Re. Comment on "Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand" by Morgenstern et al. (2015)

Dear Editor

Thank you for the opportunity to make minor revisions to our Comment paper. Please find attached a revised version of our manuscript, with changes tracked. Revisions have been made in accordance with our Author Comments, which were published online on 02 February 2016. The remainder of this letter specifies how each review comment has been addressed. As stipulated on the file upload website, I have also appended a marked up version of the full manuscript for your consideration.

Reviewer Comments from Val Smith

This ten page review states "I strongly concur with the four primary reasons identified by Abell et al. (2015)" and does not request revisions to our submission. We now cite this Reviewer's Comment in our revised manuscript. We also add reference to additional research that is cited by this reviewer (Smith *et al*. 1987 and Paerl and Otten 2013).

Interactive Comment from U. Morgenstern

Points #1 and #2: No changes made in response. We provide a detailed response to this Interactive Comment in our Author Comments.

Point #3: We have changed the text "would prevent community aspirations of lake water quality from being achieved for multiple generations" to "would prevent community aspirations of lake water quality from being achieved for some decades"

We have added the following text regarding the targeted focus of management actions on 'young' groundwater: "We recognise that these MRT estimates reflect finer–scale spatial variability in groundwater transit times and, therefore, there is potential to achieve more–rapid reductions in groundwater loads by targeting 'young' groundwater sources. The authors' results, and further work based on their methods, have potential to provide the detailed scientific understanding necessary to inform such a focused approach to managing nitrate pollution. We support using such detailed knowledge of groundwater pathways to minimise the timeframe over which load reduction targets could be achieved."

Point #4: We have added the following text in response, consistent with our Author Comments: "Further, a strategy of focusing on nitrate control is expected to result in a low N:P ratio *coupled with* high phosphorus concentrations. These are precisely the conditions that are associated with a high risk of harmful algal blooms: lake surface water total phosphorus concentrations are frequently a strong predictor of cyanobacteria abundance (Smith et al. 1987; Smith et al. *in press*), and they are often a better predictor of cyanobacteria dominance than low N:P ratio (Dokulil and Teubner 2000; Downing et al. 2001)."

Reviewer Comments from Anonymous Referee

Abell et al. (2015) could benefit by presenting a nutrient budget for the Lake, demonstrating the nutrient loading for the lake, including in lake processes and overland flow, to complement the groundwater and stream nutrient concentrations presented in Morgenstern et al. (2015). Without a complete lake budget it is difficult to comment on the relative role of phosphate loading from groundwater sources and in-lake processing.

We now present nitrogen and phosphorus budgets for the lake in a figure. The following paragraph has been added: "To provide context, we present lake and catchment P and N budgets in Figure 1. Figure 1a illustrates the significant contribution of the authors' work, as their results have been used to estimate the magnitude of the P load via deep groundwater springs (~20.2 t P/y); a component that could not previously be resolved. As the authors describe, this component represents P from natural geologic sources and makes a major contribution to the overall lake and catchment P budget. Nonetheless, Figure 1a also highlights the significant contributions of other P sources that should also be considered alongside groundwater springs when examining P cycling in the catchment. These other sources include: internal loading from the bed of the lake (Burger et al. 2008), dissolved P transported in throughflow from agricultural land, and particulate P transported in overland flow, particularly during rain storms (Abell et al. 2013). Thus, while detailed study of individual components of the cycle is important to improve understanding, the range of major nutrient fluxes should be considered when developing catchment–scale lake management policy, not just those that relate to groundwater."

"Here again, it would be useful to cite a nutrient budget for the lake, demonstrating the amount of phosphorus delivered to the lake via overland flow and the extent to which episodic phosphorus delivery contributes to eutrophication in the lake"

Surface and groundwater sources of phosphorus are separated in our figure and episodic particulate phosphorus transport is discussed in the additional text.

Rather, Abell et al (2015) can look to Morgenstern et al.'s (2015) Table 2 featuring mean residence times of Lake Rotorua's major streams to make a similar case. Average residence *times in Table 2 range from 30 to 125 years, which suggest a lag of decades in each stream before which nitrate loads would be expected to respond to management interventions."... "Abell et al. (2015) could be strengthened through incorporating a recognition of the spatial interplay between nutrient critical source areas and groundwater flow."*

Specific reference to the Hamurana Stream sub–catchment is removed. The following text is now added: "For example, Table 2 in the authors' paper shows that the mean residence times (MRTs) of sub–catchments to Lake Rotorua range from 30 to 145 years, thus indicating that there is expected to be a lag of decades on average before groundwater nitrogen loads respond to actions to reduce nitrate leaching from land." Also see edits described above regarding Point 3 made by U. Morgenstern.

Abell et al. (2015) could benefit by including Smith's (2015) additional empirical support.

We now cite the Review Comments by Smith and a recent publication (Smith et al. *in press*) that presents the empirical relationships described in the review.

Interactive Comment from T. Baisden

I support all conclusions reached by Abell et al., but offer that their case would be stronger and simpler if they provide clearer background on the substantial legislative, policy and management undertaken thus far.

The following text has now been added to the Introduction: "Specifically, these instruments comprise a set of rules enforced by regional government to manage terrestrial N and P export to water, designed to ensure that current export rates do not exceed benchmarks defined for specific land use activities (BoPRC et al. 2012). These benchmarks reflect targets for maximum N (435 t N y^{-1}) and P (37 t P y^{-1}) loads that have been set for the lake, based on a non-statutory lake Action Plan (BoPRC et al. 2009) to achieve desirable water quality. The water quality target is defined using a Trophic Level Index (TLI), which is a metric that has been designed using data for New Zealand lakes (Burns et al. 1999). The TLI is derived from equally–weighted scaled measurements of total N concentration, total P concentration, chlorophyll *a* concentration (a proxy for phytoplankton biomass) and Secchi depth (a measure of water clarity). The TLI target for Lake Rotorua is 4.2 (BoPRC et al. 2009), which is at the lower end of the eutrophic category (4.0–5.0; Burns et al. 1999). Since the mid–2000s, there has been a general decline in the TLI of Lake Rotorua (i.e., improved water quality; Abell et al. 2012; Smith et al. *in press*), and the annual average TLI reached the lake target in 2012 and 2014 (BoPRC et al. 2015). A significant factor contributing to recent improvement in water quality is the action of dosing aluminium sulphate (alum) to two stream inflows since 2006 (Hamilton et al. 2015). This action has reduced dissolved P concentrations in the two treated streams, while excess alum has also contributed to further reducing ambient dissolved P concentrations in the lake, resulting in phosphorus limitation of phytoplankton biomass accumulation at times (Hamilton et al. 2015). Despite this success, there are long term risks associated with the technique (Tempero 2015) and there is recognition that, although such geoengineering solutions can be a useful component of a wider range of restoration actions, they are not a substitute for long-term sustainable reductions in nutrient loads from the wider catchment (Abell et al. 2012; MacKay et al. 2014)."

The well-developed local government policy for Lake Rotorua includes a cap on terrestrial nitrogen and phosphorus losses to water (Rule 11, operative since 1 December 2008 http://j.mp/BOPRC), as well as a non-binding 2009 Action Plan that directs considerable investment in lake restoration (http://bit.ly/RotoruaAction). Shouldn't this be stated and referenced in the first paragraph or two?

These caps are now described in the new text presented above.

The TLI-based approach would presumably identify a single nutrient to be managed if this were in fact the most efficient action?

The Trophic Level Index is now described in the new text presented above. This includes mention that this measure is based on four separate indicators.

More elaboration on how the stabilisation and improvement in Lake Rotorua's TLI have been achieved may be relevant

The important role of controlling dissolved phosphorus in two inflowing streams is now discussed in the new text presented above.

It may be useful to also consider incorporating the simple wording in the 2009 Action Plan for the lake.

The following text has been added in relation to our fourth point in the Comment: "and the non-statutory lake Action Plan includes the aim to make "phosphorus the key limiting lake nutrient" (BoPRC et al. 2009)."

The budget is not however summarised in table or flow diagram that I'm aware of. Assembling the numbers in one or more tables would be extremely helpful in allowing the reader to assess the author's main point.

We now present a nutrient budget as a figure and discuss the key processes in the text.

Within the use of N and P budgets to drive policy frameworks, a key outcome of this discussion may be the importance of explicitly defining "manageable" components of the budget.

We build on the points raised in this paragraph by now making reference to a recent study (Tempero et al. 2016) that applied the authors' results to assist with separating phosphorus loads to the lake into 'natural' and 'anthropogenic' components. We have added the following paragraph to our Comment:

Recently, the authors' results have been used to estimate the relative proportion of the external P load from each lake sub-catchment that originates from anthropogenic sources (Tempero et al. 2016). These estimates were derived by subtracting estimated natural loads from current measured loads. Natural loads correspond to baseline conditions prior to human presence in the catchment, and were estimated as the sum of baseline groundwater loads and baseline surface loads. Baseline groundwater loads were estimated using the authors' results, while baseline surface loads were estimated using baseline concentrations estimated by McDowell et al. (2013). For the whole lake catchment, the study estimated that 48% of the total P load and 22% of the dissolved reactive P load originate from anthropogenic sources. Thus, although these values are likely to be relatively low for eutrophic lakes generally, these results highlight that an appreciable proportion of the total P load is from anthropogenic sources. In particular, these results highlight the importance of controlling particulate P loads transported in surface water, e.g., associated with soil erosion on farmland. Such loads were not considered by Morgenstern et al. (2015) when drawing conclusions about the most appropriate catchment–scale policy to manage water quality.

Rotorua is unique in certain respects that will influence its management strategies. Would it be beneficial, as a contribution to literature to briefly elaborate?

The following text has been added: "The authors' contributions are particularly significant due to the dominance of groundwater–derived baseflow in stream inflows, resulting in the lake being highly influenced by groundwater inputs, relative to lakes in general (Baisden 2016)."

Last, and perhaps most challenging is placing the opportunities for reduced N and P inputs on a timeline of progress for Lake Rotorua's TLI.

As we state in the Authors Comments, we do not believe that our Comment is the most appropriate forum to outline such a timeline due to the social and economic trade–offs inherent in developing such a plan of action. Instead, we believe it is more appropriate for such a timeline to be developed within the context of the existing lake Action Plan development process.

Your sincerely

Jonathan Abell

cc. David P. Hamilton, Chris G. McBride

Comment on “Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand” by Morgenstern et al. (2015)

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Abstract

This Comment addresses a key conclusion in the paper entitled “Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand” by Morgenstern et al. (2015). The authors analyse hydrochemistry data and conclude that “the only effective way to limit algae blooms and improve lake water quality in such environments is by limiting the nitrate load”. We undertook the crucial task of examining this conclusion because it contradicts the current strategy of limiting *both* phosphorus and nitrogen loads to the lake, supported by a multi–million dollar programme of action. Following careful consideration, we believe that the conclusion is invalid and outline four reasons to support our assessment. Our comments do not relate to the methodology or results that are presented by Morgenstern et al. (2015), and we recognise that their paper makes an otherwise highly valuable contribution to understanding hydro–chemical processes in the catchment.

1. Comment

Morgenstern et al. (2015; "the authors") report a detailed study of the hydrochemistry of Lake Rotorua: a large, volcanically–formed lake in the Taupo Volcanic Zone in New Zealand. The lake is nationally–iconic and has been the subject of a major restoration programme over recent decades to address water quality issues associated with eutrophication (Parliamentary Commissioner for the Environment 2006). The authors present water chemistry data for ~100 sites (springs, wells and streams) throughout the catchment. Variables measured included nutrient concentrations (e.g., PO_4^{3-} and NO_3^-) and concentrations of chemical tracers of water age. Output from a mixing model, supported by additional water chemistry data, was used to estimate water age based on mean residence times (MRTs) for major stream inflows to the lake, which reflect transit times through groundwater aquifers. Nutrient concentration data were analysed to provide understanding about groundwater processes and the relative importance of anthropogenic and geological sources.

The paper provides a major and important contribution to understanding groundwater processes in the lake catchment. The authors' contributions are particularly significant due to the dominance of groundwater–derived baseflow in stream inflows, resulting in the lake being highly influenced by groundwater inputs, relative to lakes in general (Baisden 2016). From an applied perspective, accurate MRT estimates are vital for understanding the temporal response of lake water quality to changes in management practices related to nutrient sources such as pastoral land. Furthermore, the relationships derived between water age and nutrient concentration help lake managers to quantify loads 'to come', as groundwater chemistry changes in a lagged response to changes in land use practices. Such knowledge is important to help lake managers to better anticipate ecosystem responses, which has been identified as vital to prevent ecological decline when managing dynamic ecosystems such as Lake Rotorua (Mueller et al. 2015).

Of importance to managing the lake is the knowledge that geological sources contribute to naturally elevated concentrations of PO_4^{3-} in the catchment; both in groundwater and in surface waters that receive high groundwater inputs. This reflects the naturally high phosphorus (P) concentrations of the rhyolitic pumice and ignimbrite that are an important component of the geology of the wider Taupo Volcanic Zone which, coupled with low calcium concentrations, result in relatively high baseline PO_4^{3-} concentrations in groundwater (Timperley 1983). Consequently, at the national scale, streams draining catchments with such acidic volcanic geology have higher baseline (i.e., natural) PO_4^{3-} concentrations than comparable streams that drain different geologies (McDowell et al. 2013). The authors demonstrate this occurrence very convincingly for the Lake Rotorua catchment in Figure 7a of their paper; this figure shows a strong positive correlation between MRT and groundwater PO_4^{3-} concentrations, with a maximum MRT of ~170 years (ignimbrite formation) corresponding to a maximum PO_4^{3-} concentration of ~ 0.1 mg P L^{-1}. Combined with MRT estimates, the authors use this evidence of high PO_4^{3-}concentrations in 'old' groundwater to support the statement that "groundwater chemistry and age data show clearly the source of nutrients that cause lake eutrophication, nitrate from agricultural activities and phosphate from geologic sources". Consequently, the authors conclude that to manage eutrophication symptoms, lake managers should not control P inputs to the lake and should only focus on limiting nitrogen (N) loads, stating three times that "the only effective way to limit algae blooms and improve lake water quality in such environments is by limiting the nitrate load".

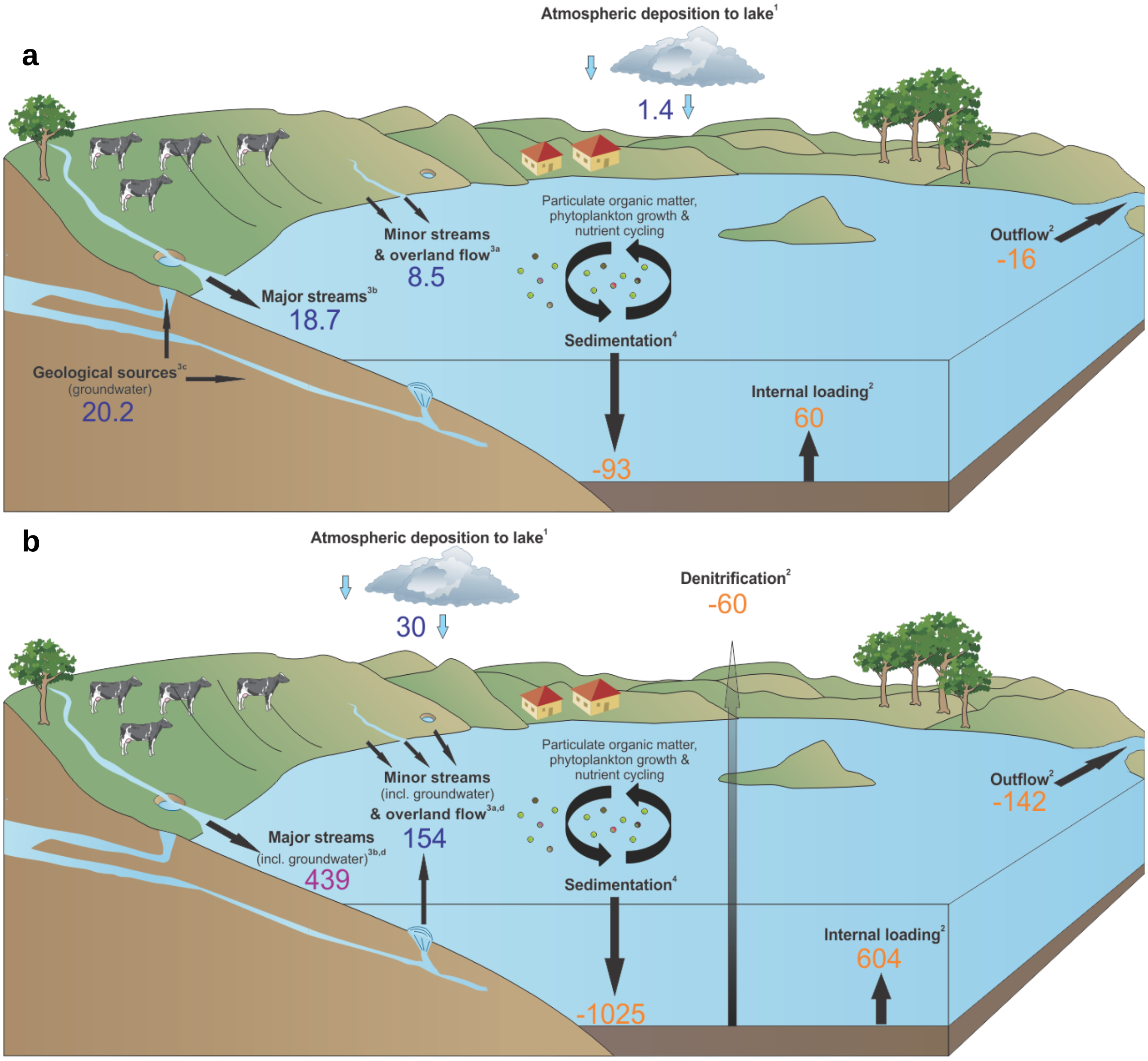
This conclusion by the authors contradicts the current approach to managing water quality in Lake Rotorua that is based on a strategy of *dual* control of N and P (BoPRC 2004; BoPRC et al. 2009; Burns et al. 2009), founded on the results of research conducted on the lake over several decades (e.g., Fish 1975; Rutherford et al. 1989; Burger et al. 2007). This strategy of dual nutrient control is supported by a multi–million dollar publically funded restoration programme, with statutory instruments now in place to help achieve load reduction targets (Parliamentary Commissioner for the Environment 2006; Burns et al. 2009). Specifically, these instruments comprise a set of rules enforced by regional government to manage terrestrial N and P export to water, designed to ensure that current export rates do not exceed benchmarks defined for specific land use activities (BoPRC et al. 2012). These benchmarks reflect targets for maximum N (435 t N y^{-1}) and P (37 t P y^{-1}) loads that have been set for the lake, based on a non-statutory lake Action Plan (BoPRC et al. 2009) to achieve desirable water quality. The water quality target is defined using a Trophic Level Index (TLI), which is a metric that has been designed using data for New Zealand lakes (Burns et al. 1999). The TLI is derived from equally–weighted scaled measurements of total N concentration, total P concentration, chlorophyll *a* concentration (a proxy for phytoplankton biomass) and Secchi depth (a measure of water clarity). The TLI target for Lake Rotorua is 4.2 (BoPRC et al. 2009), which is at the lower end of the eutrophic category (4.0–5.0; Burns et al. 1999). Since the mid–2000s, there has been a general decline in the TLI of Lake Rotorua (i.e., improved water quality; Abell et al. 2012; Smith et al. *in press*), and the annual average TLI reached the lake target in 2012 and 2014 (BoPRC et al. 2015). A significant factor contributing to recent improvement in water quality is the action of dosing aluminium sulphate (alum) to two stream inflows, initiated in one inflow in 2006 and the second in 2010 (Hamilton et al. 2015). This action has reduced dissolved P concentrations in the two treated streams, while excess alum has also contributed to further reducing ambient dissolved P concentrations in the lake to a level where ~~phosphorus~~P limitation of phytoplankton biomass accumulation is likely to occur (Hamilton et al. 2015). Despite this success, there are long term risks associated with the technique (Tempero 2015) and there is recognition that, although such geoengineering solutions can be a useful component of a wider range of restoration actions, they are not a substitute for long-term sustainable reductions in nutrient loads from the wider catchment (Abell et al. 2012; MacKay et al. 2014).

Clearly, the authors' support for a focus on ~~nitrogen~~N control ~~conclusion~~ calls into question the soundness of the current dual nutrient control strategy. ~~and, i~~If valid, their conclusion warrants major revision of the current approach to managing water quality in this nationally–important lake. After carefully considering the basis of their conclusion, we have identified four main reasons why we believe that the specific conclusion recommending N–only control is invalid.

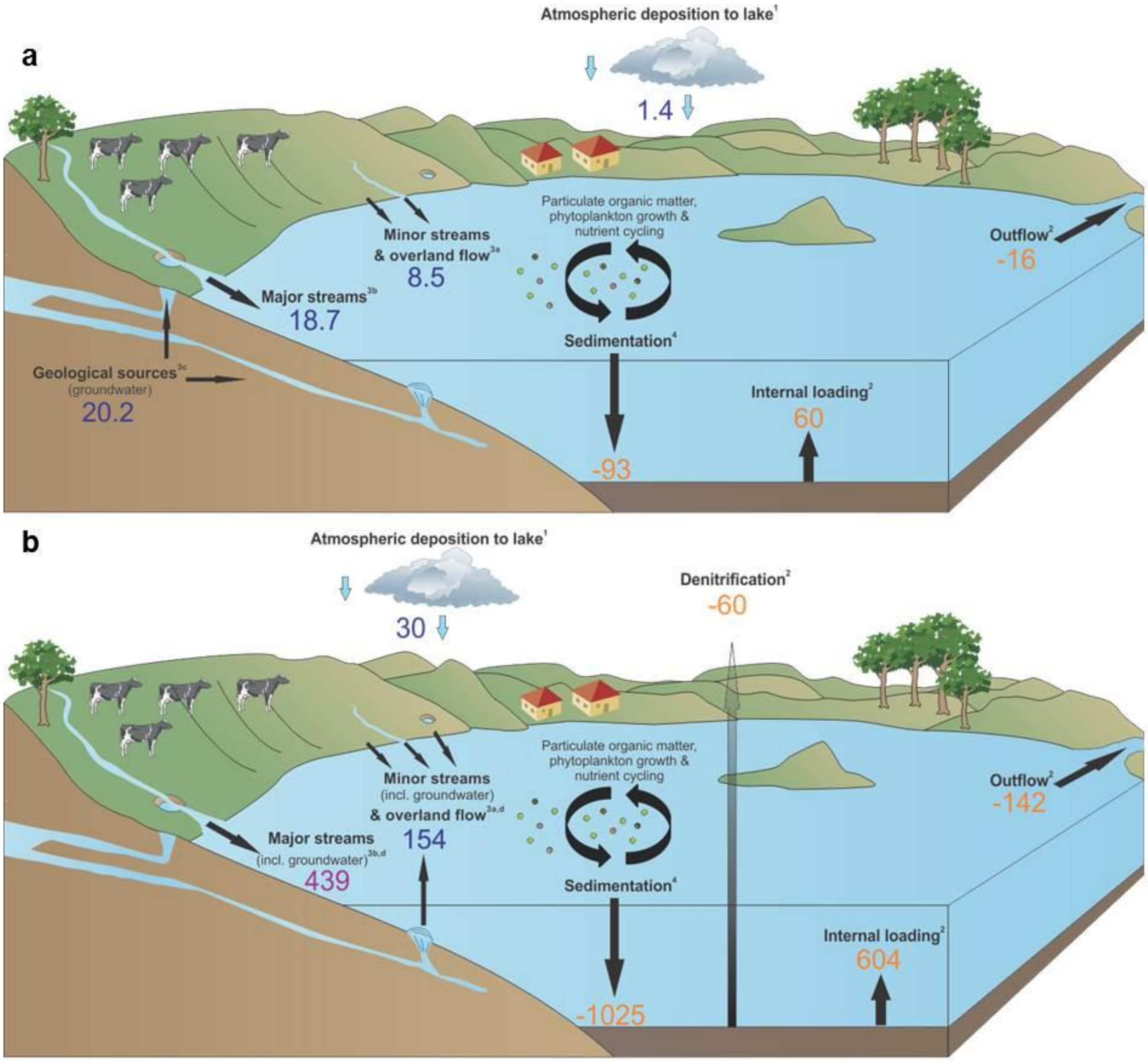
1. We agree that high phosphate concentrations in ‘old’ groundwater contribute to phosphate concentrations in many stream inflows to the lake that are relatively high from a biological perspective. However, we disagree that this fact means that P does not have potential to limit primary productivity in the lake, as implied in the final two paragraphs of Section 4.4.

   The authors imply that P control is redundant, partly based on the observation that natural P sources result in groundwater inputs to the lake having “high PO$_4$ concentrations, well above the threshold for primary algae production of ca. 0.03 mg L^{-1} total phosphate (Dodds 2007)”. Firstly, it is not clear what the “threshold for primary algae production” refers to; the only reference to this concentration in the cited reference relates to a boundary between mesotrophic and eutrophic lakes defined by Nürnberg (1996). Nevertheless, the key issue here is that the authors have considered only nutrient *sources*, and have neglected to consider nutrient *sinks* in drawing their conclusion. In–lake processes typically reduce ambient lake surface water concentrations of PO_4^{3-} to levels much lower than those in the main inflowing streams; one such important process is biological uptake and subsequent sedimentation of particulate organic material (Figure 1). Thus, while concentrations of PO_4^{3-} in inflows may exceed some defined threshold at which P does not limit net ~~primary~~ phytoplankton ~~biomass~~ production (based on other limiting factors), concentrations in the lake may be considerably below this threshold, with phytoplankton biomass accumulation in the lake P–limited at times. To illustrate, monthly monitoring data for the last eight complete years (2007–2014; BoPRC 2015) show that median PO_4^{3-} concentrations in the nine major stream inflows ranged from 0.017 to 0.094 mg P L^{-1}. By contrast, median surface water PO_4^{3-} concentration measured at two central lake sites was 0.002 mg P L^{-1}; an order of magnitude lower (range of values = <0.001–0.017 mg P L^{-1}, 95th percentile = 0.006 mg P L^{-1}). Such concentrations are generally below levels at which PO_4^{3-} concentrations have the potential to suppress phytoplankton growth rates (~0.003 mg P L^{-1}; Reynolds 2006) and, depending on the availability of other resources such as light and N, these concentrations have the potential to limit phytoplankton biomass accumulation. Indeed, phytoplankton biomass accumulation in the lake has been shown experimentally to be limited at times by P, either in isolation or in conjunction with N (Burger et al. 2007, Smith et al. *in press*). These observations are consistent with the view more generally that co-limitation of phytoplankton biomass accumulation by both N and P is commonplace in freshwater ecosystems (Elser et al. 2007).

To provide context, we present lake and catchment P and N budgets in Figure 1. Figure 1a illustrates the significant contribution of the authors' work, as their results have been used to estimate the magnitude of the P load via deep groundwater springs (~20.2 t P/y); a component that could not previously be resolved. As the authors describe, this component represents P from natural geologic sources and makes a major contribution to the overall lake and catchment P budget. Nonetheless, Figure 1a also highlights the significant contributions of other P sources that should also be considered alongside groundwater springs when examining P cycling in the catchment. These other sources include: internal loading from the bed of the lake (Burger et al. 2008), dissolved P transported in throughflow from agricultural land, and particulate P transported in overland flow, particularly during rain storms (Abell et al. 2013). Thus, while detailed study of individual components of the cycle is important to improve understanding, the range of major nutrient fluxes should be considered when developing catchment–scale lake management policy, not just those that relate to groundwater.



1. Hoare (1980)
2. Output from the DYRESM-CAEDYM lake model of Abell et al. (2015). Lake outflow volume based on hydrometric gauge data provided by the National Institute of Water and Atmospheric Science.
3. Catchment loads of N and P, as summarised in Abell et al. (2015).
    a) Load based on residual term in water balance and volumetric average concentration measured in major stream inflows. Thus, this component represents multiple sources and uncertainty is high.
    b) Increasing particulate nutrient concentrations at high discharge ('storm loads') were modelled for only three of the nine major streams. Thus, total storm loads to the lake are likely to be slightly underestimated.
    c) The proportion of catchment inputs attributable to geological sources in groundwater was estimated by Tempero et al. (2016). Groundwater P loads were estimated for individual sub-catchments based on estimated hydraulic loads and [PO$_4$-P] estimated from relationship between [PO$_4$-P] and mean residence time reported by Morgenstern et al. (2015).
    d) Includes N transported to major streams from surface and groundwater sources.
4. Calculated as the residual of the mass balance for the whole lake and catchment.



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    d) Includes N transported to major streams from surface and groundwater sources.
4. Calculated as the residual of the mass balance for the whole lake and catchment.

Figure 1. Catchment and lake nutrient budgets for Lake Rotorua for a) phosphorus (P) and b) nitrogen (N). Units are tonnes of total nutrient (P or N) per year. Values are annual averages for the period 2007–2014 when aluminium sulphate was applied to two lake inflows. Values in purple are based on annual means of observations, orange are derived from outputs from a 1–D lake model and blue are estimated using other methods (see notes). Calculation methods differ from those used to measure progress towards lake Action Plan targets.

2. The authors' conclusion that N–only control should be adopted is based on their inference that natural P loads greatly dominate those from anthropogenic sources, and the fact that anthropogenic loads are much easier to reduce than natural loads[1]. They state: "the high phosphate load to the lake via groundwater is natural", and "there is a constantly high PO_4 load reaching the lake via all streams" (Section 4.4). We disagree with the implication that anthropogenic sources of P to the lake are negligible. As we describe above, P inputs to Lake Rotorua have the potential to contribute to eutrophication, and we maintain that there is considerable scope to manage P from anthropogenic sources to support lake water quality objectives.

   To support this, we note that P loads in specific catchment streams have been shown to decline significantly in response to implementation of best management practices (e.g., riparian planting) designed to reduce P loss from agricultural land, thus implying that significant reductions in P load to the lake can be achieved by controlling anthropogenic sources (e.g., 27% reduction in particulate P load and 26% reduction in PO_4^{3-} load; Williamson et al., 1996). Crucially, lake water quality has been clearly shown to respond to such changes in anthropogenic P loads (Rutherford et al. 1989; 1996), highlighting the importance of managing P in conjunction with N to achieve lake water quality objectives. In drawing conclusions regarding nutrient management based on data regarding PO_4^{3-} in groundwater, a key consideration that has been overlooked is that P transport by overland–flow processes is often dominant to sub–surface transport (e.g., McDowell et al. 2003). As the authors indicate (Section 4.4), the local soils have a high capacity to retain PO_4^{3-} from anthropogenic sources. However, while this may limit PO_4^{3-} concentrations in 'young'

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[1] Although we note that the action of dosing aluminium sulphate to stream inflows since 2006 reduces stream PO_4^{3-} concentrations regardless of source, and has had marked success in supporting work to achieve lake water quality objectives (Hamilton et al. 2015, Smith et al. *in press*).

groundwater, this does not exclude episodic P transport to waterways following high rainfall. Indeed, stream water quality monitoring highlights spikes in total P concentrations during storm–flow periods (Abell et al. 2013), while laboratory experiments highlight the potential for farmland sediments that are enriched with particulate P to be transported in overland flow and contribute soluble P to Lake Rotorua (Peryer–Fursdon et al. 2015).

Recently, the authors' results have been used to estimate the relative proportion of the external P load from each lake sub-catchment that originates from anthropogenic sources (Tempero et al. 2016). These estimates were derived by subtracting estimated natural loads from current measured loads. Natural loads correspond to baseline conditions prior to human presence in the catchment, and were estimated as the sum of baseline groundwater loads and baseline surface loads. Baseline groundwater loads were estimated using the authors' results, while baseline surface loads were estimated using baseline concentrations estimated by McDowell et al. (2013). For the whole lake catchment, the study estimated that 48% of the total P load and 22% of the dissolved reactive P load originate from anthropogenic sources. Thus, although these values are likely to be relatively low for eutrophic lakes generally, these results highlight that an appreciable proportion of the total P load is from anthropogenic sources. In particular, these results highlight the importance of controlling particulate P loads transported in surface water, e.g., associated with soil erosion on farmland. Such loads were not considered by Morgenstern et al. (2015) when drawing conclusions about the most appropriate catchment–scale policy to manage water quality.

3. We believe that a strategy of only "limiting the nitrate load" would unduly inhibit the timelines over which lake water quality objectives could be achieved. This is due to the unresponsive nature of catchment nitrate loads, which the authors have diligently demonstrated. The authors' conclusions are based only on consideration of groundwater processes. We maintain that wider consideration of nutrient pools and transport processes (e.g., internal loading and overland flow) leads to the conclusion that dual control of N and P is more efficient than focusing solely on nitrate loading to address eutrophication.

The authors' study crucially highlights the long lag times between anthropogenic N loading to land and subsequent transport to the lake via groundwater transport. For example, Table 2 in the authors' paper shows that the mean residence times (MRTs) of sub–catchments to

Lake Rotorua range from 30 to 145 years, thus indicating that there is expected to be a lag of decades on average before groundwater ~~nitrogen~~N loads respond to actions to reduce nitrate leaching from land. ~~Figure 11 shows that the N load from one major sub catchment (Hamurana) is projected to double over approximately the next 300 years, as the quantity of ‘old’ groundwater that is relatively low in nitrate slowly declines in the contributing aquifer. The authors highlight that such long timescales “apply to activities that cause contamination, but also to remediation action”.~~ Thus, a strategy of focussing only on reducing nitrate loads to the lake would prevent community aspirations of lake water quality from being achieved for ~~multiple generations~~some decades.

We recognise that these MRT estimates reflect finer–scale spatial variability in groundwater transit times and, therefore, there is potential to achieve more–rapid reductions in groundwater loads by targeting ‘young’ groundwater sources. The authors’ results, and further work based on their methods, have potential to provide the detailed scientific understanding necessary to inform such a focused approach to managing nitrate pollution. We support using such detailed knowledge of groundwater pathways to minimise the timeframe over which load reduction targets could be achieved. Nevertheless, the differences in dominant transport mechanisms between N and P that we highlight above mean that a strategy of controlling both N and P would provide a shorter timescale for achievement of lake water quality objectives than controlling only N and being tied to long groundwater nitrate transit times. Such a strategy of dual nutrient control therefore provides for greater flexibility in the range of management actions that can be considered for managing nutrient (internal and external) loads to the lake (e.g., see Burns et al. 2009). In addition, the potential for either N, P, or N and P to limit phytoplankton biomass accumulation at times in Lake Rotorua (Burger et al. 2007) means that a focus on controlling both nutrients is expected to be more efficient that controlling only one nutrient (cf. Lewis et al. 2011). Such potential for managing eutrophication symptoms more efficiently and successfully is a key reason why a strategy of dual nutrient control is generally recommended for managing lake water quality in New Zealand (Abell et al. 2010) and more widely (Lewis et al. 2011; Paerl 2009; Paerl and Otten 2013).

4. Focussing only on controlling external nitrate loads to the lake is likely to reduce the N:P ratio in lake water. This has the potential to promote greater relative abundance of

undesirable cyanobacteria in the lake. High abundance of cyanobacteria is generally undesirable due to propensity for some species to produce toxins and form unsightly scums.

Some species of cyanobacteria can use atmospheric N gas as a partial N source (i.e., N–fixation), and thus gain a competitive advantage over other phytoplankton species when N availability in lake water is relatively low, implicit when the N:P ratio is low (Smith 1983). Potential N–fixing species include those from genera associated with toxin production (e.g., *Anabaena*; Reynolds 2006). Multiple studies have demonstrated that conditions which cause low N: P in lake water can result in increased dominance of cyanobacteria (Smith 1983; Nõges et al. 2008; Vrede et al. 2009). Further, a strategy of focusing on nitrate control is expected to result in a low N:P ratio *coupled with* high ~~phosphorus~~P concentrations. These are precisely the conditions that are associated with a high risk of harmful algal blooms: lake surface water total ~~phosphorus~~P concentrations are frequently a strong predictor of cyanobacteria abundance (Smith et al. 1987; Smith et al. *in press*), and they are often a better predictor of cyanobacteria dominance than low N:P ratio (Dokulil and Teubner 2000; Downing et al. 2001).

Thus, although the relationship is complex and mediated by factors such as temperature and P concentrations (Håkanson et al. 2007), a strategy of controlling only nitrate and not P has the potential to increase the dominance of N–fixing cyanobacteria as a consequence of reduced N:P ratios and accompanying high in–lake P concentrations. Proliferation of such species also has the potential to partly offset any reductions in external N load (Schindler et al. 2008), and the potential for increased dominance of cyanobacteria is a key reason why a strategy of N–only control has ~~been~~ previously been rejected for the lake (Rutherford et al. 1989; BoPRC 2004) and the non-statutory lake Action Plan includes the aim to make “phosphorus the key limiting lake nutrient” (BoPRC et al. 2009).

In closing, we conclude that the results presented by Morgenstern et al. (2015) do not support a rationale of N–only control, and therefore the current strategy of controlling both N and P in the catchment of Lake Rotorua should be maintained. Our Comment does not relate to the methods or results presented by the authors, and we recognise the very valuable contribution that their detailed work otherwise makes to understanding hydro–chemical processes in the catchment.

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