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Discussions

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. Parameters 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 our understanding of groundwater processes in the lake catchment. 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 Fig. 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 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). Clearly, the authors’ conclusion calls into question the soundness of the current strategy and, 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 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 Sect. 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. Thus, while concentrations of PO_4^{3-} in inflows may exceed some defined threshold at which P does not limit net primary 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 range from 0.017 to 0.094 $\mathrm{mg\,P\,L^{-1}}$. By contrast, median surface water PO_4^{3-} concentration measured at two central lake sites is 0.002 $\mathrm{mg\,P\,L^{-1}}$; an order of magnitude lower (range of values $=<$ 0.001–0.017 $\mathrm{mg\,P\,L^{-1}}$, 95th percentile = 0.006 $\mathrm{mg\,P\,L^{-1}}$). Such concentrations are generally below levels at which PO_4^{3-} concentrations have the potential to suppress phytoplankton growth rates ($\sim$ 0.003 $\mathrm{mg\,P\,L^{-1}}$; 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).

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"

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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).

(Sect. 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 (Sect. 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" 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).

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' study crucially highlights the long lag times between anthropogenic N loading to land and subsequent transport to the lake via groundwater transport. For example, Fig. 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. 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). 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).

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). 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. 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 rejected for the lake (Rutherford et al., 1989; BoPRC 2004).

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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