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Discussions

Interactive comment on "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)" *by* J. M. Abell et al.

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Abell et al. (2015), in their comment on Morgenstern et al. (2015), acknowledge and highlight the importance of Morgenstern et al.'s (2015) contribution to understanding of the groundwater processes and dynamics in the Lake Rotorua catchment. Abel et al. (2015) do not comment on Morgenstern et al.'s (2015) methodology and results, but rather challenge the validity of one conclusion presented in the paper, specifically that "the only effective way to limit algae blooms and improve lake water quality in such environments is by limiting nitrate load". Abell et al. (2015) highlight that this

conclusion of Morgenstern et al. (2015) contradicts the current catchment strategy of limiting both phosphorus and nitrogen loads to the lake and present four reasons for rejecting this conclusion of Morgenstern et al. (2015). In this review of the comment on Morgenstern et al. (2015), I will begin with an overall assessment of Abell et al.'s challenge to Morgenstern et al.'s (2015) conclusion to recommend a single nutrient strategy to managing eutrophication in Lake Rotorua and will then examine each of Abell et al.'s four reasons independently.

Abell et al.'s (2015) comment raises an important challenge to Morgenstern et al. (2015) call for a single nutrient strategy to manage eutrophication in Lake Rotorua. Abell et al.'s (2015) defense of a management approach taking into account both phosphorus and nitrogen is well supported by the literature on lake eutrophication management, as articulated by V. Smith in a previous comment in this interactive discussion (Smith, 2015). Abell et al.'s (2015) comment could benefit by more explicitly drawing from the ample literature on nutrient co-limitation and dynamics, as Smith (2015) has done. While Morgenstern et al. (2015) explicitly deals only with groundwater sources of nutrients to Lake Rotorua, the conclusion suggesting a nitrogen-only management strategy for the lake implicitly expands the factors under consideration to include the whole hydrologic system of Lake Rotorua, including in-lake processes. Pragmatically, the large natural geologic loading of phosphorus is difficult to manage and it may be easier to manage agricultural nitrate inputs than phosphate loading to the lake, but as suggested by Abell et al. (2015) this single nutrient strategy overlooks the potential for nitrate reductions in the lake to favor nitrogen-fixing cyanobacteria that can produce toxic algae blooms. The dynamic interactions between nitrate and phosphate in in-lake processes suggest that any recommendation for a single nutrient management strategy is ill-advised, as supported by substantial literature (see Smith (2015)).

Abell et al.'s (2015) first rationale posits that Morgenstern et al.'s (2015) recommendation of a single nutrient management approach fails to take into account for in-lake processes. Abell et al. (2015) present data from Lake Rotorua to show that phosphorus can act as a limiting nutrient to lake primary productivity, despite high groundwater delivery of natural phosphate, due to in-lake processing of phosphate. I agree with Abell et al.'s assessment that Morgenstern's conclusion for a nitrate only management regime does not take into account in-lake processing, and therefore oversteps. However, in order to draw a conclusion on the appropriate nutrient management regime for Lake Rotorua, 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.

Abell et al.'s (2015) second rationale proposes that the Morgenstern et al.'s (2015) conclusion for a single nutrient management regime implies incorrectly that the anthropogenic phosphorus inputs to the lake are negligible and that anthropogenic management of phosphorus inputs to the lake are ineffective. Specifically, Abell et al. (2015) call into question Morgenstern et al.'s (2015) "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". To support this challenge, Abell et al. (2015) convincingly cite successful reduction of phosphorus loads to Lake Rotorua through management of phosphorus runoff from agricultural fields. Additionally, Abell et al. (2015) raises the question of overland-flow inputs of phosphorus, which are not accounted for in Morgenstern et al.'s (2015) groundwater analysis. Broadly speaking, particulate phosphorus losses via overland-flow events, as compared to dissolved phosphorus losses, are the dominant from soil phosphorus loss and primarily occur during storm events (Bennet et al, 2001). 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. While I do agree with Morgenstern's (2015) interactive comment on Abell et al.'s (2015) that Morgenstern et al. (2015) never explicitly state that the

management of phosphorus sources can not improve lake water quality, I also agree with Abell et al.'s (2015) assertion that Morgenstern et al.'s (2015) conclusion implies that the influence of other sources of phosphorus, e.g. via overland flow, is negligible. Indeed, Morgenstern (2015) appears to concede this point to Abell et al. (2015) by stating that "anthropogenic sources of P and N should be reduced wherever possible".

Abell et al.'s third rationale states that following Morgenstern et al.'s (2015) nitrogen-only management recommendation would greatly inhibit the flexibility and timeline over which lake water quality could be improved. I agree with Abell et al.'s (2015) basic logic that if it takes nitrate loads decades on average to flow through the groundwater system, it would take a similar amount of time for reductions in anthropogenic nitrate to move through the groundwater system. However, as Morgenstern (2015) points out in an interactive comment on Abell et al (2015), the example of Hamurana Stream's projected nitrate load doubling in 300 years is not the strongest evidence to support this logic. Morgenstern et al.'s (2015) Figure 11 draws from current "land-use impacted" young water nitrate loads to extrapolate loads into the future based on the assumption that the anthropogenic nitrate load stays constant. In the event that management reduces nitrate groundwater loading, there would be a reduction in future young water nitrate concentration levels, theoretically bringing down the overall Hamurana Stream load at an earlier time point. 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. Even in this case, however, the question is less about the average mean residence time, and more about the interaction between the spatial distribution of differential ground water flow paths and critical source areas of anthropogenic nitrogen and phosphorus. The potential for management intervention of anthropogenic nitrogen and phosphorus sources would depend on whether the sources are located over fast or slow moving ground water flow paths. Abell et al. (2015) could be strengthened through incorporating a recognition of the spatial interplay between nutrient critical source areas and groundwater flow. Additionally, Abell et al.'s (2015) third rational rests upon the assumption that reducing phosphorus will improve lake water quality in the long term and will not just serve as a short term solution, as Morgenstern et al. (2015) suggests. However, Abell et al.'s (2015) does not address the question of whether in-lake control of phosphorus loading will contribute to a long term solution rather than a temporary fix. To strengthen this rationale, Abell et al. (2015) should address this question and cite relevant examples.

Abell et al.'s (2015) fourth and final rational is the crux of the invalidation of Morgenstern et al.'s (2015) single nutrient control solution. Abell et al. (2015) claim that the reduction of nitrogen alone in the lake will give nitrogen fixing cyanobacteria a competitive advantage in the lake, thereby potentially increasing the risk of toxic harmful algal blooms. Rutherford et al. (1998), while focusing more narrowly on sewage treatment inputs to Lake Rotorua, draws the same conclusion as Abell et al. (2015); namely, that a focus on nitrate reduction in the lake could allow the algal community to be dominated by heterocystous blue-green algae. Smith's (2015) interactive comment on Abell et al. (2015) provides strong supporting evidence for Abell et al.'s (2015) fourth rationale, and Abell et al. (2015) could benefit by including Smith's (2015) additional empirical support.

In conclusion, Abell et al. (2015) raises important and well-grounded challenges to Morgenstern et al.'s (2015) conclusion calling for a nitrate-only management regime. Morgenstern (2015) in an interactive comment to Abell et al. (2015) states that Abell et al.'s (2015) comment goes beyond conclusions stated in the paper by discussing the behavior of algae to N and P, in-lake treatment options, and evaluating all N and P management options for the Lake. However, each of these factors interact with groundwater inputs and are relevant to the dynamics of eutrophication in Lake Rotorua. Furthermore, eutrophication of the Lake can not be considered without taking into account a whole system approach that includes these factors. Therefore, I find Abell et al.'s (2015) comments on Morgenstern et al.'s (2015) sweeping conclusion that managing

nitrogen inputs is the only feasible way to effectively reduce eutrophication in the lake, both relevant and appropriate.

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