted $TN_{retained}$ – observed $TN_{retained}$. See Table B-17 for comparison.

Lake	TN_{ext} ($t\ y^{-1}$)	TN_{out} ($t\ y^{-1}$)	$TN_{retained}$ observed ($t\ y^{-1}$)	R_{pred}	R_{obs}	Net TN_{int} ($t\ y^{-1}$)	Net TN_{int} ($mg\ m^{-2}\ y^{-1}$)	Net TN_{int} (% of TN_{ext})
Rotorua	755.0	227.0	528.0	0.78	0.70	63.1	784	8
Okataina	22.3	10.5	11.7	0.73	0.53	4.5	421	20
Okareka	11.0	3.4	7.6	0.88	0.69	2.1	631	19
Tarawera	84.6	24.0	60.6	0.86	0.72	11.9	288	14
Rotokakahi	15.4	3.5	11.9	0.93	0.77	2.5	576	16
Rotomahana	39.9	18.2	21.7	0.66	0.54	4.7	520	12
Okaro	2.6	4.1	-1.5	0.56	-0.59	3.0	9861	115
Rerewhakaaitu	47.5	13.0	34.5	0.78	0.73	2.8	537	6
Rotoehu	53.3	27.7	25.6	0.71	0.48	12.0	1522	23
Rotoiti	364.0	194.6	169.4	0.39	0.47	-28.5	-846	-8
Rotoma	18.1	1.7	16.4	1.00	0.90	1.7	156	10
Tikitapu	2.5	0.5	2.0	1.00	0.78	0.5	368	21

Table B-12: The budget for TP, as Table 10, but using external loads obtained with CLUES. The external load includes atmospheric deposition. Compare with Table B-18.

Lake	TP_{ext} ($t\ y^{-1}$)	TP_{out} ($t\ y^{-1}$)	$TP_{retained}$ observed ($t\ y^{-1}$)	R_{pred}	R_{obs}	Net TP_{int} ($t\ y^{-1}$)	Net TP_{int} ($mg\ m^{-2}\ y^{-1}$)	Net TP_{int} (% of TP_{ext})
Rotorua	64.92	21.48	43.44	0.55	0.67	-7.52	-93	-12
Okataina	2.52	0.63	1.89	0.71	0.75	-0.12	-11	-5
Okareka	1.39	0.11	1.28	0.67	0.92	-0.35	-105	-25
Tarawera	7.07	2.08	4.99	0.77	0.71	0.43	10	6
Rotokakahi	0.80	0.19	0.61	0.69	0.76	-0.06	-13	-7
Rotomahana	4.13	2.53	1.59	0.71	0.39	1.32	146	32
Okaro	0.47	0.37	0.10	0.49	0.22	0.13	424	27
Rerewhakaaitu	3.42	0.28	3.14	0.51	0.92	-1.39	-270	-41
Rotoehu	3.28	2.43	0.85	0.49	0.26	0.77	98	24
Rotoiti	15.35	17.17	-1.82	0.55	-0.12	10.30	306	67
Rotoma	0.19	0.05	0.14	0.86	0.74	0.02	2	12
Tikitapu	0.11	0.01	0.10	0.76	0.88	-0.01	-9	-12

Table B-13: The budget for TN, as Table 11, but using external loads obtained with CLUES. The external load includes atmospheric deposition. Compare with Table B-19.

Lake	TN_{ext} ($t\ y^{-1}$)	TN_{out} ($t\ y^{-1}$)	$TN_{retained}$ observed ($t\ y^{-1}$)	R_{pred}	R_{obs}	Net TN_{int} ($t\ y^{-1}$)	Net TN_{int} ($mg\ m^{-2}\ y^{-1}$)	Net TN_{int} (% of TN_{ext})
Rotorua	500.3	227.0	273.3	0.78	0.55	118.4	1471	24
Okataina	12.9	10.5	2.3	0.73	0.18	7.1	658	55
Okareka	6.8	3.4	3.3	0.88	0.49	2.6	781	39
Tarawera	36.9	24.0	12.9	0.86	0.35	18.7	455	51
Rotokakahi	5.0	3.5	1.5	0.93	0.29	3.2	735	64
Rotomahana	45.2	18.2	27.0	0.66	0.60	2.9	320	6
Okaro	4.4	4.1	0.2	0.56	0.06	2.2	7280	50
Rerewhakaaitu	47.3	13.0	34.3	0.78	0.72	2.8	546	6
Rotoehu	27.7	27.7	0.0	0.71	0.00	19.6	2475	71
Rotoiti	275.9	194.6	81.2	0.39	0.29	25.5	757	9
Rotoma	2.0	1.7	0.2	1.00	0.12	1.7	157	88
Tikitapu	0.5	0.5	0.0	1.00	-0.03	0.5	374	103

Table B-14: Total TP loading and the proportion retained in the lake. Data of external loads from BOPRC (2012a) and Hamilton et al. (2006). Compare with Table B-20.

Lake	$TP_{ext}+TP_{int}$ = TP_{total} t y^{-1}	$TP_{total}-TP_{out}$ TP retained t y^{-1}	$(TP_{total}-TP_{out})/TP_{total}$ TP retained %	TP_{int}/TP_{total} TP_{int} %
Rotorua	43.1	21.6	50	9
Okataina	2.7	2.1	77	-9
Okareka	0.4	0.3	72	-7
Tarawera	10.1	8.0	79	-3
Rotokakahi	1.2	1.0	84	-22
Rotomahana	6.4	3.9	61	14
Okaro	0.6	0.2	34	30
Rerewhakaaitu	3.2	2.9	91	-79
Rotoehu	3.6	1.2	33	33
Rotoiti	33.2	16.0	48	13
Rotoma	0.7	0.6	93	-8
Tikitapu	0.1	0.1	87	-15

Table B-15: Total TN loading and the proportion retained in the lake. Data of external loads from BOPRC (2012a) and Hamilton et al. (2006). Compare with Table B-21.

Lake	$TN_{ext}+TN_{int}$ = TN_{total} t y^{-1}	$TN_{total}-TN_{out}$ TN retained t y^{-1}	$(TN_{total}-TN_{out})/TN_{total}$ TN retained %	TN_{int}/TN_{total} TN_{int} %
Rotorua	818	591	72	8
Okataina	27	16	61	17
Okareka	13	10	74	16
Tarawera	96	72	75	12
Rotokakahi	18	14	80	14
Rotomahana	45	26	59	11
Okaro	6	1	26	53
Rerewhakaaitu	50	37	74	6
Rotoehu	65	38	58	18
Rotoiti	336	141	42	-8
Rotoma	20	18	91	9
Tikitapu	3	2	82	18

Table B-16: The budget for TP, with predicted retention using Eq. 16. TP_{ext} = external TP load (includes atmospheric deposition), TP_{out} = the load flushed from the lake through the outlet (mean flow x mean lake concentration), $TP_{retained}$ = TP_{ext} - TP_{out}, R_{pred} = predicted retention (Eq. 16), R_{obs} = observed retention, net TP_{int} = the net internal TP load = predicted $TP_{retained}$ – observed $TP_{retained}$ (presented in 3 different units).

Lake	TP_{ext} (t y^{-1})	TP_{out} (t y^{-1})	$TP_{retained}$ observed (t y^{-1})	R_{pred}	R_{obs}	Net TP_{int} (t y^{-1})	Net TP_{int} (mg m^{-2} y^{-1})	Net TP_{int} (% of TP_{ext})
Rotorua	39.10	21.48	17.62	0.74	0.45	11.32	141	29
Okataina	2.93	0.63	2.31	0.85	0.79	0.18	16	6
Okareka	0.41	0.11	0.30	0.82	0.73	0.04	11	9
Tarawera	10.41	2.08	8.33	0.88	0.80	0.86	21	8
Rotokakahi	1.44	0.19	1.25	0.84	0.87	-0.04	-10	-3
Rotomahana	5.53	2.53	3.00	0.85	0.54	1.69	187	30
Okaro	0.40	0.37	0.03	0.69	0.07	0.24	811	62
Rerewhakaaitu	5.69	0.28	5.41	0.71	0.95	-1.39	-269	-24
Rotoehu	2.45	2.43	0.01	0.69	0.00	1.68	213	69
Rotoiti	29.00	17.17	11.83	0.74	0.41	9.62	286	33
Rotoma	0.74	0.05	0.68	0.93	0.93	0.00	0	0
Tikitapu	0.13	0.01	0.11	0.88	0.89	0.00	-1	-1

Table B-17: The budget for TN, with predicted retention using Eq. 17. TN_{ext} = external TN load (includes atmospheric deposition), TN_{out} = the load flushed from the lake through the outlet (mean flow x mean lake concentration), $TN_{retained}$ = TN_{ext} - TN_{out}, R_{pred} = predicted retention (Eq. 17), R_{obs} = observed retention, net TN_{int} = the net internal TN load = predicted $TN_{retained}$ – observed $TN_{retained}$.

Lake	TN_{ext} (t y^{-1})	TN_{out} (t y^{-1})	$TN_{retained}$ observed (t y^{-1})	R_{pred}	R_{obs}	Net TN_{int} (t y^{-1})	Net TN_{int} (mg m^{-2} y^{-1})	Net TN_{int} (% of TN_{ext})
Rotorua	755.0	227.0	528.0	0.71	0.70	7.5	93	1
Okataina	22.3	10.5	11.7	0.69	0.53	3.7	345	17
Okareka	11.0	3.4	7.6	0.74	0.69	0.6	183	6
Tarawera	84.6	24.0	60.6	0.73	0.72	1.6	38	2
Rotokakahi	15.4	3.5	11.9	0.77	0.77	0.0	-3	0
Rotomahana	39.9	18.2	21.7	0.67	0.54	5.2	571	13
Okaro	2.6	4.1	-1.5	0.64	-0.59	3.2	10569	123
Rerewhakaaitu	47.5	13.0	34.5	0.71	0.73	-0.8	-150	-2
Rotoehu	53.3	27.7	25.6	0.69	0.48	11.0	1387	21
Rotoiti	364.0	194.6	169.4	0.59	0.47	44.5	1320	12
Rotoma	18.1	1.7	16.4	0.90	0.90	0.0	-4	0
Tikitapu	2.5	0.5	2.0	0.85	0.78	0.2	109	6

Table B-18: The budget for TP, as Table 16, but using external loads obtained with CLUES. The external load includes atmospheric deposition. R_{pred} is according to Eq. 16.

Lake	TP_{ext} (t y^{-1})	TP_{out} (t y^{-1})	$TP_{retained}$ observed (t y^{-1})	R_{pred}	R_{obs}	Net TP_{int} (t y^{-1})	Net TP_{int} (mg m^{-2} y^{-1})	Net TP_{int} (% of TP_{ext})
Rotorua	64.92	21.48	43.44	0.74	0.67	4.61	57	7
Okataina	2.52	0.63	1.89	0.85	0.75	0.24	22	9
Okareka	1.39	0.11	1.28	0.82	0.92	-0.14	-41	-10
Tarawera	7.07	2.08	4.99	0.88	0.71	1.25	30	18
Rotokakahi	0.80	0.19	0.61	0.84	0.76	0.06	15	8
Rotomahana	4.13	2.53	1.59	0.85	0.39	1.90	211	46
Okaro	0.47	0.37	0.10	0.69	0.22	0.22	734	47
Rerewhakaaitu	3.42	0.28	3.14	0.71	0.92	-0.73	-141	-21
Rotoehu	3.28	2.43	0.85	0.69	0.26	1.42	180	43
Rotoiti	15.35	17.17	-1.82	0.74	-0.12	13.17	391	86
Rotoma	0.19	0.05	0.14	0.93	0.74	0.04	3	20
Tikitapu	0.11	0.01	0.10	0.88	0.88	0.00	0	0

Table B-19: The budget for TN, as Table 17, but using external loads obtained with CLUES. The external load includes atmospheric deposition. R_{pred} is according to Eq. 17.

Lake	TN_{ext} (t y^{-1})	TN_{out} (t y^{-1})	$TN_{retained}$ observed (t y^{-1})	R_{pred}	R_{obs}	Net TN_{int} (t y^{-1})	Net TN_{int} (mg m^{-2} y^{-1})	Net TN_{int} (% of TN_{ext})
Rotorua	500.3	227.0	273.3	0.71	0.55	81.6	1014	16
Okataina	12.9	10.5	2.3	0.69	0.18	6.6	614	51
Okareka	6.8	3.4	3.3	0.74	0.49	1.7	506	25
Tarawera	36.9	24.0	12.9	0.73	0.35	14.2	346	39
Rotokakahi	5.0	3.5	1.5	0.77	0.29	2.4	547	48
Rotomahana	45.2	18.2	27.0	0.67	0.60	3.4	378	8
Okaro	4.4	4.1	0.2	0.64	0.06	2.6	8472	59
Rerewhakaaitu	47.3	13.0	34.3	0.71	0.72	-0.7	-137	-1
Rotoehu	27.7	27.7	0.0	0.69	0.00	19.0	2404	69
Rotoiti	275.9	194.6	81.2	0.59	0.29	80.8	2399	29
Rotoma	2.0	1.7	0.2	0.90	0.12	1.5	139	78
Tikitapu	0.5	0.5	0.0	0.85	-0.03	0.5	320	88

Table B-20: Total TP loading, the proportion retained in the lake, and the proportion of the internal load using data of Table 16. External loads from BOPRC (2012a) and Hamilton et al. (2006). R_{pred} is according to Eq. 16.

Lake	$TP_{ext}+TP_{int}$ = TP_{total} t y^{-1}	TP_{total}-TP_{out} TP retained t y^{-1}	(TP_{total}-TP_{out})/TP_{total} TP retained %	TP_{int}/ TP_{total} TP_{int} %
Rotorua	50.4	28.9	57	22
Okataina	3.1	2.5	80	6
Okareka	0.4	0.3	76	8
Tarawera	11.3	9.2	82	8
Rotokakahi	1.4	1.2	86	-3
Rotomahana	7.2	4.7	65	23
Okaro	0.6	0.3	42	38
Rerewhakaaitu	4.3	4.0	94	-32
Rotoehu	4.1	1.7	41	41
Rotoiti	38.6	21.5	56	25
Rotoma	0.7	0.7	93	0
Tikitapu	0.1	0.1	89	-1

Table B-21: Total TN loading, the proportion retained in the lake, and the proportion of the internal load using data of Table 17. External loads from BOPRC (2012a) and Hamilton et al. (2006). R_{pred} is according to Eq. 17.

Lake	$TN_{ext}+TN_{int}$ = TN_{total} t y^{-1}	TN_{total}-TN_{out} TN retained t y^{-1}	(TN_{total}-TN_{out})/TN_{total} TN retained %	TN_{int}/ TN_{total} TN_{int} %
Rotorua	763	535	70	1
Okataina	26	15	59	14
Okareka	12	8	71	5
Tarawera	86	62	72	2
Rotokakahi	15	12	77	0
Rotomahana	45	27	60	11
Okaro	6	2	29	55
Rerewhakaaitu	47	34	72	-2
Rotoehu	64	37	57	17
Rotoiti	408	214	52	11
Rotoma	18	16	90	0
Tikitapu	3	2	80	6

Table B-22: Total TP loading, the proportion retained in the lake, and the proportion of the internal load using data of Table 18. External loads obtained with CLUES. R_{pred} is according to Eq. 16.

Lake	$TP_{ext}+TP_{int}$ = TP_{total} t y^{-1}	$TP_{total}-TP_{out}$ TP retained t y^{-1}	$(TP_{total}-TP_{out})/TP_{total}$ TP retained %	TP_{int}/TP_{total} TP_{int} %
Rotorua	69.5	48.1	69	7
Okataina	2.8	2.1	77	9
Okareka	1.2	1.1	91	-11
Tarawera	8.3	6.2	75	15
Rotokakahi	0.9	0.7	77	7
Rotomahana	6.0	3.5	58	32
Okaro	0.7	0.3	47	32
Rerewhakaaitu	2.7	2.4	90	-27
Rotoehu	4.7	2.3	48	30
Rotoiti	28.5	11.4	40	46
Rotoma	0.2	0.2	78	16
Tikitapu	0.1	0.1	88	0

Table B-23: Total TN loading, the proportion retained in the lake, and the proportion of the internal load using data of Table 19. External loads obtained with CLUES. R_{pred} is according to Eq. 17.

Lake	$TN_{ext}+TN_{int}$ = TN_{total} t y^{-1}	$TN_{total}-TN_{out}$ TN retained t y^{-1}	$(TN_{total}-TN_{out})/TN_{total}$ TN retained %	TN_{int}/TN_{total} TN_{int} %
Rotorua	582	355	61	14
Okataina	19	9	46	34
Okareka	8	5	60	20
Tarawera	51	27	53	28
Rotokakahi	7	4	52	32
Rotomahana	49	30	63	7
Okaro	7	3	41	37
Rerewhakaaitu	47	34	72	-2
Rotoehu	47	19	41	41
Rotoiti	357	162	45	23
Rotoma	4	2	51	44
Tikitapu	1	0	45	47

Appendix C Figures

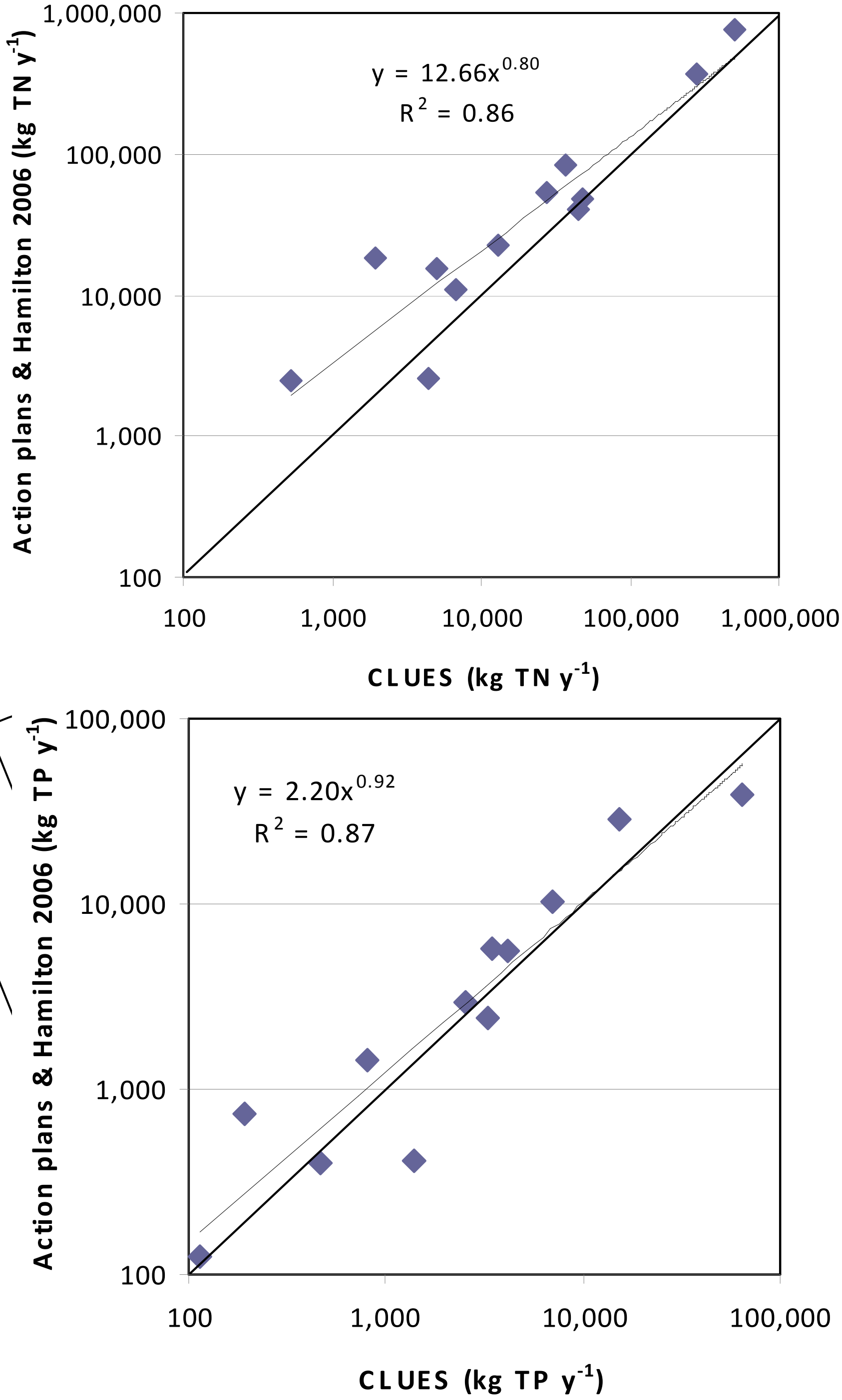

Figure C-1: Comparison of TN and TP loads to each of the 12 Bay of Plenty lakes. Estimated with CLUES versus loads reported in action plans (BOPRC 2012a, except BOPRC2012 for TN in Lake Rotorua) or in Hamilton et al. (2006) when no action plan is available for a lake, on log-log scale. The 1:1 line and a power fit are indicated by straight lines, with the equation and R^2 for the latter.

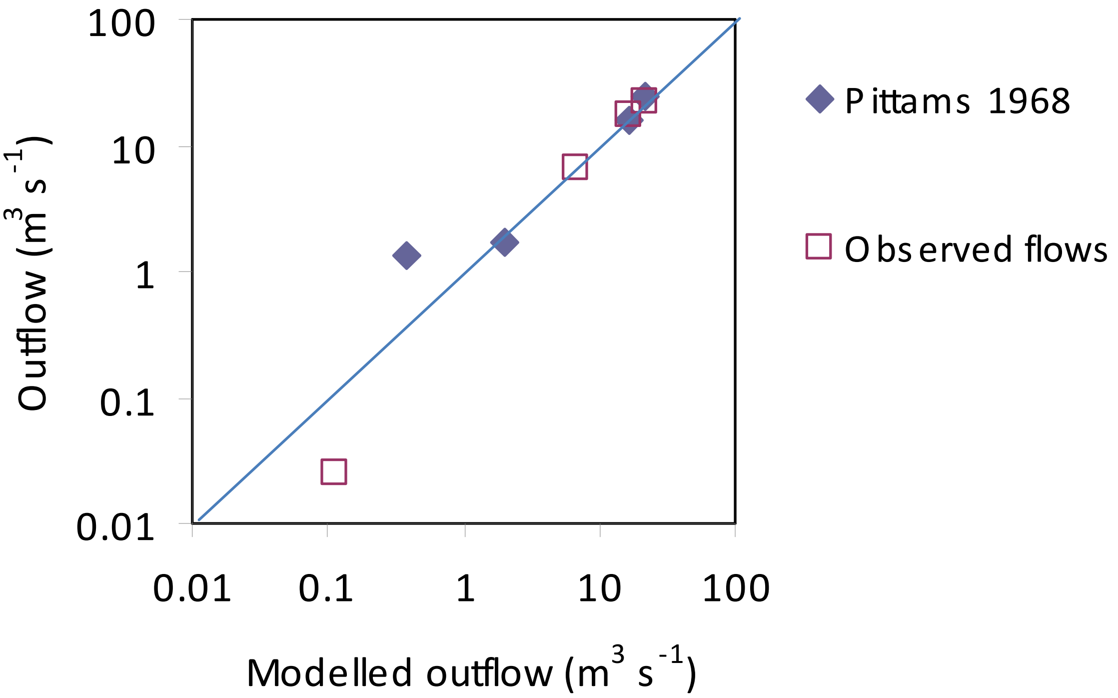

Figure C-2: Modelled flows (Wood et al. 2006) against flows estimated from water balances (Pittams 1968) and observed mean annual flows (NIWA records, and D. Ozkundakci for Lake Okaro). Log-log scale, linear R^2 = 0.997.

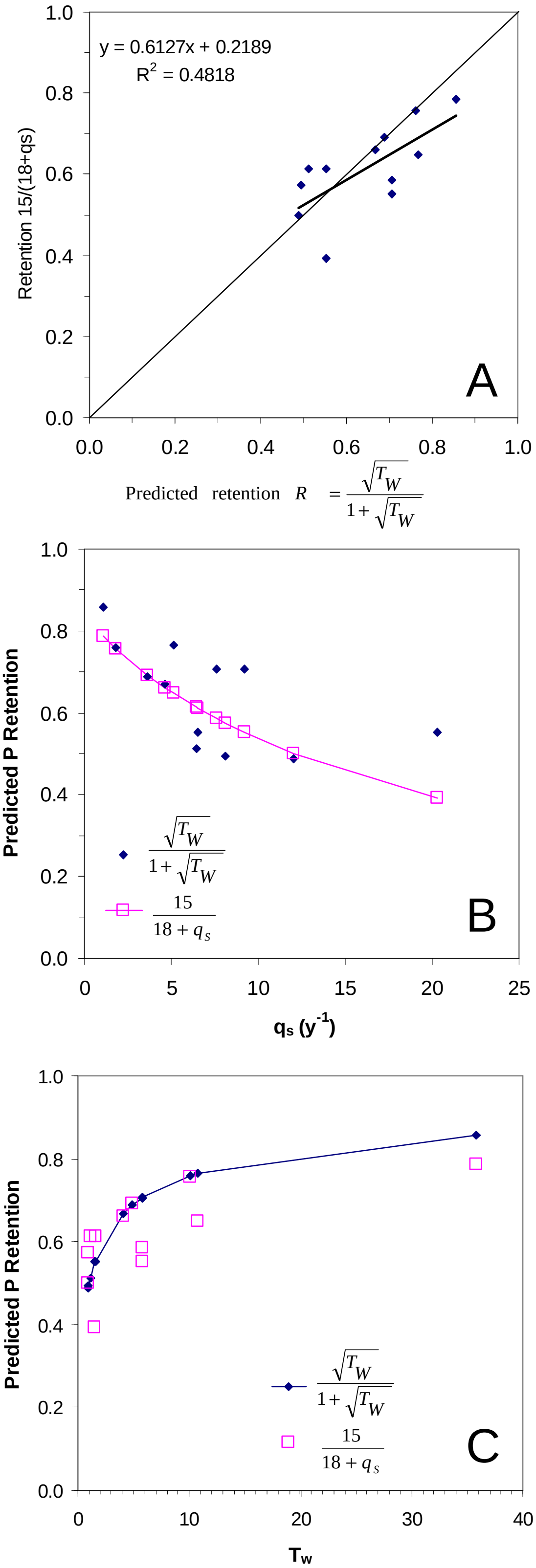

Figure C-3: Comparison of two methods for the prediction of the retention (R) of P, the method of Vollenweider (1976) which is based on water residence time (T_w) and the method of Nurnberg (1984) which is based on hydraulic load (q_s). A. Predictions following the two methods plotted against each other, with the 1:1 line. For the 12 lakes in the Bay of Plenty the Vollenweider method tends to predict higher R values than the Nurnberg method. B. Predicted R for each of the Bay of Plenty lakes following both methods, plotted against q_s. C. Predicted R following both methods, plotted against T_w. As a result of plotting versus T_w the results following Vollenweider (1976) appear regular while the Nurnberg (1984) results appear more variable, in other words this is an artefact (vice versa in plot B).

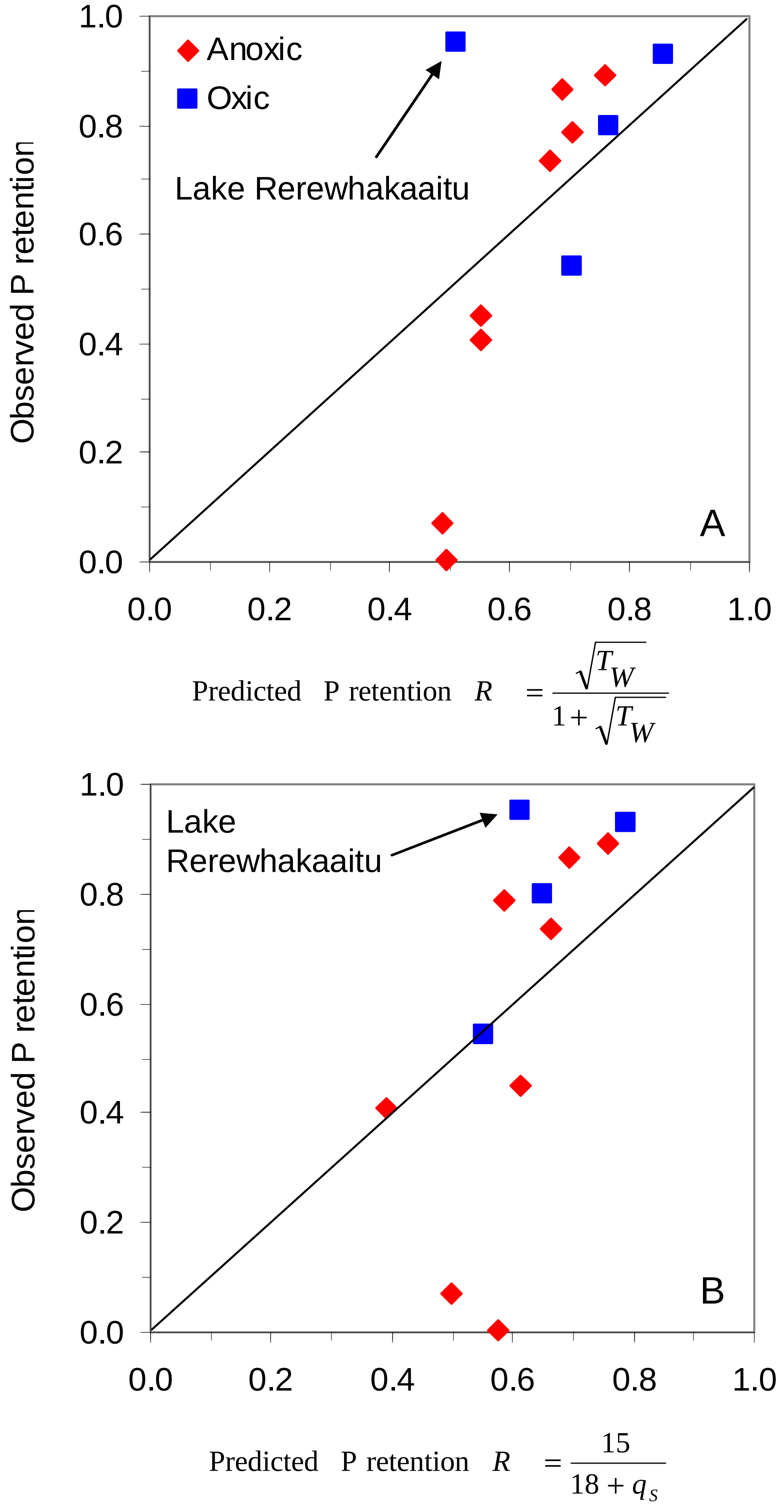

Figure C-4: Comparison of predicted P retention with observed P retention. The 1:1 line and Lake Rerewhakaaitu are indicated. The lakes with permanent oxygenated hypolimnia are given in blue and lakes where anoxia is known to occur are in red. A. Retention predicted with the Vollenweider method. In seven of the lakes observed retention was higher than predicted. For all data points combined $R^2 = 0.49$. B. Retention predicted with the Nurnberg method. In eight of the lakes observed retention was higher than predicted. For all data points combined $R^2 = 0.44$.

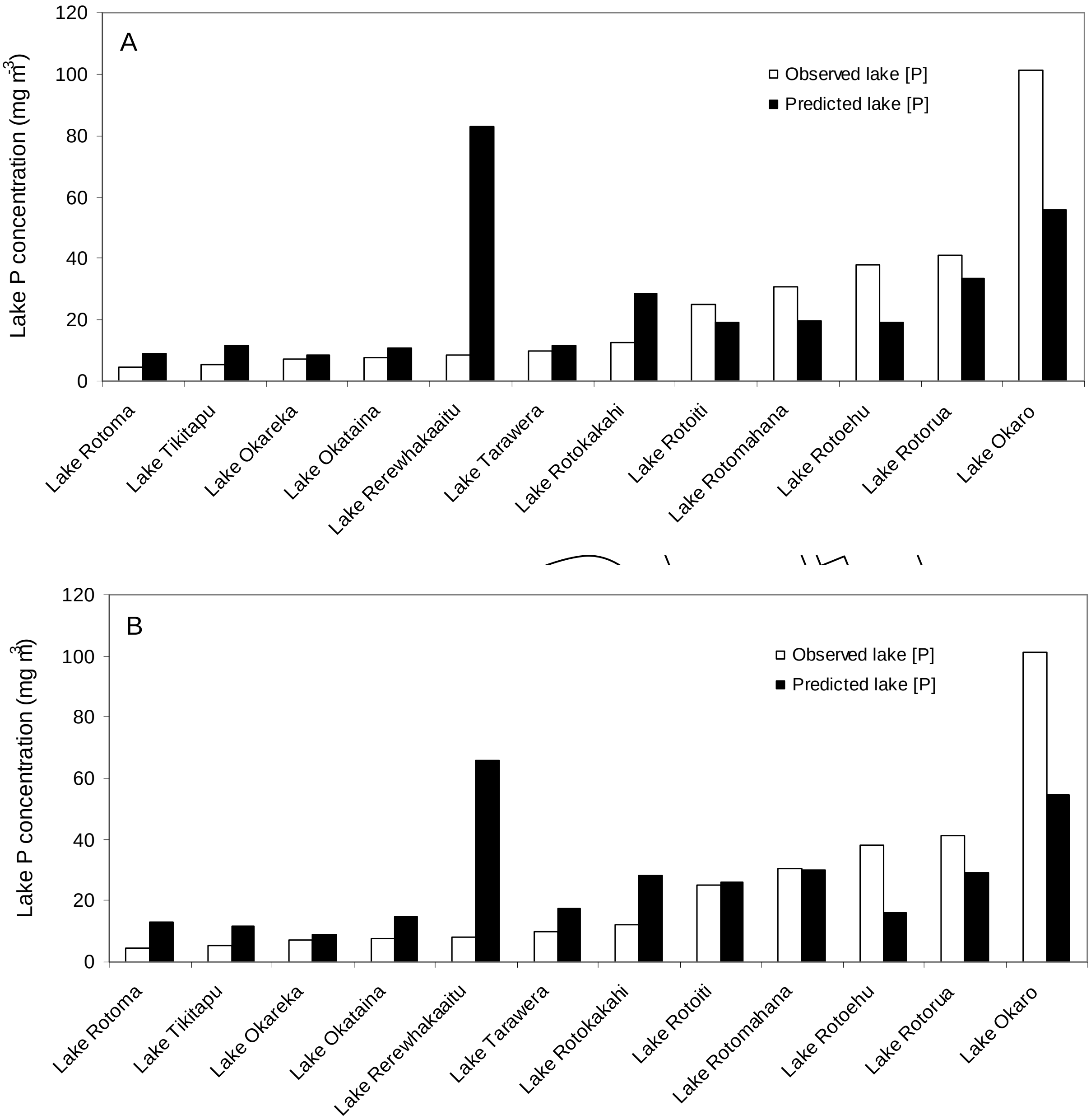

Figure C-5: Observed lake TP concentrations and concentrations predicted (Eq. 1) from external loading, with lakes in order of the observed concentrations. In lakes with lowest TP concentrations the lake TP concentrations are over-predicted indicating that retention in these lakes is under-predicted by both the Vollenweider and Nurnberg equations. In contrast, in the high TP concentration lakes, lake TP concentrations are under-predicted as a result of internal loading, causing retention to be over-predicted. Lake Rerewhakaaitu is an outlier, probably because of an error in the input data (see text). A. Retention was estimated following the Vollenweider (1976) model. B. Retention was estimated following the Nurnberg (1984) model.

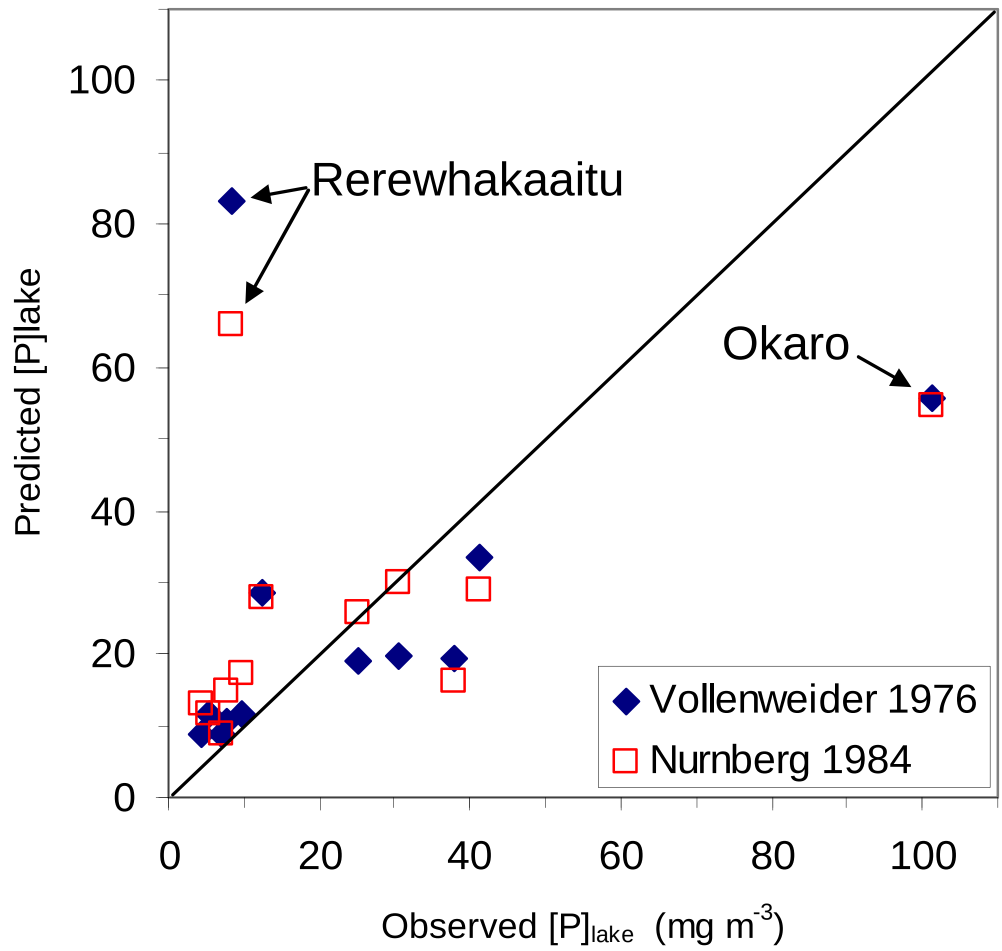

Figure C-6: Predicted (Eq. 1) against observed lake TP concentrations, for two different methods for the estimation of P retention. The two outliers with largest distance from the 1:1 line are indicated. Observed P concentrations are underestimated by the predictions from external loading in lakes where internal loading occurs. In five of the lakes, lakes Rotoiti, Rotomahana, Rotoehu, Rotorua and Okaro, observed TP concentrations were larger than predicted concentrations with retention estimated following Vollenweider (1976) and four lakes with retention estimated following Nurnberg (1984). The latter group did not include Lake Rotoiti, meaning that the method following Nurnberg (1984) suggests minimal internal P loading in Lake Rotoiti.

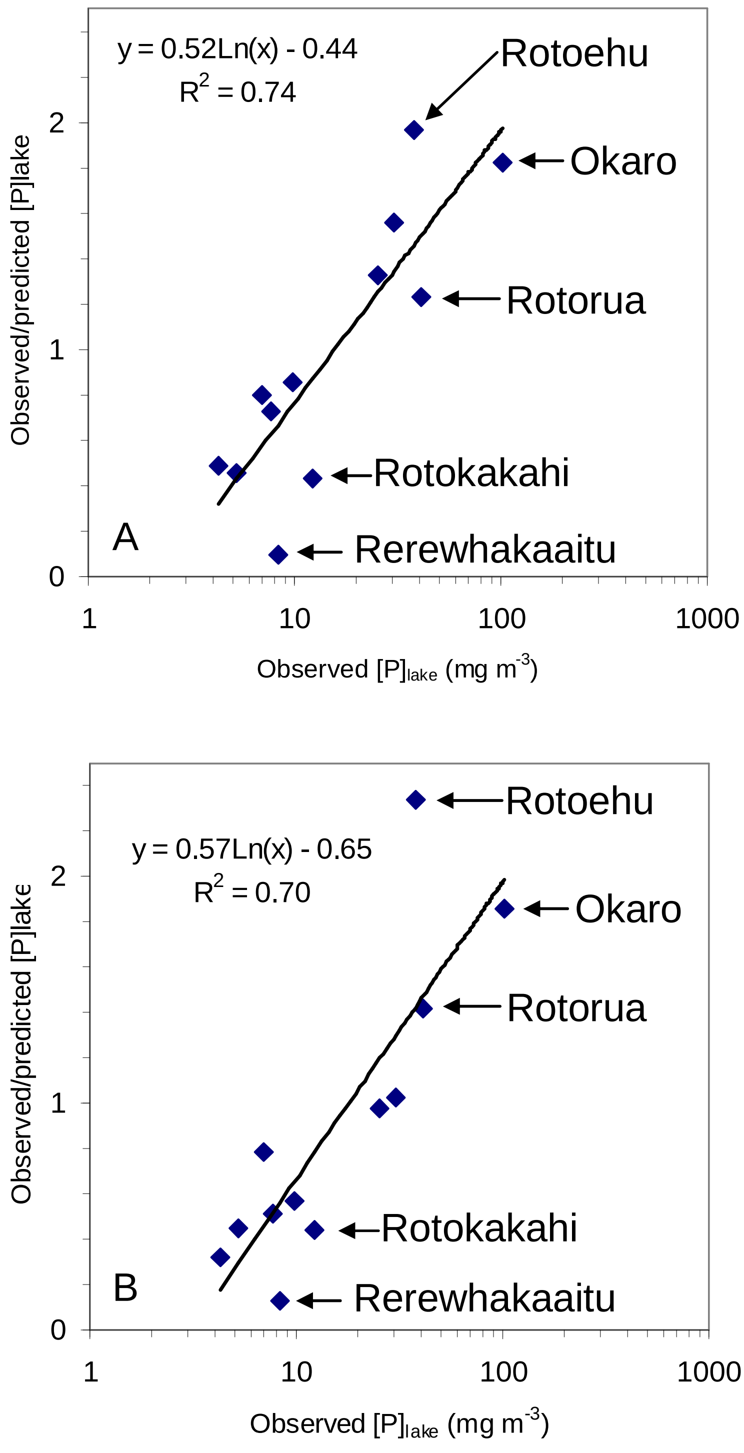

Figure C-7: The ratio of observed to predicted (Eq. 1) lake TP concentration against the observed concentration. Several lakes are indicated. A. Retention estimated following the Vollenweider (1976) model. B. Retention estimated following the Nurnberg (1984) model. Lake TP concentrations are underestimated by the models when observed:predicted > 1, and overestimated when <1. These plots show that the more eutrophic a lake is the more the lake TP concentrations are underestimated by the predictions.

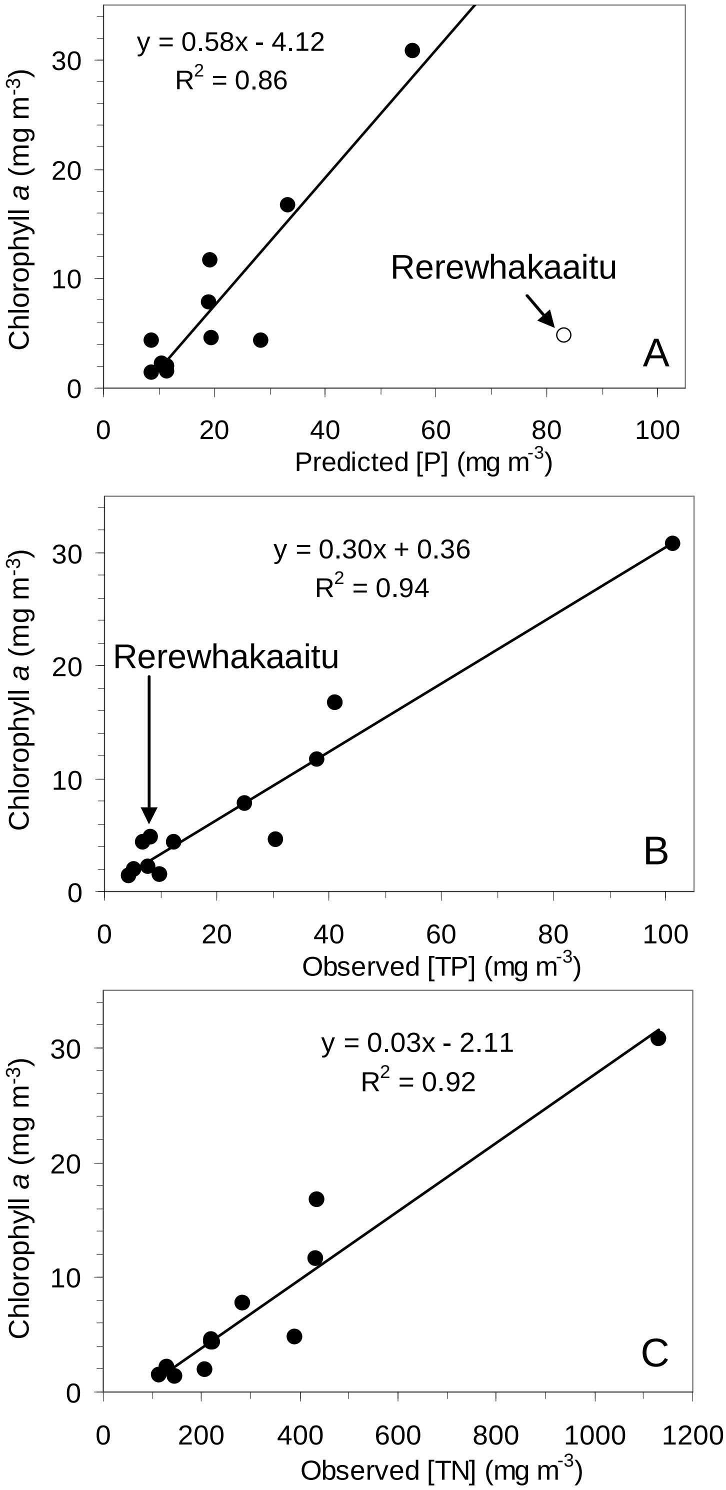

Figure C-8: Mean chlorophyll *a* concentrations (Scholes 2010) against lake TP and TN concentrations. A. Against predicted lake TP concentrations (following the Vollenweider model for P retention, Eq. 1). Lake Rerewhakaaitu was not included in the linear fit. B. Against observed lake TP concentrations. C. Against observed lake TN concentrations.

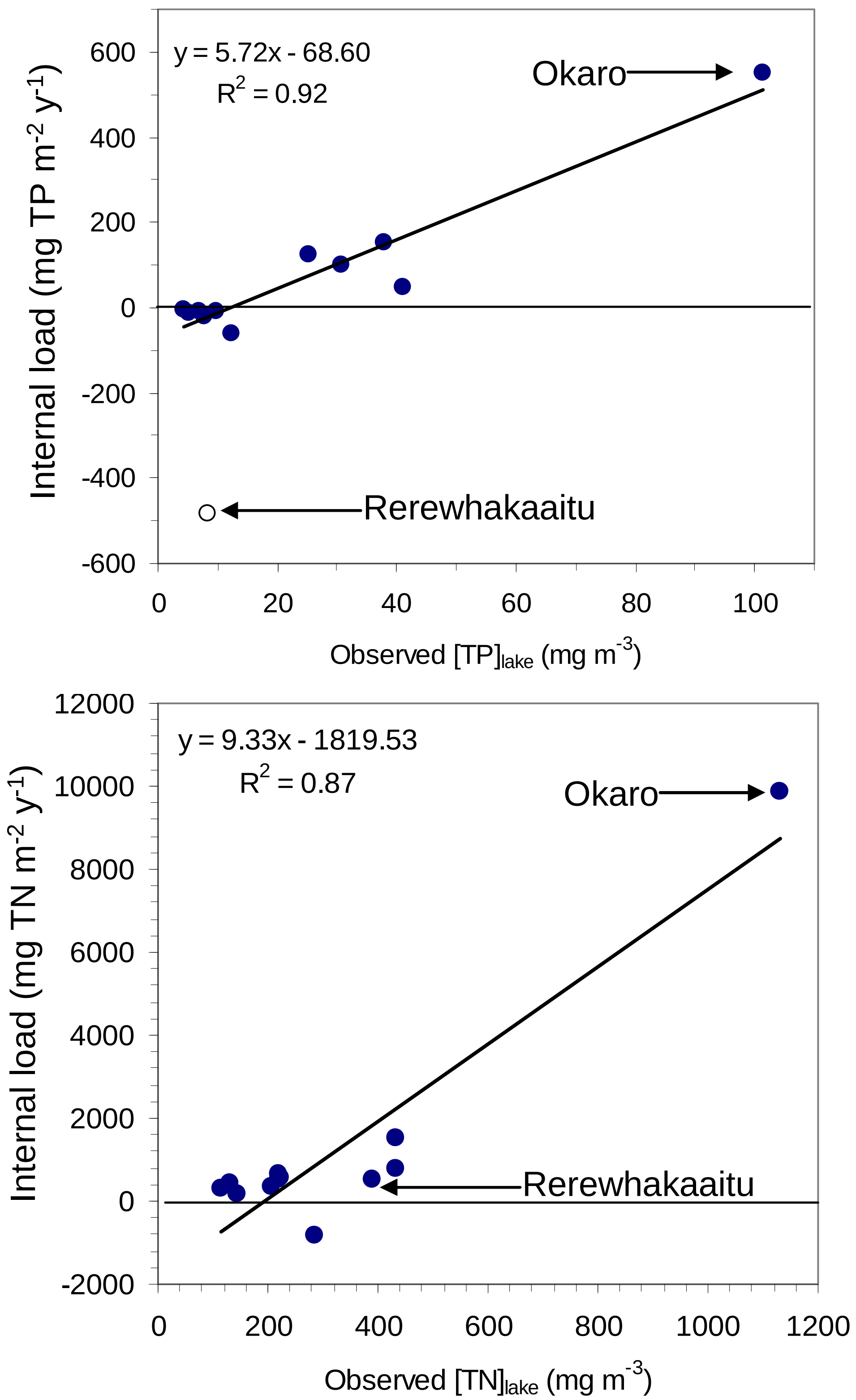

Figure C-9: Internal loading of TP and TN against observed mean concentrations in the lakes. The estimation of retention is following the method of Vollenweider (1976). Lake Rerewhakaaitu was excluded from the regression in the plot for TP. Negative values result when retention of TN or TP is under-predicted or external loading overestimated.

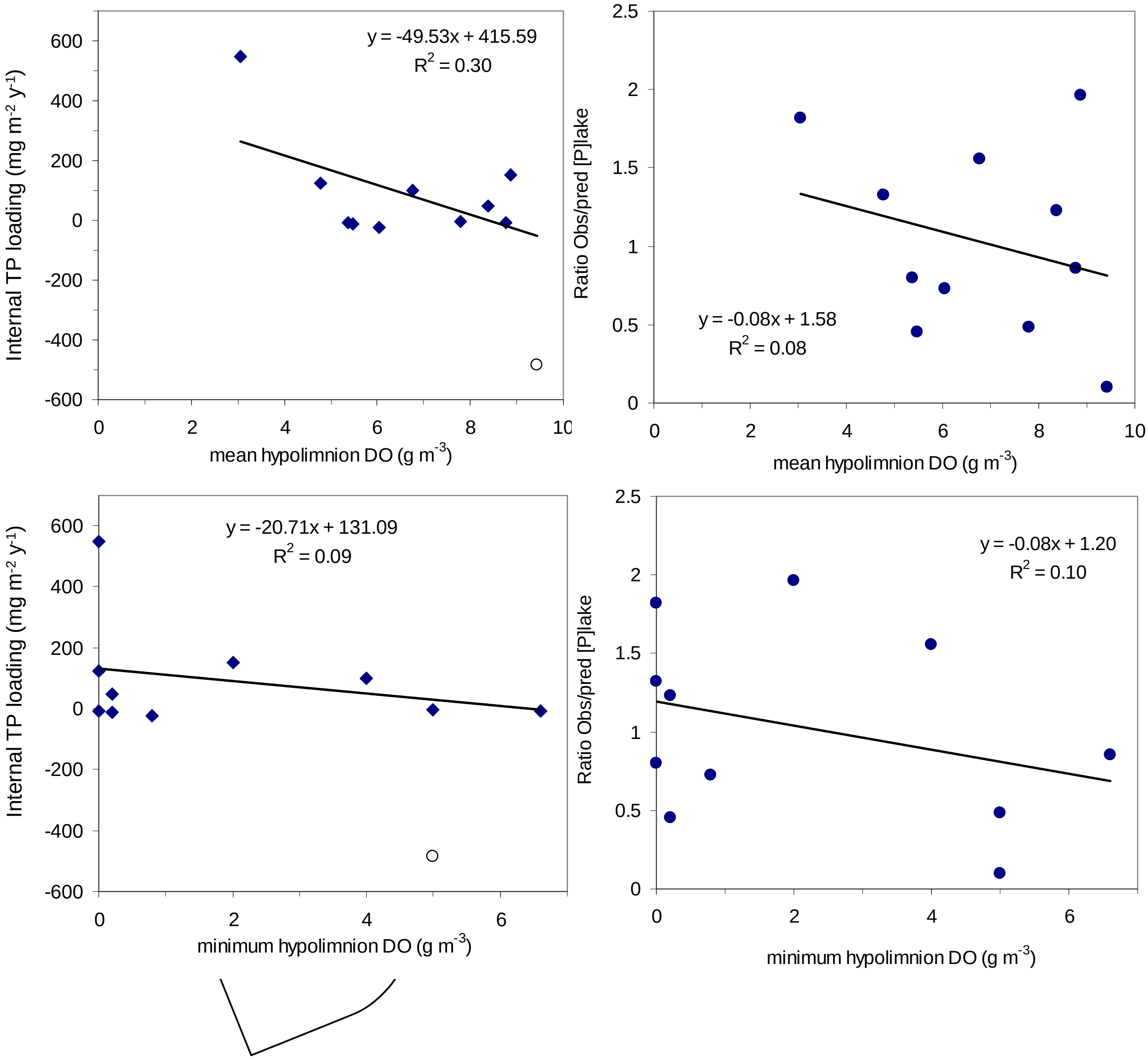

Figure C-10: Relationships between mean and minimum dissolved oxygen (DO) concentrations in near-bottom water and the internal load of TP (left panels) and the ratio of observed to predicted lake TP concentration (right panels). Lake Rerewhakaaitu (open circle) was excluded from the regressions of internal P loading against DO. The relationships are all negative, as expected, but they are not strong.

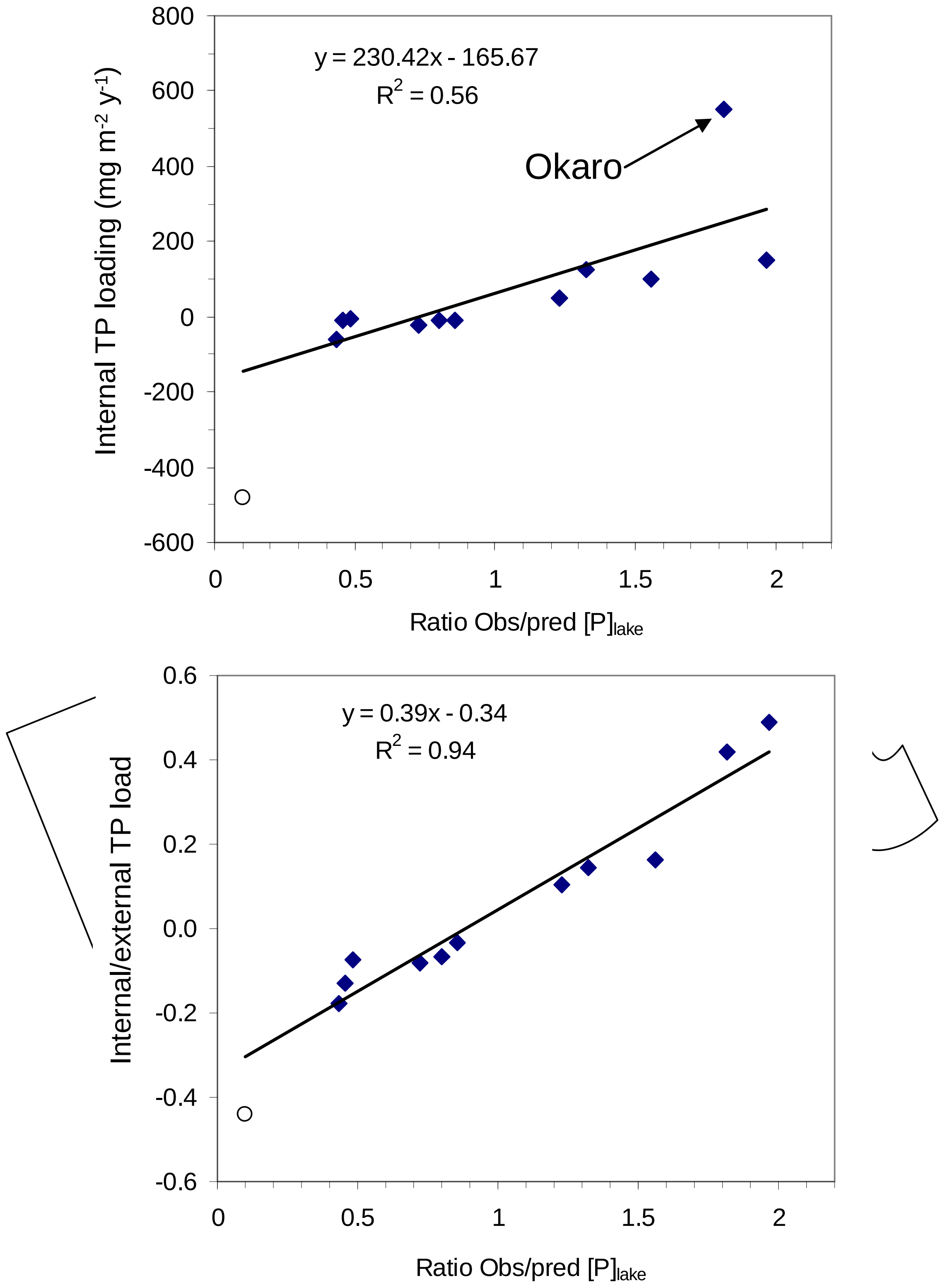

Figure C-11: The internal load of TP and the ratio of internal to external load against the ratio of observed to predicted (Eq. 1) TP concentration in the lakes. Lake Rerewhakaaitu (open circle) was excluded from the regressions. Internal load estimates were negative when observed lake TP concentrations were less than predicted.

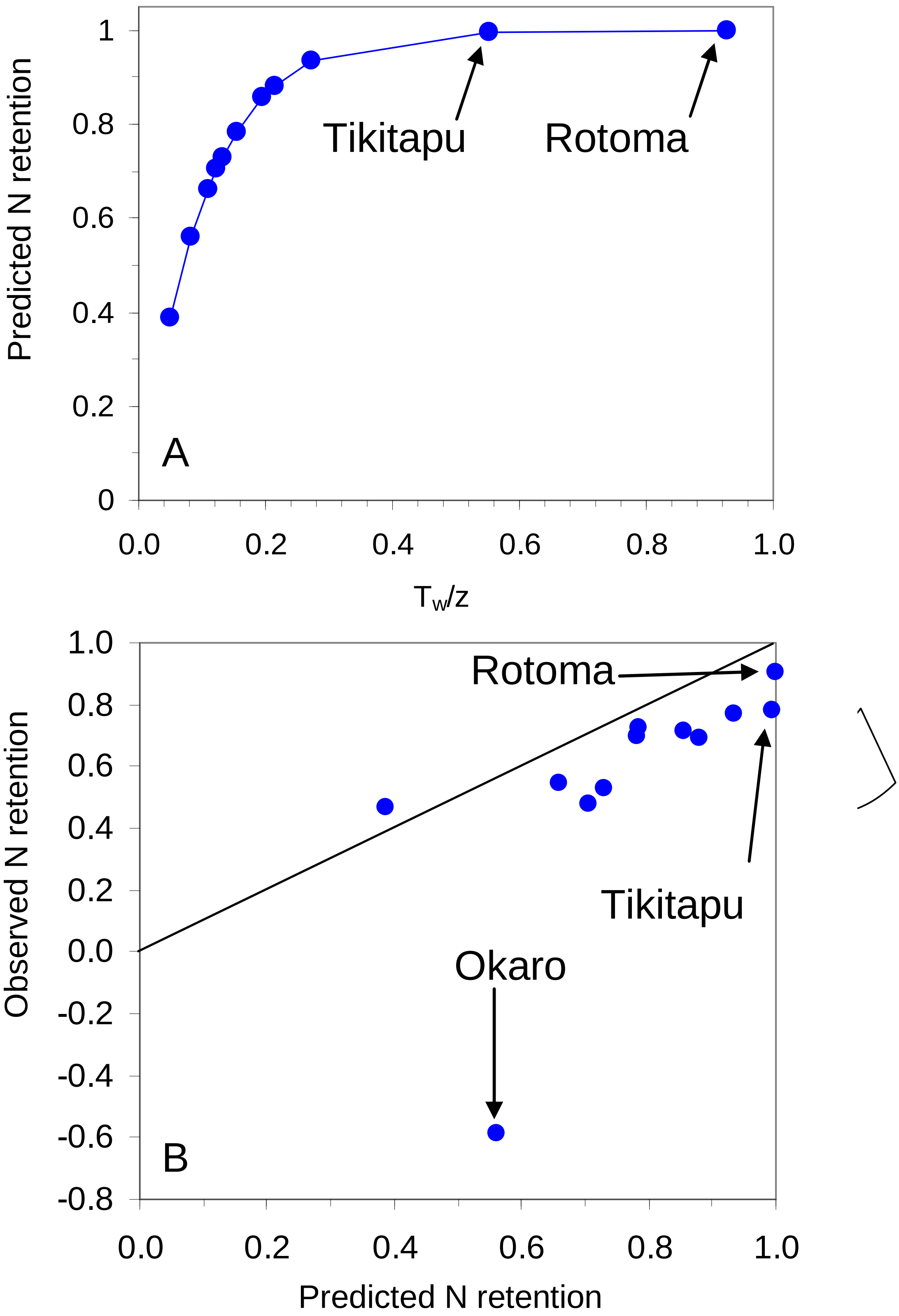

Figure C-12: **Nitrogen retention.** A. Predicted N retention (Eq. 15) against the ratio T_w/z. The expression for retention of nitrogen probably overestimates retention for lakes with high values of T_w/z (in particular lakes Rotoma and Tikitapu). B. Observed N retention against predicted N retention. The 1:1 line is indicated. In all but one (Lake Rotoiti) of the lakes N retention was overestimated, partly because of internal loading, most markedly in Lake Okaro, but possibly also because Eq. 15 over estimates retention in oxic lakes.

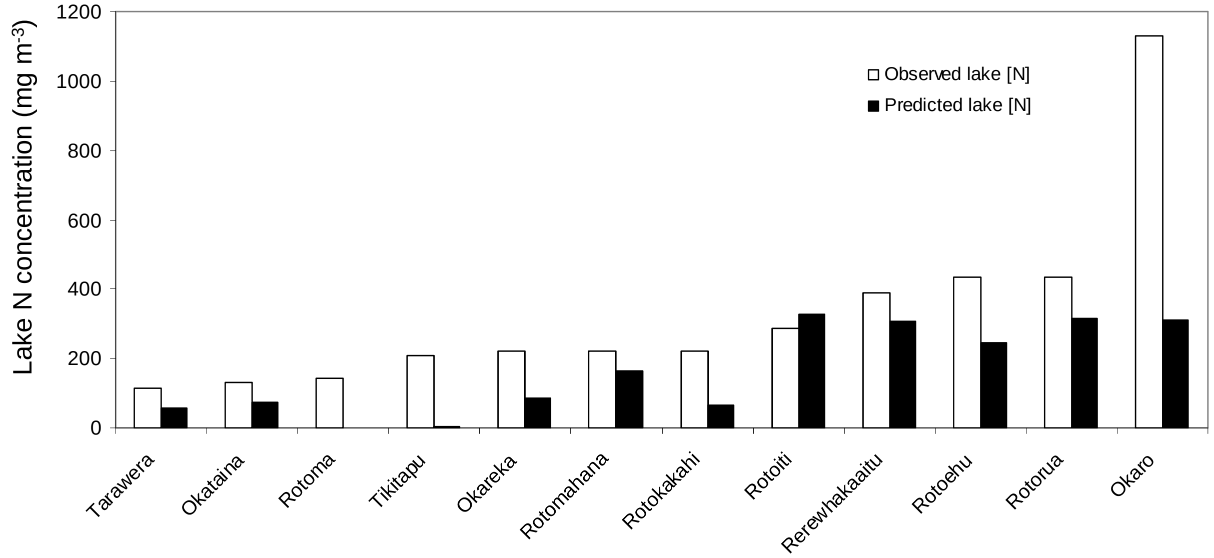

Figure C-13: Observed lake TN concentrations and concentrations predicted from external loading, with lakes in order of the observed concentrations. In all lakes, except Lake Rotoiti, lake TN concentrations are under predicted which indicates that Eq. 15 over estimates TN retention.

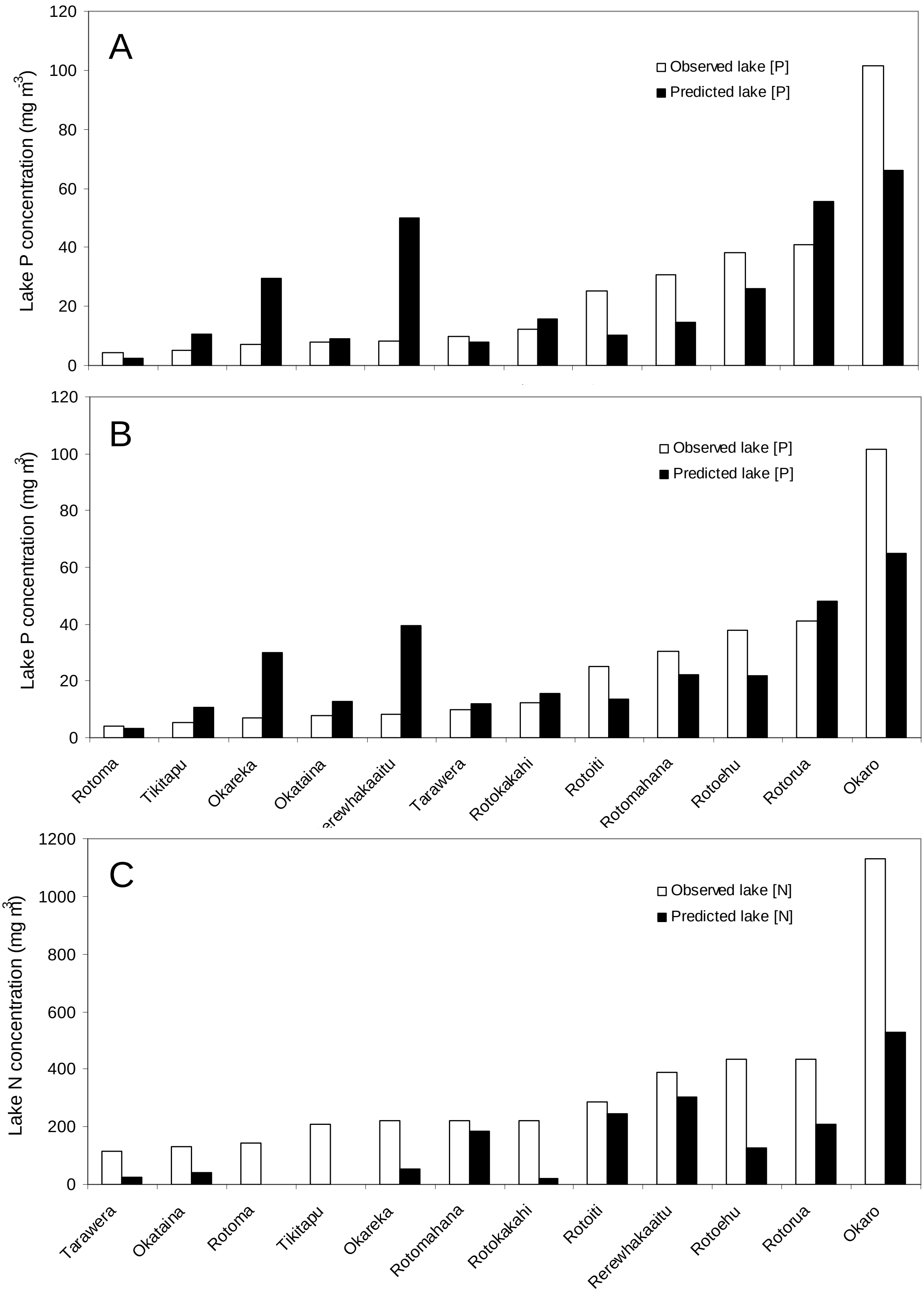

Figure C-14: Observed lake nutrient concentrations and concentrations predicted (Eq. 1) from external loading, with lakes in order of the observed concentrations. As Figs. 5 and 13, but with external loads obtained from CLUES. A. TP, with retention estimated following Eq. 3. B. TP, with retention estimated following Eq. 5. C. TN, with retention estimated following Eq. 15.

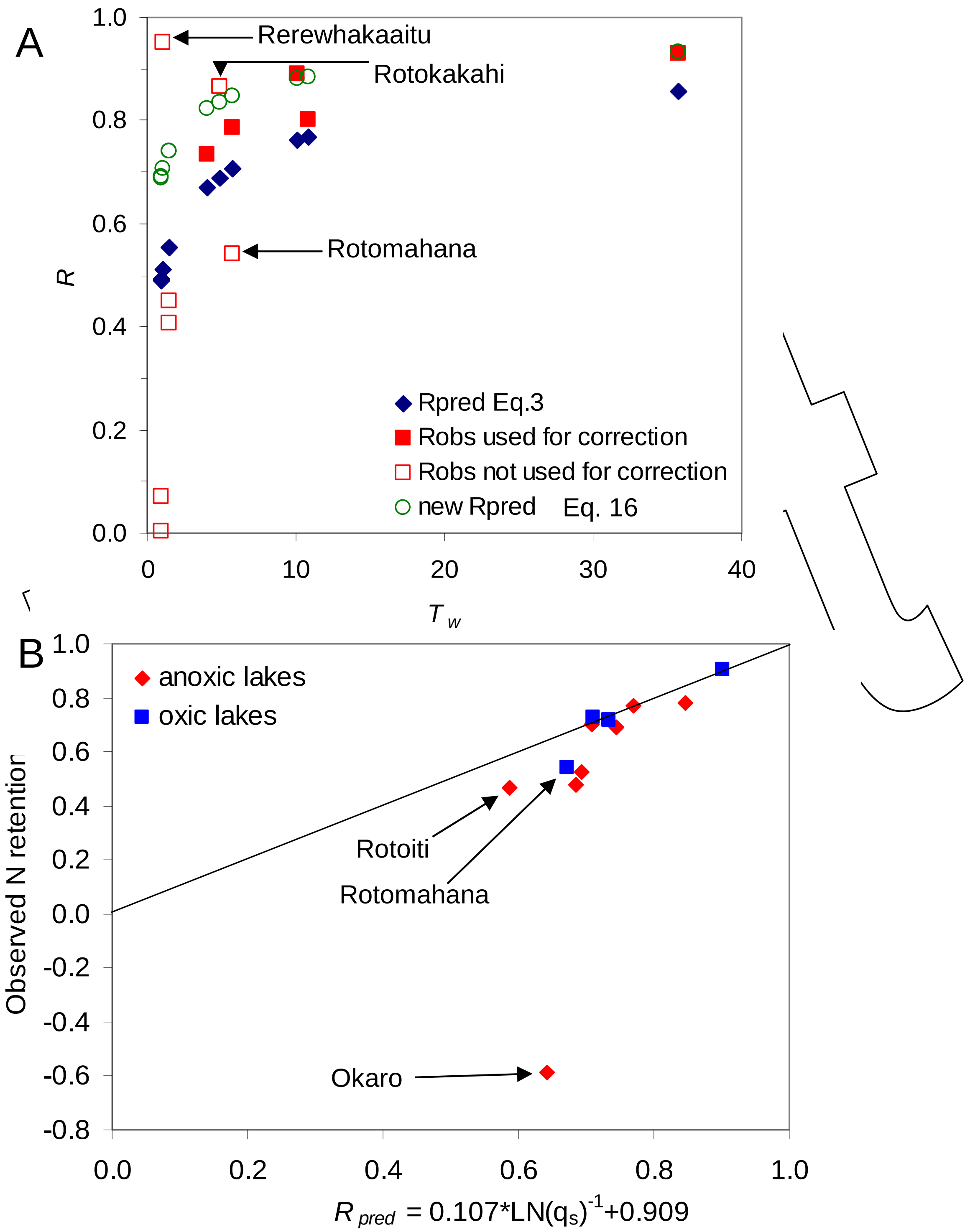

Figure C-15: Adjustment of the estimation of predicted P and N retention under oxic conditions. A. Shown are observed P retention, predicted P retention using Eq. 3, and the adjusted predicted retention of Eq. 16, against T_w. B. Observed N retention in oxic lakes and in the remaining lakes where lower levels of oxygen can occur, against the adjusted predicted N retention of Eq. 17. The 1:1 line is shown. Eq. 17 was determined by fitting observed N retention in three of the oxic lakes, not including Lake Rotomahana (see text). Compare with Fig. 12.

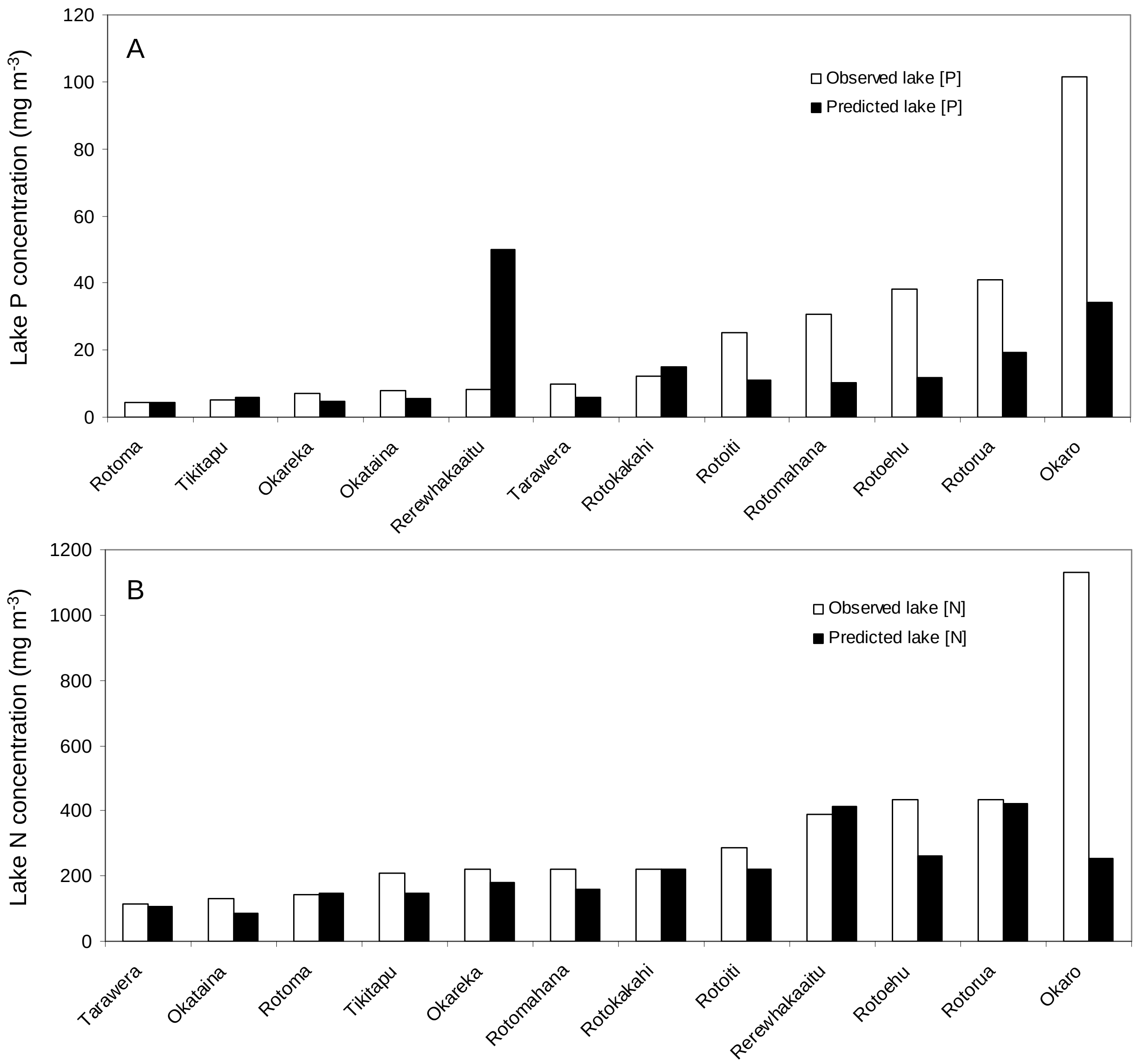

Figure C-16: Observed lake nutrient concentrations and concentrations predicted from external loading (BOPRC2012a and Hamilton et al. 2006). Lakes are in order of the observed concentrations. A. Phosphorus, with retention estimated following Eq. 16. B. Nitrogen, with retention estimated following Eq. 17. Compare with Figures C-5A and C-13.

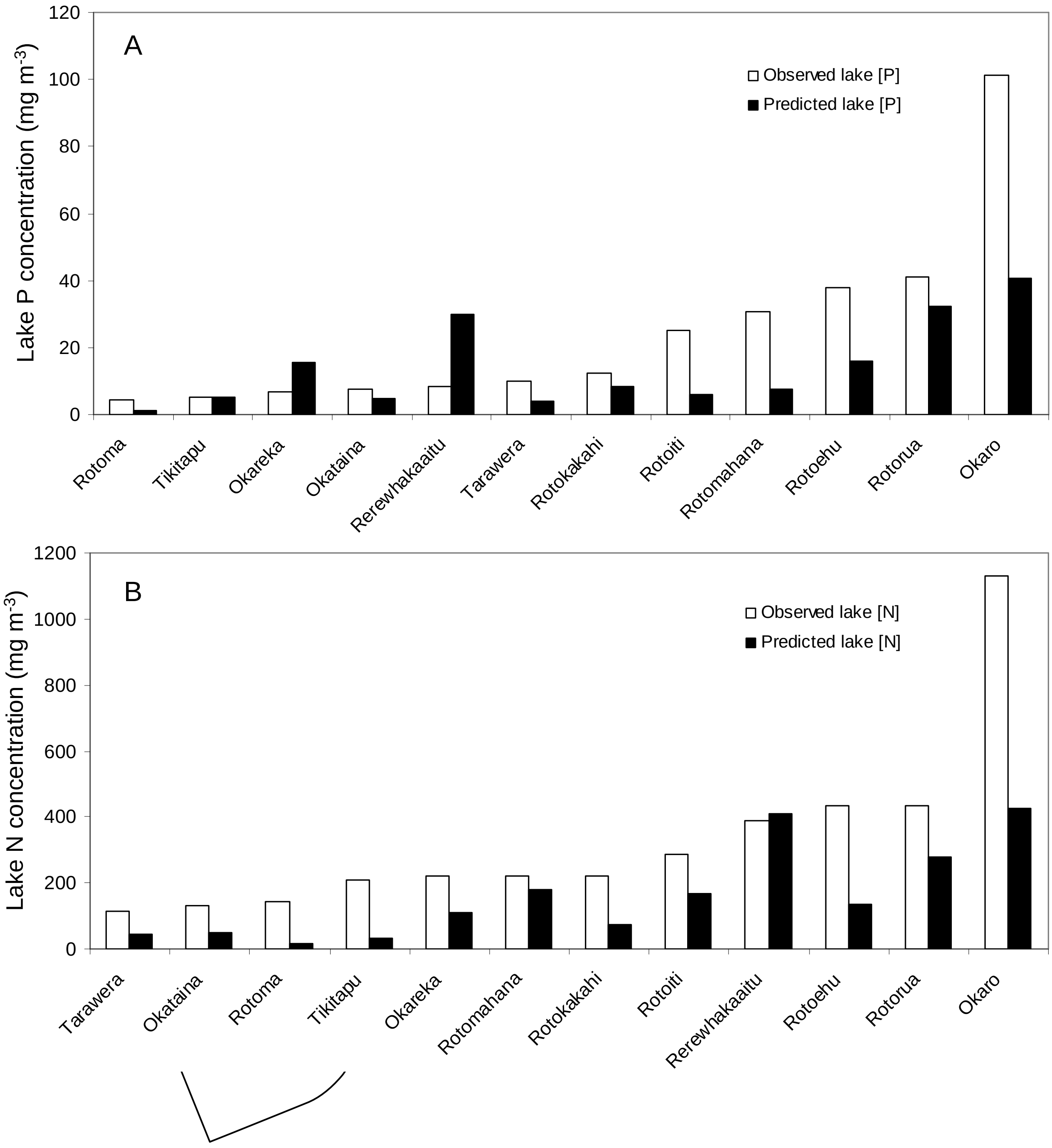

Figure C-17: Observed lake nutrient concentrations and concentrations predicted from external loading derived from CLUES. Lakes are in order of the observed concentrations. A. Phosphorus, with retention estimated following Eq. 16. B. Nitrogen, with retention estimated following Eq. 17. Compare with Figure C-14.

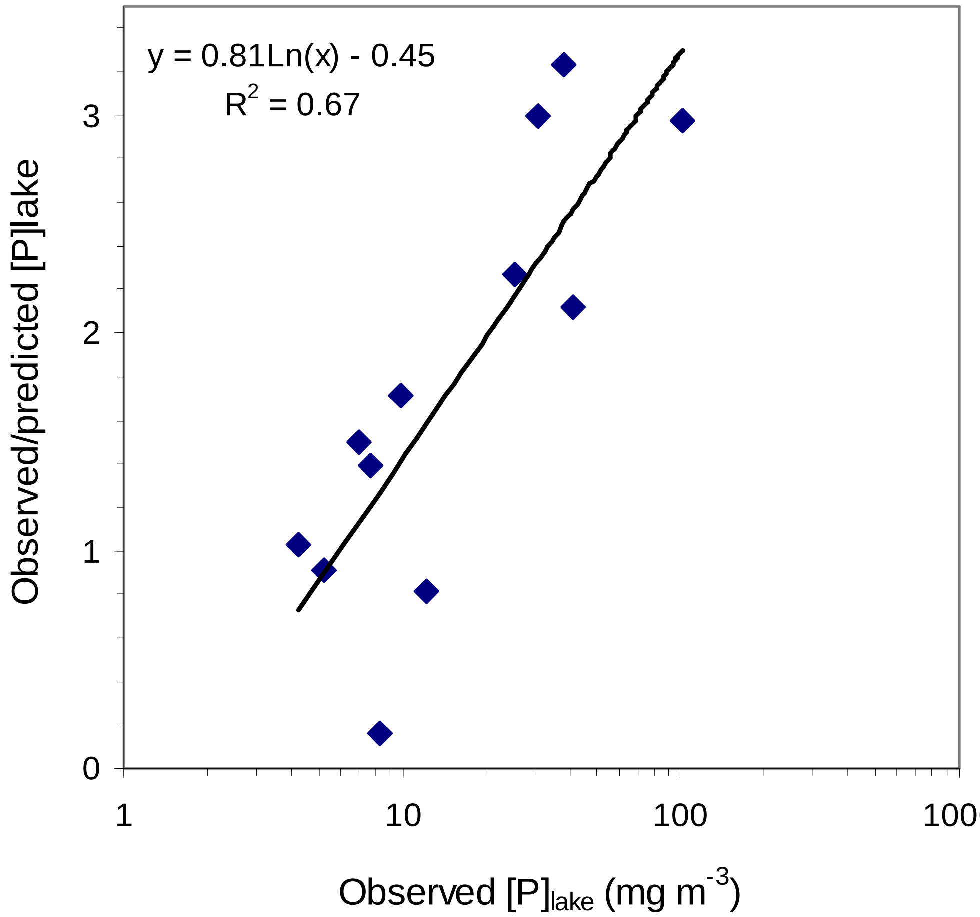

Figure C-18: The ratio of observed to predicted lake P concentrations against the observed concentration. Lake TP concentrations are underestimated by the models when observed:predicted > 1, and overestimated when <1. This plot shows that the more eutrophic a lake is the more the lake P concentrations are underestimated by the predictions. Lake P concentrations were predicted with retention estimated following Eq. 16. Compare with Figure C-7A.

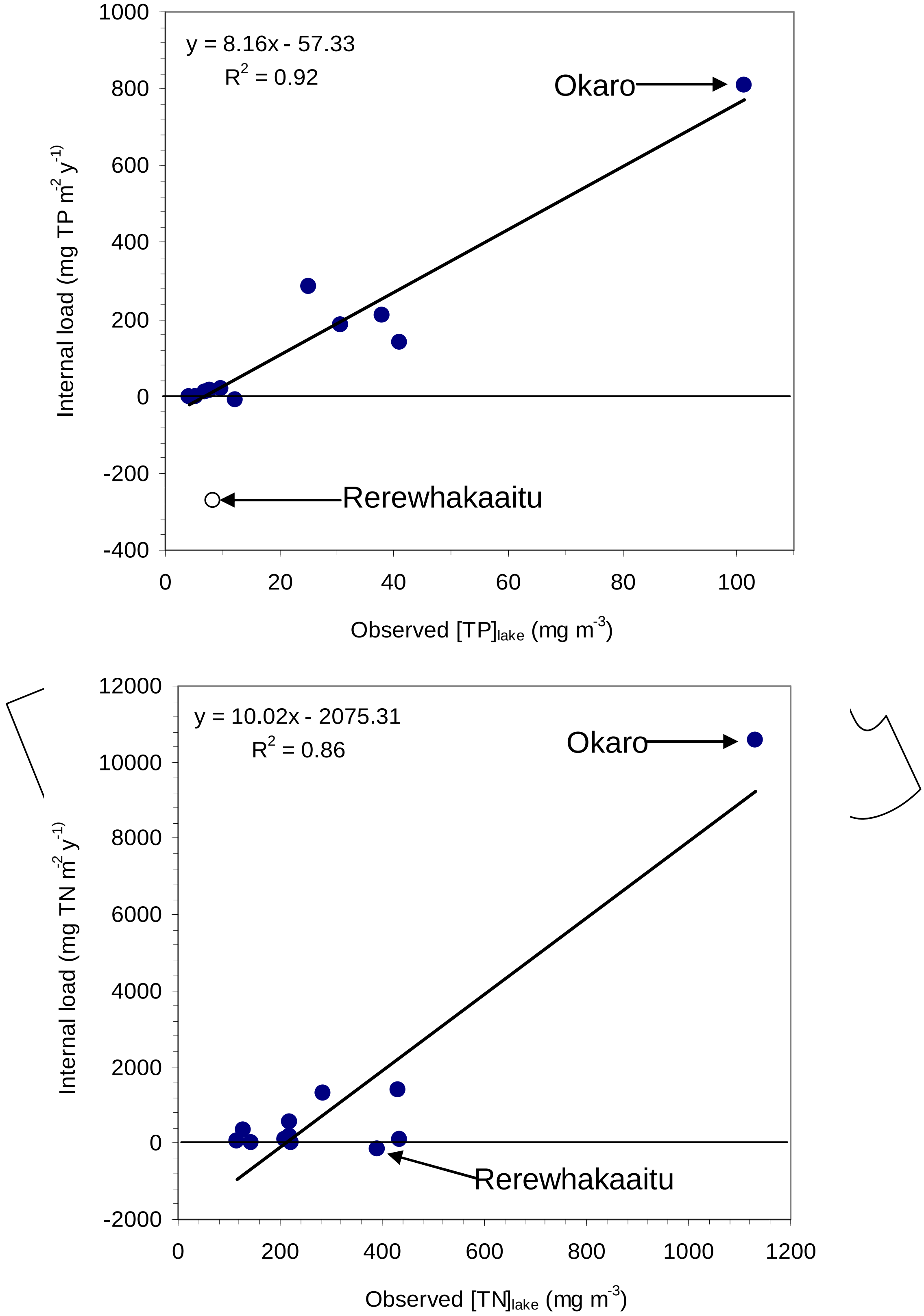

Figure C-19: Internal loading of TP and TN against observed mean concentrations in the lakes. External loading is from BOPRC2012a and Hamilton et al. (2006). The prediction of retention is following Eq. 16 for TP and Eq. 17 for TN. Lake Rerewhakaaitu was excluded from the regression in the plot for TP. Negative values result when retention of TN or TP is under-predicted or external loading overestimated. Compare with Figure C-9.

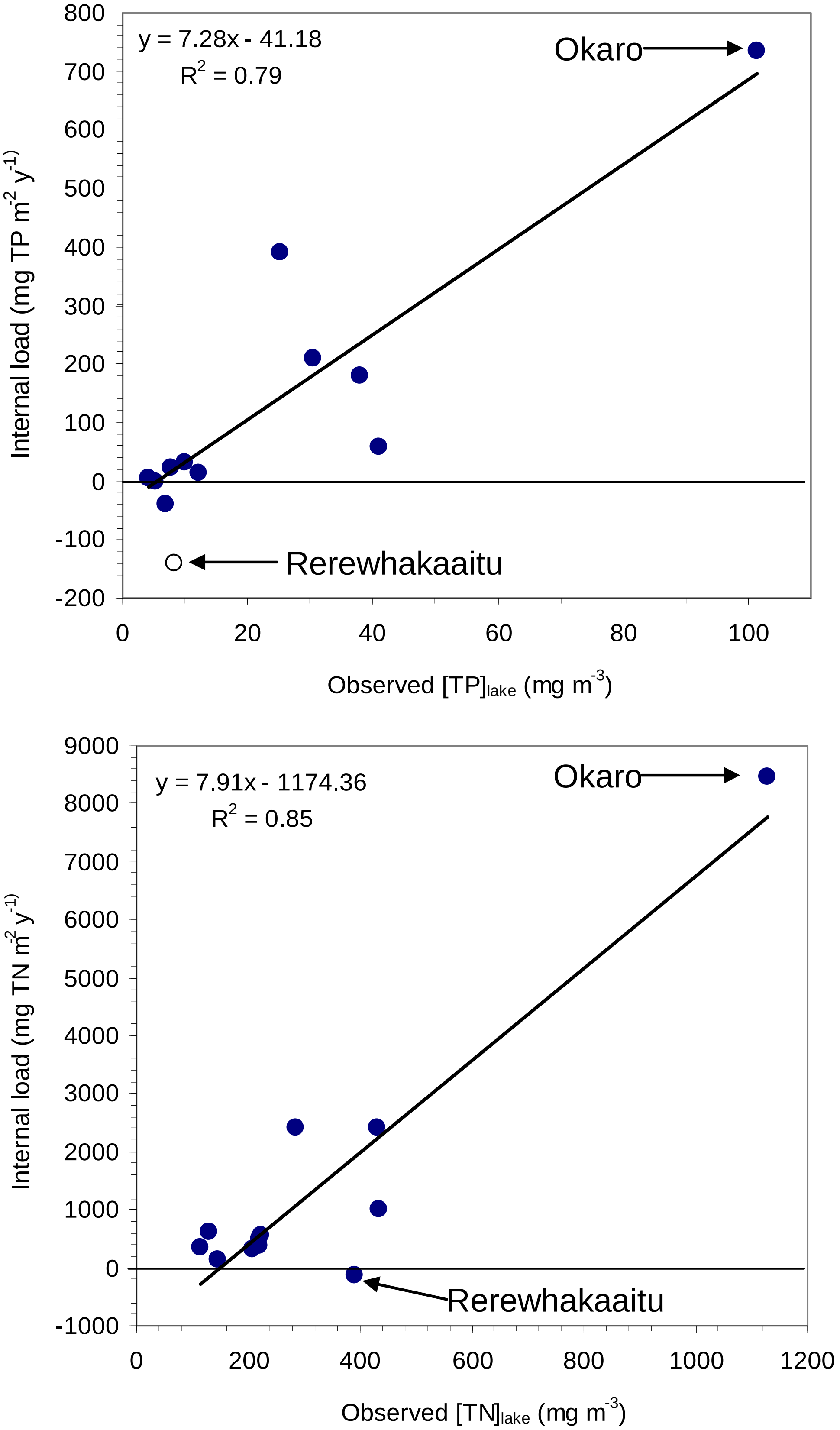

Figure C-20: Internal loading of TP and TN against observed mean concentrations in the lakes, with external obtained from CLUES. The prediction of retention is following Eq. 16 for TP and Eq. 17 for TN. Lake Rerewhakaaitu was excluded from the regression in the plot for TP. Negative values result when retention of TN or TP is under-predicted or external loading overestimated. Compare with Figures C-9 and C19.

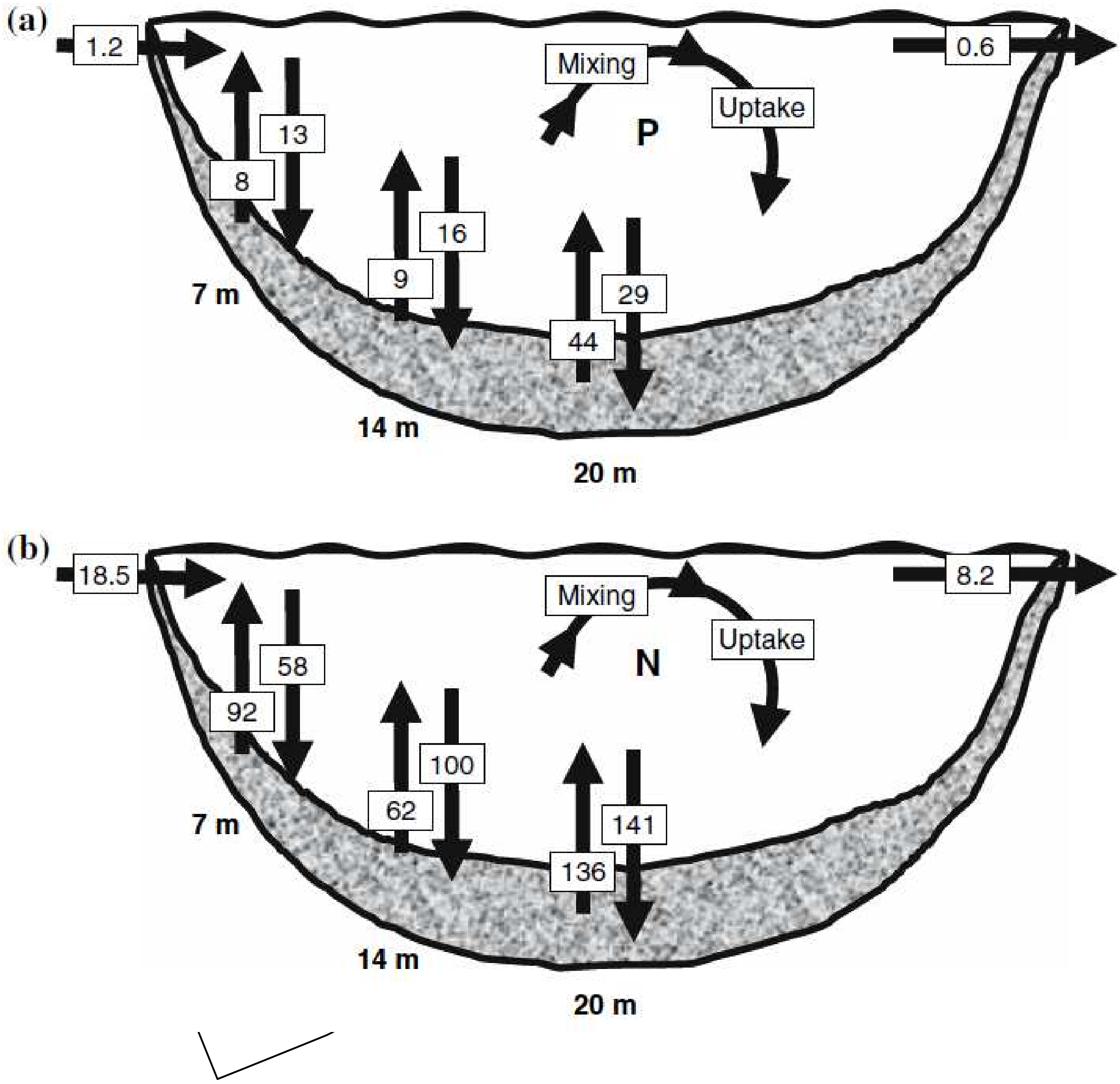

Figure C-21: Diagrams showing that (less than) half of (TN) TP that enters the lake from external sources leaves Lake Rotorua through the outlet. Reproduced from Burger et al. (2007). This suggests there is net retention in the lake for both TN and TP, and therefore the average sedimentation flux must be higher than the release of P and N from the sediment. Figure text as given by Burger et al. (2007): "Cycling of (a) phosphorus and (b) nitrogen in Lake Rotorua. All units are expressed as aerial rates (mg m–2 d–1). Inflow, outflow and sedimentation rates represent total concentrations (TP or TN) and sediment release rates represent soluble reactive phosphorus (SRP) or ammonium (NH4, secondary release rate). Sedimentation and sediment release rates are expressed as a seasonal mean calculated over the four sampling periods. Inflow and outflow concentrations are derived from Burger (2006) and Beyá et al. (2005), respectively, and sedimentation rates are derived from Burger (2006)." For references see Burger et al. (2007). Data are from January 2001 to January 2004.

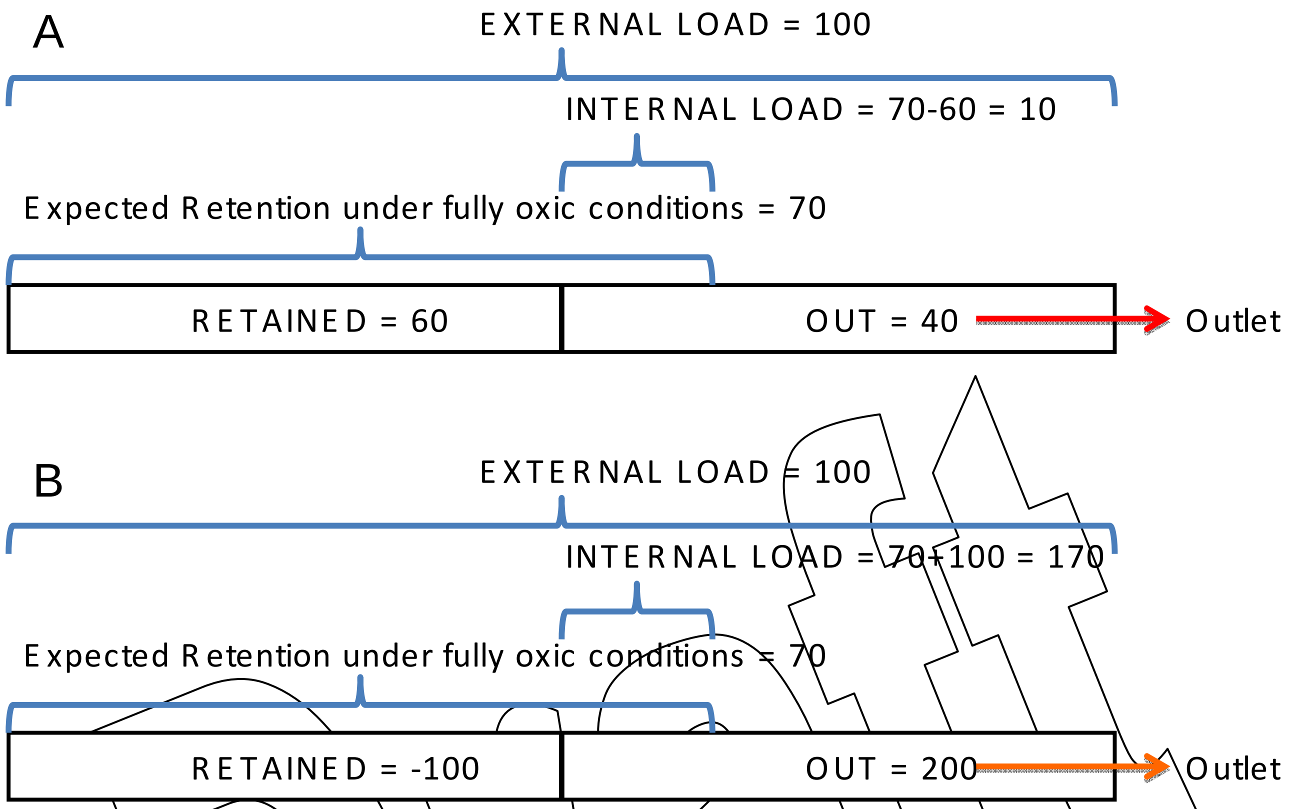

Figure C-22: Sources and fates of different compartments of nutrient loading in lakes, expressed as a percentage relative to the external load. Retention of nutrients in lakes occurs by permanent burial in the sediment, and, for nitrogen, removal by denitrification. Total loads, the sum of external and internal loads, are 110% in example A and 270% in example B. A. In this example less nutrient mass leaves the lake through the outlet than entered the lake. This is typically the case, also in eutrophic lakes. The internal load is estimated as the difference between the retained mass and the nutrient mass that is expected to be retained if only oxic conditions would occur throughout the lake. B. In some lakes the mass of nutrients in the “OUT” compartment can be larger than the external load. In the Bay of Plenty lakes this occurs only in Lake Okaro for TN (or alternatively, in Lake Rotoiti for TP when using the CLUES external inputs) and in none of the lakes for TP. In the example no nutrients are retained and retention is in fact negative (-100%) because OUT is 100% more than the external load, resulting in an internal load that is greater than the external load. Naturally, a situation where OUT > EXTERNAL LOAD can only be maintained temporarily until the nutrients in the sediment are depleted. It is typical for lakes with alternative stable states, where phytoplankton dominated phases of high internal loading and low water quality alternate with macrophyte dominated phases of net sedimentation, sequestering of nutrients and higher water quality. A good example is Lake Omapere (Verburg et al. 2012).