Temperature stratification and dissolved oxygen dynamics in Lake Rotorua

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Temperature stratification and dissolved oxygen dynamics in Lake Rotorua

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Lake Rotorua monitoring buoy (W.Powrie)

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Executive Summary

Lake Rotorua is polymictic, meaning that more than once per year its surface waters become isolated from bottom waters due to density differences and subsequently mix again after days or weeks. During these periods of stratification oxygen is consumed in bottom waters and cannot be replenished by atmospheric exchange. This can stimulate remineralisation of dissolved nutrients that would otherwise have been retained within lake sediments, back into the water column ('internal loading') which can enhance phytoplankton growth.

Very high loads of dissolved nitrogen (N) and phosphorus (P) were conveyed to Lake Rotorua by treated wastewater discharge until 1991 when spray irrigation to the Whakarewarewa forest was commissioned as an alternative disposal method. This along with increasing intensity of land use in the catchment, has been linked to water quality degradation and algal blooms observed since the late 1960s. Internal nutrient loading has been linked to the legacy of catchment and wastewater nutrient loading, and has been widely documented and discussed as a potentially important driver of water quality in the lake (Rutherford et al. 1989, Burger et al. 2008, Hamilton et al. 2015). Since 2006, two inflows to the lake have been dosed with aluminium sulfate (alum) to mitigate catchment phosphorus loads, and some studies have suggested potential secondary effects of this dosing through removal of water column P and reduction of internal loading (Ozkundakci et al., 2014, Hamilton et al., 2015).

Rotorua is one of the most-monitored lakes in New Zealand, and a programme of monthly water chemistry and vertical profile analysis has been in place since 2000. To understand polymictic dynamics of temperature and dissolved oxygen (DO), a high-frequency monitoring buoy was operated in the lake from 2007 to 2021. Here we use a hydrodynamic model of Lake Rotorua to fill gaps in the monitoring buoy record to synthesise a complete best-estimate of the number, duration and timing of stratification events in the lake 2007-2017 and present an exploration of water chemistry data in this context, as well as nutrient and alum loading.

Stratification periods were identified by temperature (~density) difference between surface and bottom waters. Patterns of stratification were highly variable interannually. Sustained periods of stratification were relatively rare but lasted as long as 8 weeks (maximum observed 58 days). Stratification was generally accompanied by steep draw-down of bottom oxygen, and complete anoxia of bottom waters was reached at least once in most years. Determination of long-term change in oxygen depletion rate during stratification (HVOD) was confounded by the relatively stronger apparent influence of seasonal timing (and hence bottom water temperature) than interannual change. For monthly water chemistry samples collected during periods of stratification, a strong response was observed to stratification, with bottom water concentrations well in excess of any observations in surface waters when collected after a week or more of stratification. No clear pattern of interannual change was evident, likely due to multiple interacting factors, and whether or which stratification events happened to be captured by samples over given year.

The monitoring buoy record was merged with model simulations to infill gaps in the record, and annual statistics for the number and duration of stratification events were determined along with annual alum dosing statistics and nutrient loading estimates (McBride 2022). Lake total nitrogen did not show a strong response to stratification events of any length, nor to annual hydraulic or nitrogen load. A strong relationship to total alum dose was observed, although this was likely highly influenced by the years 2007-2008 which had relatively higher TN concentrations and were prior to substantial dosing. Lake total phosphorus was strongly negatively related to the number of short-term stratification events and somewhat positively related to long-term stratification events. Interestingly lake TP was strongly inversely related to annual estimated hydraulic and nutrient load. This could be because wet years are less likely to have the warm stable summers that lead to stratification. A strong relationship to total alum dose was observed, although as for TN this was likely influenced by pre-dosing years.

This study presents an initial exploration of the datasets and models employed, and opportunity exists to further exploit these approaches to generate additional insights to dynamics of Lake Rotorua. Under a changing climate in years to come, duration and timing of stratification are likely to change. Preliminary findings here suggest that if long-duration events become more common under changing climate then internal loading may drive increased nutrient supply (particularly P) to surface waters. High-frequency monitoring remains essential to understanding Lake Rotorua, and targeted water chemistry sampling over the duration of stratification events could be a useful addition to its monitoring program.

Introduction

Lake Rotorua is polymictic, meaning that more than once per year its surface waters become isolated from the bottom waters for at least two days, due to density differences ('thermal stratification'), and subsequently mix again ('turnover'). Stratification is caused by a combination of surface heating and low wind energy, and during these periods oxygen is consumed by aerobic decomposition of organic matter in sediments and bottom waters but cannot be replenished by atmospheric exchange. These processes create a strongly reducing chemical environment in which can lead to remineralisation of dissolved nutrients into the water column that would have otherwise remained adsorped to materials in bottom sediments (e.g., phosphorus bound to Iron). This stock of released nutrients (internal loading) is then mobilised to surface waters following mixing, where it can drive primary production in the lake ecosystem.

Very high loads of dissolved nitrogen (N) and phosphorus (P) were conveyed to Lake Rotorua by treated wastewater discharge until 1991 when spray irrigation to the Whakarewarewa forest was commissioned as an alternative disposal method. This excess loading, along with increasing intensity of land use in the catchment, has been linked to water quality degradation and algal blooms observed since the late 1960s. Specifically, internal loading has been linked to this legacy of catchment and wastewater nutrient loading, and has been widely documented and discussed as a potentially important driver of water quality in the lake (Rutherford et al. 1989, Burger et al. 2008, Hamilton et al. 2015). Since 2006, two inflows to the lake have been dosed with aluminium sulfate to mitigate catchment phosphorus loads, and some studies have focussed on potential secondary effects of this dosing to supress in-lake P and internal P-loading (Ozkundakci et al., 2014, Hamilton et al., 2015).

Rotorua is one of the most-monitored lakes in New Zealand, and a programme of monthly water chemistry and vertical profile analysis has been in place since 2000, continuing from various other programmes of monitoring and study since 1967 (see McBride 2022). However, because of the polymictic nature of Rotorua–where periods of stratification can last a few weeks or less but can potentially cause substantial changes in water chemistry–monthly monitoring can create a sometimes-incomplete picture of water quality dynamics. To address this in part, a high-frequency monitoring buoy was operated in the lake from 2007 to 2021, collecting water temperature profiles, dissolved oxygen, and weather measurements every 15 minutes.

Objectives

High-resolution monitoring buoy data present a unique opportunity to better understand the drivers of water quality in Lake Rotorua. Here we use a hydrodynamic model of Lake Rotorua to fill gaps in the monitoring buoy record in order to synthesise a complete best-estimate of the number, duration and timing of stratification events in the lake 2007-2017, and present an exploration of water chemistry data in this context, as well as nutrient and alum loading.

Methods

Monitoring buoy data

The Rotorua monitoring buoy was deployed in July 2007 and operated until late-2021, when it was replaced by a ‘vertical profiler buoy’. The buoy was located at a central lake site where the water column depth was approximately 21.5 m deep. It measured water temperature every 2 m through the water column from 0.5 m to 20.5 m (depth from surface). Two dissolved oxygen sensors were installed at depths of 1 m and 20 m, and a weather station was installed at a height of 1.5 m above the lake surface. Monitoring buoy data were edited for outliers or spurious measurements and aggregated to daily median values for ease of analysis and to minimise bias caused by any remaining outliers. Many gaps are present in the record, due to wear and tear and maintenance requirements, although long periods of continuous data were also achieved.

DYRESM model

In order to ‘infill’ gaps in the buoy temperature record, a 1-D hydrodynamic model was constructed for the lake (DYRESM, v2 geothermal). DYRESM has a long history of application to Lake Rotorua (Burger et al. 2008, Ozkundakci et al., 2012, Hamilton et al. 2015). The model was calibrated manually (c. 100 simulations) until performance improvements were negligible. An ensemble modelling approach was also tested (LakeEnsemblr, Moore et al. 2021), however, due to similar model performance with DYRESM, the DYRESM model was selected for simplicity and consistency with previous studies. Both the monitoring buoy record and the model output were analysed for temperature differences, Schmidt Stability and thermocline metrics (R statistics, package RLakeAnalyzer).

Observations analysis

Oxygen dynamics during stratification were investigated using monitoring buoy data only (i.e., when the temperature and oxygen sensors were all functional). Stratification periods were identified by difference between surface and bottom waters using a threshold value of 0.25 ^{o}C. Each event was identified and assessed for the duration of consecutive days meeting this criterion. Water chemistry data were merged with the stratification analysis, to determine which measurements were collected during periods of stratification, and if so, how long the lake had been stratified at the time of collection. It was then possible to relate duration of stratification to dissolved nutrient concentrations in the water column for various depth ranges.

Relationships between annual stratification, loading, alum dosing and water quality

The monitoring buoy record was merged with model simulations to infill gaps in the record. Annual statistics (hydrological year June to previous July) were calculated for the number and duration of stratification events. These were then synthesised alongside annual alum dosing statistics and nutrient loading estimates (McBride 2022) and linear regression was used to assess potential relationships between these metrics and overall water quality expressed as annual mean surface concentrations of total N and total P.

Results

Monitoring buoy data

The Rotorua monitoring buoy operated from July 2007 until October 2021. Figure 1 presents surface and bottom water temperature recorded by the buoy, with frequent periods of thermal stratification evident by the regular divergence of surface and bottom measurements over warmer months of the year. Figure 2 presents surface and bottom dissolved oxygen measurements. Although the record is somewhat more complete than for water temperature, it should be noted that surface measurements prior to 2015 are relatively unreliable due to bio-fouling of the sensor (a wiped sensor was installed in 2015). The steep draw-down of bottom oxygen during stratification is shown, and complete anoxia of bottom waters is reached at least once in most years.

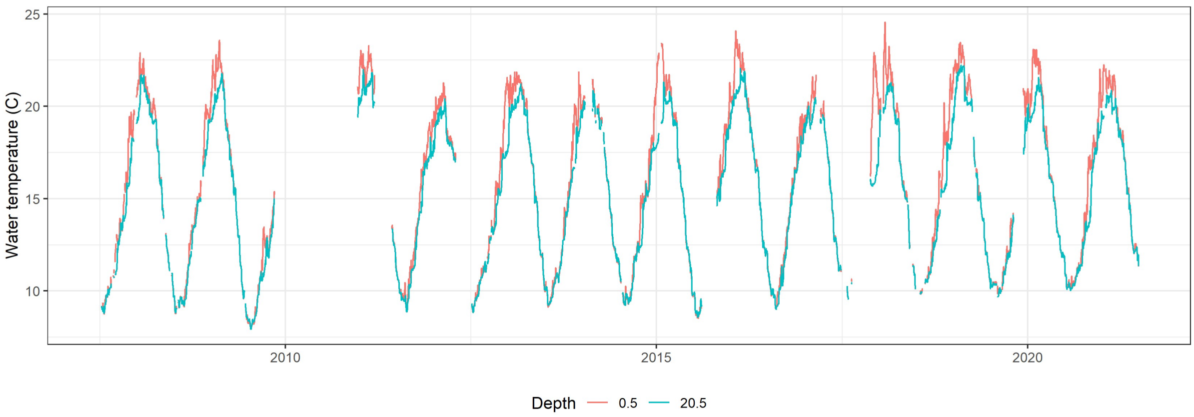

Figure 1. Summary of water temperature record form the Lake Rotorua monitoring buoy, showing daily median surface and bottom temperature for all days with measurements between July 2007 and June 2021.

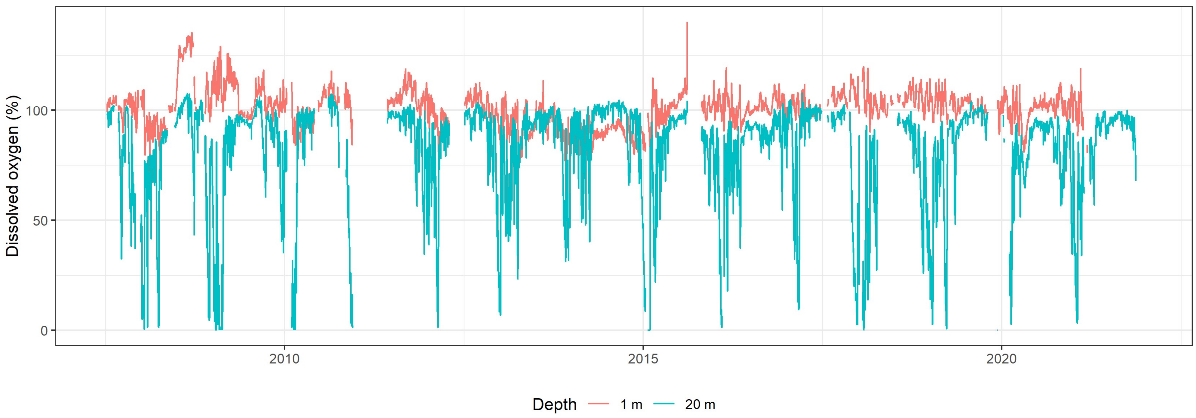

Figure 2. Dissolved oxygen measurements from the Lake Rotorua monitoring buoy for surface (0.5 m) and near-bottom (20.5) water temperature. (Note surface measurements prior to 2016 are less reliable due to bio-fouling of the sensor lens (a wiper was installed in later years).

Figure 3 shows the water temperature record as a temperature difference heat map (i.e., each measurement minus the minimum observed water column temperature from the matching timestamp. Periods of stratification are clearly identified by warmer colours in surface waters. Particularly long-duration and stable stratification events were observed in 2015 and 2018.

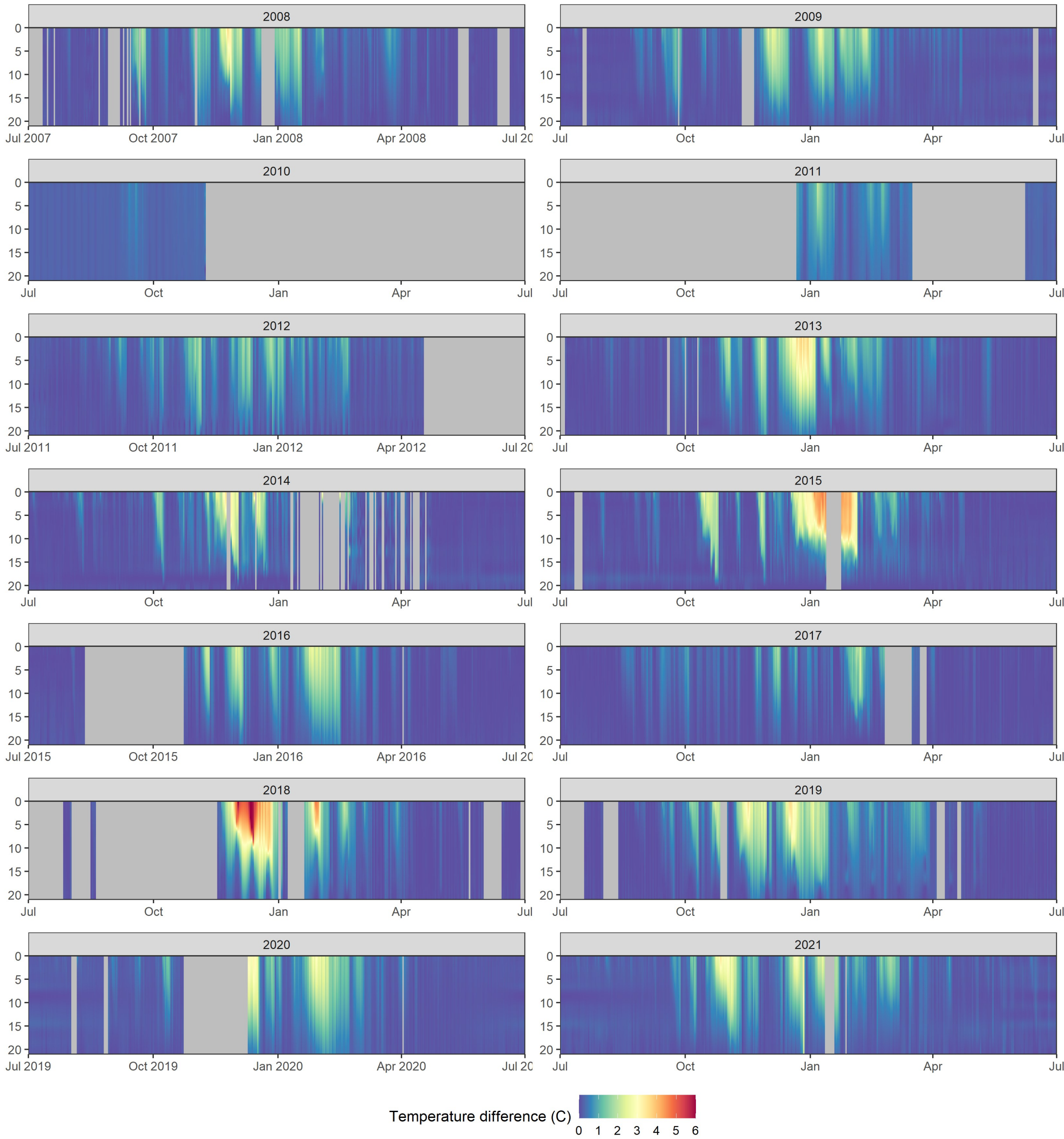

Figure 3. Heat maps for each hydrological year of monitoring buoy operation, where colour intensity represents the difference between water temperature and the minimum recorded temperature across all depths for that day (of daily median data). Grey areas indicate periods where the buoy was not operational. The y-axis represents depth in the water column.

Figure 4 presents dissolved oxygen saturation (DO) over the course of each individual continuous period of thermal stratification observed by the Lake Rotorua monitoring buoy between July 2007 and June 2021. Each DO trace is coloured by the water temperature of bottom waters at the time. In this respect Figure 4 shows that how difficult it is to estimate HVOD in Rotorua, and to assess any potential interannual changes. stratification happens at differing and unpredictable times over warmer months, and rate of decline in bottom DO appears to relate more to water temperature than to any discernible interannual change. This is further reinforced by the presentation of all measurements together in Appendix 2.

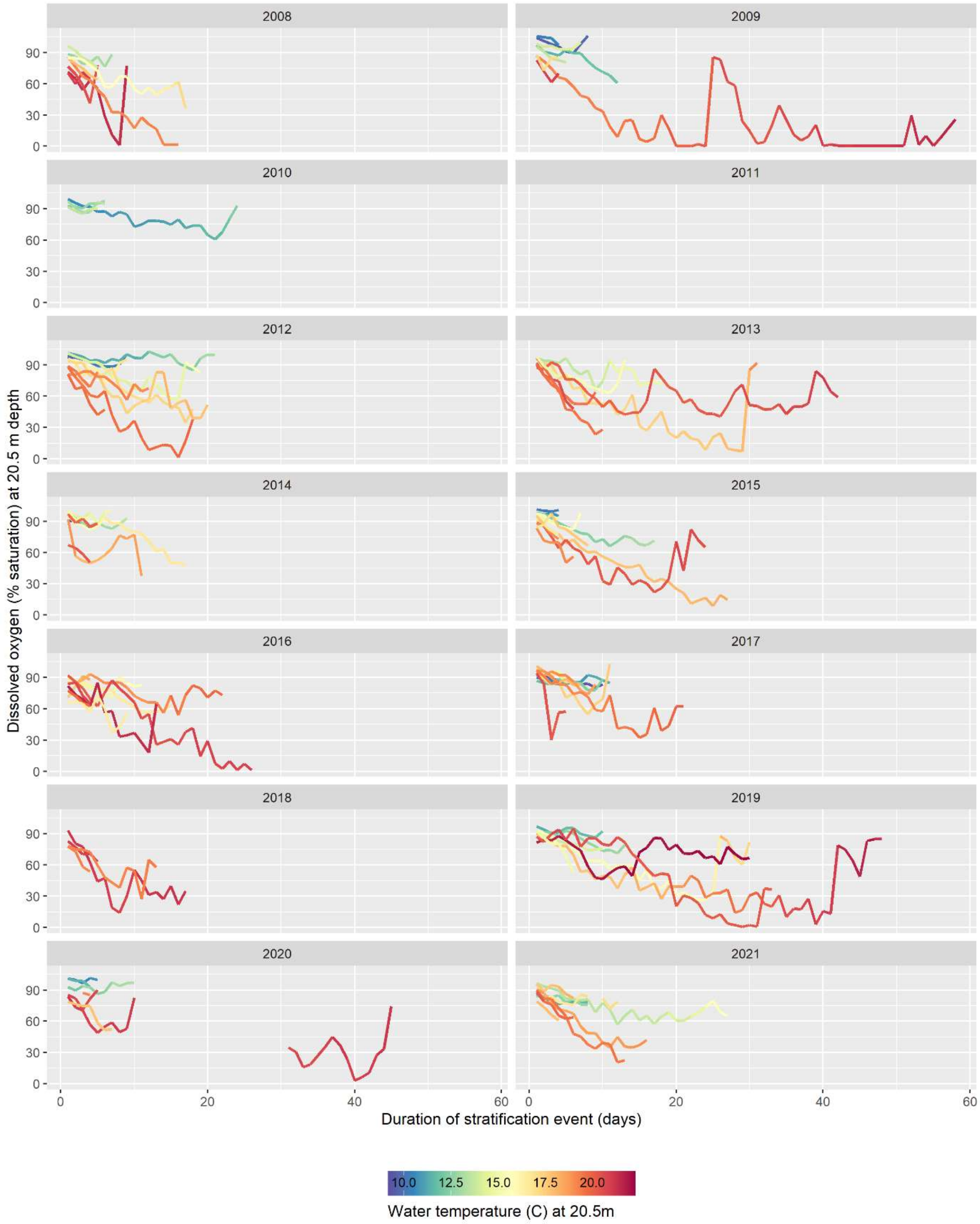

Figure 4. Dissolved oxygen saturation in bottom waters (20m) over the course of each continuous period of thermal stratification observed by the Lake Rotorua monitoring buoy between July 2007 and June 2021. Each panel shows all events observed for a single hydrological year (30-June back to the previous 01-July). Stratification was here defined as continuous periods with an observed temperature difference between surface and bottom waters of at least 0.25 degrees C, lasting at least 3 days. "Duration of stratification event' refers to the number of days since the onset of stratification (surface temperature – bottom temperature > 0.25 °C).

Water chemistry data for dissolved reactive phosphorus (DRP) and ammoniacal nitrogen (NH4-N) are shown in Figure 5, against the number of days if stratification prior to sample collection (only measurements collected during a stratification event are shown). A strong response was observed to stratification, with bottom water concentrations substantially higher than any observations in surface waters when collected after a week or more of stratification. No clear pattern of interannual change was evident, likely due to multiple interacting drivers of stratification and nutrient dynamics, as well as the role of chance in whether and how many stratification events happened to be captured by monthly sampling for a given year.

Model of water temperature

The DYRESM model achieved satisfactory performance (see Appendix 1) and predicted the daily presence or absence of stratification with 89% accuracy. Figure 6 presents a temperature difference heat map, similar to Figure 3, but for a combined synthesis of monitoring buoy observations (when available) and model results (when the buoy data are not available). In this respect the synthesis of observations and model output enables a consistent and complete best-estimate of annual statistics for the number and duration of stratification events. The number and duration of stratification events was highly variable among years, although obvious pattern of long-term change was observed (Table 1).

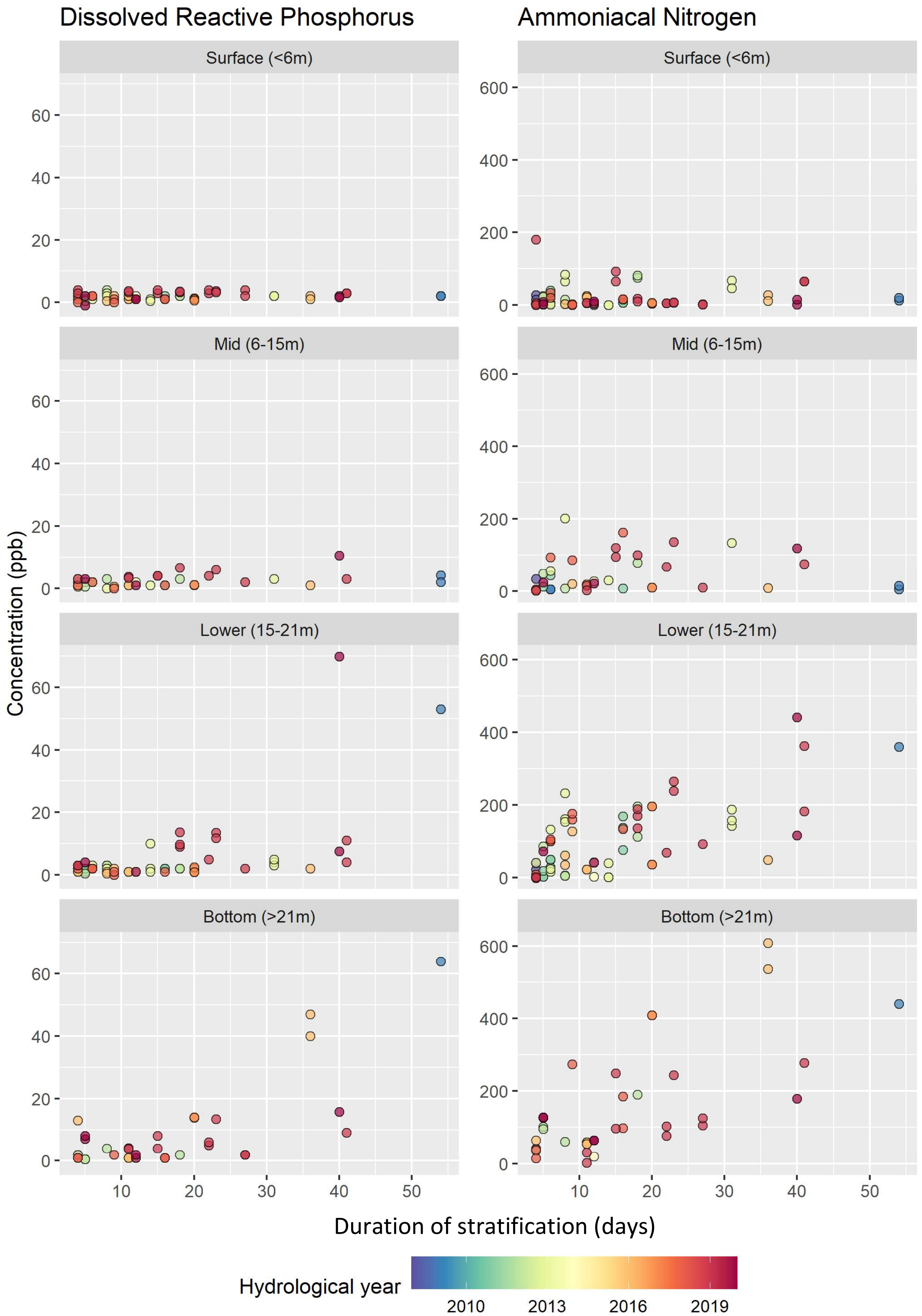

Figure 5. Observations of dissolved reactive phosphorus (left column) and ammoniacal nitrogen (right column) concentrations at different depth ranges (plot rows) against the number of consecutive days of stratification prior to sample collection. Only those measurements collected during a stratification event are presented. Points are coloured by the year of observation.

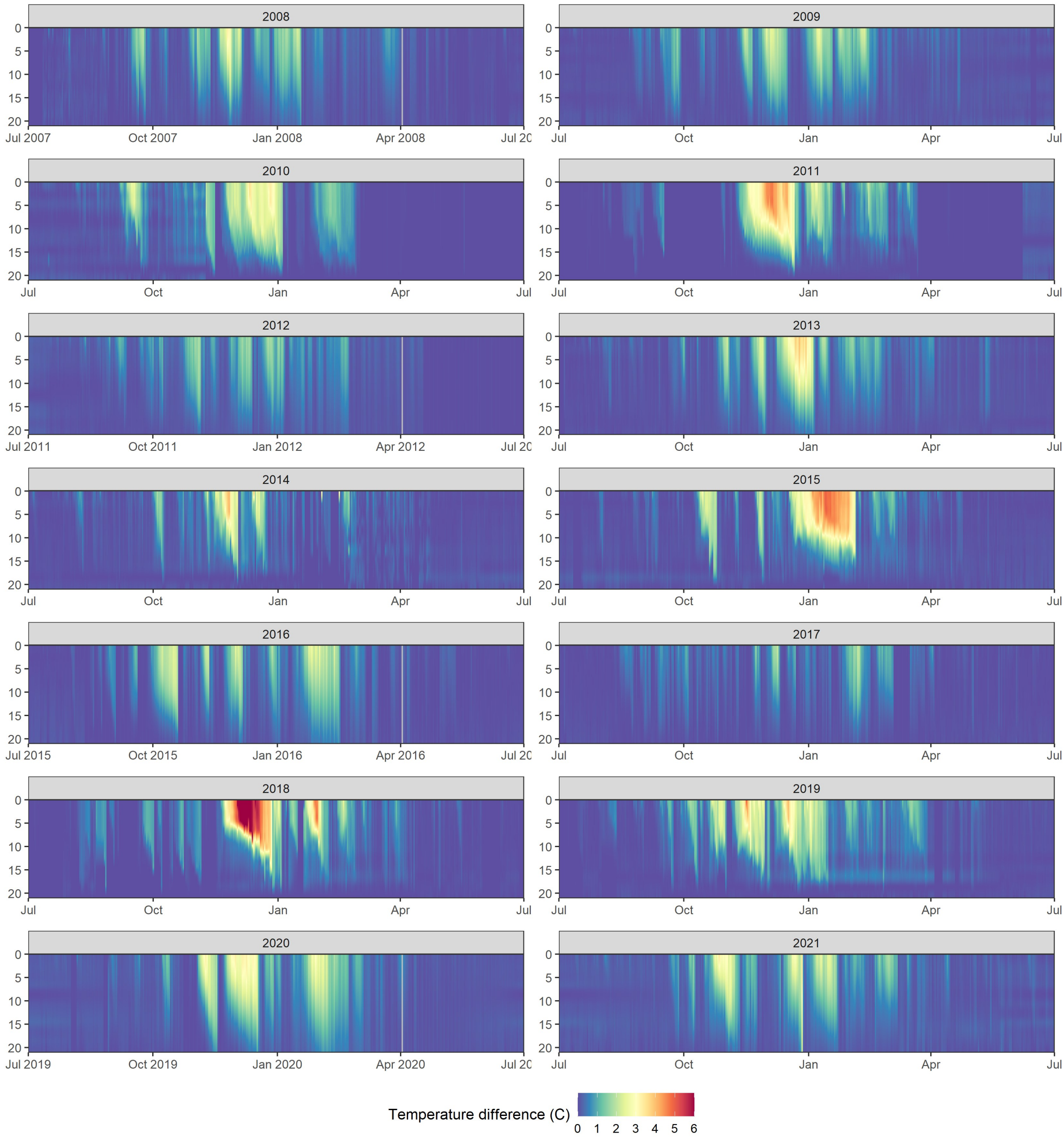

Figure 6. Combined record of surface and bottom water temperature, using modelled water temperature to fill gaps in the monitoring record. Each panel represents a hydrological year.

Table 1. Summary of best estimates for number and duration of stratification events in Lake Rotorua from July 2007 to June 2021.

Hydrological	Stratifications lasting at least				
year	3 days	7 days	14 days	28 days	50 days
2008	13	6	6		
2009	10	3	3	2	1
2010	7	3	3	2	
2011	8	5	4	2	
2012	15	6	5		
2013	16	5	3	2	
2014	13	2	2		
2015	14	3	3	1	1
2016	15	6	4	1	
2017	18	6	1		
2018	15	5	3	1	
2019	12	7	5	4	
2020	12	6	4	2	
2021	13	6	5		

Alum dosing

Figure 7 presents daily aluminium dose (delivered as aluminium sulfate) to the Puarenga and Utuhina Streams. Annual dose for each stream and total dose was calculated to assess against annual water quality.

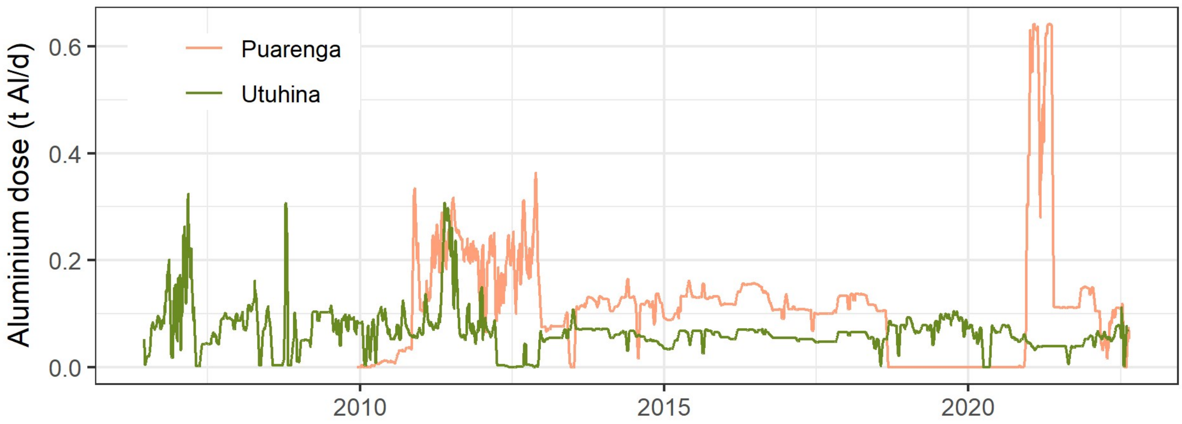

Figure 7. Daily aluminium dose as measured at the two alum dosing plants, expressed as tonnes aluminium per day.

Stratification dynamics, alum dose, and lake loading and overall water quality

Figures 9 and 10 assess relationships between annual mean surface total P (Figure 9) and total N (Figure 10), and annual statistics for a range of potential drivers of water quality, including number of stratified periods (>3, 7 and 14 days length), nutrient and hydraulic loading, and aluminium dose (Puarenga, Utuhina, and Total).

Total nitrogen did not show a strong response to stratification events of any length, nor to annual hydraulic or nitrogen load ($r^2 < 0.05$ in all cases). A strong relationship to total alum dose was observed ($r^2 > 0.4$, $p < 0.02$), although this was likely highly influenced by the years 2007-2008 which had relatively higher TN concentrations and were prior to substantial dosing.

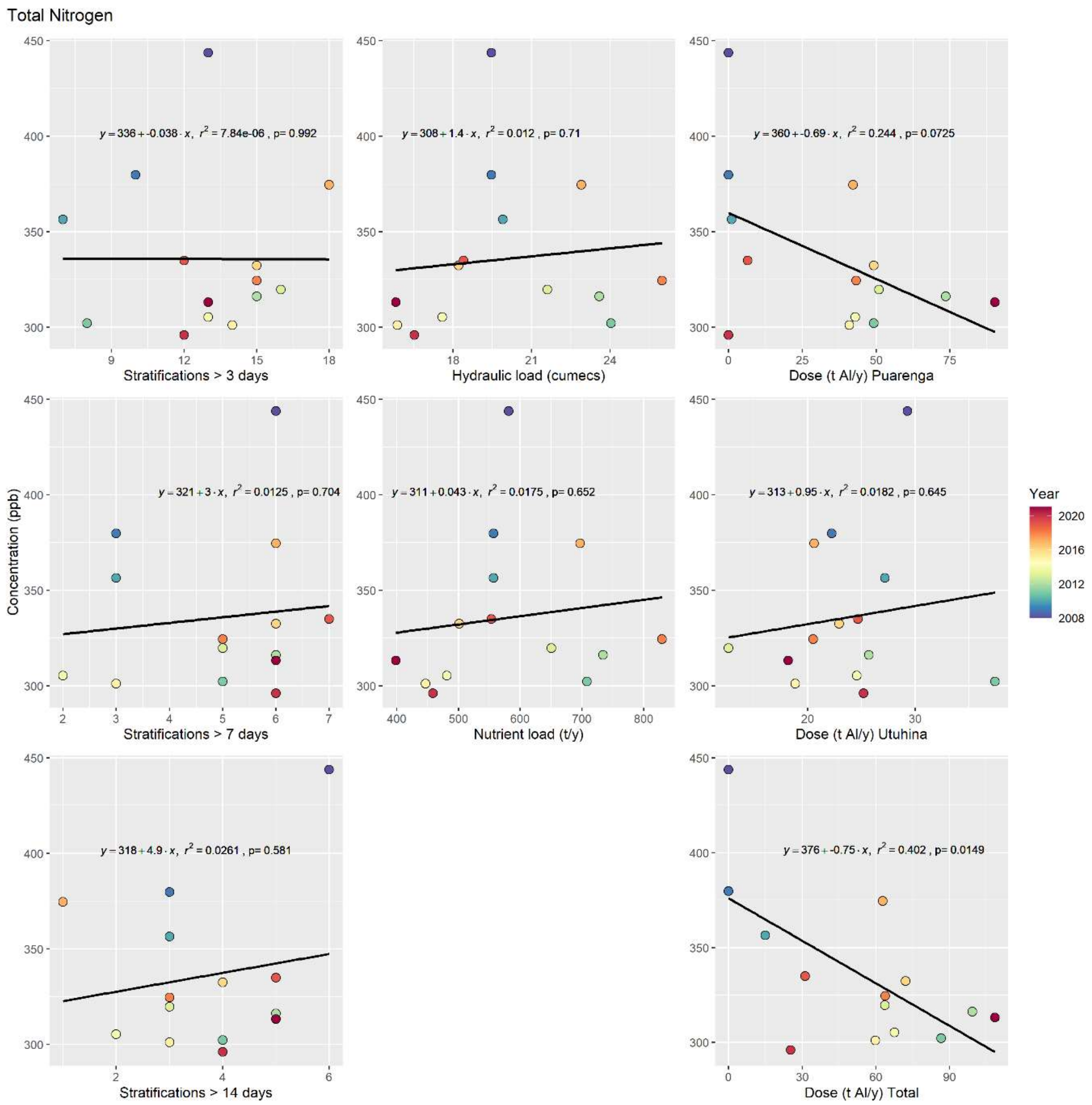

Figure 8. Annual mean surface TN concentration in Lake Rotorua against annual statistics for several potential drivers of water quality.

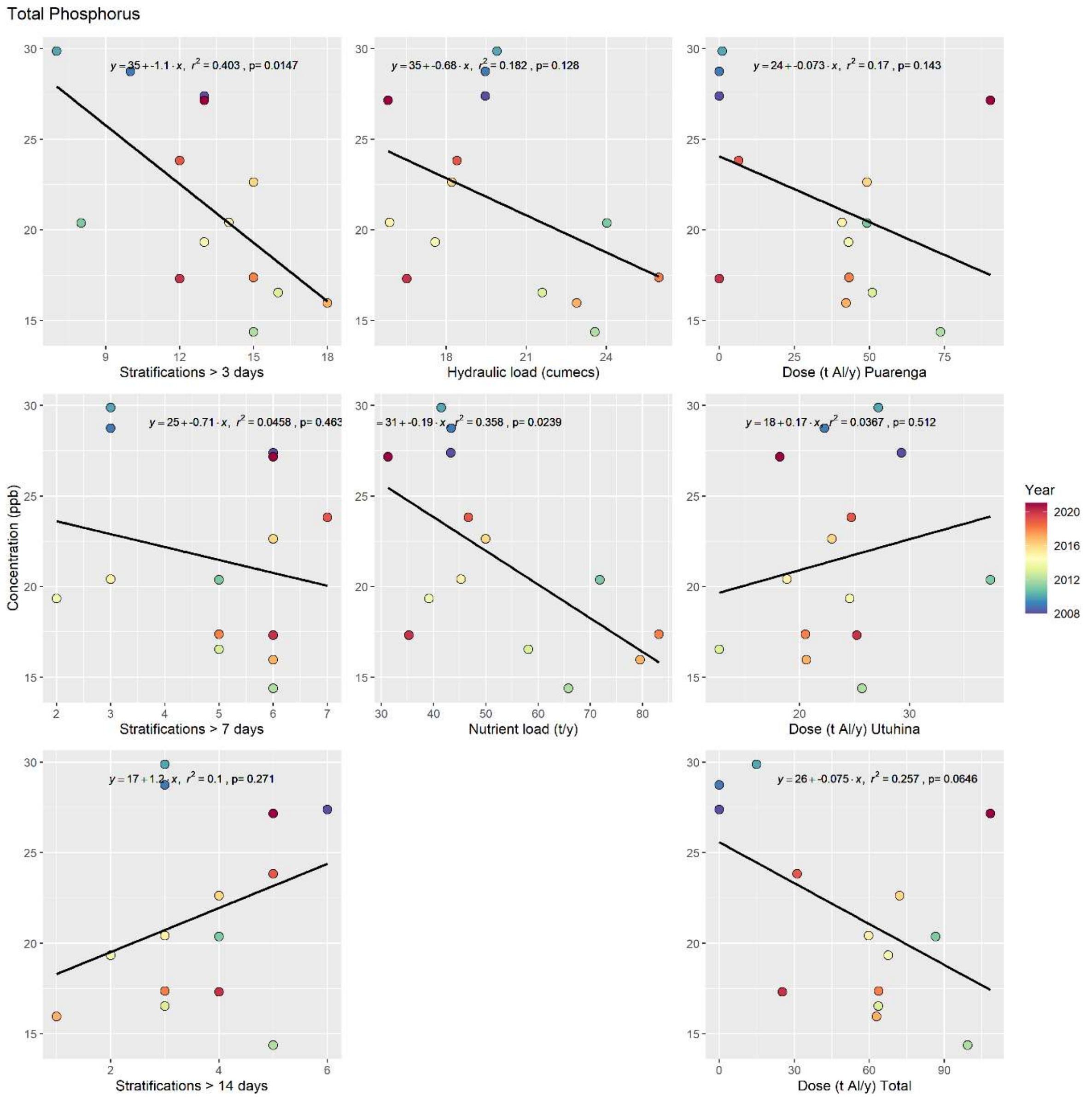

Figure 9. Annual mean surface TP concentration in Lake Rotorua against annual statistics for several potential drivers of water quality.

Total phosphorus was strongly negatively related to the number of short-term stratification events (r^2 = 0.403, p < 0.02) and weakly positively related to long-term stratification events. This follows from the idea that years with more frequent short-term stratifications are less likely to have long-term events (see Table 1), and that bottom water oxygen levels reach hypoxia only after sustained period of stratification (~10 days or more depending on water temperature). Interestingly lake TP was *inversely* related to annual estimated nutrient load (r^2 = 0.36, p < 0.02). This could be because wet years are less likely to have the warm stable summers that lead to stratification. A relationship to total alum dose was observed (r^2 = 0.26, p = 0.06) despite the year 2021 being an outlier in having a very high alum dose but also very high lake TP–it should be noted that for this year a large majority of the alum was dose to the Puarenga Stream over a relatively short period (see Figure 8).

Discussion

The key motivation of this study was to explore the drivers and extent of internal nutrient loading to Lake Rotorua, leveraging data sources including a high-resolution buoy, hydrodynamic modelling and monthly water chemistry observations. When placed in the context of other potential drivers including alum dosing and hydraulic and nutrient loading, several insights emerge.

Patterns of stratification are highly variable interannually. Sustained periods of stratification are relatively rare but can last for as long as 8 weeks (maximum observed 58 days). The monitoring record does provide an opportunity to estimate hypolimnetic oxygen demand, however, analysis of long-term changes in oxygen demand is confounded by the relatively stronger apparent influence of timing (and hence bottom water temperature) than interannual change.

Rotorua is frequently hypoxic to anoxic during warmer months, and although only monthly measurements are available, a strong response of both dissolved N and P was observed in the hypolimnion to the duration of stratification prior to sample collection. This suggests internal loading may be substantial, and although outside the scope of the present study, an opportunity exists for further analysis to estimate the total internal load by assessing daily hypolimnion volume against the average rate of concentration increase identified here.

Annual hydraulic and nutrient loading does not appear related (positively) to water quality, although antecedent correlation over longer preceding periods may prove more revealing. Total alum dose was a strong predictor of both N and P, although the influence of the few pre-dosing years as outliers cannot be ruled out. Stratification events did not appear related to overall TN concentration, however, long-term stratification events were related to TP, possibly indicating that internal loading is a relatively greater source to total loading for P than for N. It was not possible to assess a (potentially more direct) link between actual bottom DO concentrations with lake TN and TP, because of gaps in the monitoring record. However, future studies could employ a biogeochemical model to fill the (relatively fewer) gaps in the DO record in the same fashion as the hydrodynamic model was used here.

This study represents an initial exploration of the datasets and models employed, and opportunity exists to further exploit these approaches to generate additional insights to dynamics of Lake Rotorua. Under a changing climate in years to come, duration and timing of stratification are likely to change. Preliminary findings here suggest that if long-duration events become more common under changing climate then internal loading may drive increased nutrient supply (particularly P) to surface waters. High-frequency monitoring remains essential to understanding Lake Rotorua, and targeted water chemistry sampling over the duration of stratification events could be a useful addition to its monitoring program.

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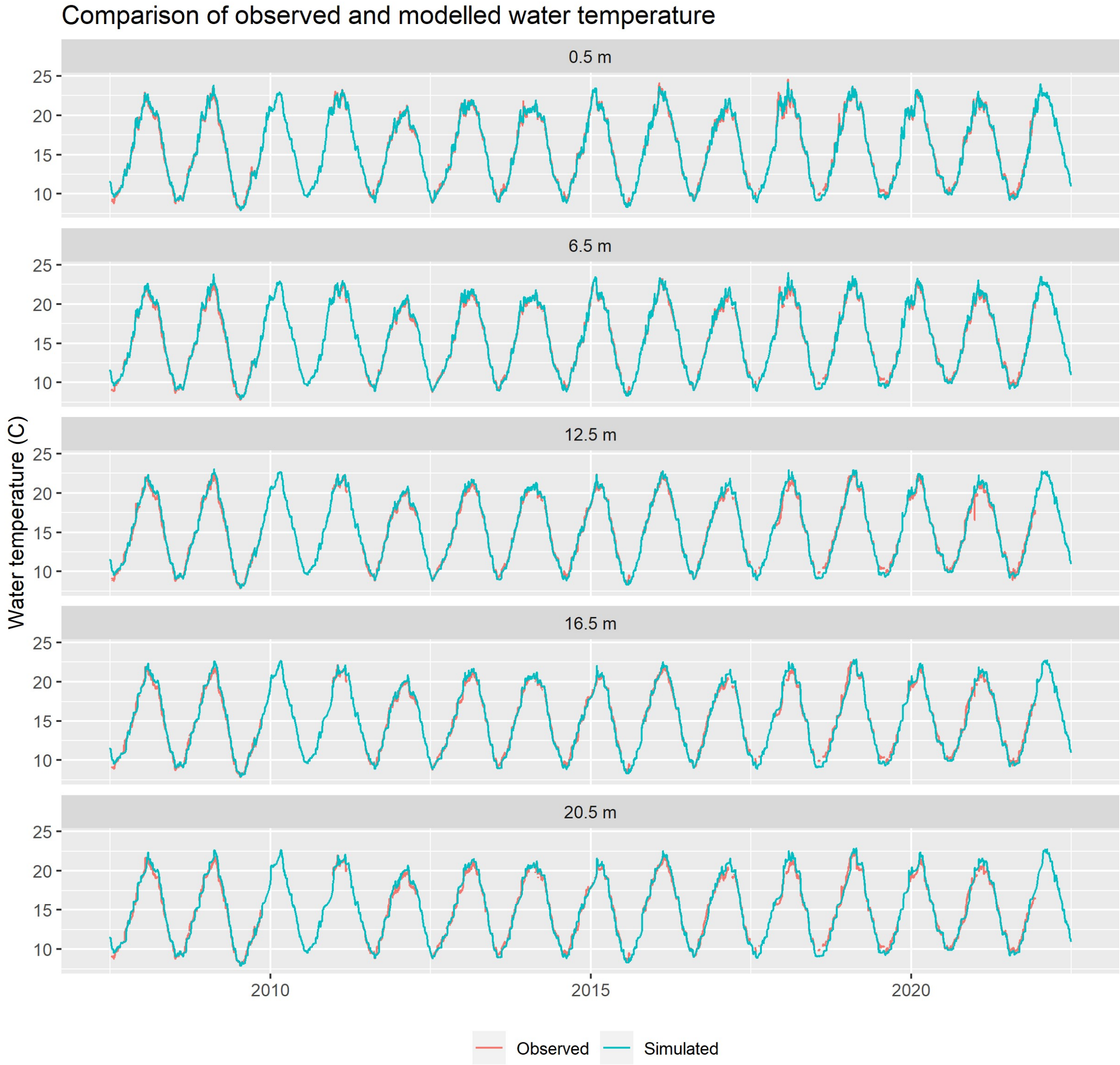
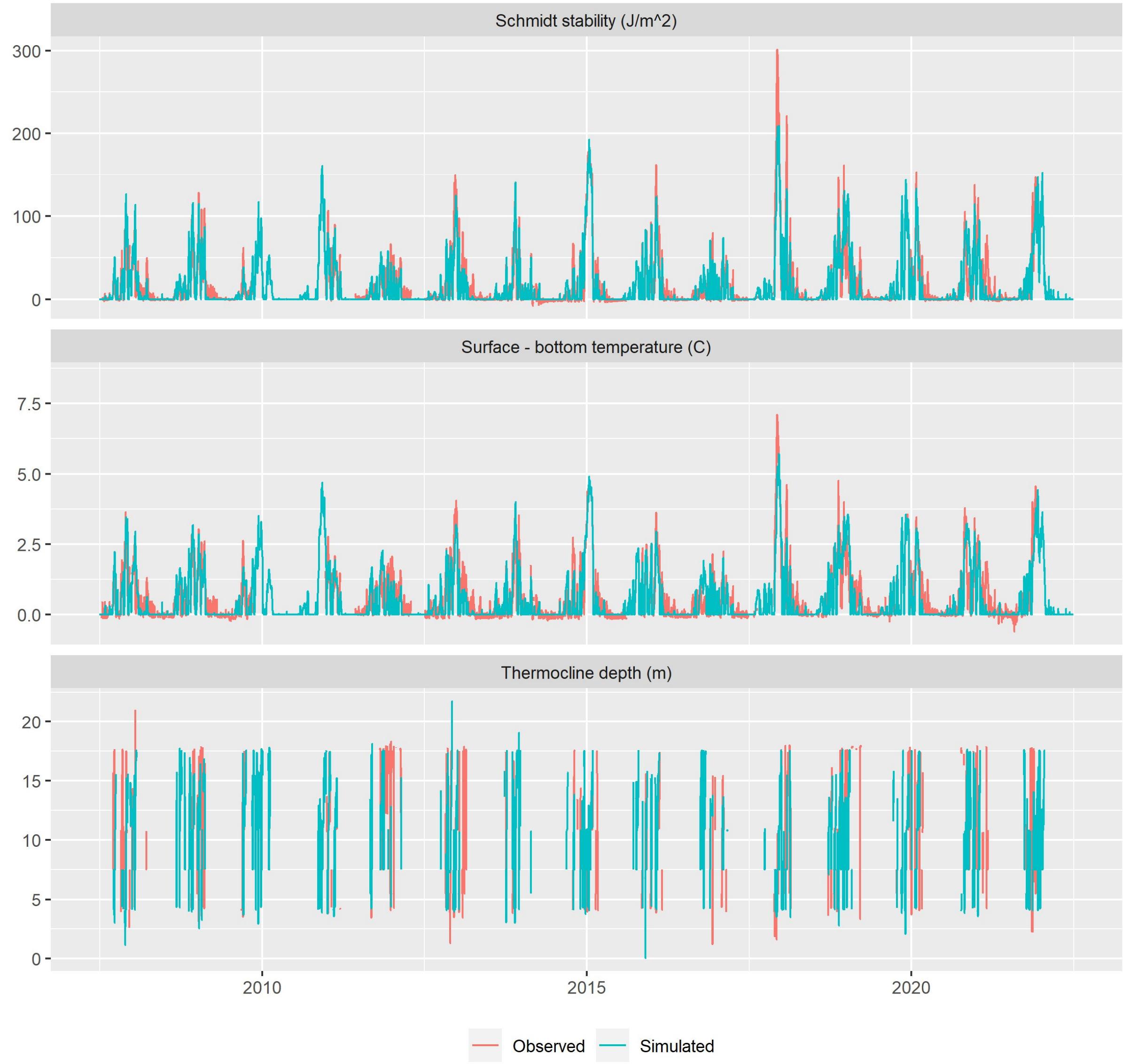
Appendices

Appendix 1. Model performance

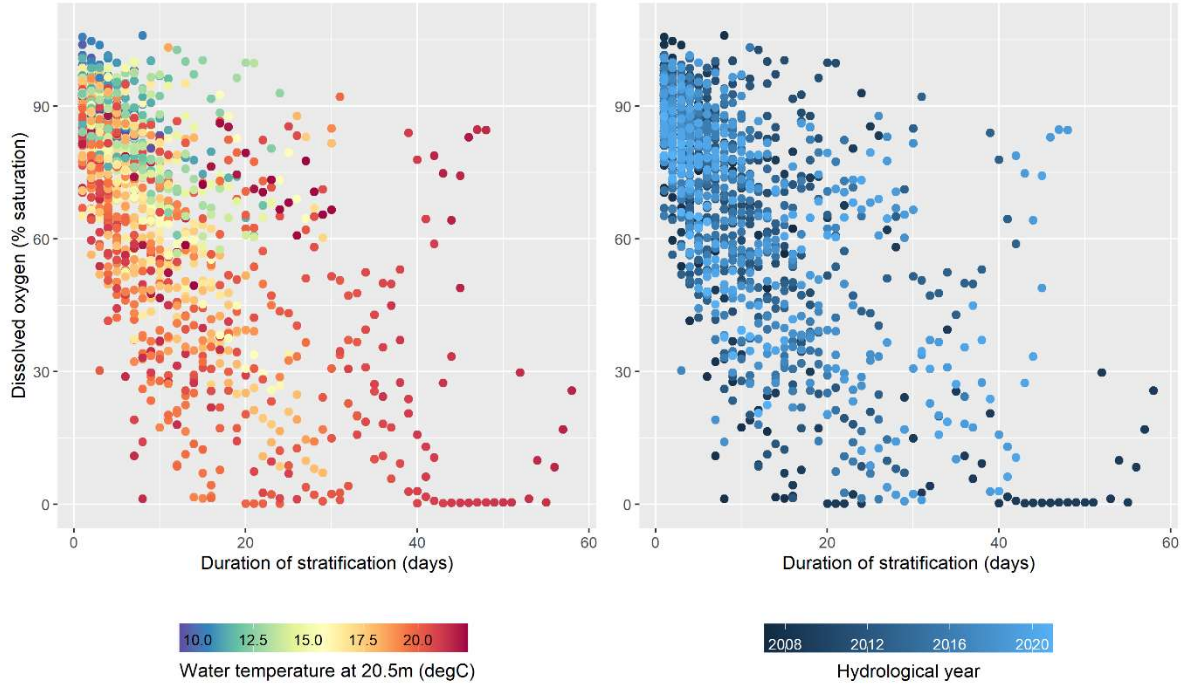


Appendix 1a. Comparison of observed (red) and simulated (blue) water temperature using the DYRESM model, at various depths.



Appendix 1b. Comparison of observed (red) and simulated (blue) water column metrics.

Appendix 2. Monitoring buoy oxygen and stratification.



Appendix 2. Dissolved oxygen saturation against duration of stratification for all days where Lake Rotorua was observed to be stratified by the monitoring buoy (surface minus bottom temperature > 0.25 degrees C). The left panel shows each daily observation coloured by water temperature, whereas the right panel shows the same data coloured by the hydrological year of observation.