Lake Rotorangi

State of the Environment Monitoring

Annual Report

2020-2021

Technical Report 2021-63

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Taranaki Regional Council

Taranaki Regional Council
Private Bag 713
Stratford

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Executive summary

Lake Rotorangi was formed in May 1984 by the construction of an earth fill dam on the Patea River for hydroelectric power generation. In recognition of both the regionally significant recreational resource created, and the considerable environmental impacts which might occur, a comprehensive monitoring programme was developed and implemented for the lake. This report presents the results of monitoring for the period July 2020-June 2021.

Four water quality surveys were undertaken at two sites during the period under review. One site is located in the mid reaches of the lake, while the second site is located nearer the dam.

Thermal stratification is when the upper and lower water columns separate into different layers within the lake. Processes occurring within these layers can cause substantial differences in water quality between the layers. Stratification was beginning to form in the spring survey, was fully developed in the later summer and early autumn surveys, and had overturned by the winter survey. Oxygen depletion was evident in the late summer and early autumn surveys, and persisted at the lower lake site in the winter survey despite the uniform water temperatures throughout the water column. This pattern has been typical of Lake Rotorangi since monitoring began.

Physicochemical monitoring showed that lake water chemistry largely remained within the range which has been typical of the lake over the past 25 years. *E. coli* levels were within the 'surveillance' level (green traffic light) under contact recreational guidelines for the entire period in the lower lake (site L3), and in the mid lake (site L2) in late summer and early autumn, while in spring and winter the 'action' level (red traffic light) was reached at this site.

The trend analysis methodology implemented for this report was updated in the 2019-2020 period. This has resulted in changes to the results when compared to those previously reported. The methodology is briefly described in Section 2.4, with more detail provided in Appendix I.

Increasing trends in chlorophyll-a, conductivity and total phosphorus were detected, while total nitrogen showed a decreasing trend for the period 1996-2021. When analysed over the most recent ten year period, decreasing trends in dissolved reactive phosphorus, total phosphorus and chlorophyll-a, and an increasing trend in conductivity were detected.

National Objectives Framework (NOF) attributes for ammonia and phytoplankton classify the lake in the 'B' band, or as being slightly impacted compared to reference conditions, while total nitrogen concentrations classify the lake as being in the 'C' band, or moderately impacted compared to reference conditions. Total phosphorus classifies the upper lake as moderately impacted and the lower lake as mildly impacted.

The trophic state of the lake remains eutrophic, while on the basis of individual sites L2 is eutrophic and site L3 is mesotrophic.

The monitoring of Lake Rotorangi will continue in its present format for the 2021-2022 monitoring year, with the triennial biological monitoring next due for inclusion in the 2023-2024 year. This report also includes recommendations for the 2021-2022 monitoring year.

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1 Introduction

1.1 General

The *Resource Management Act 1991* (RMA) sets out requirements for local authorities to undertake environmental monitoring. Section 35 of the RMA requires local authorities to monitor, among other things, the state of the environment of their region or district, to the extent that is appropriate to enable them to effectively carry out their functions under the Act.

To this effect, the Taranaki Regional Council (Council) has established a state of the environment monitoring (SoE) programme for the region. This programme is outlined in the Council's 'State of the Environment Monitoring Procedures Document', which was prepared in 1997. The monitoring programme is based on the significant resource management issues that were identified in the *Council's Regional Policy Statement for Taranaki (1994)*.

Council's SoE programme encompasses a number of individual monitoring activities, many of which are undertaken and managed on an annual basis (from 1 July to 30 June). Where possible, individual consent monitoring programmes have been integrated within the SoE programme to save duplication of effort and minimise costs. The purpose of SoE reporting is to summarise and interpret regional environmental monitoring activity results and report on any changes (trends) in these data. These reports in turn provide key information for Council's five yearly regional state of environment report, which is due to be published in the first half of 2022. Copies of these reports are made available on Council's website.

1.2 Lake Rotorangi

Lake Rotorangi was formed in May 1984 by the construction of an earth fill dam on the Patea River for the purpose of a hydro-electric power scheme. An initial sampling programme was designed to assess the state and environmental consequences of the new lake. The results of this intensive monitoring programme were published in the 'Lake Rotorangi - Monitoring a New Hydro Lake' (Taranaki Catchment Board, 1988) report. Results of monitoring since this time are published in annual reports listed in the references of this report.

This initial monitoring determined that the lake was mildly eutrophic or mesotrophic. Further, the annual thermal stratification cycle which the lake undergoes was identified as the single most important factor influencing water quality within the lake.

Since monitoring began, the trophic state of Lake Rotorangi has been increasing (degrading) at a very slow rate, in the order of 0.02±0.01 units per year. Initial monitoring showed the lake was in a mesotrophic state, and has over time moved to a mildly eutrophic state. Previous analysis has determined that the trophic level is heavily influenced by high turbidity values and therefore not a true indication of actual trophic status (as determined by primary production) of the lake (Burns 2006).

The Patea catchment upstream of the dam covers an area of 86,944 ha. This includes both the Patea River sub-catchment and the Mangaehu River sub-catchment. Approximately 841 ha (1%) of this area is urban, while another 6589 ha (8%) is conservation land. The remainder of the catchment (71,514 ha, 91%) is in pastoral land, with a mixture of dry stock and dairy farming in the catchment. Identifying and implementing actions to address hill country erosion is a significant focus for this catchment. Farm plans addressing land management and sediment issues cover around 43055 ha (50%) of the catchment, primarily in the area where dry stock faming is the dominant land use.

The trophic level of Lake Rotorangi has been increasing at a very slow rate since monitoring began. Initial monitoring showed the lake was in a mesotrophic state, and has over time moved to a mildly eutrophic state. Previous analysis has determined that the trophic level is heavily influenced by high turbidity values and therefore not a true indication of actual trophic status (as determined by primary production) of the lake (Burns 2006).

1.2.1 Lake stratification processes

Thermal stratification is a seasonal process, which occurs when the upper water column near the surface warms much faster than the lower water column. Changes in the density of water at differing temperatures creates a physical barrier separating the upper water column (epilimnion) and lower water column (hypolimnion). Biological and chemical processes differ between the epilimnion and hypolimnion, causing substantial differences in water quality between the layers. In Lake Rotorangi, is one of the primary factors impacting observed water quality.

Substantial differences in water quality can occur between the epilimnion and hypolimnion as a result of stratification. Typically, the epilimnion has the majority of primary production because light levels are highest in the upper water column. Organic detritus sinks from the epilimnion though the water column, resulting in the transfer of nutrients to the hypolimnion. Therefore over time, the concentrations of bioavailable nutrients decreases in the epilimnion compared to the hypolimnion.

Oxygen depletion may occur in the hypolimnion, because oxygen consumed by biological and chemical processes cannot be replaced due to the physical separation from the more oxygenated surface waters. Replacement of oxygen in the hypolimnion results from mixing caused by either the natural overturn processes or as a results of flood events in the river inflow.

Furthermore, as oxygen depletion occurs in the hypolimnion, this can in turn alter the pH of the hypolimnion. The increased pH in anoxic waters creates a risk of nutrient release from the lakebed sediment into the water column.

2 Monitoring methodology

The current Lake Rotorangi Monitoring programme consists of two primary components; physicochemical and biological monitoring. Sampling is undertaken at two sites along the lake, on four occasions each year. The sampling occasions are timed to target particular conditions with regard to stratification of the lake. Details of the sites are provided in Table 1 and Figure 1.

Table 1 Monitoring site locations in Lake Rotorangi

Site code	Site	Location
LRT000300	L2 (near Tangahoe Valley Road)	E1729856 N5626435
LRT000450	L3 (near Patea Dam)	E1734948 N5621974

The targeted conditions are described in Table 2. Sampling in the specified months is aimed to be undertaken on or near the 20th of the month. The dates sampled in the 2020-2021 year are also provided in Table 2.

Table 2 Seasonal sampling and targeted stratification conditions

Season	Month	Target conditions	Sampling date
Spring	October	Pre-stratification	16 Oct 2020
Late Summer	February	Stable stratification	25 Feb 2021
Early Autumn	March	Pre-overturn	23 Mar 2021
Winter	June	Post-overturn	24 Jun 2021

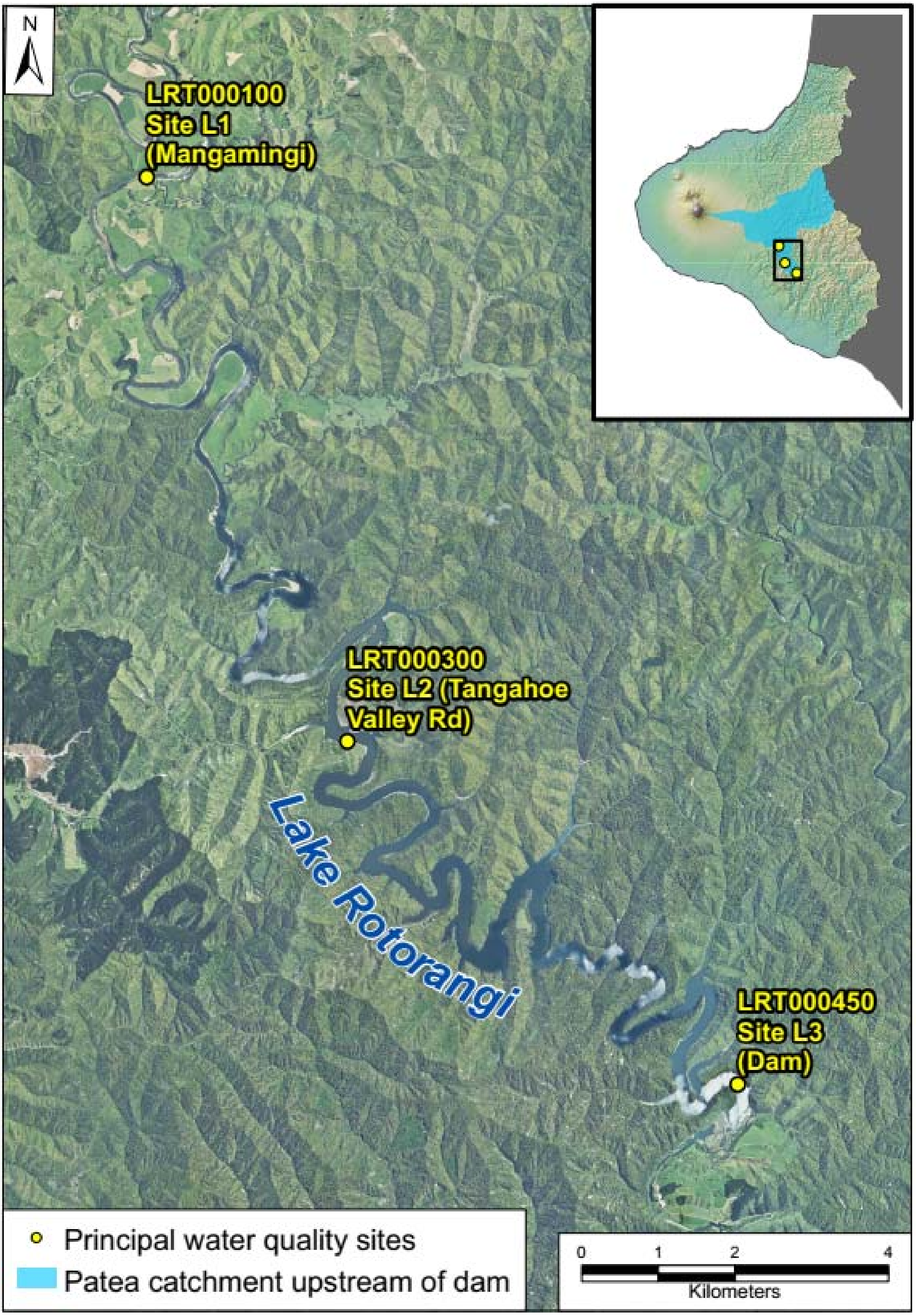

Figure 1 Location of monitoring sites in Lake Rotorangi with inset showing the location and catchment of the lake. Sites L2 and L3 are currently monitored, while monitoring at Site L1 was discontinued in 2010 due to the predominantly riverine nature of the lake at this northern location

2.1 Physicochemical monitoring

At each site a depth profile is collected measuring temperature and dissolved oxygen. On all sampling occasions, water samples are collected using a grab sample to reflect conditions at the surface, and using a van-Dorn sampler at points in the water column to represent conditions in the epilimnion and the hypolimnion. In February and March (under stratified conditions), additional water samples are collected near the base of the water column to assess the impact of anoxia at the sediment-water interface.

Table 3 Physicochemical parameters monitored at each sampling depth in Lake Rotorangi

Parameter	Units	Surface	Epilimnion	Hypolimnion	Lower hypolimnion[1]
Black disc transparency	m	x			
Secchi disc transparency	m	x			
pH	pH units	x	x	x	x
Conductivity	µS/cm	x	x	x	
Turbidity	FNU	x	x	x	x
Suspended solids	$g\ m^{-3}$	x	x	x	
E. coli	MPN/100mL	x			
Dissolved reactive phosphorus	$g\ m^{-3}$ P		x	x	x
Total phosphorus	$g\ m^{-3}$ P		x	x	x
Ammoniacal nitrogen	$g\ m^{-3}$ N		x	x	x
Nitrite nitrogen	$g\ m^{-3}$ N		x	x	
Nitrate nitrogen	$g\ m^{-3}$ N		x	x	
Nitrate and nitrite nitrogen	$g\ m^{-3}$ N		x	x	x
Total Kjeldahl nitrogen	$g\ m^{-3}$ N		x	x	
Total nitrogen	$g\ m^{-3}$ N		x	x	

[1] Sampled in late summer and early autumn only

Samples are collected in accordance with the National Environmental Monitoring Standard (NEMS) for discrete lake water quality data (NEMS, 2019).

2.2 Biological monitoring

Sampling of the photic zone is undertaken in conjunction with physicochemical monitoring. A depth integrated sample is collected and analysed for chlorophyll-a, and a subsample used to identify the phytoplankton species present.

Triennially, a benthic macroinvertebrate sample is collected at each site in conjunction with the spring physicochemical monitoring. A macrophyte survey is also undertaken triennially in autumn. Both the benthic macroinvertebrate and the macrophyte survey were due to be carried out in the 2020-2021 monitoring year.

2.3 Trophic state

The trophic level index (TLI) is calculated for the lake as a whole as well as for individual sites. The equations used vary from those used by Burns (1999), and are consistent with those used by Lakewatch (which was previously used to calculate the TLI). This change to the equation for secchi disc was made after removal of peat-stained lakes, and is appropriate for Lake Rotorangi which is not affected by peat.

Furthermore, following the Lakewatch methodology, the calculation of TLI is dependent on the stratification of the lake. Epilimnetic data is used during stratified periods, while both epilimnetic and hypolimnetic data is used when the lake is isothermal (defined as less than 3°C differences between the surface and lake bottom water temperature). In calculating the TLI, censored values have been treated as the detection limit. Annual average values of the four parameters used are calculated, and are then input into equations to calculate the four components of the TLI as follows:

$$TLc = 2.22 + 2.54 \log(Chla)$$
$$TLs = 5.56 + 2.60 \log((1/Secchi) - (1/40))$$
$$TLp = 0.218 + 2.92 \log(TP)$$
$$TLn = -3.61 + 3.01 \log(TN)$$

These four component values are then averaged to obtain the overall TLI.

It should be noted that in previous reports the TLI has been calculated per calendar year. In this report an adjustment has been made to this calculation, so that the analysis year is from July-June to align with the reporting period. Furthermore, this change aligns with the recommendation in Burns et al, (2000) and Schallenberg & van der Zon (2021) by ensuring that the calculation year includes an entire period of stratification. Although Burns et al, (2000) and Schallenberg & van der Zon (2021) recommend using a September to August calculation period to best align with the stratification cycle, in this instance the standardised sampling regime used in Lake Rotorangi does not include sampling between July-October. Because of this the calculation on the existing dataset will provide the same result whether the annual period starts in July or September.

2.4 Analysis

A number of changes to data analysis methodologies have been implemented in this report. A brief description of the current methods used is given below, with a more detailed discussion in Appendix I. A discussion of how these differ from methods used in previous TRC SEM lake reports is provided in the 2019-2020 Lake Rotorangi report (Taranaki Regional Council 2021).

In this report, trend analysis has been carried out using the LWP-Trends library R package (version 1901), developed by Land Water People Ltd. (Snelder & Fraser, 2019). The methods employed have the primary purpose of establishing the direction and rate of any trend, along with a measure of the uncertainty in the result. The use of the LWP-Trends package represents a major change in trend analysis methodology compared to previous TRC Lake SEM reports, in part due to different methods used in the past, but also due to a recent conceptual shift in how to assess confidence in trend analysis results (Greenland et al. 2016, McBride 2019, Helsel et al. 2020).

The data is assessed using a Kruskal-Wallis test to determine whether the data is seasonal. Either a Mann-Kendall or seasonal Kendall test is used to determine the trend direction. A trend rate and confidence in the trend are also generated using a sen-slope regression. Censored data is handled using the methods of Helsel (2011). A note is included when this is affected by censored data, which generally indicates that the trend rate is smaller than can be detected.

The confidence in the trend direction is assessed following the credible interval assessment method of McBride (2019). The confidence in the reported trend direction (ranging from 50% to 100%) is categorised based on the categories in Table 4.

Table 4 Confidence categorisation for trend direction results

Confidence Category	Confidence in reported trend direction
Very Likely Improving	90 – 100%
Likely Improving	67 – 90%
Indeterminate	50 – 67%
Likely Degrading	67 – 90%
Very Likely Degrading	90 – 100%

The trend methods implemented are limited to identifying a single direction (monotonic) trend over time. In many cases, trend in environmental data may fluctuate throughout the time series, due to changes in conditions or individual events resulting in changed trends. A Loess curve has been overlaid on the trend analysis to assist with assessment of non-monotonic trends and investigation into causes of any changes in trends. In addition, a comparison of long term (25 year) and short term (10 year) quantitative trends is undertaken.

In the case of parameters which are sampled at multiple depths within the lake, trend analysis has been carried out on the data from the epilimnion. Differences in the water chemistry between the epilimnion and hypolimnion during the stratified period mean that combining the data from both stratified layers may mask any trends present. For the analysis of the lake as a whole, results taken at different sites, within the same layer of the water column and on the same day, are averaged to provide a single result. These average values are analysed as described above. Both the use of epilimnion data and averaging across the whole lake are consistent with national reporting (Larned et al, 2015).

3 Results

3.1 General observations/hydrological conditions

Sampling was undertaken on the dates specified in Table 2. General observations made on each of the sampling occasions during the period under review are presented in Table 5.

Table 5 Observations at Lake Rotorangi monitoring sites on sampling occasions during 2020-2021

Date	Lake level (m asl)	Weather	Wind		Lake appearance	
			L2	L3	L2	L3
16 Oct 2020	76.78	Fine, rain 3 days prior	Light NE breeze	No wind	Turbid, brown-green; surfaced rippled	Turbid, green-brown; surface rippled
25 Feb 2021	76.65	Fine, dry weather preceding	No wind	Light breeze	Clear, dark green; surface flat	Clear, dark green; surface rippled
23 Mar 2021	76.66	Fog clearing, fine weather preceding	No wind	No wind	Clear, dark green; surface flat	Clear, dark green; surface flat
24 Jun 2021	76.56	Broken cloud, rain week prior	No wind	Light NW	Slightly turbid, brown-green; surface flat	Slightly turbid, brown-green; surface rippled

The synthetic inflow data for Lake Rotorangi is presented in Figure 2. This synthetic inflow is the flow entering the head of the lake (at Mangamingi) and equates to flows form the Patea River and Mangaehu River catchments above Mangamingi.

The spring and winter surveys were carried out under fresh recession inflow conditions, with two small freshes in the month preceding the spring survey and three small freshes in the month preceding the winter survey. The late summer and early autumn surveys were carried out under baseflow conditions with two minor freshes in the month preceding the late summer survey and one minor fresh in the month preceding the early autumn survey.

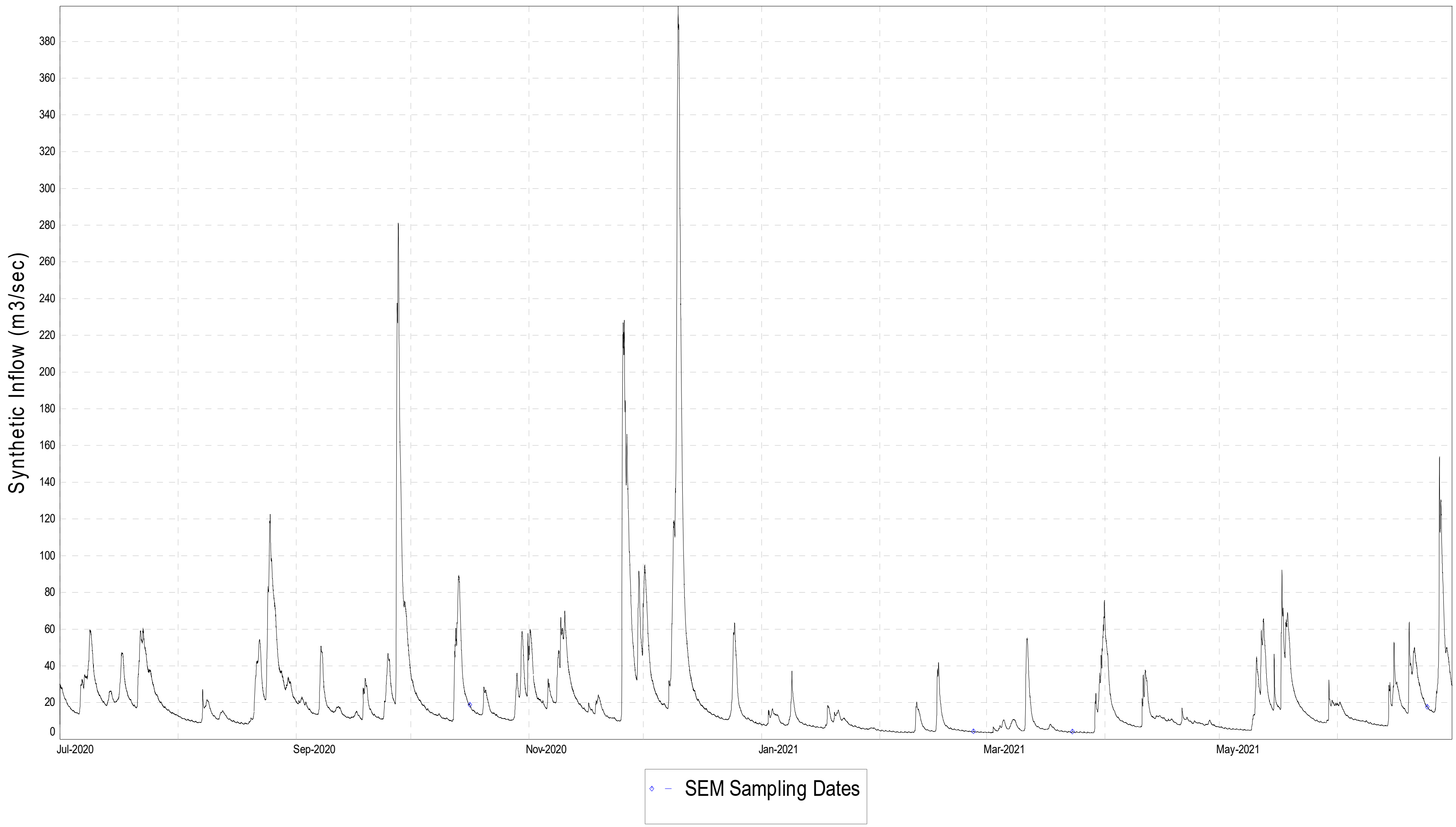

Figure 2 Synthetic inflow at Lake Rotorangi for the period 1 July 2020 to 30 June 2021

3.2 Physicochemical

Physicochemical monitoring data collected during the period under review are provided in full in Appendix II.

3.2.1 Stratification

Thermal stratification was developed at site L2 and weakly developed at site L3 during the spring sampling. In both the late summer and early autumn sampling, the stratification was strongly developed, and the lake was isothermal during the winter sampling (Figure 3).

Dissolved oxygen stratification was evident at both sites during all four sampling occasions in 2020-2021 (Figure 3). This pattern of dissolved oxygen stratification remaining site L3 has been typical of Lake Rotorangi in previous monitoring years and indicates that although temperatures are similar throughout the water column, vertical mixing of the water column was not complete.

Surface water temperatures were below seasonal medians in 2020-2021, except in the winter sampling. Water temperatures above the lakebed were above median throughout the period under review.

Surface dissolved oxygen concentrations were above medians at site L2 throughout the period under review. Site L3 had lower than typical concentrations in spring and early autumn, and similar to median concentrations in late summer and early autumn. Dissolved oxygen concentrations near the bottom of the water column were below medians at both sites throughout the period under review.

Anoxic conditions, when dissolved oxygen is less than 0.5 g/m^3, were observed in the hypolimnion at site L2 below 28 metres in late summer and below 26 metres in early autumn. At site L3, anoxia occurred below 42 metres in late summer, 32 metres in early autumn and below 26 metres in winter.

Assessment of lake-bottom and mid-hypolimnetic dissolved oxygen concentrations against the National Objectives Framework (NOF) numeric attribute state (New Zealand Government, 2020) places both sites in the D band for both attributes (Table 6). This does not meet the National Bottom line. Further work will be required to assess whether this is naturally occurring and if any action should be required as a result.

Table 6 Minimum dissolved oxygen concentrations (g/m^3) in Lake Rotorangi assessed against National Objective Framework attributes.

Site	Minimum	Level	Band	Narrative Attribute State
L2	0	Lake-bottom	D	Likelihood from lake-bottom dissolved oxygen of biogeochemical conditions resulting in nutrient release from sediments
L3	0		D	Likelihood from lake-bottom dissolved oxygen of biogeochemical conditions resulting in nutrient release from sediments
L2	0	Mid-hypolimnion	D	Significant stress on a range of fish species seeking thermal refuge in the hypolimnion. Likelihood of local extinctions of fish species and loss of ecological integrity
L3	0		D	Significant stress on a range of fish species seeking thermal refuge in the hypolimnion. Likelihood of local extinctions of fish species and loss of ecological integrity

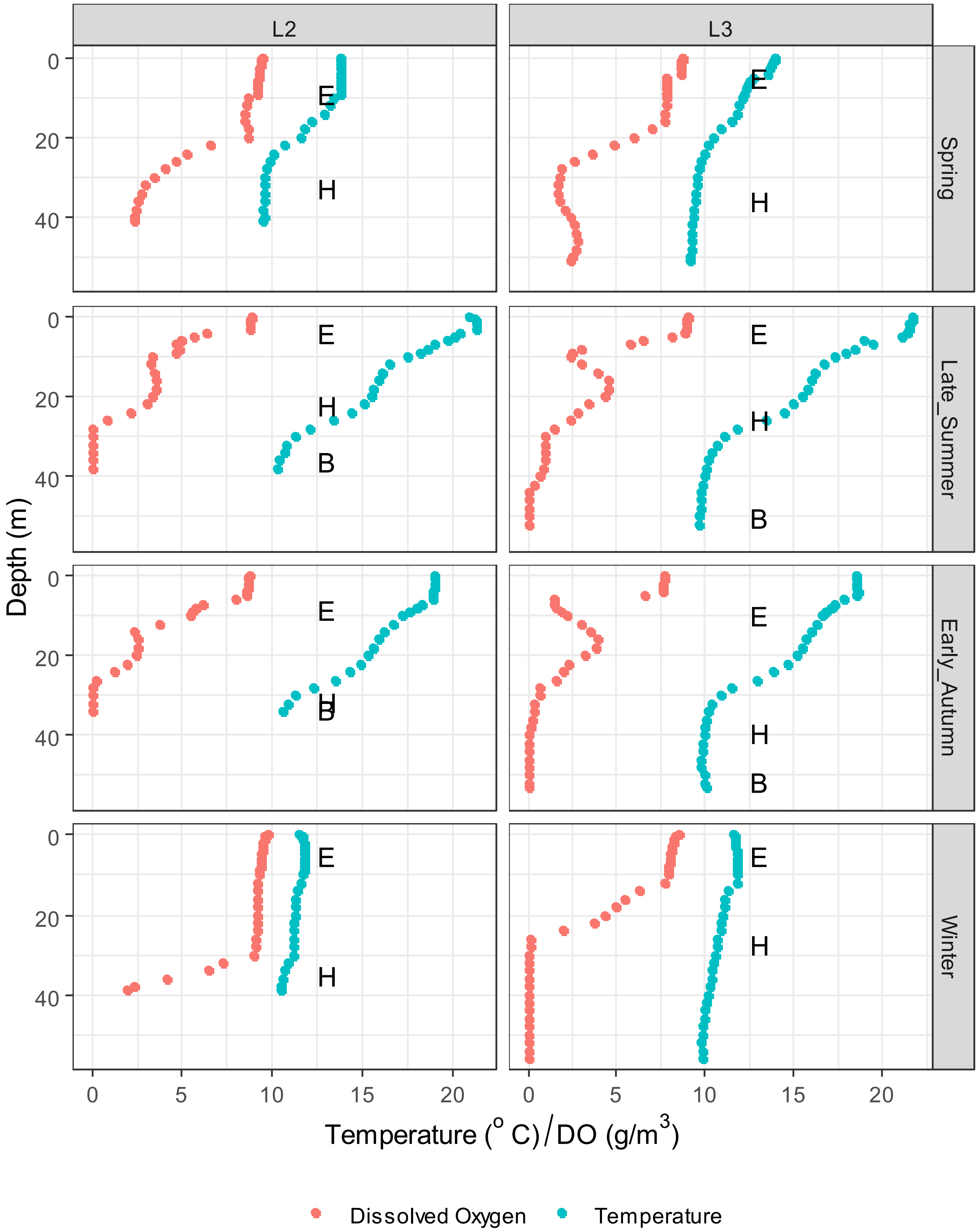

Figure 3 Temperature (°C) and dissolved oxygen (g/m³) profiles for sites L2 and L3 on sampling occasions in 2020-2021. Sampling depths are indicated by letters (E = epilimnion; H = hypolimnion; B = near benthos)

3.2.2 Water chemistry

The full physicochemical monitoring results collected during the period under review are provided in Appendix II. Selected results and associated historical data are discussed in more detail below.

Black disc measurements provide an estimate of horizontal water clarity, while secchi disc provides an estimate of vertical water clarity. Together, these measurements can be used to provide information on the penetration of diffuse light into the water column. As might be expected, there is a direct relationship between the two measurements, with the secchi disc greater than the black disc by a ratio of about 1.2:1 in Lake Rotorangi.

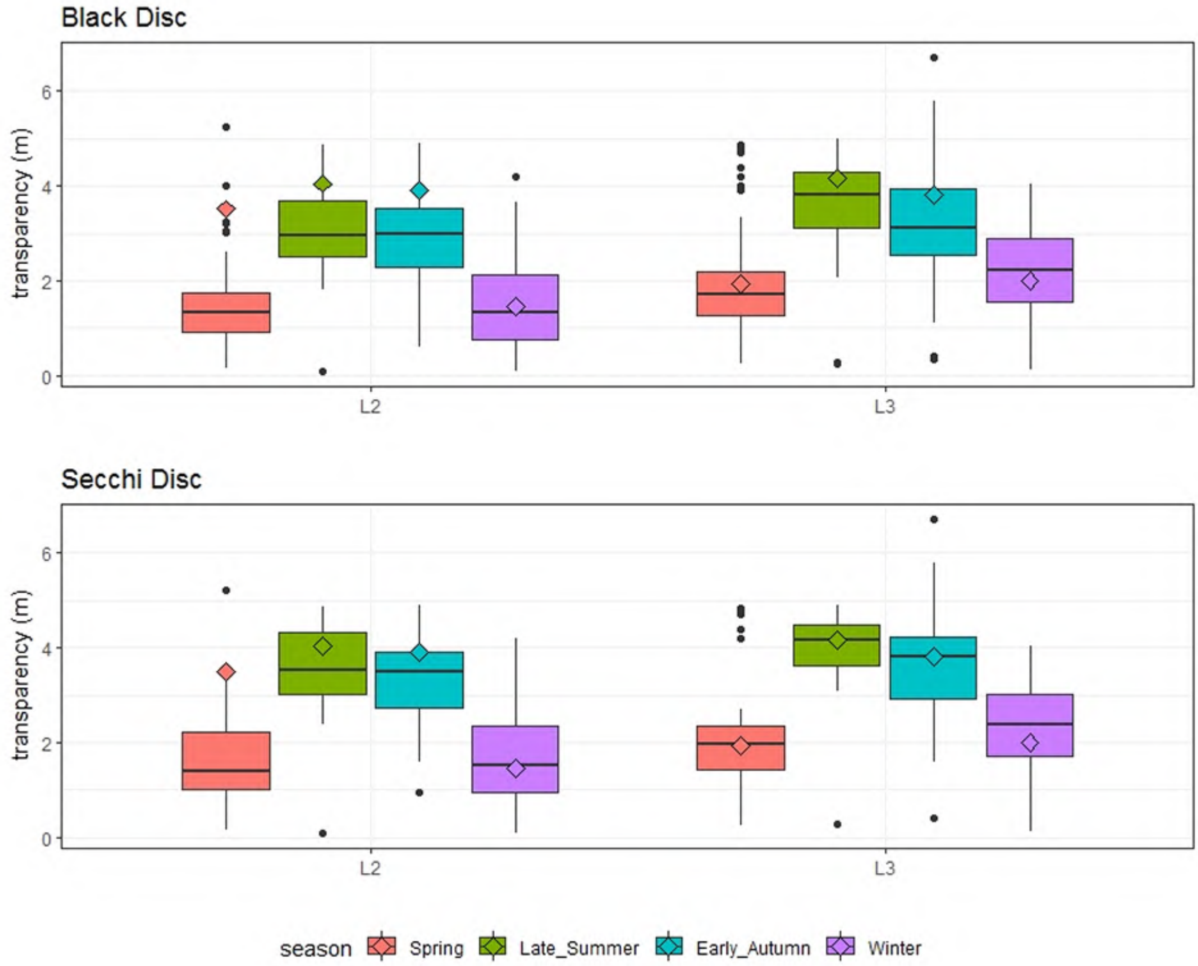

Figure 4 Measures of visual clarity in Lake Rotorangi. Historical summary data for the period 1996-2020 is represented by boxplots, while the measurement recorded in the period under review is represented as a diamond

During the period under review, black disc and secchi disc measurements were generally within a typical range. At site L2 in spring, both clarity measurements were higher than usual, albeit within the previously recorded range (Figure 4).

Conductivity at site L2 was generally above median. In late summer, this was particularly pronounced at the surface, while the hypolimnion recorded a lower than typical conductivity. Site L3 recorded lower than median conductivity in the upper water layers in spring. The epilimnion also recorded an atypically low conductivity in early autumn.

Turbidity was generally low at site L2, except in the upper water column in spring. At site L3, turbidity remained below seasonal median values throughout the period under review.

Suspended solids remained at low concentrations at both sites L2 and L3 throughout the period under review. It should be noted that the majority of suspended solids results during this period, including all results from L3, were below the detection limit of this test. Suspended solids data has not been presented in the body of this report due to the extremely high proportion of censored data for this parameter.

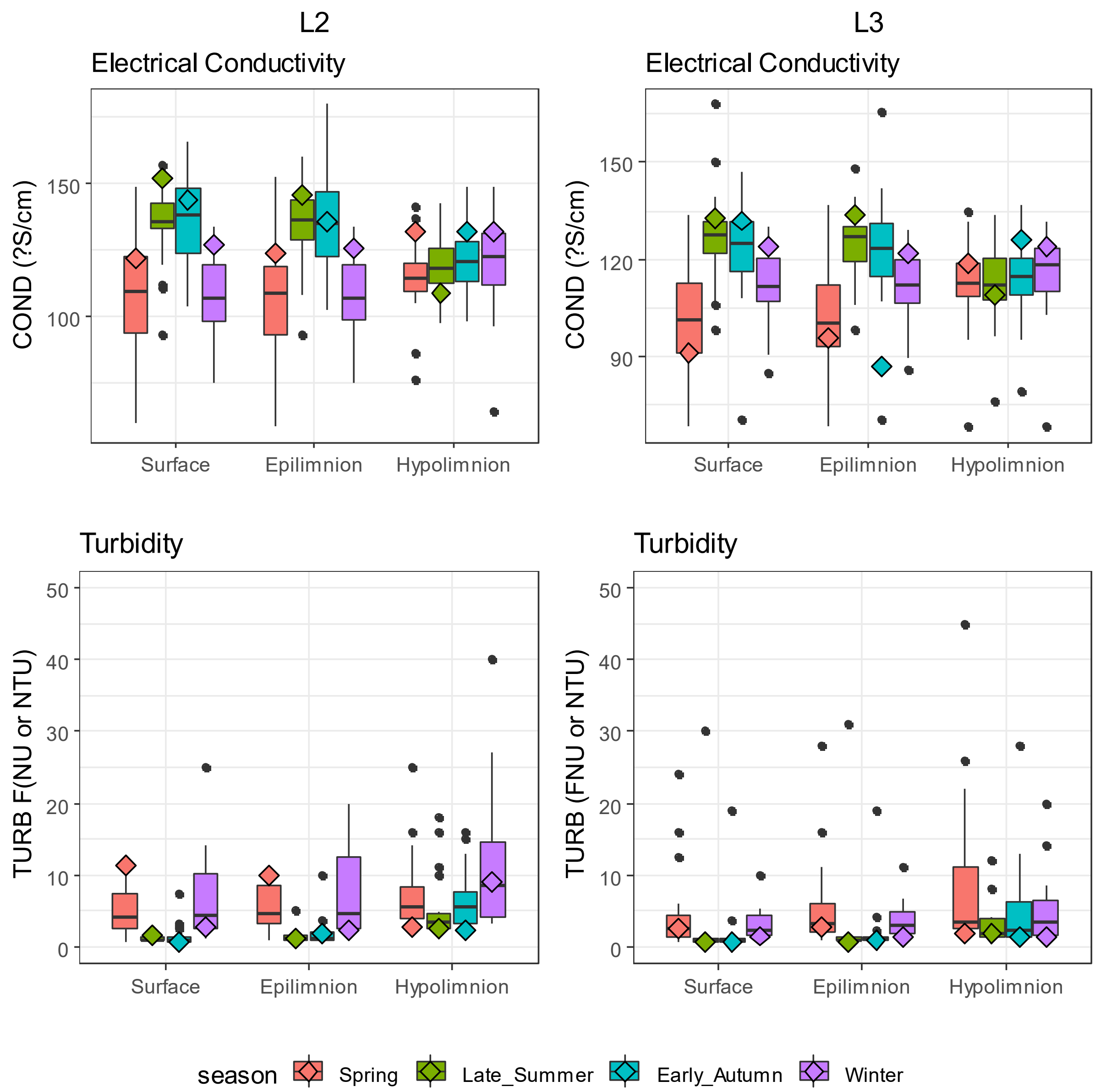

Figure 5 Epilimnetic and hypolimnetic physicochemical parameters in Lake Rotorangi. Historical summary data for the period 1996-2020 is represented by boxplots, while the concentration recorded in the period under review is represented as a diamond

3.2.2.1 Bacteria (E. coli)

In recognition of the recreational uses of Lake Rotorangi (mainly boating and waterskiing at site L2, but also at site L3; see Taranaki Regional Council, 2008a), samples taken at the surface are tested for E. coli. These results are presented in Figure 6. During the period under review, no samples at either site reached the alert level for primary contact recreation (MfE, 2003).

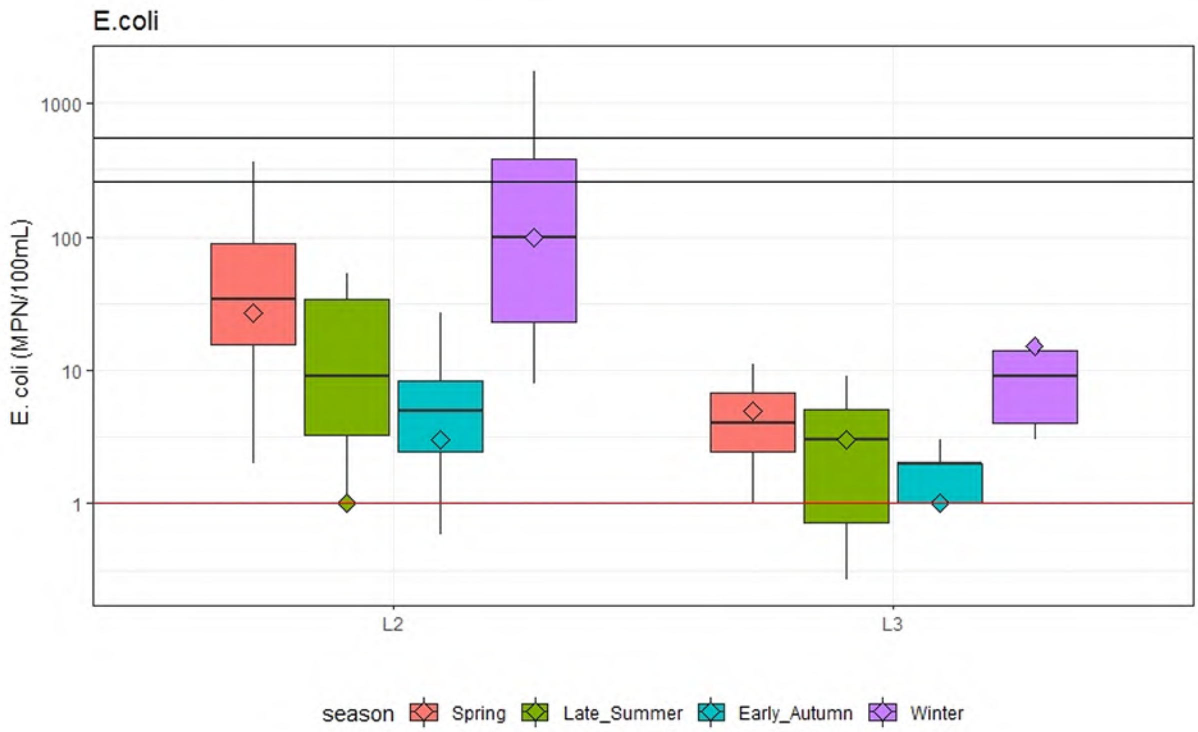

Figure 6 *E. coli* measured at the surface of Lake Rotorangi. Historical summary data for the period 1996-2020 is represented by boxplots, while the measurement recorded in the period under review is represented as a diamond. The red line indicates the threshold below which data is censored. Statistics below this threshold should be interpreted with caution. Black threshold lines represent guidelines for recreational use

3.2.2.2 Nutrients

Ammoniacal nitrogen was above detection limits at site L2, except in late summer in the hypolimnion (Figure 7). Nitrate-nitrite nitrogen and total nitrogen showed the typical reduction in the epilimnion during the stratified period, while concentrations in the hypolimnion showed a similar, but less pronounced pattern. Total Kjeldahl nitrogen remained at concentrations around the detection limit in the epilimnion, and had slightly higher concentrations in the hypolimnion in early autumn and winter. Dissolved reactive phosphorus was below detection limits in both the hypolimnion and epilimnion during the late summer, and in the hypolimnion in spring. Concentrations were relatively high in the epilimnion in early autumn and the hypolimnion in winter, whilst total phosphorus remained within typical concentrations throughout the period under review.

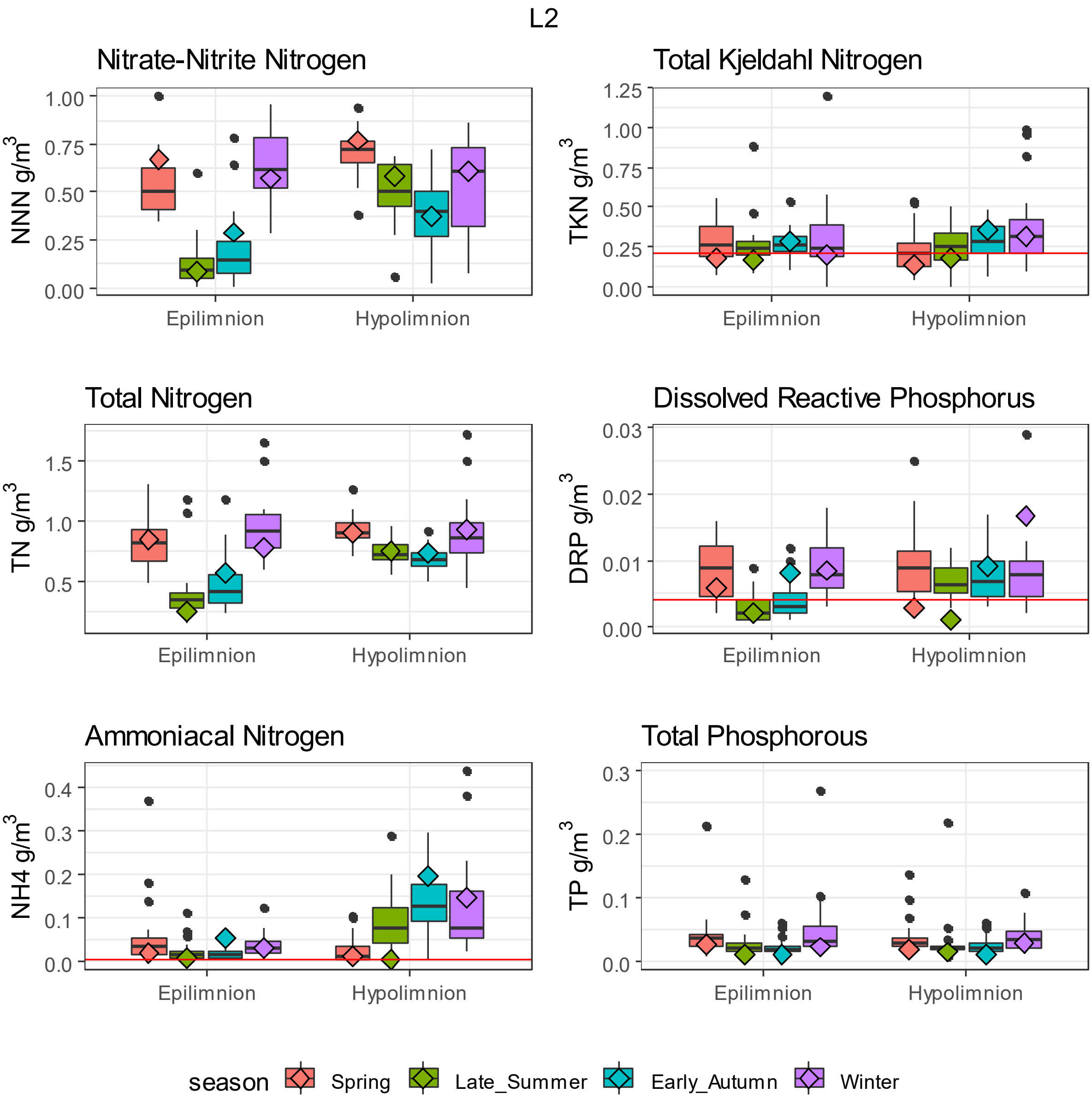

Figure 7 Epilimnetic and hypolimnetic nutrient concentrations at site L2 in Lake Rotorangi. Historical summary data for the period 1996-2020 is represented by boxplots, while the concentration recorded in the period under review is represented as a diamond. Red lines indicate the threshold below which data is censored for each parameter. Statistics below this threshold should be interpreted with caution

Site L3 recorded ammoniacal nitrogen concentrations around the detection limit for the majority of the period under review. Higher concentrations were recorded in the epilimnion in spring, and the hypolimnion in early autumn and winter. The recorded concentration in early autumn was atypically high for that season. Nitrate-nitrite nitrogen and total nitrogen were within a relatively typical range in the hypolimnion; while in the epilimnion the typical decrease during the stratified period was seen only in late summer and not the early autumn sampling. Dissolved reactive phosphorus was below detection limits throughout the period under review, except in the epilimnion in spring. Total phosphorus remained at low concentrations for the entire period under review.

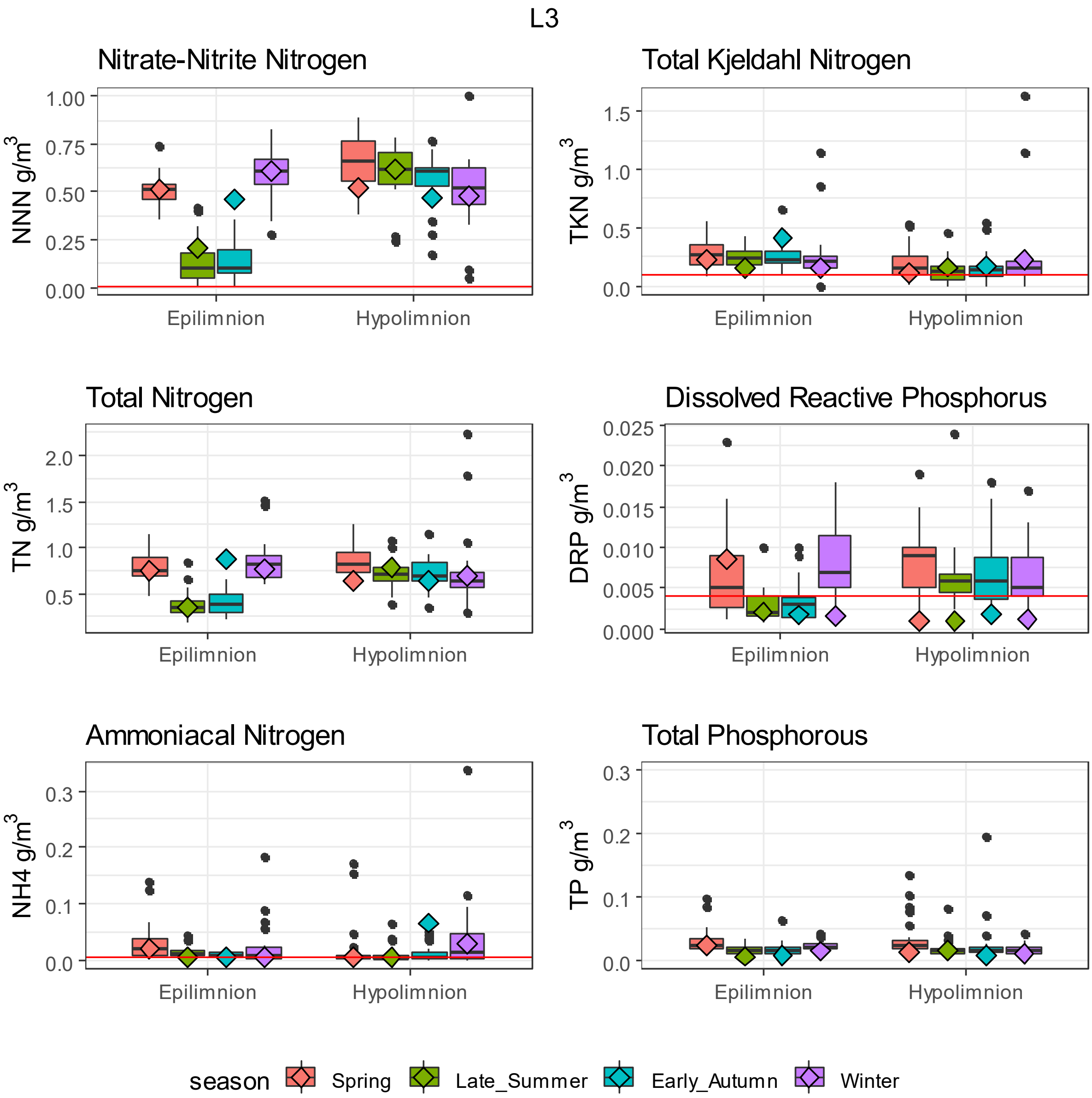

Figure 8 Epilimnetic and hypolimnetic nutrient concentrations at site L3 in Lake Rotorangi. Historical summary data for the period 1996-2020 is represented by boxplots, while the concentration recorded in the period under review is represented as a diamond. Red lines indicate the threshold below which data is censored for each parameter. Statistics below this threshold should be interpreted with caution

Assessment of ammonia, total nitrogen and total phosphorus concentrations against the National Objectives Framework (NOF) numeric attribute state (New Zealand Government, 2020) places both sites in the B band for ammonia and the C band for total nitrogen. Total phosphorus classes site L2 in the C band and site L3 in the B band. It should be noted that Lake Rotorangi is a seasonally stratified lake. This assessment is based on data collected in the epilimnion.

Table 7 Trophic State of Lake Rotorangi based on total nitrogen and total phosphorus National Objective Framework attributes. (Note that units used in the NOF differ between parameters and from the units primarily used throughout this report)

Parameter (unit)	Site	Median	Maximum	Band	Narrative Attribute State
NH4 (mg/L)	L2	0.011	0.062	B	95% species protection level: Starts impacting occasionally on the 5% most sensitive species
	L3	0.004	0.009	B	95% species protection level: Starts impacting occasionally on the 5% most sensitive species
TN (mg/m^3)	L2	600	960	C	Lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrient levels that are elevated well above natural reference conditions. Reduced water clarity is likely to affect habitat available for native macrophytes
	L3	730	880	C	Lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrient levels that are elevated well above natural reference conditions. Reduced water clarity is likely to affect habitat available for native macrophytes
TP (mg/m^3)	L2	23.0	66.0	C	Lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrient levels that are elevated well above natural reference conditions. Reduced water clarity is likely to affect habitat available for native macrophytes
	L3	13.5	23.0	B	Lake ecological communities are slightly impacted by additional algal and/or plant growth arising from nutrient levels that are elevated above natural reference conditions

3.2.2.2.1 Sediment/water interface

Anoxia in the lower hypolimnion means the biogeochemical conditions are likely to cause release of nutrients from lakebed sediment into water column during periods of stratification. In recognition of this, water samples have been taken for nutrients at the bottom of the water column during stratified periods since 1996. Over this time period, the data has shown a small increase in ammoniacal nitrogen and a very small decrease in nitrate nitrogen near the lakebed compared to in the hypolimnetic water column. This change may result from the reduction of nitrate to ammonia in the water column or the release of ammonia from anoxic sediments. At site L2 no change has been seen in phosphorus levels, while at site L3 an increase in total phosphorus has been observed near the lakebed, in conjunction with an increase in turbidity. This is likely related to disturbance of the lakebed during sampling rather than hypoxic nutrient release because no such increase in DRP is observed.

Anoxic conditions were present at both sites during the late summer and early autumn sampling in the hypolimnion as well as near the bottom of the water column. During the period under review, nitrate concentrations remained relatively similar near the lakebed compared to higher in hypolimnion at both sites L2 and L3 (Figure 9 and Figure 10). Ammonia concentrations were elevated near the lakebed compared to higher in the hypolimnion in late summer, but were similar in the early autumn sampling for both sites. DRP concentrations remained largely similar, or were at slightly lower concentrations, in the water column near the lakebed compared to higher in the hypolimnion. Both total phosphorus and turbidity were relatively low in the hypolimnion and near the lake bed at both sites. These results provide no evidence of nutrient release or reduction in the anoxic environment.

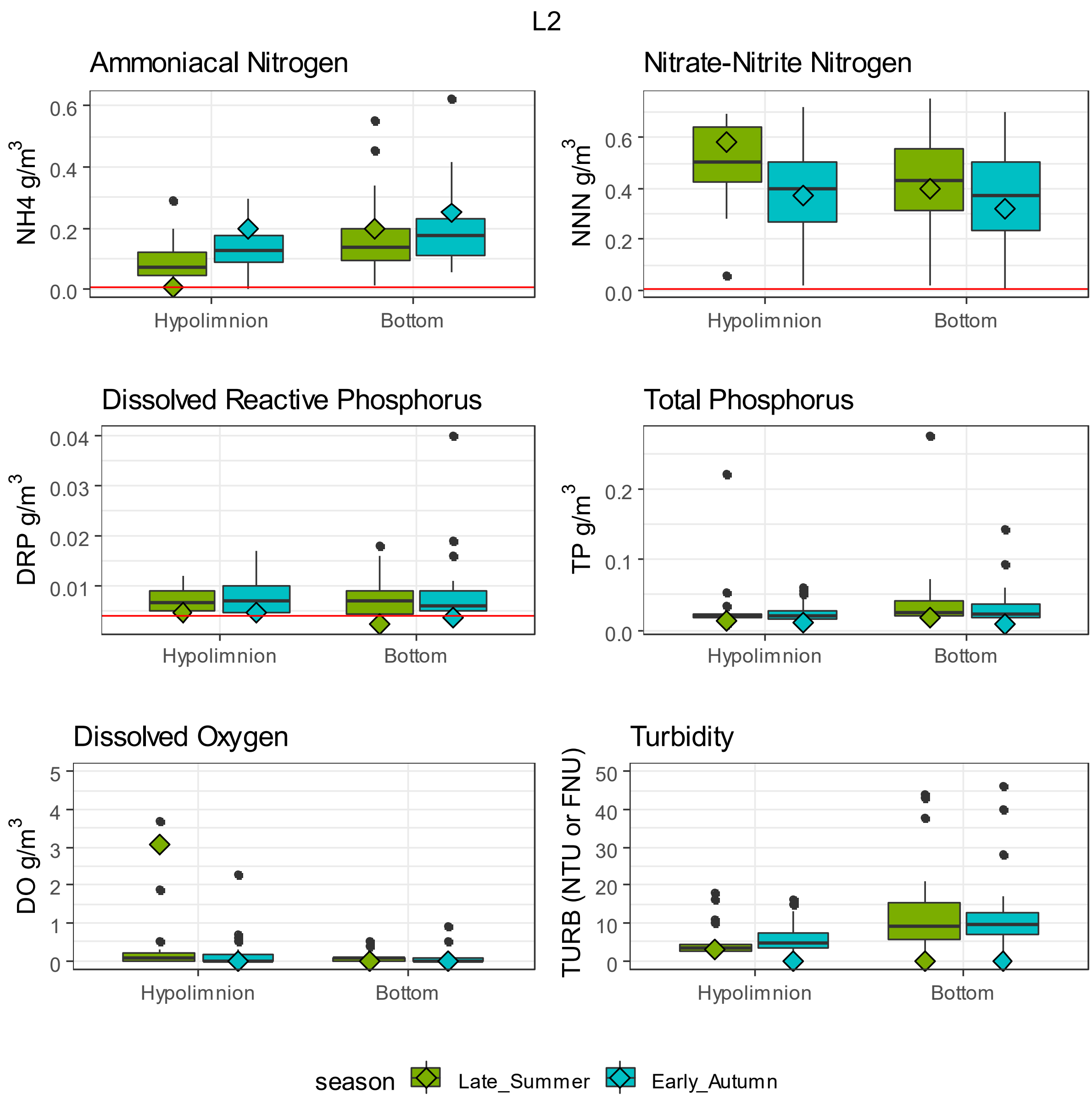

Figure 9 Selected parameters sampled in Lake Rotorangi in the hypolimnion and near the bottom of the water column at site L2. Historical summary data for the period 1996-2020 is represented by boxplots, while the concentration recorded in the period under review is represented as a diamond. Red lines indicate the threshold below which data is censored for each parameter. Statistics below this threshold should be interpreted with caution

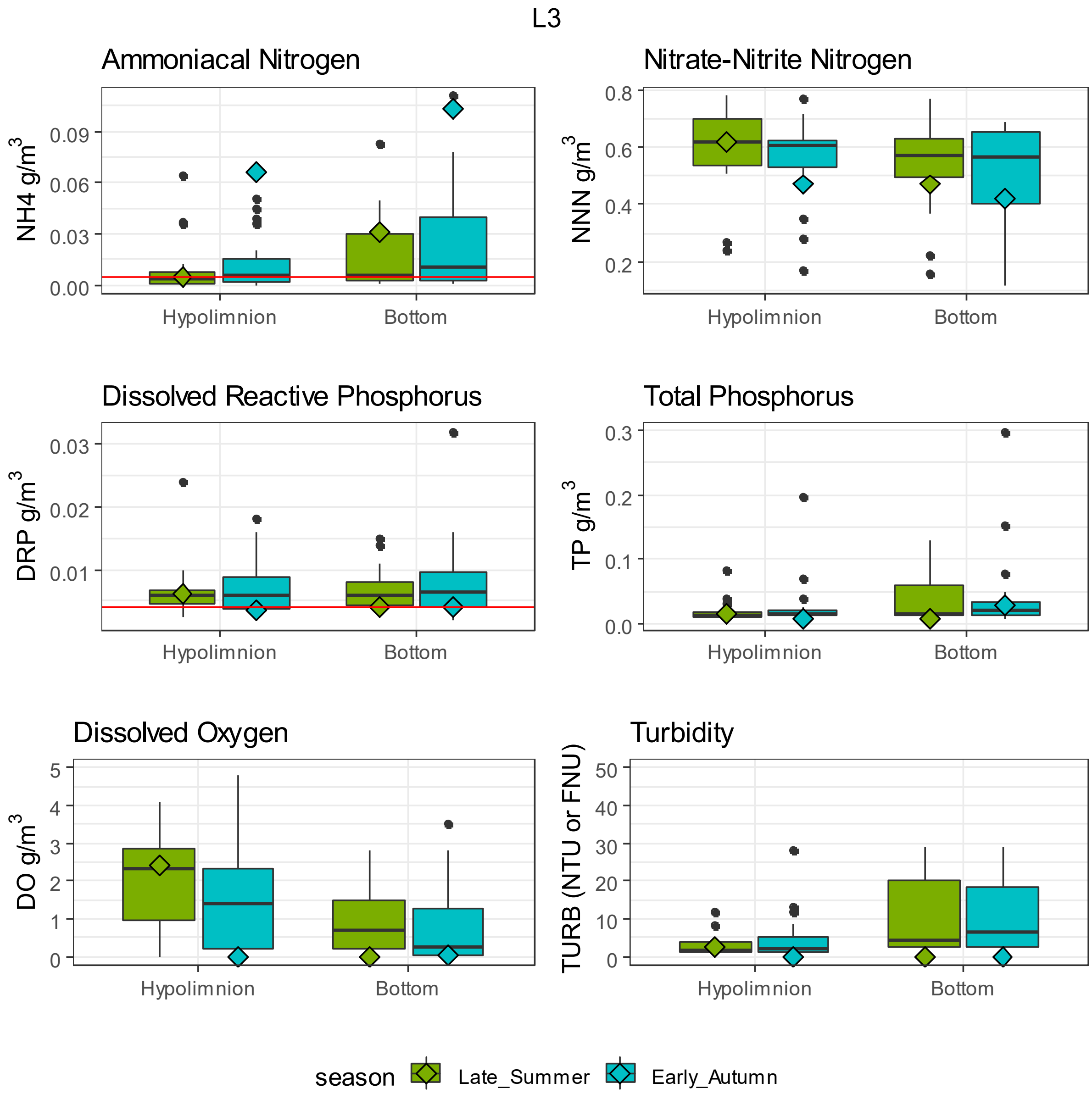

Figure 10 Selected parameters sampled in Lake Rotorangi in the hypolimnion and near the bottom of the water column at site L3. Historical summary data for the period 1996-2020 is represented by boxplots, while the concentration recorded in the period under review is represented as a diamond. Red lines indicate the threshold below which data is censored for each parameter. Statistics below this threshold should be interpreted with caution

3.3 Biological

3.3.1 Phytoplankton

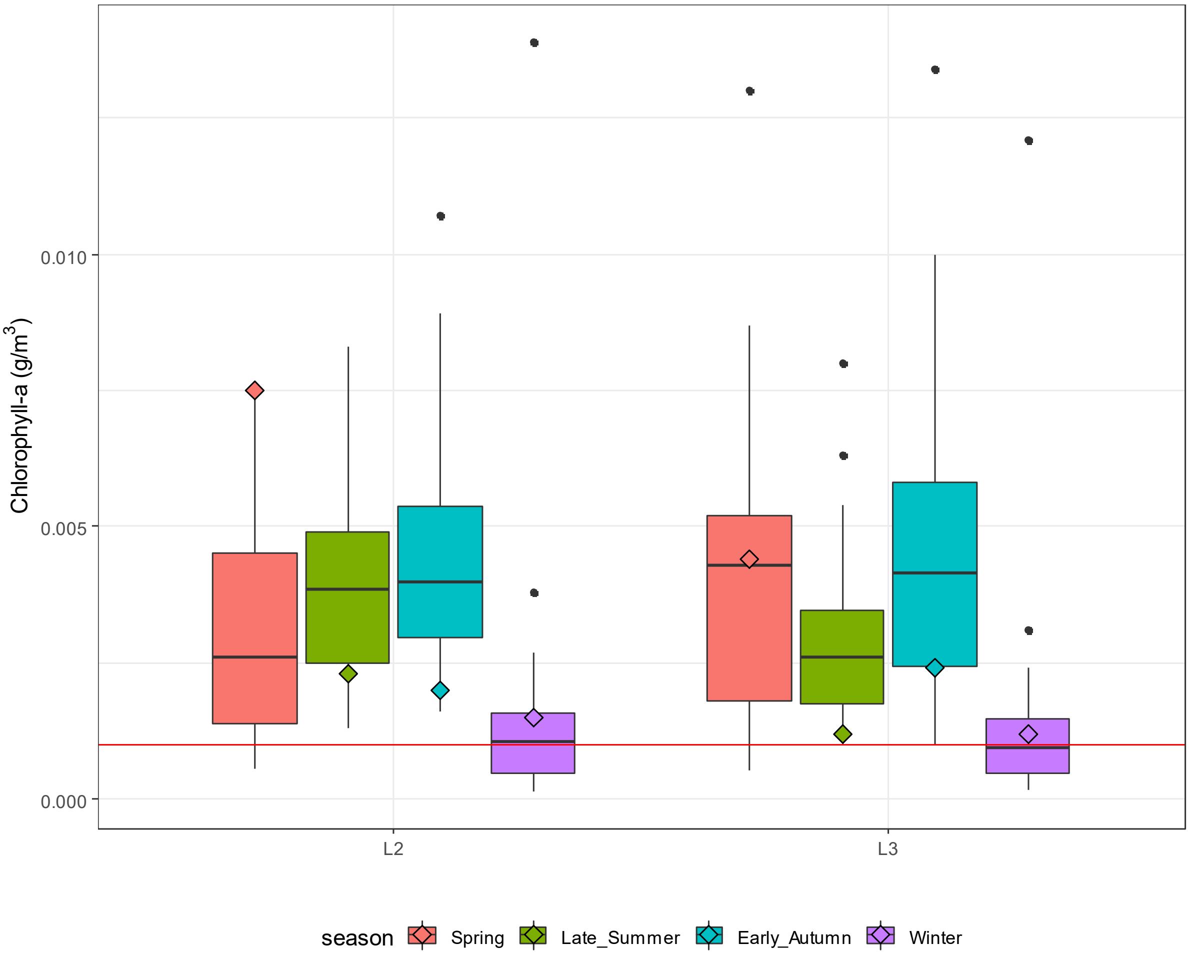

Figure 11 Seasonal chlorophyll-a concentrations in the photic zone of Lake Rotorangi. Historical summary data is represented by boxplots, while the concentration recorded in the period under review is represented as a diamond. Red lines indicate the threshold below which data is censored for each parameter. Statistics below this threshold should be interpreted with caution

Chlorophyll-a concentrations during the period under review were within the previously recorded ranges, except for site L2 in spring which recorded the highest spring chlorophyll concentration to date. Concentrations at both sites in late summer and early autumn were lower than seasonal medians, while spring and winter results were higher than medians.

Assessment of chlorophyll concentrations in Lake Rotorangi is based on three years of data against the phytoplankton NOF attribute places both sites in the B band for phytoplankton (Table 8 and Figure 11) (New Zealand Government, 2020).

Table 8 Phytoplankton attribute state of Lake Rotorangi under the National Objectives Framework. (Note that units used in the NOF differ from the units primarily used throughout this report)

Site	Median (mg/m^3)	Maximum (mg/m^3)	Band	Narrative Attribute State
L2	2.6	7.5	B	Lake ecological communities are slightly impacted by additional algal and/or plant growth arising from nutrient levels that are elevated above natural reference conditions
L3	2.3	4.4	B	Lake ecological communities are slightly impacted by additional algal and/or plant growth arising from nutrient levels that are elevated above natural reference conditions

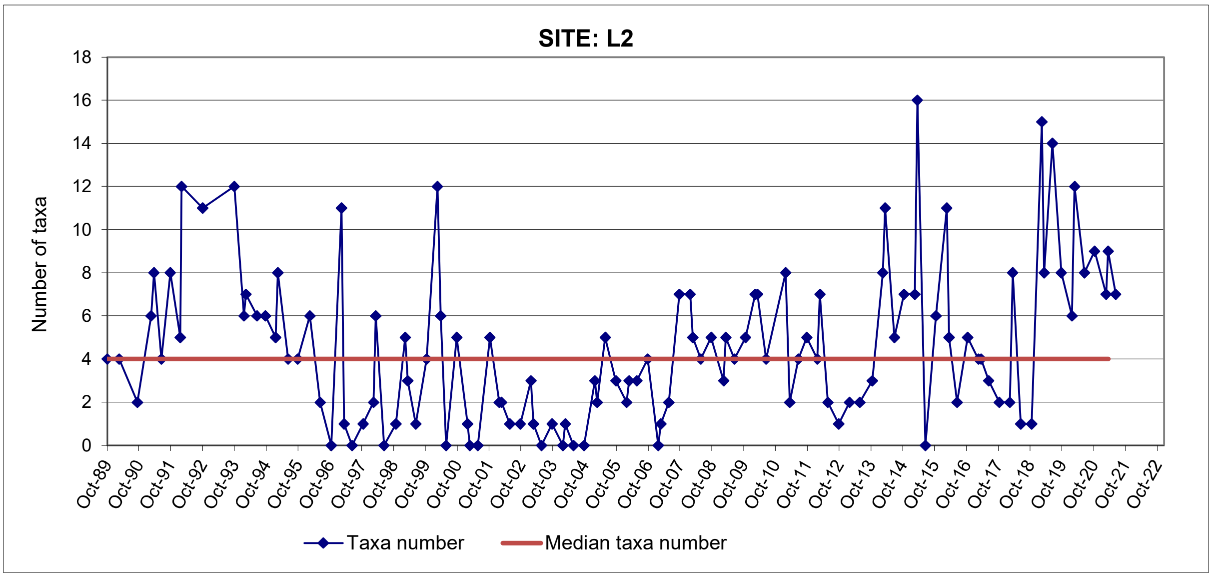

Figure 12 Phytoplankton taxa richness at site L2 since 1989

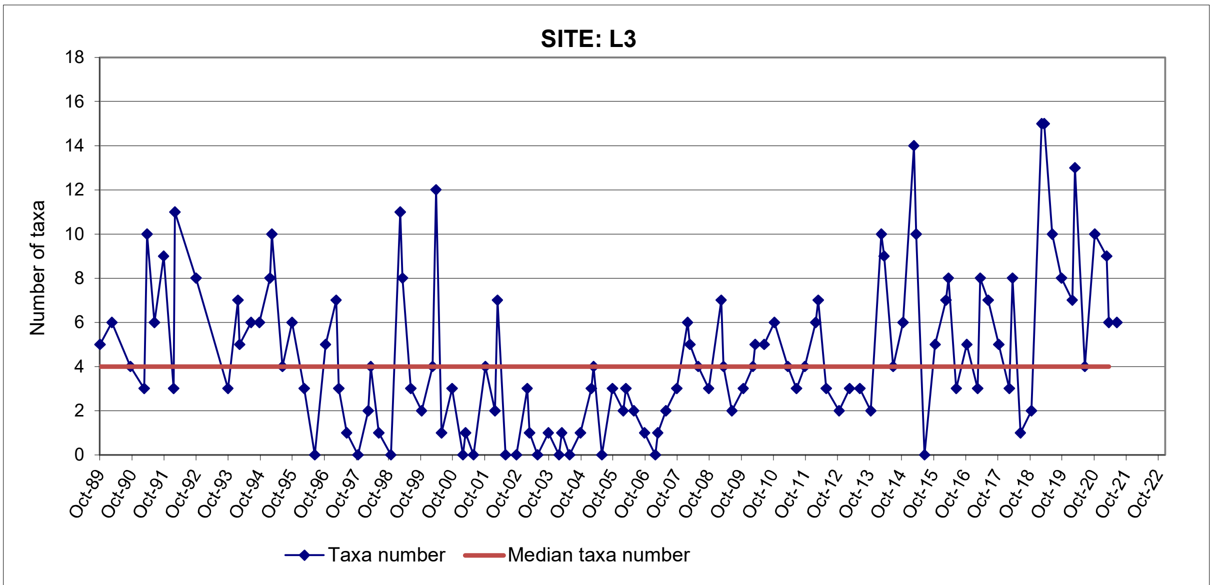

Figure 13 Phytoplankton taxa richness at site L3 since 1989

Phytoplankton taxa richness was higher than has been typical for both sites L2 and L3 during the 2020-2021 period (Figure 12 and Figure 13). Richness was between 7 and 9 taxa at site L2 and 6 and 10 taxa at site L3.

3.3.2 Benthic macroinvertebrates

Macroinvertebrate sampling was scheduled to be undertaken in the period under review. This was unable to be undertaken due to sampling equipment failure. Given the paucity of macroinvertebrates that are typically recorded in the benthos at these sites, macroinvertebrate sampling is considered to add negligible value to the lake monitoring. This is likely to primarily relate to the both the depth of the lakebed and the anoxic conditions typical of the lakebed. See TRC 2018 for detailed results of the most recent macroinvertebrate survey.

3.3.3 Macrophytes

The scheduled macrophyte survey was undertaken on 16 April 2021. This survey recorded hornwort (*Ceratophyllum demersum*) as the dominant macrophyte in the lake. Hornwort is highly invasive and this has been predicted since it was first recorded in Lake Rotorangi in 2012. Other species recorded included the invasive oxygen weeds *Egeria densa* and *Lagarosiphon major*, and patches of *Nitella hookeri* and *Potamogeton ochreatus*.

The dominance of hornwort is not predicted to cause significant impacts on the ecology of Lake Rotorangi. However, it increases the potential for spread to other lakes in the region. In 2021, hornwort was confirmed to be present in Lake Herengawe, south of Lake Rotorangi for the first time. Hornwort has also reportedly spread to the nearby Lake Rotokare, where the impacts are expected to be much more severe, although this is yet to be confirmed. It may be worthwhile controlling *C. demersum* in the vicinity of boat ramps to help prevent further spread. The usefulness of this may be subject to further investigation by Taranaki Regional Council.

The full report is provided in Appendix III.

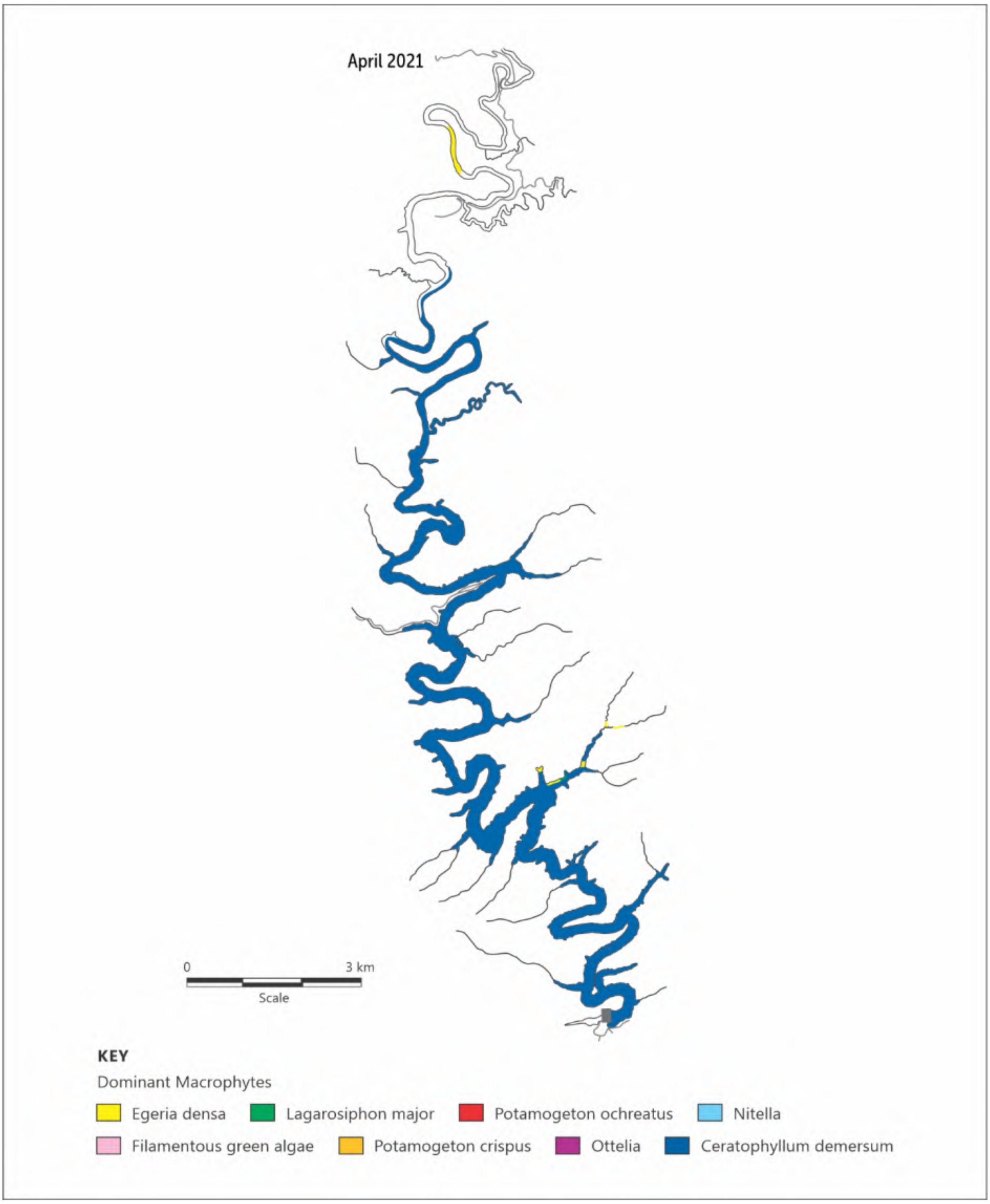

Figure 14 Dominant macrophytes recorded in Lake Rotorangi on 16 April 2021

The full macrophyte survey report is provided in Appendix II.

3.4 Trophic state

The trophic state of Lake Rotorangi is shown in Table 8. Annual trophic level values are provided in Appendix II for the lake as a whole and for the individual sites. The trophic level for the year under review was 4.02 TLI units, classifying the lake as eutrophic. When the individual components of the TLI are considered, chlorophyll-a, secchi depth and total phosphorus concentrations categorise the lake as mesotrophic, while total nitrogen categorise the lake as eutrophic.

Table 9 Trophic level and values of key variables defining the trophic status* of Lake Rotorangi in 2020-2021. (Note that units used in the trophic level calculations differ from the units primarily used throughout this report)

Trophic Level Component	Unit	L2	L3	Whole Lake
Overall Trophic Status		Eutrophic	Mesotrophic	Eutrophic
Trophic Level	TLI units	4.10	3.92	4.02
Chlorophyll a	mg m^{-3}	3.33 (M)	2.30 (M)	2.81 (M)
Secchi Depth	m	3.23 (M)	2.98 (M)	3.10 (M)
Total Nitrogen	mg N m^{-3}	676 (E)	686 (E)	681 (E)
Total Phosphorus	mg P m^{-3}	16.8 (M)	12.2 (M)	14.7 (M)

* Letters in brackets relate to the trophic status of individual trophic level components. O=Oligotrophic, M=Mesotrophic, E=Eutrophic

The trophic level of Lake Rotorangi has shown an increase over time (Figure 15), albeit at a very slow rate of change (see Table 10). The loess curve shown in Figure 15 shows distinct peaks in 2004 and 2015, both years in which flood inflows affected the water chemistry of the lake, and illustrates the relatively riverine nature of Lake Rotorangi.

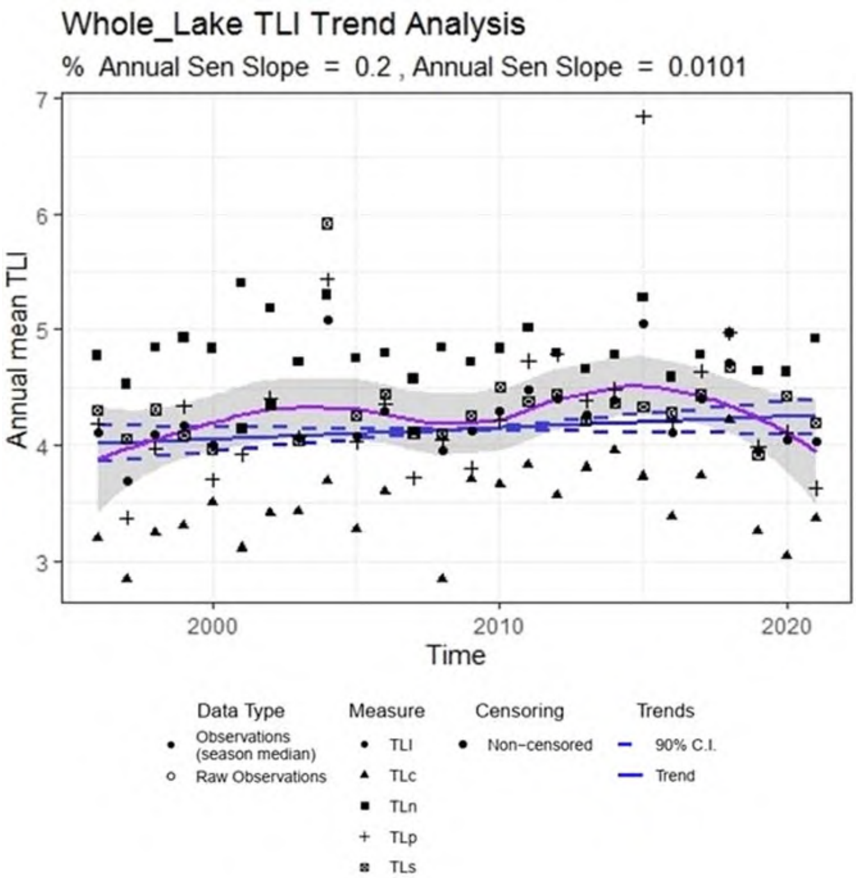

Figure 15 Trophic level index in Lake Rotorangi over the period 1996-2021. The four components of the TLI (chlorophyll-a, secchi depth, total nitrogen and total phosphorus) are plotted individually, as well as the overall TLI. The trend shown relates to the overall TLI. The lowess curve for the overall TLI is in purple

3.5 Temporal trends

Where possible, trend analysis is carried out based upon data from the epilimnion. In the case of chlorophyll-a and secchi distance, which are not measured in the epilimnion, data is from the photic zone and surface, respectively. Hypolimnetic data is not trended due to the magnitude of change occurring seasonally as a result of stratification processes, which has the potential to mask changes in the data over longer time frames. This is consistent with national analyses (Larned *et al.*, 2015).

Trend analysis results for the period 1996-2021 are provided in Table 10 and for the most recent ten years (2012-2021) in Table 11. The shorter trend period provides useful information to assess whether changes are consistent over time. This can provide information as to the effectiveness of management actions, or alternatively can show when interventions might be required. Although it is typical to report statistical analysis for a lake holistically, the riverine nature of Lake Rotorangi means that there are substantial differences in water chemistry between the mid and lower lake sites. Therefore, the trend analysis for the whole lake should be interpreted with caution.

Trend plots for each variable are provided in Appendix III for the period 1996-2021 and Appendix IV for the period 2012-2021.

Table 10 Trend analysis of selected variables in Lake Rotorangi for the period 1996-2021. Trends of high confidence are identified in red (degrading trend) or blue (improving trend)

Measure	Site	No. of Surveys	Seasonality	Proportion censored	Median Slope	Percent Annual Change	Trend	Confidence (%)
CHLA	L2	102	Seasonal	0.16	0.00004	1.46	Very Likely Increasing	99.30
	L3	102	Seasonal	0.13	0.00003	1.36	Very Likely Increasing	98.36
	Whole Lake	102	Seasonal	0.10	0.00005	1.71	Very Likely Increasing	99.79
COND	L2	104	Seasonal	0.00	0.03679	0.30	Very Likely Increasing	95.65
	L3	104	Seasonal	0.00	0.03678	0.31	Very Likely Increasing	98.25
	Whole Lake	104	Seasonal	0.00	0.03318	0.28	Very Likely Increasing	99.12
DRP	L2	104	Seasonal	0.36	0.00000	0.00	Likely Decreasing	76.11
	L3	104	Seasonal	0.47	0.00000	0.00	Very Likely Decreasing	97.98
	Whole Lake	104	Seasonal	0.39	0.00000	0.00	Likely Decreasing	82.70
NH4	L2	104	Seasonal	0.10	0.00000	0.00	Indeterminate	54.84
	L3	104	Seasonal	0.19	-0.00031	-2.86	Very Likely Decreasing	99.68
	Whole Lake	104	Seasonal	0.01	-0.00017	-0.95	Likely Decreasing	85.00
NNN	L2	96	Seasonal	0.00	-0.00061	-0.16	Indeterminate	66.37

Measure	Site	No. of Surveys	Seasonality	Proportion censored	Median Slope	Percent Annual Change	Trend	Confidence (%)
	L3	96	Seasonal	0.02	0.00022	0.06	Indeterminate	66.85
	Whole Lake	96	Seasonal	0.00	0.00000	0.00	Indeterminate	53.46
SECCHI	L2	104	Seasonal	0.00	-0.00216	-0.08	Indeterminate	55.26
	L3	104	Seasonal	0.00	-0.00767	-0.25	Likely Increasing	77.35
	Whole Lake	104	Seasonal	0.00	0.00000	0.00	Indeterminate	50.00
TLI	L2	26	NonSeasonal (Annual Mean)	0.00	0.00432	0.10	Likely Increasing	77.32
	L3	26	NonSeasonal (Annual Mean)	0.00	0.00778	0.19	Very Likely Increasing	91.41
	Whole Lake	26	NonSeasonal (Annual Mean)	0.00	0.01011	0.24	Likely Increasing	85.50
TN	L2	104	Seasonal	0.00	-0.00500	-0.80	Very Likely Decreasing	98.52
	L3	104	Seasonal	0.00	-0.00400	-0.65	Very Likely Decreasing	97.59
	Whole Lake	104	Seasonal	0.00	-0.00464	-0.72	Very Likely Decreasing	99.30
TP	L2	104	Seasonal	0.00	0.00044	1.85	Very Likely Increasing	99.76
	L3	104	Seasonal	0.00	0.00008	0.42	Likely Increasing	76.37
	Whole Lake	104	Seasonal	0.00	0.00029	1.30	Very Likely Increasing	97.70
TURB	L2	97	Seasonal	0.00	0.02438	1.06	Very Likely Increasing	96.57
	L3	97	Seasonal	0.00	0.01272	0.85	Very Likely Increasing	91.07
	Whole Lake	97	Seasonal	0.00	0.01666	0.93	Very Likely Increasing	94.92

Improving trends in total nitrogen were detected with high confidence at both sites L2 and L3 and for the lake as a whole, albeit at a relatively slow rate of change of 0.6 to 0.8 % per year. Dissolved reactive phosphorus and ammonia also showed improving trends with high confidence at site L3 only.

Both sites show a degrading trend in chlorophyll-a, with increases of 1.4-1.5% per year. For the lake as a whole, a similar trend is detected, with a magnitude of 1.7% per year. This long term increasing trend in chlorophyll-a merits further attention, although absolute concentrations remain low.

A degrading trend in conductivity was detected with high confidence at both sites and for the lake as a whole, however the magnitude of this trend is relatively minor at around 0.3 % per year.

Site L2, and the lake as a whole show degrading trends of high confidence for total phosphorus, with an increase of approximately 1.3 % per year for the lake as a whole. Turbidity also showed degrading trends for both sites and for the lake as a whole.

The trophic level index shows an increasing trend of high confidence for site L3, while site L2 and the lake as a whole also show an increasing trend but with a lower level of confidence in the result. It should be noted that because this is a calculation resulting in one annual data point, the ability to detect a trend is reduced compared to parameters which are sampled four times a year. Consequently a ten year trend has not been calculated for the TLI due to insufficient data.

Table 11 Trend analysis of selected variables in Lake Rotorangi for the period 2012-2021. Trends of high confidence are identified in red (degrading trend) or blue (improving trend)

Measure	Site	No. of Surveys	Seasonality	Proportion censored	Median Slope	Percent Annual Change	Trend	Confidence (%)
CHLA	L2	38	Seasonal	0.11	-0.00007	-1.89	Likely Decreasing	84.54
	L3	38	Seasonal	0.08	-0.00029	-9.57	Very Likely Decreasing	99.88
	Whole Lake	38	Seasonal	0.08	-0.00019	-5.58	Very Likely Decreasing	97.87
COND	L2	40	Seasonal	0.00	0.12835	1.04	Very Likely Increasing	90.27
	L3	40	Seasonal	0.00	0.11895	1.01	Very Likely Increasing	93.00
	Whole Lake	40	Seasonal	0.00	0.10103	0.86	Very Likely Increasing	96.69
DRP	L2	40	Seasonal	0.40	0.00000	0.00	Very Likely Decreasing	97.20
	Whole Lake	40	Seasonal	0.32	-0.00025	-5.55	Very Likely Decreasing	98.93
NH4	L2	40	Non-Seasonal	0.12	0.00007	0.31	Indeterminate	57.41
	L3	40	Seasonal	0.28	0.00000	0.00	Likely Decreasing	85.53
	Whole Lake	40	Non-Seasonal	0.00	-0.00025	-1.49	Indeterminate	65.41
NNN	L2	40	Seasonal	0.00	0.00413	1.07	Indeterminate	63.99
	L3	40	Seasonal	0.05	0.00535	1.16	Likely Increasing	87.08
	Whole Lake	40	Seasonal	0.00	0.00470	1.13	Likely Increasing	77.69
SECCHI	L2	40	Seasonal	0.00	0.06050	2.15	Likely Decreasing	77.65
	L3	40	Seasonal	0.00	0.02245	0.69	Likely Decreasing	77.69
	Whole Lake	40	Seasonal	0.00	0.04410	1.43	Likely Decreasing	88.64

Measure	Site	No. of Surveys	Seasonality	Proportion censored	Median Slope	Percent Annual Change	Trend	Confidence (%)
TN	L2	40	Seasonal	0.00	0.00211	0.34	Indeterminate	65.69
	L3	40	Seasonal	0.00	0.00343	0.59	Indeterminate	64.04
	Whole Lake	40	Seasonal	0.00	0.00056	0.09	Indeterminate	51.79
TP	L2	40	Non-Seasonal	0.00	-0.00209	-7.22	Very Likely Decreasing	98.54
	L3	40	Seasonal	0.00	-0.00177	-8.84	Very Likely Decreasing	100.00
	Whole Lake	40	Seasonal	0.00	-0.00193	-7.57	Very Likely Decreasing	99.97
TURB	L2	33	Seasonal	0.00	0.06319	2.75	Indeterminate	66.00
	L3	33	Seasonal	0.00	-0.00743	-0.53	Indeterminate	57.04
	Whole Lake	33	Seasonal	0.00	0.02913	1.62	Indeterminate	59.33

A 10 year trend was unable to be carried out for DRP at site L3 due to an insufficient number of unique values in each season.

Over the most recent ten year period, decreasing trends of relatively low confidence were found in chlorophyll-a for the lake as a whole, and at site L3. The magnitude of this trend is relatively large, at approximately 6 % per year for the lake as a whole and 10% per year at site L3. This is in contrast to the long-term increasing trends found in chlorophyll-a.

Conductivity showed a similar pattern in the short term trend as over the longer record, although the magnitude of the trend over the shorter term was much greater, at around 0.8 % for the lake as a whole.

Dissolved reactive phosphorus at site L2 and for the whole lake showed an improving trend of high confidence, with a magnitude of around 5.5% for the lake as a whole.

An improving trend with very high confidence was detected in total phosphorous at site L3, and for the lake as a whole. The magnitude of this trend is significant, with a decrease of approximately 8 % per year at site L3 and for the whole lake. This is in contrast with the 25 year trend where total phosphorus is increasing. This trend is influenced somewhat by some particularly high results in 2015.

4 Discussion

During 2020-2021 stratification was recorded in Lake Rotorangi at both the mid and lower sites in late summer and early autumn. Anoxia was recorded in the hypolimnion in both late summer and early autumn. Overturn was complete at site L2 and only partially complete at site L3 at the time of the winter sampling.

The anoxic conditions in the lower hypolimnion have the potential to result in the release of nutrients from the lakebed sediments, particularly during periods when the lake is stratified. Monitoring of the water column near the lakebed during the stratified period shows very slight increases in ammonia concentrations and very slight decreases in nitrate concentrations compared to higher in the hypolimnion. Dissolved reactive phosphorus concentrations do not show any increase lower in the water column. It is unclear whether the increase in ammonia results from hypoxic nutrient release, or simply occurs due to anoxia causing the reduction of nitrate in the water column to ammonia. A lack of hypoxic nutrient release would indicate that nutrient concentrations in the lakebed sediments remain relatively low (Burns 2006). There is insufficient evidence to conclude whether hypoxic nutrient release is occurring in Lake Rotorangi, however given the small magnitude of the changes in water chemistry this is considered unlikely. For both lake-bottom and mid-hypolimnetic dissolved oxygen attributes, Lake Rotorangi does not meet minimum standards (national bottom line) as set out in the NPS-FM.

Total nitrogen was improving at both sites, while total phosphorus shows a degrading trend at L2. Dissolved reactive phosphorus and ammonia both showed an improving trend at L3 over the twenty five year period. All other nutrients measured did not show any trend over time at individual sites. It is worth noting that because of the low nutrient concentrations in Lake Rotorangi, several parameters have a large amount of censored data, impacting upon the ability to determine the change over time. This is particularly relevant for suspended solids, which has been removed from the trend analysis because approximately two-thirds of the data is censored.

When only the most recent ten years of data is considered, dissolved reactive phosphorus was decreasing at site L2, and total phosphorus was decreasing at both sites. A trend was unable to be calculated for dissolved reactive phosphorus at site L3 due to insufficient unique values. This indicates that concentrations likely remain stable. The remainder of the nutrients did not show a trend with any confidence at an individual site over this period.

Chlorophyll concentrations in Lake Rotorangi remain relatively low, as does phytoplankton species diversity. However, trend analysis indicates that chlorophyll- a concentrations are increasing over time at both sites L2 and L3. The rate of change at both sites is less than 2 % per year, and based on the current annual medians, at site L3 chlorophyll-a concentrations would need to increase by more than double to reach eutrophic status based on this parameter (Burns, 1999; Appendix III). Site L2 currently has chlorophyll-a concentrations around the oligotrophic/mesotrophic boundary. The shorter term trend shows improving chlorophyll-a concentrations in Lake Rotorangi, with a high level of confidence at site L3. It is unclear what is driving this change.

The trends for Lake Rotorangi have been calculated for the lake as a whole as well as for the individual sites. It is typical to analyse lakes holistically, however Lake Rotorangi is quite riverine in nature and this is more pronounced at the mid lake site compared to the lower lake site. This leads to differences in the water chemistry and ecology between the sites which makes the individual site analysis potentially more insightful than the analyses of the whole lake.

The trends for the lake as a whole showed degrading chlorophyll-a, conductivity and total phosphorus; and improving total nitrogen over the 25 year record. In contrast, the most recent ten year period shows a degrading trend in conductivity and improving trends in dissolved reactive phosphorus and total phosphorus over this period. Drivers of lake water quality are complex. It is plausible that the total phosphorus levels are related to the suspended sediment within the water column, however, the high amount of censored data for suspended solids prevents analysis of any correlation between these parameters.

The trophic level index is increasing over time. However, the magnitude of this change is almost imperceptible, meaning that this trend is of minor ecological importance.

Ecosystem health is assessed against NOF attributes. Ammonia and chlorophyll-a concentrations classify the lake as being in a mildly impacted state, while total nitrogen classifies the lake as moderately impacted. Total phosphorus classes the upper lake as moderately impacted and the lower lake as mildly impacted.

The macrophyte survey, carried out in April 2021, recorded several invasive species. Hornwort (*Ceratophyllum demersum*) continued to spread, and is now the dominant macrophyte in a large portion on the lake. While the effects on the ecology of Lake Rotorangi and the hydroelectric scheme are not anticipated to be significant, there is the potential for spread to other lakes where the effects may be more severe. Appropriate warning signage regarding the potential problems caused by aquatic weeds and the responsibilities of recreational lake users are in place at the three principal boat ramps in Lake Rotorangi. These were updated in the 2015-2016 monitoring year to include specific reference to hornwort.

The triennial macroinvertebrate survey was not undertaken during the period under review for logistical reasons. Given the anoxic conditions at the lakebed, and the paucity of fauna recorded in previous surveys, the value of this survey is considered to be negligible. It is therefore recommended that this component of the monitoring is discontinued.

The frequency of reporting the results of Lake Rotorangi monitoring should also be reviewed. It is recommended that the frequency of the technical report is reduced to triennial, and is aligned with the triennial biological components of the monitoring programme. The report would next be undertaken in the 2023-2024 year, covering the period 2021-2024. Results would continue to be updated annually on LAWA.

5 Recommendations

The following recommendations are based on the results of the 2020-2021 water quality and biological monitoring programmes and the contractual requirements of the resource consents held by Trustpower for the Patea Hydro Electric Power Scheme on Lake Rotorangi:

1. THAT the Lake Rotorangi physicochemical and biological water quality monitoring programme continue on an annual basis as a component of Council's State of the Environment monitoring programme, with every third year of the programme also undertaken in conjunction with the Patea Hydro Electric Power Scheme – aquatic monitoring plan (next in 2023-2024).
2. THAT the triennial benthic macroinvertebrate survey be discontinued due to negligible value provided by the resulting data.
3. THAT in future the Lake Rotorangi physicochemical and biological water quality monitoring programme is reported on a triennial basis, in the year in which the triennial biological components are undertaken (next in 2023-2024).

Glossary of common terms and abbreviations

The following abbreviations and terms are used within this report:

anoxia	absence of dissolved oxygen (defined as dissolved oxygen concentrations less than 0.5 g/m^3)
aquatic macrophyte	water plants
benthic	bottom living
black/secchi disc	measurement of visual clarity (metres) through the water (horizontally/vertically)
biomonitoring	assessing the health of the environment using aquatic organisms
chlorophyll-a	productivity using measurement of phytoplankton pigment (mg/m^3)
cumec	volumetric measure of flow (cubic metre per second)
conductivity	Conductivity, an indication of the level of dissolved salts in a sample, usually measured at 25°C and expressed in µS/cm
DO	dissolved oxygen measured as g/m^3 (or saturation (%))
DRP	dissolved reactive phosphorus
E.coli	*Escherichia coli*, an indicator of the possible presence of faecal material and pathological micro-organisms. Expressed as the number of organisms per 100ml
epilimnion	lake zone above the thermocline (mixed surface layer)
Faecal coliforms	an indicator of the possible presence of faecal material and pathological micro-organisms. Expressed as the number of organisms per 100ml
FNU	formazin nephelometric unit, a measure of the turbidity of water
fresh	elevated flow in a stream, such as after heavy rainfall
g/m^3	grammes per cubic metre, and equivalent to milligrammes per litre (mg/L). In water, this is also equivalent to parts per million (ppm), but the same does not apply to gaseous mixtures
hypolimnion	zone below the thermocline in a stratified lake
imputed value	a calculated estimate of value produced when an exact value cannot be obtained
isothermal	thermally mixed lake; defined in this report as less 3°C difference in water temperature between the lake surface and lake bottom
L/s	litres per second
mesotrophic	intermediate condition of nutrient enrichment between oligotrophic and eutrophic in lakes
mS/m	millisiemens per metre
µS/cm	microsiemens per centimetre.
NH_4	ammonium, normally expressed in terms of the mass of nitrogen (N)
NO_3	nitrate, normally expressed in terms of the mass of nitrogen (N)
NTU	Nephelometric Turbidity Unit, a measure of the turbidity of water
overturn	remixing of a lake after stratification

pH	a numerical system for measuring acidity in solutions, with 7 as neutral. Numbers lower than 7 are increasingly acidic and higher than 7 are increasingly alkaline. The scale is logarithmic i.e. a change of 1 represents a ten-fold change in strength. For example, a pH of 4 is ten times more acidic than a pH of 5
photic zone	upper section of lake penetrated by light
physicochemical	measurement of both physical properties(e.g. temperature, clarity, density) and chemical determinants (e.g. metals and nutrients) to characterise the state of an environment
plankton	Small and microscopic plants and animals living in the water column
resource consent	refer Section 87 of the RMA. Resource consents include land use consents (refer Sections 9 and 13 of the RMA), coastal permits (Sections 12, 14 and 15), water permits (Section 14) and discharge permits (Section 15)
RMA	Resource Management Act 1991 and subsequent amendments
SS	suspended solids
stratification	formation of thermal layers in lakes
temp	temperature, measured in ˚C (degrees Celsius)
thermocline	zone of most rapid temperature change in stratified lakes
TLI	trophic level index, a method of measuring the trophic level of a lake
trophic level	amount of nutrient enrichment of a lake
turb	turbidity, expressed in NTU or FNU
UI	Unauthorised Incident
UIR	Unauthorised Incident Register – contains a list of events recorded by the Council on the basis that they may have the potential or actual environmental consequences that may represent a breach of a consent or provision in a Regional Plan
VHOD	Volumetric hypolimnetic oxygen depletion. The note of dissolved oxygen decrease in the lower layer of the lake under stratified conditions. A measure of lake productivity
water column	water overlying the lake bed

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Appendix I

Trend analysis methodology

A number of changes to data analysis methodologies have been implemented in this report. A brief description of the current methods used is given below, while a discussion of how these differ from methods used in previous TRC SEM lake reports is given in Section 4.1 and Appendix VI of this report.

When assessing point (state) statistics, such as those used to construct the boxplots in this report, censored data has been handled using the NADA R package (vers. 1.6-1.1; Lopaka Lee, 2020). Left censored data has been replaced with imputed values using regression on order statistics (ROS). This method fits a distribution to the non-censored values in the data record and uses the resulting model to impute replacement values for the censored data. The resulting calculated summary statistics and boxplots are more robust than those used in previous reports, where summary statistics were biased by censored data being replaced with a value equal to half the censor limit. Even with this improved method of handling censored data, however, summary statistics (e.g. 25^{th} percentile, median) that are less than the highest common censor limit, should not be directly interpreted.

In this report, trend analysis has been carried out using the LWP-Trends library R package (version 1901), developed by Land Water People Ltd. (Snelder & Fraser, 2019). The methods employed have the primary purpose of establishing the direction and rate of any trend, along with a measure of the uncertainty in the result. The use of the LWP-Trends package represents a major change in trend analysis methodology compared to previous TRC Lake SEM reports, in part due to different methods used in the past, but also due to a recent conceptual shift in how to assess confidence in trend analysis results (Greenland et al. 2016, McBride 2019, Helsel et al. 2020).

As a first step in the trend analysis, a visual inspection of the raw time-series data is undertaken, giving a view of the proportion and temporal distribution of censored data. A Kruskal-Wallis test, using a threshold of $\alpha=0.05$, is employed to determine whether data is seasonal or not over the four separate annual samplings.

Depending on the result of the seasonality test, a non-parametric Mann-Kendall or seasonal Kendall test is used to determine the direction of a monotonic trend through the time-series data. Trend rate and the confidence in trend rate are evaluated using Sen-slope regression of observations against time. This is a non-parametric regression procedure, where the Sen-slope estimate (SSE) is taken as the median of all possible inter-observation slopes (Hirsch et al. 1982). In calculating the Kendall S statistic, censored data are dealt with as robustly as possible, following the methods of Helsel (2011), this allows inter-observation increases and decreases to be identified whenever possible (Snelder and Fraser, 2019). In calculating the SSE, censored data are replaced by a value 0.5 times the highest common censor limit. While this biases inter-observation slopes associated with censored data, in most cases with a small proportion of censored data, the median slope will be unaffected. A note is included in the reported results when the median Sen-slope is affected by censored data. In general, when the SSE is affected by censored data, this usually indicates that the trend rate is smaller than can be detected. Trends noted as being affected by censored data are critically analysed to assess if the resulting statistics are meaningful or not. In a small number of cases, trend assessment is not carried out due to insufficient unique data. This occurs when there are <5 non-censored data, or if there are 3 or less unique non-censored values.

While past trend analysis has reported on the 'significance' of any reported trend, in this report the assessment of confidence in a trend direction moves away from the traditional null hypothesis significance testing (NHST) approach and instead follows the recommended credible interval assessment method of McBride (2019). As a result of this change, the confidence in the reported trend direction (ranging from 50 to 100%) is now categorised as in Table 4. A comparison between the results of the confidence grading system and the previous p-value based significance method is given in Appendix V.

Table 1 Confidence categorisation for trend direction results

Confidence Category	Confidence in reported trend direction
Very Likely Improving	90 – 100%
Likely Improving	67 – 90%
Indeterminate	50 – 67%
Likely Degrading	67 – 90%
Very Likely Degrading	90 – 100%

It is noted that the trend analysis methods implemented above are constrained to identifying a monotonic (single direction) trend through any time-series. In many cases, however, environmental time-series data is not monotonic, with a change of conditions or individual events resulting in changes of behaviour at monitoring sites. To account for this, a Loess curve has been overlaid on trend-analysis plots to allow for a qualitative assessment of any non-monotonic trends, and further investigation into the possible cause of any change of behaviour. In addition, a comparison of long term (25 year) and short term (10 year) quantitative trends is undertaken.

In the case of parameters which are sampled at multiple depths within the lake, trend analysis has been carried out on the data from the epilimnion. Differences in the water chemistry between the epilimnion and hypolimnion during the stratified period mean that combining the data from both stratified layers may mask any trends present. Furthermore, the magnitude of the seasonal change in the hypolimnion is greater for many parameters, and the magnitude of seasonal variation may hinder the ability to detect the trend over time. The use of epilimnion data in trend analysis is consistent with national reporting (Larned et al, 2015).

For the analysis of the lake as a whole, results taken at different sites, within the same layer of the water column and on the same day, are averaged to provide a single result. These average values are analysed as described above. This is consistent with the methodology used in Larned et al, 2015).

Appendix II

Physicochemical Monitoring Results 2020-2021

Physicochemical monitoring results collected at Lake Rotorangi on 16 October 2020

Parameter	Unit	L2					L3				
		Surface	Photic	Epilimnion	Hypolimnion	Near benthos	Surface	Photic	Epilimnion	Hypolimnion	Near benthos
Sample depth	m	0	8.75	8.75	32.5	N/S	0	4.83	4.5	35.5	N/S
Temperature	° C	13.8	-	13.8	9.6	N/S	13.9	-	13.5	9.4	N/S
Black disc transparency	m	1.43	-	-	-	N/S	1.26	-	-	-	N/S
Secchi disc transparency	m	3.51	-	-	-	N/S	1.93	-	-	-	N/S
Dissolved oxygen	g/m^3	9.46	-	9.16	2.92	N/S	8.76	-	8.63	1.79	N/S
pH	pH units	7.1	-	7	6.8	N/S	6.8	-	6.9	6.7	N/S
Conductivity	µS/cm	122	-	124	132	N/S	91	-	96	119	N/S
Turbidity	FNU	2.3	-	2.7	3.3	N/S	3.6	-	3.8	1.75	N/S
Suspended solids	g/m^3	< 3	-	< 3	< 3	N/S	< 3	-	< 3	< 3	N/S
E. coli	MPN/100mL	27	-	-	-	N/S	5	-	-	-	N/S
Dissolved reactive phosphorus	g/m^3 P	-	-	0.0038	0.0036	N/S	-	-	0.0026	0.0023	N/S
Total phosphorus	g/m^3 P	-	-	0.025	0.019	N/S	-	-	0.023	0.013	N/S
Ammoniacal nitrogen	g/m^3 N	-	-	0.018	0.012	N/S	-	-	0.021	< 0.005	N/S
Nitrite nitrogen	g/m^3 N	-	-	0.0059	0.0029	N/S	-	-	0.0086	< 0.0010	N/S
Nitrate nitrogen	g/m^3 N	-	-	0.67	0.77	N/S	-	-	0.51	0.52	N/S
Nitrate and nitrite nitrogen	g/m^3 N	-	-	0.67	0.77	N/S	-	-	0.51	0.52	N/S
Total Kjeldahl nitrogen	g/m^3 N	-	-	0.18	0.13	N/S	-	-	0.23	0.11	N/S
Total nitrogen	g/m^3 N	-	-	0.85	0.9	N/S	-	-	0.74	0.63	N/S
Chlorophyll-a	g/m^3	-	0.0075	-	-	N/S	-	0.0044	-	-	N/S

N/S = not sampled

Physicochemical monitoring results collected at Lake Rotorangi on 25 February 2021

Parameter	Unit	L2					L3				
		Surface	Photic	Epilimnion	Hypolimnion	Near benthos	Surface	Photic	Epilimnion	Hypolimnion	Near benthos
Sample depth	m	0	10.1	3.6	22	36	0	10.4	3.6	25.5	50
Temperature	° C	20.9	-	20.4	15.1	10.4	21.7	-	21.4	13.4	9.7
Black disc transparency	m	1.86	-	-	-	-	2.52	-	-	-	-
Secchi disc transparency	m	4.05	-	-	-	-	4.16	-	-	-	-
Dissolved oxygen	g/m^3	8.87	-	6.4	3.06	0	9.02	-	8.84	2.42	0
pH	pH units	7.7	-	7.6	7	7.2	7.7	-	7.5	6.9	7
Conductivity	µS/cm	-	-	146	109	-	133	-	134	109	-
Turbidity	FNU	0.95	-	1.03	3.3	10.1	0.95	-	0.85	4	2.6
Suspended solids	g/m^3	-	-	< 3	< 3	-	< 3	-	< 3	< 3	-
E. coli	MPN/100mL	No result	-	-	-	-	3	-	-	-	-
Dissolved reactive phosphorus	g/m^3 P	< 0.0010	-	< 0.0010	0.0046	0.0021	-	-	0.0014	0.0061	0.004
Total phosphorus	g/m^3 P	0.006	-	0.009	0.014	0.017	-	-	0.006	0.015	0.009
Ammoniacal nitrogen	g/m^3 N	0.005	-	0.006	< 0.005	0.2	-	-	< 0.005	< 0.005	0.031
Nitrite nitrogen	g/m^3 N	-	-	0.0021	0.0011	-	-	-	0.0021	< 0.0010	-
Nitrate nitrogen	g/m^3 N	-	-	0.081	0.58	-	-	-	0.21	0.62	-
Nitrate and nitrite nitrogen	g/m^3 N	0.069	-	0.083	0.58	0.4	-	-	0.21	0.62	0.47
Total Kjeldahl nitrogen	g/m^3 N	-	-	0.17	0.18	-	-	-	0.15	0.16	-
Total nitrogen	g/m^3 N	-	-	0.25	0.75	-	-	-	0.35	0.78	-
Chlorophyll-a	g/m^3	-	0.0023	-	-	-	-	0.0012	-	-	-

Physicochemical monitoring results collected at Lake Rotorangi on 23 March 2021

Parameter	Unit	L2					L3				
		Surface	Photic	Epilimnion	Hypolimnion	Near benthos	Surface	Photic	Epilimnion	Hypolimnion	Near benthos
Sample depth	m	0	7.7	8	31	33	0	9.5	9.5	39	51
Temperature	° C	19	-	18	11.3	10.6	18.5	-	16.6	10	10
Black disc transparency	m	3.09	-	-	-	-	2.47	-	-	-	-
Secchi disc transparency	m	3.91	-	-	-	-	3.81	-	-	-	-
Dissolved oxygen	g/m^3	8.73	-	5.75	0	0	7.74	-	2.22	0	0.05
pH	pH units	7.5	-	7.1	6.9	6.9	7.4	-	6.7	6.9	6.7
Conductivity	µS/cm	144	-	136	132	-	132	-	87	126	-
Turbidity	FNU	0.97	-	2	3.5	5.5	0.95	-	2.5	3.4	24
Suspended solids	g/m^3	< 3	-	< 3	< 3	-	< 3	-	< 3	< 3	-
E. coli	MPN/100mL	3	-	-	-	-	1	-	-	-	-
Dissolved reactive phosphorus	g/m^3 P	-	-	0.0027	0.0045	0.0035	-	-	0.0015	0.0036	0.004
Total phosphorus	g/m^3 P	-	-	0.01	0.01	0.008	-	-	0.008	0.008	0.029
Ammoniacal nitrogen	g/m^3 N	-	-	0.053	0.197	0.25	-	-	< 0.005	0.066	0.103
Nitrite nitrogen	g/m^3 N	-	-	0.0081	0.0092	-	-	-	0.0017	0.0018	-
Nitrate nitrogen	g/m^3 N	-	-	0.28	0.36	-	-	-	0.46	0.47	-
Nitrate and nitrite nitrogen	g/m^3 N	-	-	0.29	0.37	0.32	-	-	0.46	0.47	0.42
Total Kjeldahl nitrogen	g/m^3 N	-	-	0.28	0.36	-	-	-	0.41	0.17	
Total nitrogen	g/m^3 N	-	-	0.57	0.73	-	-	-	0.88	0.64	-
Chlorophyll-a	g/m^3	-	0.002	-	-	-	-	0.0024	-	-	-

Physicochemical monitoring results collected at Lake Rotorangi on 24 June 2021

Parameter	Unit	L2					L3				
		Surface	Photic	Epilimnion	Hypolimnion	Near benthos	Surface	Photic	Epilimnion	Hypolimnion	Near benthos
Sample depth	m	0	3.65	5	34.5	N/S	0	5	5	27	N/S
Temperature	° C	11.5	-	11.8	10.7	N/S	11.6	-	11.8	10.7	N/S
Black disc transparency	m	1.04	-	-	-	N/S	1.82	-	-	-	N/S
Secchi disc transparency	m	1.46	-	-	-	N/S	2.01	-	-	-	N/S
Dissolved oxygen	g/m^3	9.79	-	9.41	6.43	N/S	8.57	-	8.04	0.2	N/S
pH	pH units	6.8	-	7.1	6.7	N/S	7.1	-	7	6.7	N/S
Conductivity	µS/cm	127	-	126	132	N/S	124	-	122	124	N/S
Turbidity	FNU	3.7	-	4.4	9.8	N/S	2.6	-	2.5	1.85	N/S
Suspended solids	g/m^3	< 3	-	< 3	3	N/S	< 3	-	< 3	< 3	N/S
E. coli	MPN/100mL	99	-	-	-	N/S	15	-	-	-	N/S
Dissolved reactive phosphorus	g/m^3 P	-	-	0.0073	0.0062	N/S	-	-	0.0032	0.0032	N/S
Total phosphorus	g/m^3 P	-	-	0.022	0.029	N/S	-	-	0.014	0.01	N/S
Ammoniacal nitrogen	g/m^3 N	-	-	0.03	0.145	N/S	-	-	< 0.005	0.028	N/S
Nitrite nitrogen	g/m^3 N	-	-	0.0085	0.0167	N/S	-	-	0.0016	0.0012	N/S
Nitrate nitrogen	g/m^3 N	-	-	0.56	0.6	N/S	-	-	0.61	0.48	N/S
Nitrate and nitrite nitrogen	g/m^3 N	-	-	0.57	0.61	N/S	-	-	0.61	0.48	N/S
Total Kjeldahl nitrogen	g/m^3 N	-	-	0.2	0.31	N/S	-	-	0.15	0.22	N/S
Total nitrogen	g/m^3 N	-	-	0.78	0.93	N/S	-	-	0.76	0.7	N/S
Chlorophyll-a	g/m^3	-	0.0015	-	-	N/S	-	0.0012	-	-	N/S

N/S = not sampled

Appendix III

Macrophyte Survey Report

To	Job Manager, Katie Blakemore
From	Environmental Scientist – Freshwater Ecology, Katie Blakemore
Document	2763233
Date	28 April 2021

Aquatic macrophyte survey of Lake Rotorangi, April 2021

A survey of the aquatic macrophytes in Lake Rotorangi was carried out on 16 April 2021. The survey was undertaken by the Taranaki Regional Council under contract to Trustpower Ltd. The survey began at the Patea Dam boat ramp and the true left of the lake was surveyed on the way up the lake to Mangamingi. The true right of the lake was surveyed on the return to the Patea Dam. Larger arms of the lake were entered in order to identify the macrophytes present. Despite these arms making up a small proportion of the lake area, they are generally shallower than the main body of the lake and as such provide a disproportionately large habitat for macrophytes. At regular intervals the macrophyte species seen on the lake edges were recorded on a map of Lake Rotorangi, and the dominant species noted. The dominant taxa were then colour coded and their distributions are shown in Figure 1, with previous data shown in Figure 2. Surveys are now undertaken as a requirement of consent 0489-2, which requires the survey to be undertaken every three years (commencing in 2012). The last survey was conducted in April 2018.

Previous macrophyte monitoring, which began in March 1987, found *Egeria densa* dominating the greatest proportion of the lake edges, increasing as time progressed (Figure 2). Since then, *E. densa* has dominated the lake in most previous surveys, with the exception of the 2005 and 2008 surveys, when *Lagarosiphon major* was dominant. In surveys prior to 2018, *E. densa* has always dominated the upper end of the lake. In 2018, macrophytes were not recorded in the upper end of the lake, whilst *E. densa* was recorded only in the lower lake. It should be noted that the 2018 survey was impacted by high turbidity. The current survey recorded *E. densa* as the dominant macrophyte in the upper lake, while in the lower lake it was not the dominant macrophyte but it was still present. Five species of macrophyte were recorded in the current survey (Table 1). *Lagarosiphon major* was present, but as in the April 2018 survey, was not dominant in any part of the lake.

The macrophyte survey undertaken in 2012 was the first to document *Ceratophyllum demersum* (hornwort) in Lake Rotorangi. Since this survey, when *C. demersum* was only dominant on the true left bank downstream of the Hawera water ski club rooms, its distribution has increased markedly, as predicted in a report prepared by NIWA[1]. In the two most recent surveys, *C. demersum* was the dominant macrophyte, and it should be noted that although the April 2018 survey recorded no macrophytes through the mid-section of the lake, it is possible that it may have been present and obscured by high turbidity.

E. densa, *L. major* and *C. demersum* are introduced aquatic plants which are listed in the Pest Plant Accord[2] and are thereby considered an 'unwanted organism'. This means that it is illegal to sell, propagate or distribute these plants in New Zealand. All three species are distributed throughout the North Island, and *C. demersum* especially can have significant impacts on hydroelectric schemes. Trustpower commissioned NIWA to perform an assessment of *C. demersum*, and its potential impact on the scheme and ecology of the lake. They concluded that due to a number of factors, there was unlikely to be a significant impact on the hydroelectric scheme or the ecology of the lake.

E. densa tends to thrive in turbid and enriched waters of lakes, whereas *L. major* is more common in clear water of low fertility. In is interesting to note that *L. major* has typically been dominant in the middle and

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[1] Lake Rotorangi hornwort assessment. Prepared for Trustpower by NIWA (Rohan Wells). NIWA client report No. HAM2012-062.

[2] The National Pest Plant Accord (NPPA) is a cooperative agreement between the Nursery and Garden Industry Association, regional councils and government departments with biosecurity responsibilities.

lower reaches of the lake, which tend to have clearer water. *E. densa* is more dominant in the more riverine upper reaches, and has in the past been often associated with clumps of filamentous green algae, indicating a more enriched environment in these reaches. The upper reaches are also more regularly affected by flooding in the Patea River upstream of the lake, and are generally more turbid than the lower reaches.

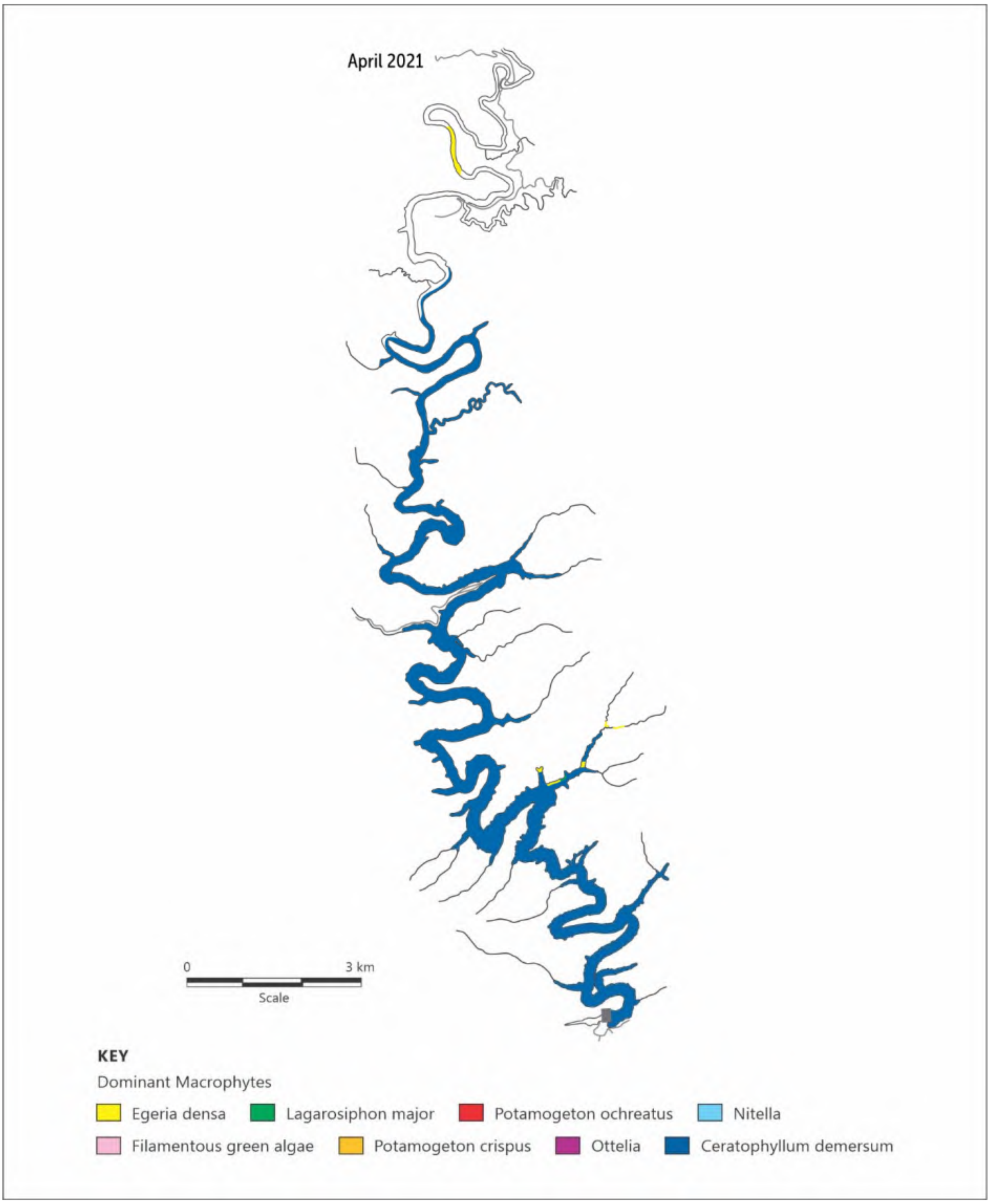


Figure 1 Dominant macrophytes recorded in Lake Rotorangi on 16 April 2021

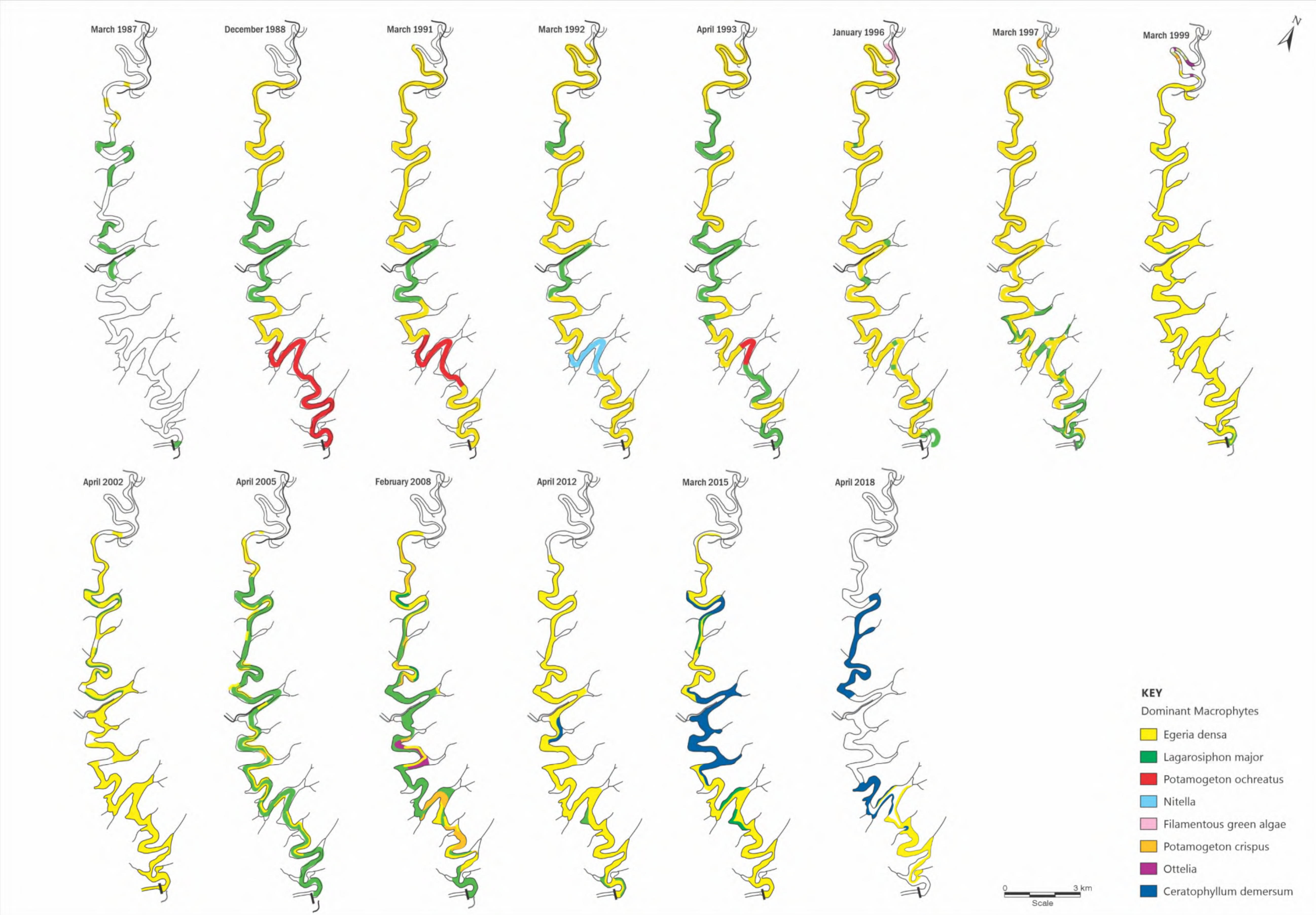


Figure 2 Dominant macrophytes recorded in Lake Rotorangi from 1987 to 2018

Actual coverage of macrophytes throughout the lake remains restricted to the edges of the lake and extends further into the middle of the lake only on the inside of large wide bends where shallow areas permit the spread of these macrophytes. In areas where the banks drop away quickly the macrophytes have been previously recorded in patches rather than large continuous thick growths. However, the presence of *C. demersum* is causing this to change, as this species can grow taller and in deeper water than *E. densa* and *l. major*, enabling it to colonise more of the lakebed. *C. demersum* has been observed growing as deep as 8 metres. Despite this, in the areas with the steepest banks there are still patches of lakebed clear of macrophytes. In the current survey, species diversity was greatest in the inlets at the lower end of the lake.

A summary of the aquatic macrophyte species found in Lake Rotorangi by the summer-autumn surveys performed between 1986 and 2021 is presented in Table 1.

Table 1 Aquatic macrophytes recorded in Lake Rotorangi between 1986 and 2021

Species	Date															
	Mar 86	Mar 87	Dec 88	Mar 91	Mar 92	Apr 93	Jan 96	Mar 97	Mar 99	Apr 02	Apr 05	Feb 08	Mar 12	Mar 15	Apr 18	Apr 21
Aponogeton distachyon	✓	✓														
Ceratophyllum demersum													✓	✓	✓	✓
Chara australis													✓*			
Egeria densa	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Elodea canadensis												✓				
Glossostigma elatinoides													✓	✓	✓	
Lagarosiphon major	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Lilaeopsis ruthiana													✓*			
Nasturtium officinale						✓										
Nitella cristata													✓*			
Nitella hookeri					✓											✓
Ottelia ovalifolia				✓		✓			✓	✓	✓	✓		✓		
Potamogeton cheesmanii	✓	✓	✓													
Potamogeton crispus	✓	✓		✓		✓		✓		✓	✓	✓		✓		
Potamogeton ochreatus				✓	✓	✓										✓
Potamogeton pectinatus	✓	✓														
Filamentous green algae				✓	✓	✓	✓		✓	✓	✓		✓	✓		

* Recorded by NIWA in April 2012

A total of 16 aquatic macrophytes have been recorded in Lake Rotorangi over the thirty-five year record. Only *E. densa* has been recorded on all survey occasions, although *L. major* has been recorded on all occasions except the 2018 survey. It is likely that *L. major* was present on this occasion but was not recorded due to high turbidity at the time of this survey. Another species frequently recorded is *Potamogeton crispus*, with this species even dominating parts of the lake in 2008. However in the 2015 survey, this species was recorded only at the head of the lake, and not in abundance. It has not been recorded in the most recent two surveys. *Potamogeton ochreatus* was recorded, although this was only noted in one small patch and was not dominant in any part of the lake. The distribution of *Potamogeton* spp. may be influenced by the large rudd (*Scardinius erythrophthalmus*) population in the lake. A 2002 study[3] found that rudd preferred eating *P. ochreatus* over *E. densa* and *l. major*, while *C. demersum* was least

[3] Lake MD, Hicks BJ, Wells RDS & Dugdale TM. 2002. Consumption of submerged aquatic macrophytes by rudd (*Scardinius erythrophthalmus* L.) in New Zealand. Hydrobiologia 470: 13-22.

preferred. Although *P. crispus* was not included in this study, its similar appearance to *P. ochreatus* indicates that it also would be preferentially eaten by rudd, explaining the reduced abundance of *Potamogeton* spp. in Lake Rotorangi in recent years.

A survey undertaken by NIWA in 2012 recorded four species that had not previously been recorded in Lake Rotorangi. It is unlikely that these species were new additions to the lake. Rather, these species were either not widespread, had growth habits that caused them to be relatively discreet eg. low growing plants that inhabit deep water. These species were only recorded when the boat was stationary (*G. elatinoides*) or by divers (*C. australis*, *L. ruthiana* and *N. cristata*). It is unlikely that these species will ever become abundant.

C. demersum is considered highly invasive, and as predicted is becoming dominant in the lake. While this is not expected to cause significant impacts on the ecology of Lake Rotorangi, there is now greater potential for it to spread to nearby lakes where such impacts could be much more severe. In 2021, hornwort was recorded in Lake Herengawe, south of Lake Rotorangi, for the first time. Considering the proximity of Lake Rotokare to the Glen Nui boat ramp, it may be worthwhile controlling *C. demersum* in the vicinity of the Glen Nui boat ramp to help prevent its spread. The usefulness of this may be subject to further investigation by the Taranaki Regional Council.

Appendix IV

Trophic Level Index

Trophic level and state, with trophic level components and annual average values used in to calculate the trophic level of Lake Rotorangi as a whole

Monitoring Year	Chlorophyll-a (mg m^{-3})	Secchi Depth (m)	Total Nitrogen (mg m^{-3})	Total Phosphorus (mg m^{-3})	TLc	TLs	TLn	TLp	TLI	Trophic State
1996	2.29	2.84	610	22.8	3.13	4.3	4.77	4.18	4.1	Eutrophic
1997	1.67	3.46	505	12	2.78	4.06	4.53	3.37	3.68	Mesotrophic
1998	2.35	2.81	643.75	19.38	3.16	4.31	4.84	3.98	4.07	Eutrophic
1999	2.6	3.38	687.5	25.75	3.27	4.09	4.93	4.34	4.16	Eutrophic
2000	3.06	3.71	641	15.6	3.45	3.97	4.84	3.7	3.99	Mesotrophic
2001	2.24	3.22	989	18.5	3.11	4.14	5.41	3.92	4.14	Eutrophic
2002	2.83	2.73	836	27.1	3.37	4.35	5.19	4.4	4.32	Eutrophic
2003	2.91	3.52	586.25	20.88	3.4	4.03	4.72	4.07	4.06	Eutrophic
2004	3.61	0.71	914	61.2	3.64	5.92	5.3	5.44	5.07	Supertrophic
2005	2.52	2.94	601	20.2	3.24	4.26	4.75	4.03	4.07	Eutrophic
2006	3.49	2.53	624	26.2	3.6	4.44	4.8	4.36	4.3	Eutrophic
2007	5.56	3.32	523.75	15.75	4.11	4.11	4.57	3.71	4.13	Eutrophic
2008	1.69	3.34	643	20.4	2.8	4.1	4.84	4.04	3.94	Mesotrophic
2009	3.84	2.95	586	16.8	3.7	4.25	4.72	3.8	4.12	Eutrophic
2010	3.61	2.4	640	23.3	3.64	4.5	4.84	4.21	4.3	Eutrophic
2011	4.19	2.65	732	35	3.8	4.38	5.01	4.73	4.48	Eutrophic
2012	3.4	2.52	621	36.7	3.57	4.45	4.8	4.79	4.4	Eutrophic
2013	4.21	3.05	558	26.8	3.81	4.21	4.66	4.39	4.27	Eutrophic
2014	4.8	2.7	616	28.8	3.95	4.36	4.79	4.48	4.39	Eutrophic
2015	3.8	2.76	900	186.2	3.69	4.33	5.28	6.85	5.04	Supertrophic
2016	2.87	2.88	530	23.12	3.38	4.28	4.59	4.2	4.11	Eutrophic
2017	3.98	2.54	614	32.7	3.74	4.43	4.78	4.64	4.4	Eutrophic
2018	5.58	2.07	707	42.4	4.12	4.68	4.97	4.97	4.68	Eutrophic
2019	2.55	3.86	552	19.5	3.25	3.92	4.64	3.98	3.95	Mesotrophic
2020	2.08	2.57	549	21.6	3.03	4.42	4.64	4.11	4.05	Eutrophic
2021	2.81	3.1	681	14.73	3.36	4.19	4.92	3.63	4.02	Eutrophic

Trophic level and state, with trophic level components and annual average values used in to calculate the trophic level at site L2 in Lake Rotorangi

Monitoring Year	Chlorophyll-a (mg m^{-3})	Secchi Depth (m)	Total Nitrogen (mg m^{-3})	Total Phosphorus (mg m^{-3})	TLc	TLs	TLn	TLp	TLI	Trophic State
1996	2.12	2.51	620	28	3.05	4.45	4.8	4.44	4.18	Eutrophic
1997	1.43	2.68	520	15.75	2.62	4.37	4.57	3.71	3.82	Mesotrophic
1998	1.9	2.36	690	23.25	2.93	4.52	4.93	4.21	4.15	Eutrophic
1999	2.02	2.5	728	72.8	3	4.45	5.01	5.66	4.53	Eutrophic
2000	4.22	3.52	676	18.2	3.81	4.03	4.91	3.9	4.16	Eutrophic
2001	2.72	3.34	1010	16	3.33	4.1	5.43	3.73	4.15	Eutrophic
2002	2.02	2.5	894	32.8	3	4.45	5.27	4.64	4.34	Eutrophic
2003	2.8	3.2	674	24.2	3.36	4.15	4.9	4.26	4.17	Eutrophic
2004	2.93	0.83	981.43	102.29	3.4	5.74	5.4	6.09	5.16	Supertrophic
2005	2.42	2.59	628	24.8	3.2	4.41	4.81	4.29	4.18	Eutrophic
2006	3.9	2.04	784	32.6	3.72	4.7	5.1	4.64	4.54	Eutrophic
2007	6.4	2.94	580	22.2	4.27	4.26	4.71	4.15	4.35	Eutrophic
2008	1.83	2.94	718.33	23.67	2.88	4.26	4.99	4.23	4.09	Eutrophic
2009	3.85	3.24	578	19.8	3.71	4.14	4.7	4	4.14	Eutrophic
2010	3.62	2	678	27.4	3.64	4.72	4.91	4.42	4.42	Eutrophic
2011	4.53	2.56	808	43.4	3.89	4.42	5.14	5	4.61	Eutrophic
2012	3.2	2.23	628	46.4	3.5	4.59	4.81	5.08	4.5	Eutrophic
2013	4	2.88	580	34	3.75	4.28	4.71	4.69	4.36	Eutrophic
2014	2.65	2.5	700	35.4	3.3	4.45	4.95	4.74	4.36	Eutrophic
2015	3.85	2.56	854	159.6	3.71	4.43	5.21	6.65	5	Supertrophic
2016	2.8	2.76	644	27.6	3.36	4.33	4.84	4.43	4.24	Eutrophic
2017	4.32	2.27	638	42.6	3.84	4.57	4.83	4.98	4.55	Eutrophic

Monitoring Year	Chlorophyll-a (mg m^{-3})	Secchi Depth (m)	Total Nitrogen (mg m^{-3})	Total Phosphorus (mg m^{-3})	TLc	TLs	TLn	TLp	TLI	Trophic State
2018	5.2	1.6	780	63.4	4.04	4.98	5.1	5.48	4.9	Eutrophic
2019	2.78	3.28	532	25.4	3.35	4.12	4.59	4.32	4.1	Eutrophic
2020	2.17	2.19	574	29.8	3.08	4.61	4.69	4.52	4.23	Eutrophic
2021	3.33	3.23	676	16.83	3.55	4.14	4.91	3.8	4.1	Eutrophic

Trophic level and state, with trophic level components and annual average values used in to calculate the trophic level at site L3 in Lake Rotorangi

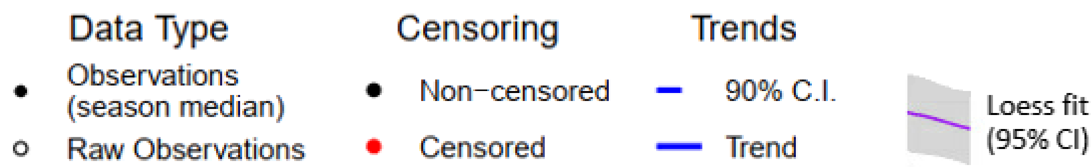
Monitoring Year	Chlorophyll-a (mg m^{-3})	Secchi Depth (m)	Total Nitrogen (mg m^{-3})	Total Phosphorus (mg m^{-3})	TLc	TLs	TLn	TLp	TLI	Trophic State
1996	2.45	3.16	600	17.6	3.21	4.17	4.75	3.85	4	Eutrophic
1997	2.72	3.7	560	11.2	3.33	3.97	4.66	3.28	3.81	Mesotrophic
1998	2.8	3.26	604	14	3.36	4.13	4.76	3.56	3.95	Mesotrophic
1999	2.67	3.47	685	13.75	3.3	4.05	4.93	3.54	3.96	Mesotrophic
2000	1.9	3.9	606	13	2.93	3.91	4.77	3.47	3.77	Mesotrophic
2001	1.75	3.1	968	21	2.84	4.19	5.38	4.08	4.12	Eutrophic
2002	3.62	2.96	778	21.4	3.64	4.25	5.09	4.1	4.27	Eutrophic
2003	3.02	3.85	555	23	3.44	3.92	4.65	4.19	4.05	Eutrophic
2004	4.3	0.59	840	50.8	3.83	6.13	5.19	5.2	5.09	Supertrophic
2005	2.62	3.28	574	15.6	3.28	4.12	4.69	3.7	3.95	Mesotrophic
2006	3.08	3.03	464	19.8	3.46	4.22	4.42	4	4.02	Eutrophic
2007	4.72	3.7	517.5	15.25	3.93	3.97	4.56	3.67	4.03	Eutrophic
2008	1.55	3.75	634	17.8	2.7	3.96	4.82	3.87	3.84	Mesotrophic
2009	3.83	2.66	594	13.8	3.7	4.38	4.74	3.55	4.09	Eutrophic
2010	3.6	2.8	602	19.2	3.63	4.32	4.76	3.97	4.17	Eutrophic
2011	3.85	2.73	656	26.6	3.71	4.34	4.87	4.38	4.32	Eutrophic
2012	3.6	2.8	614	27	3.63	4.32	4.78	4.4	4.28	Eutrophic
2013	4.42	3.22	536	19.6	3.86	4.14	4.6	3.99	4.15	Eutrophic
2014	6.95	2.91	532	22.2	4.36	4.27	4.59	4.15	4.34	Eutrophic
2015	3.75	2.96	946	212.8	3.68	4.25	5.35	7.02	5.07	Supertrophic
2016	2.93	3.01	502.5	21	3.41	4.23	4.52	4.08	4.06	Eutrophic
2017	3.62	2.81	590	22.8	3.64	4.31	4.73	4.18	4.22	Eutrophic

Monitoring Year	Chlorophyll-a (mg m^{-3})	Secchi Depth (m)	Total Nitrogen (mg m^{-3})	Total Phosphorus (mg m^{-3})	TLc	TLs	TLn	TLp	TLI	Trophic State
2018	5.95	2.54	634	21.4	4.19	4.44	4.82	4.1	4.39	Eutrophic
2019	2.33	4.45	572	13.6	3.15	3.74	4.69	3.53	3.78	Mesotrophic
2020	1.97	2.95	524	13.4	2.97	4.25	4.58	3.51	3.83	Mesotrophic
2021	2.3	2.98	686	12.2	3.14	4.24	4.93	3.39	3.92	Mesotrophic

Appendix V

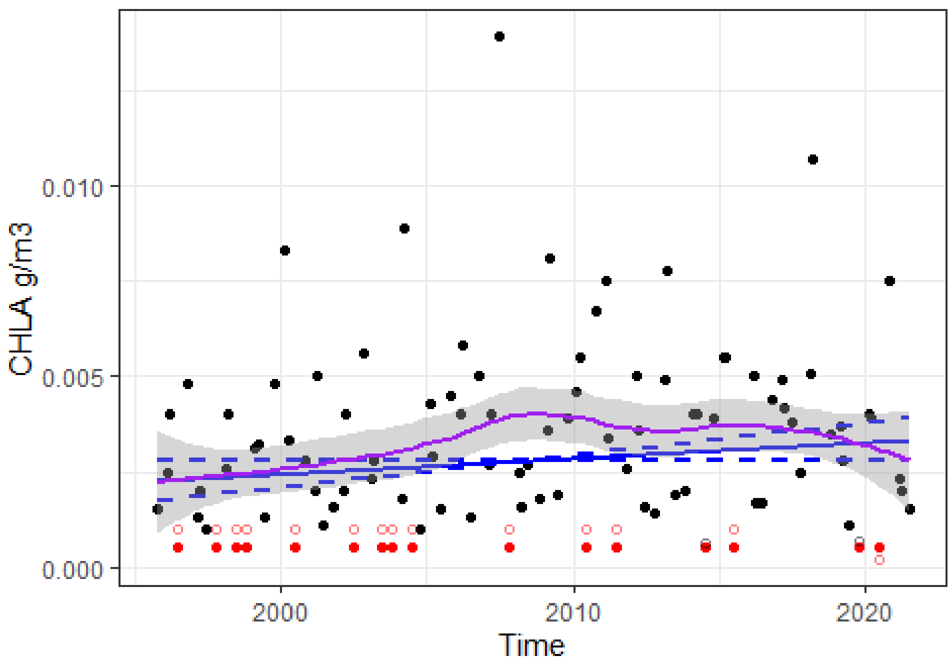
Trend plots for the period 1996-2021

Legend for all trend plots:



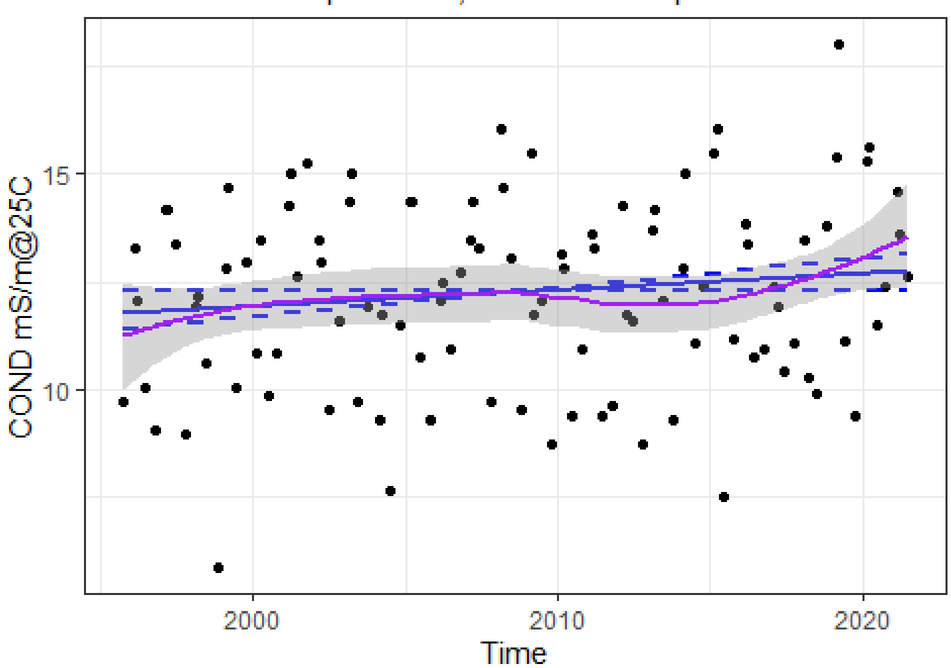
L2 CHLA Seasonal Trend Analysis

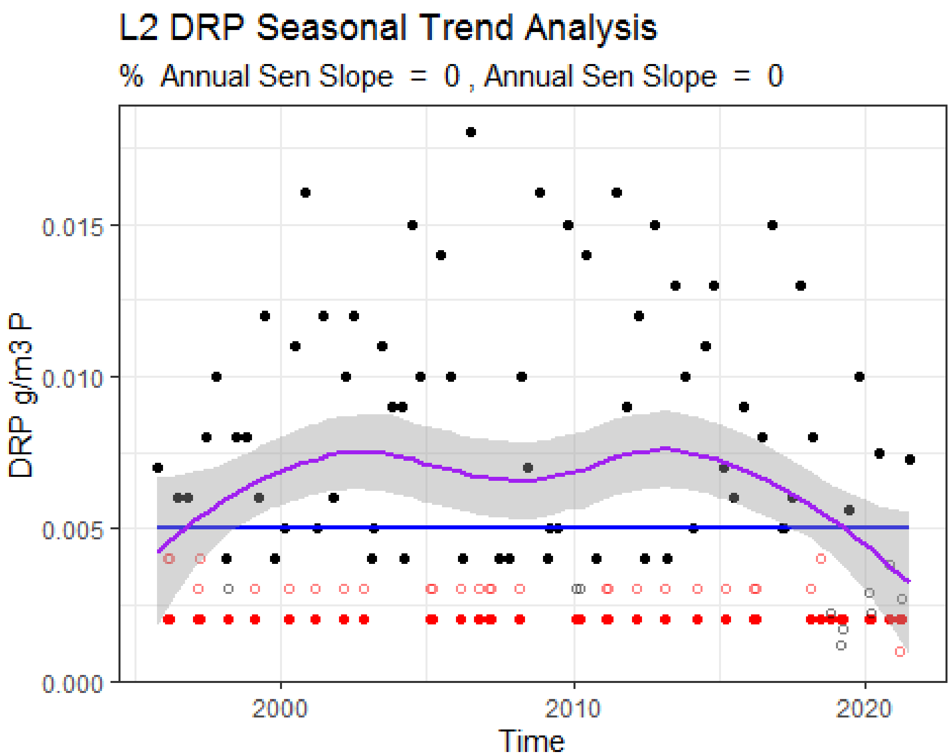
% Annual Sen Slope = 1.5 , Annual Sen Slope = 4.09e-05

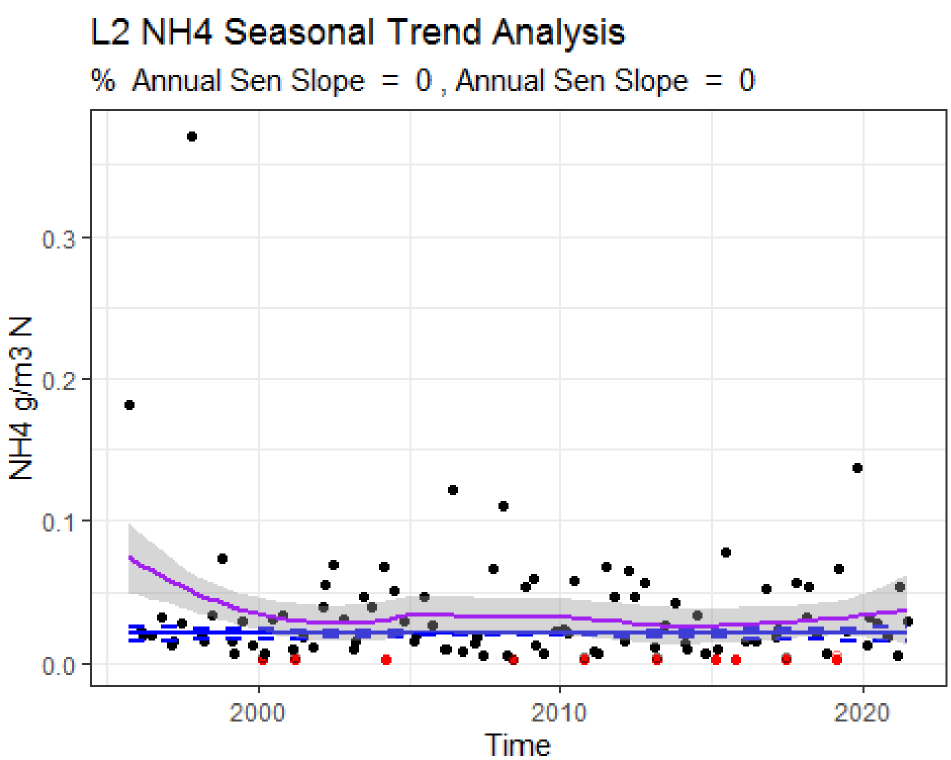


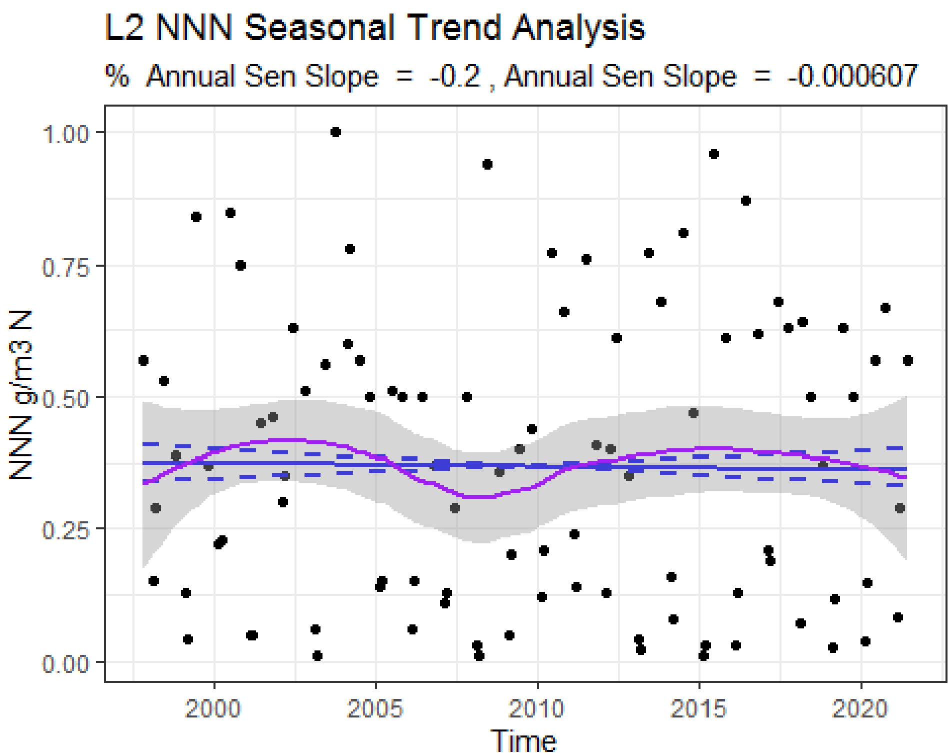
L2 COND Seasonal Trend Analysis

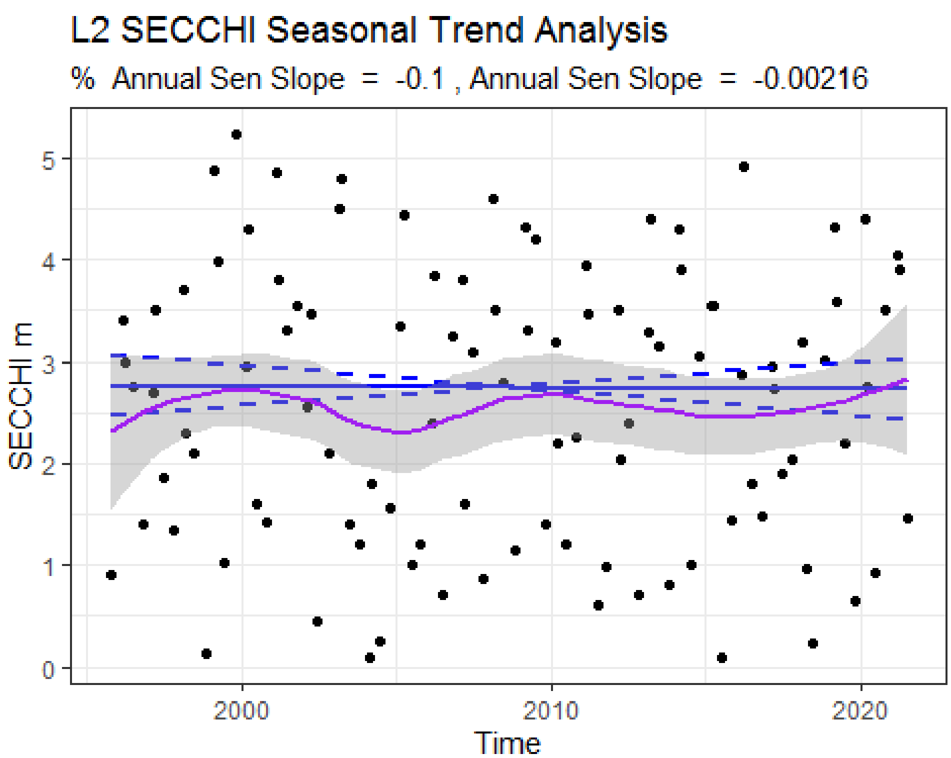
% Annual Sen Slope = 0.3 , Annual Sen Slope = 0.0368

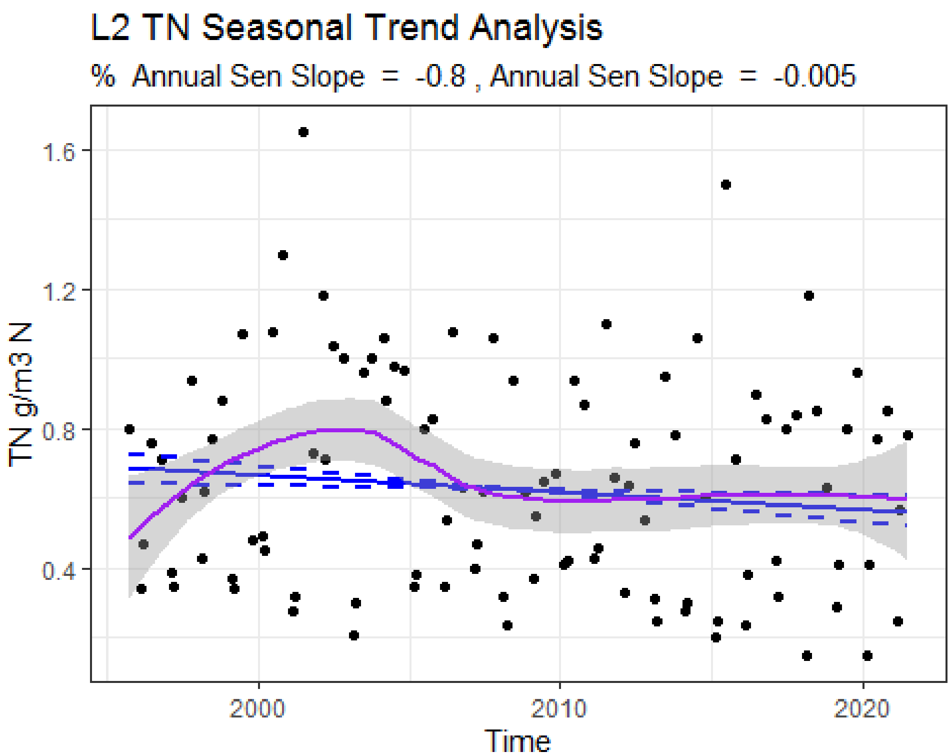


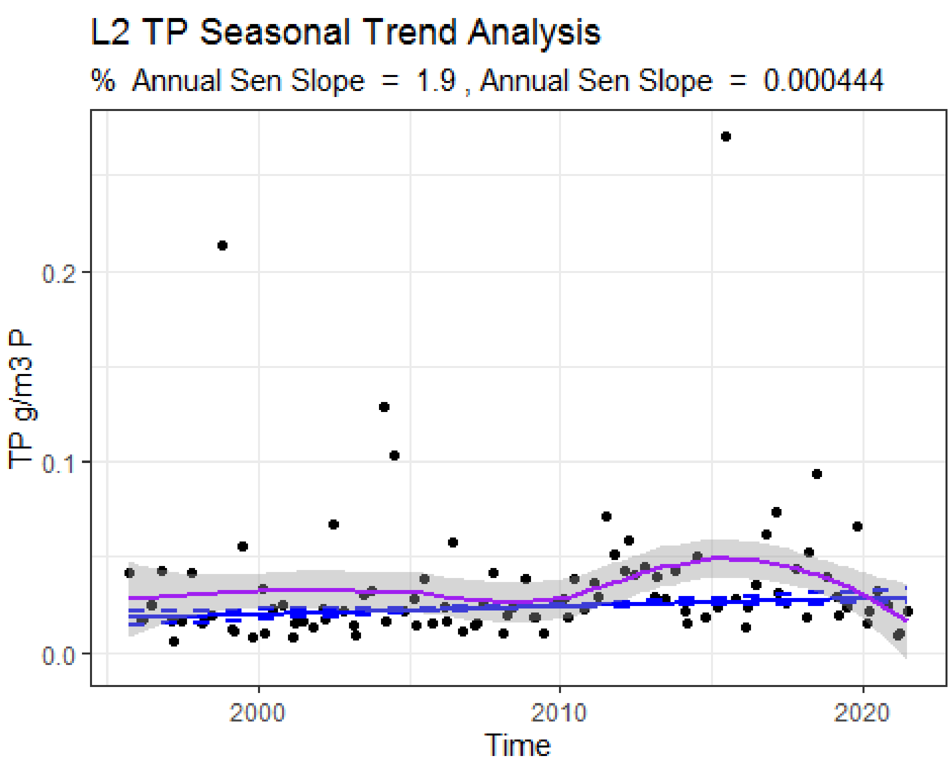

L2 DRP Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
DRP g/m3 P
0.015
0.010
0.005
0.000
2000
2010
2020
Time

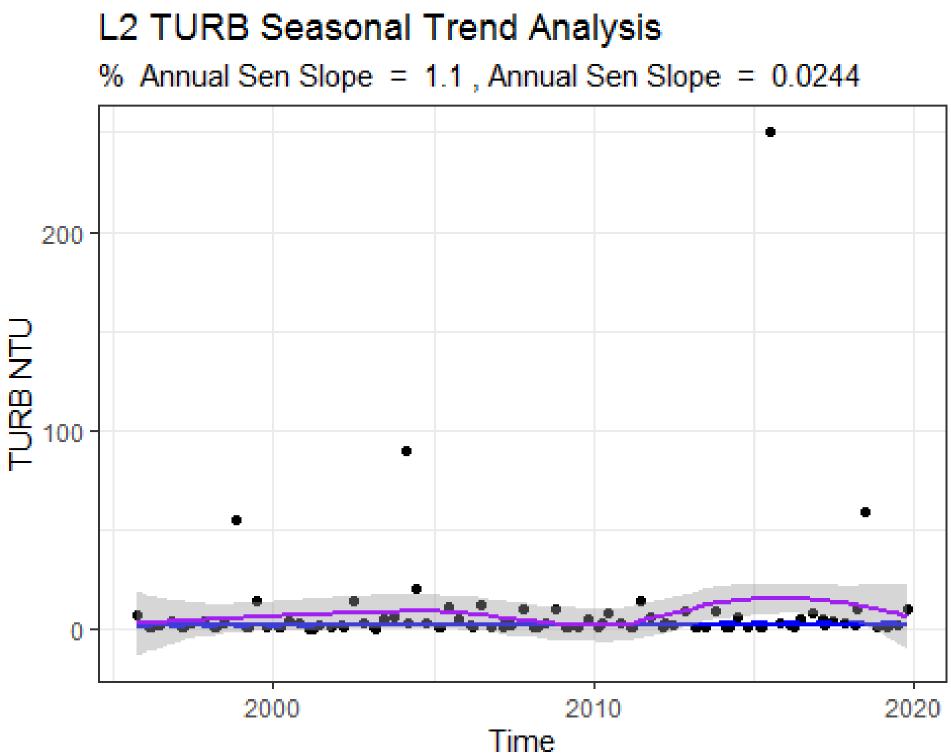

L2 NH4 Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
NH4 g/m3 N
0.3
0.2
0.1
0.0
2000
2010
2020
Time

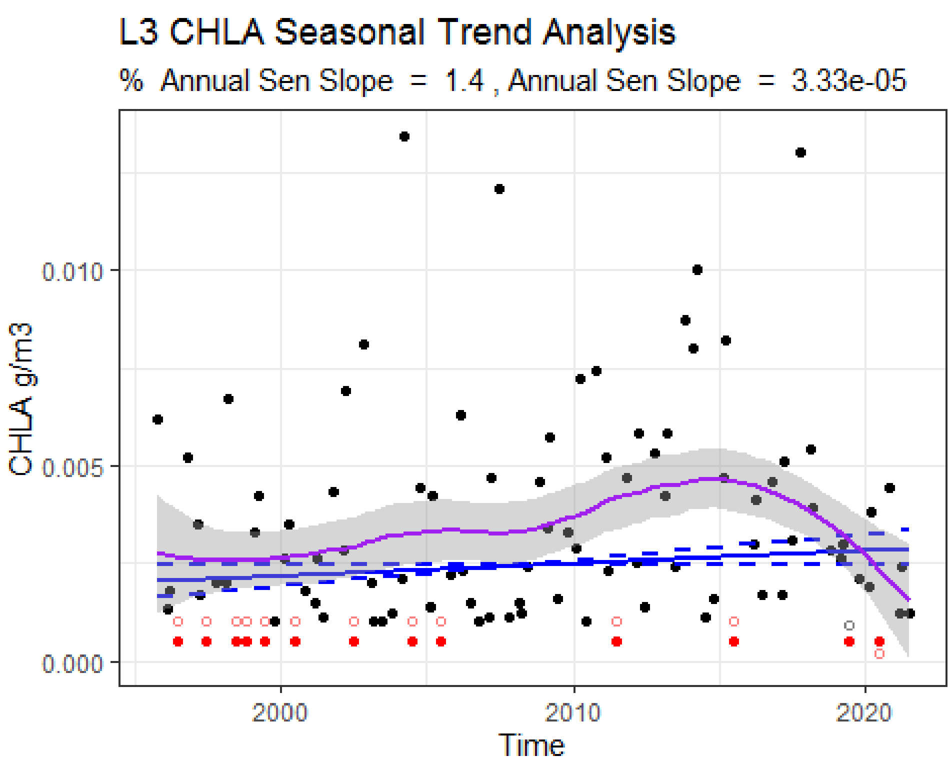

L2 NNN Seasonal Trend Analysis
% Annual Sen Slope = -0.2 , Annual Sen Slope = -0.000607
NNN g/m3 N
1.00
0.75
0.50
0.25
0.00
2000
2005
2010
2015
2020
Time

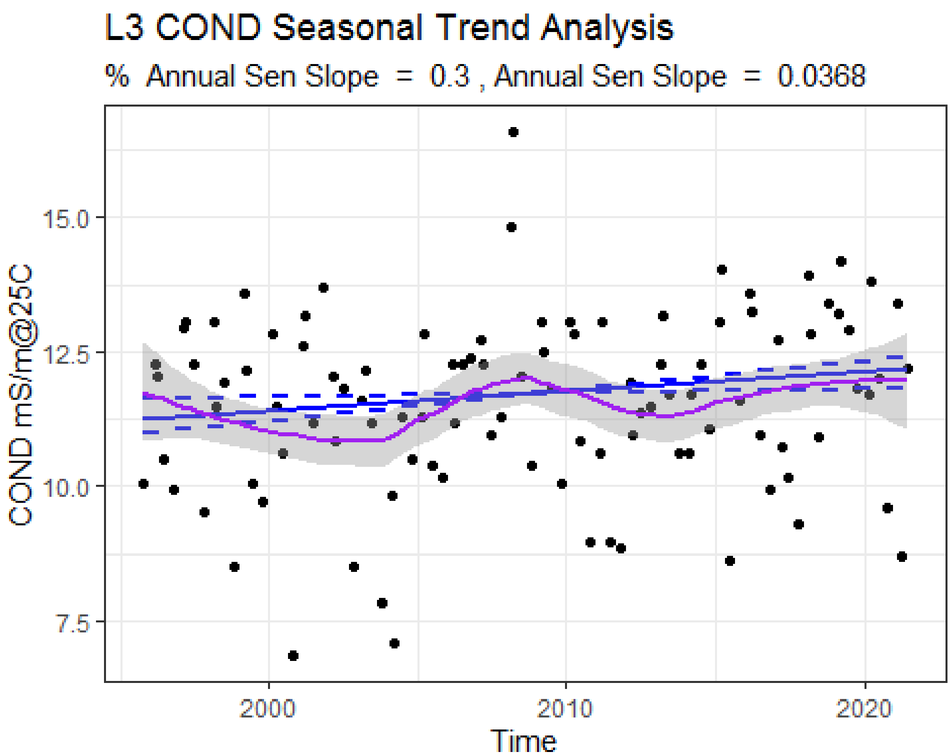

L2 SECCHI Seasonal Trend Analysis
% Annual Sen Slope = -0.1 , Annual Sen Slope = -0.00216
SECCHI m
5
4
3
2
1
0
2000
2010
2020
Time

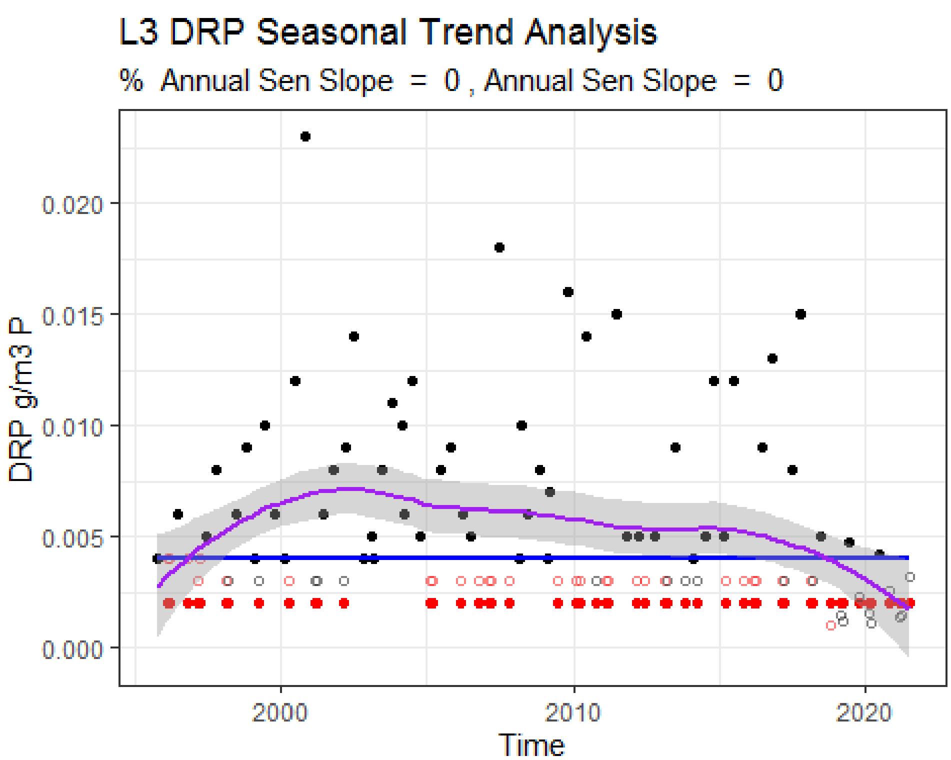

L2 TN Seasonal Trend Analysis
% Annual Sen Slope = -0.8 , Annual Sen Slope = -0.005
TN g/m3 N
1.6
1.2
0.8
0.4
2000
2010
2020
Time

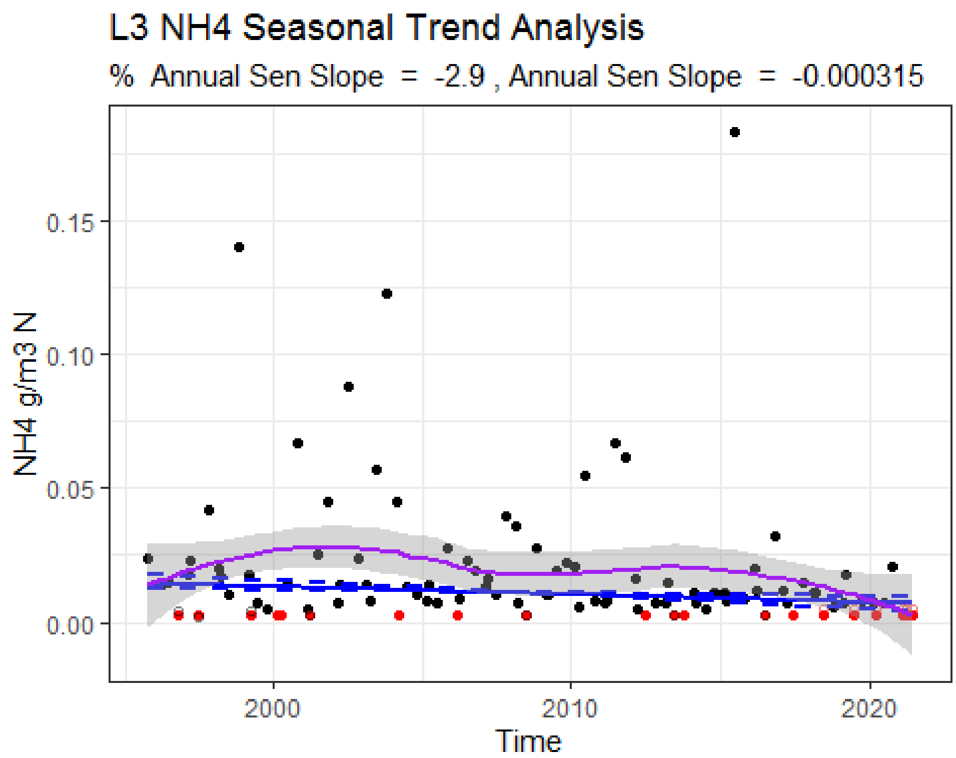

L2 TP Seasonal Trend Analysis
% Annual Sen Slope = 1.9 , Annual Sen Slope = 0.000444
TP g/m3 P
0.2
0.1
0.0
2000
2010
2020
Time

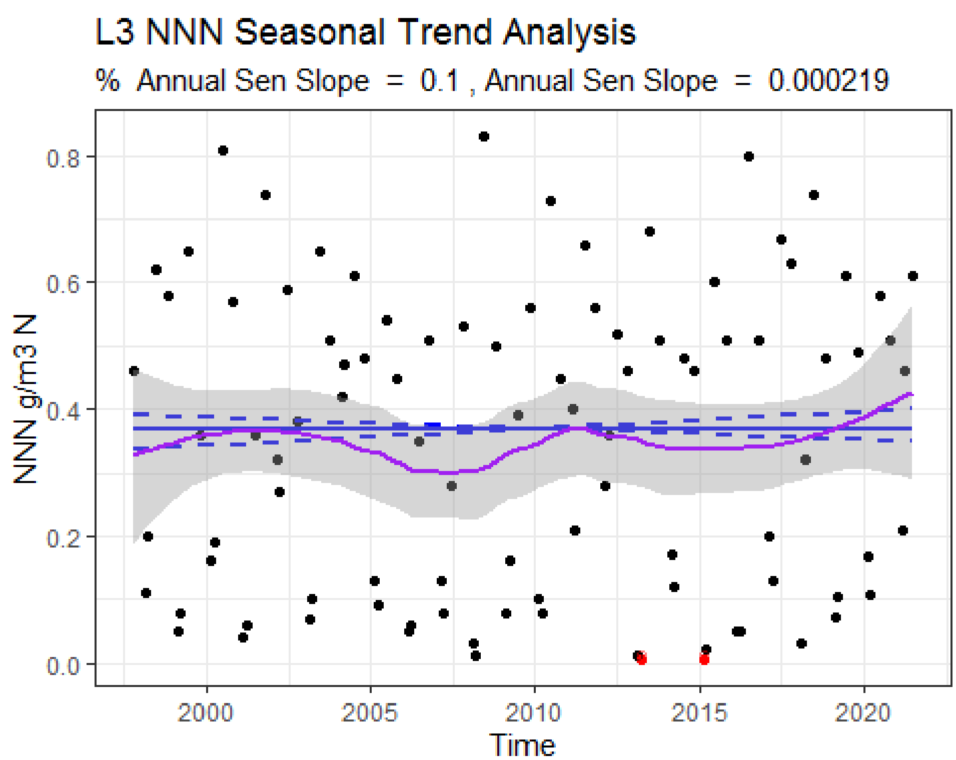

L2 TURB Seasonal Trend Analysis
% Annual Sen Slope = 1.1 , Annual Sen Slope = 0.0244
TURB NTU
200
100
0
2000
2010
2020
Time

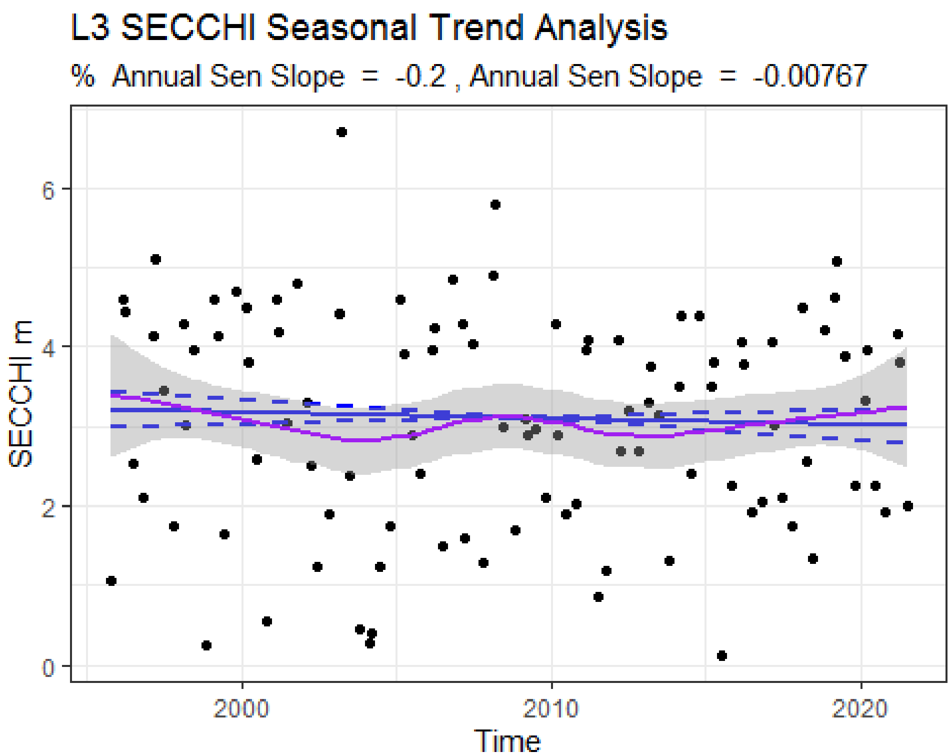

L3 CHLA Seasonal Trend Analysis
% Annual Sen Slope = 1.4 , Annual Sen Slope = 3.33e-05
CHLA g/m3
0.010
0.005
0.000
2000
2010
2020
Time

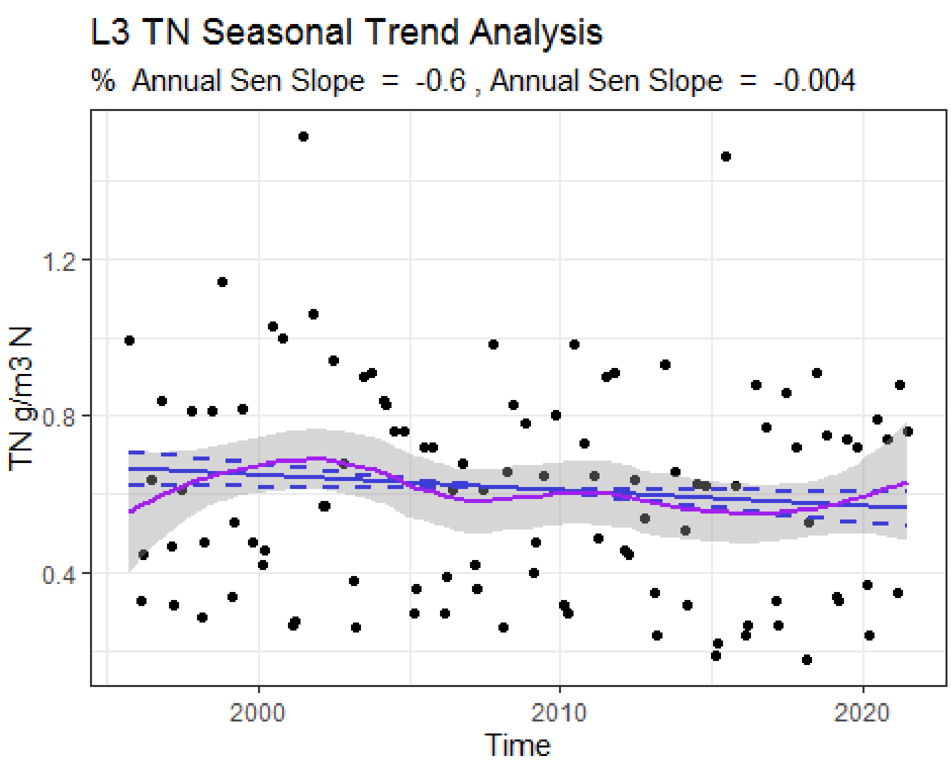

L3 COND Seasonal Trend Analysis
% Annual Sen Slope = 0.3 , Annual Sen Slope = 0.0368
COND mS/m@25C
15.0
12.5
10.0
7.5
2000
2010
2020
Time


L3 DRP Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
DRP g/m3 P
0.020
0.015
0.010
0.005
0.000
2000
2010
2020
Time


L3 NH4 Seasonal Trend Analysis
% Annual Sen Slope = -2.9 , Annual Sen Slope = -0.000315
NH4 g/m3 N
0.15
0.10
0.05
0.00
2000
2010
2020
Time

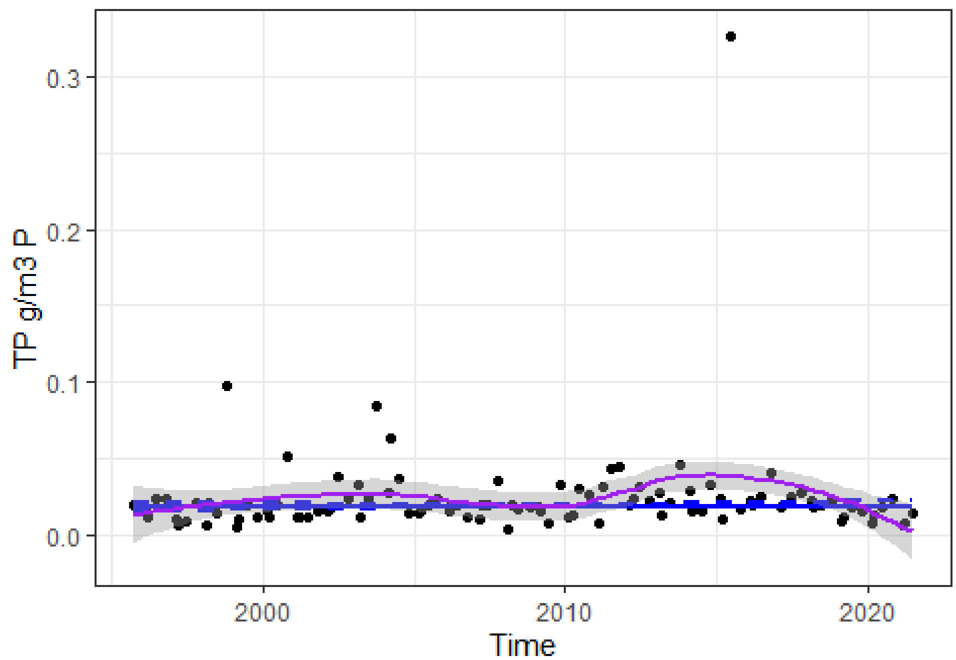

L3 NNN Seasonal Trend Analysis
% Annual Sen Slope = 0.1 , Annual Sen Slope = 0.000219
NNN g/m3 N
0.8
0.6
0.4
0.2
0.0
2000
2005
2010
2015
2020
Time


L3 SECCHI Seasonal Trend Analysis
% Annual Sen Slope = -0.2 , Annual Sen Slope = -0.00767
SECCHI m
0
2
4
6
2000
2010
2020
Time


L3 TN Seasonal Trend Analysis
% Annual Sen Slope = -0.6 , Annual Sen Slope = -0.004
TN g/m3 N
0.4
0.8
1.2
2000
2010
2020
Time

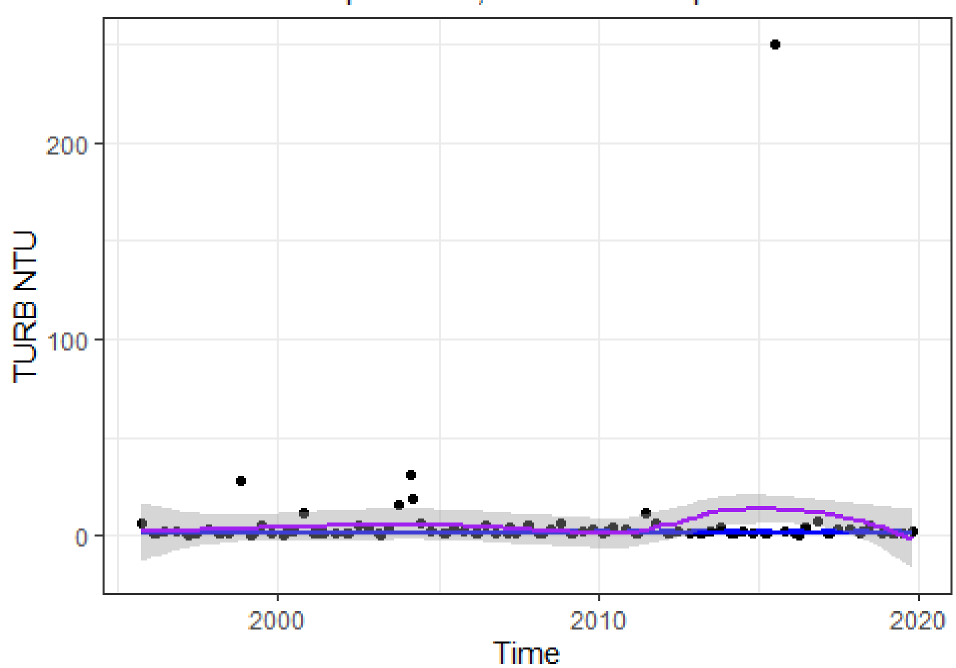
L3 TP Seasonal Trend Analysis

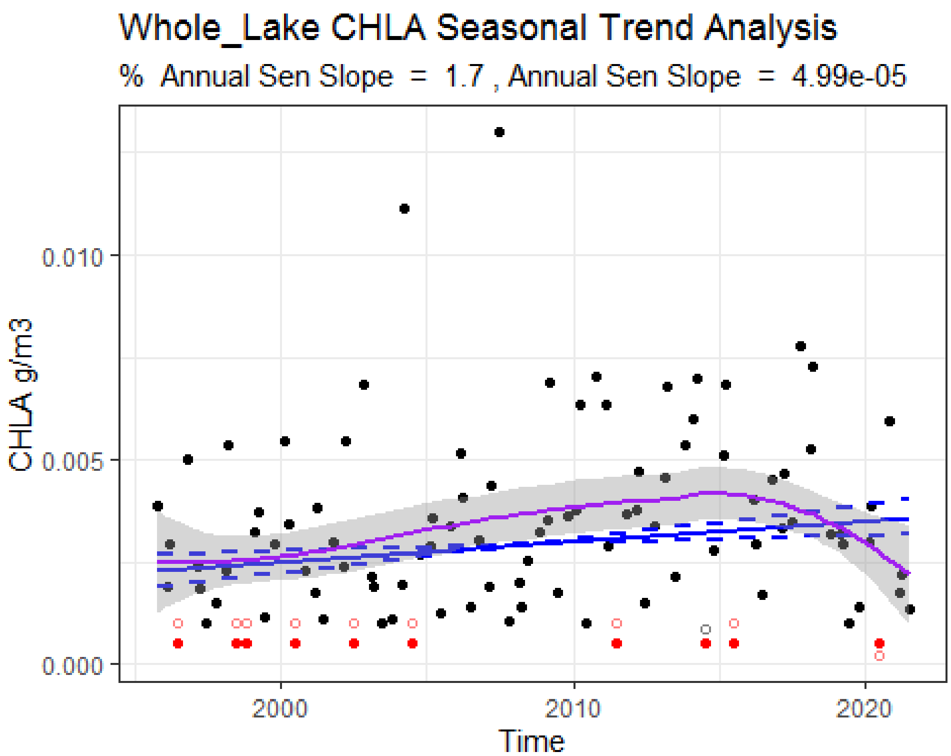
% Annual Sen Slope = 0.4 , Annual Sen Slope = 8.01e-05

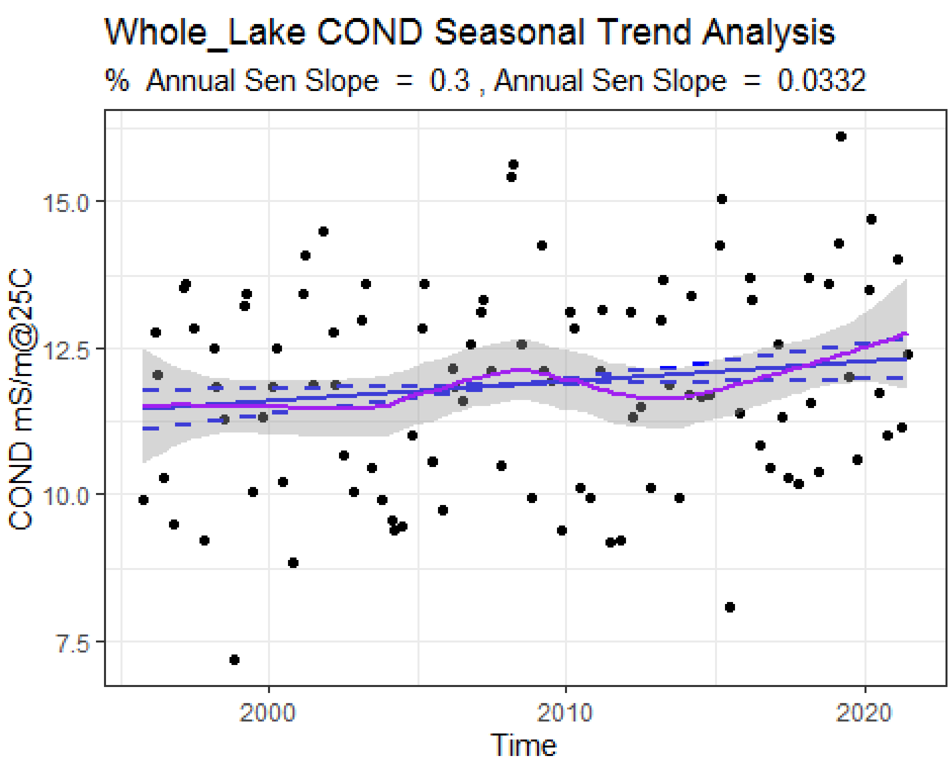


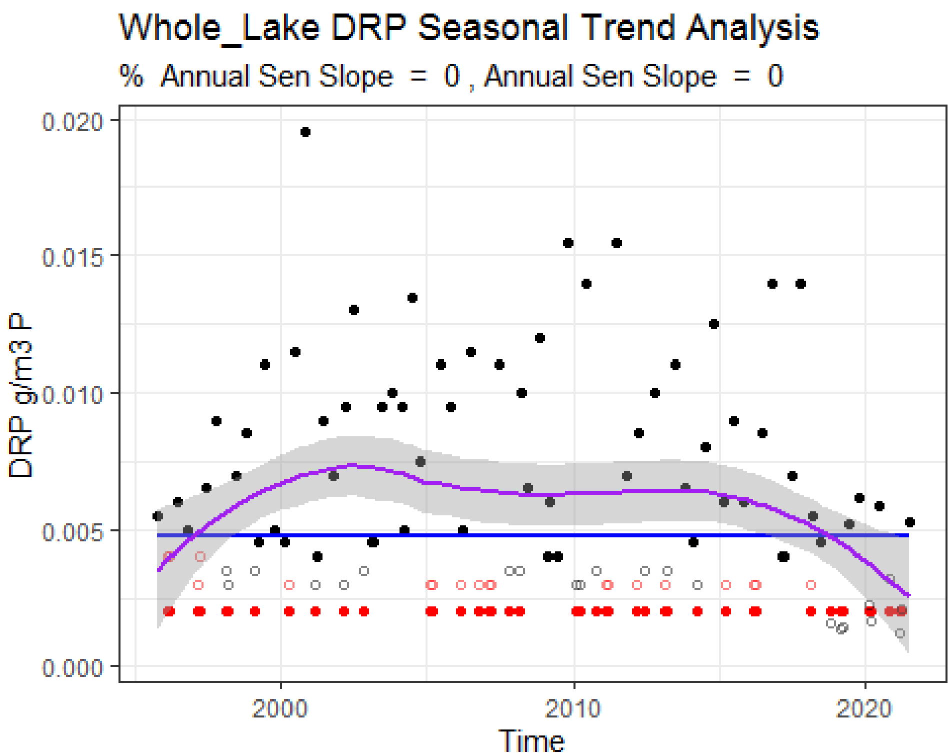
L3 TURB Seasonal Trend Analysis

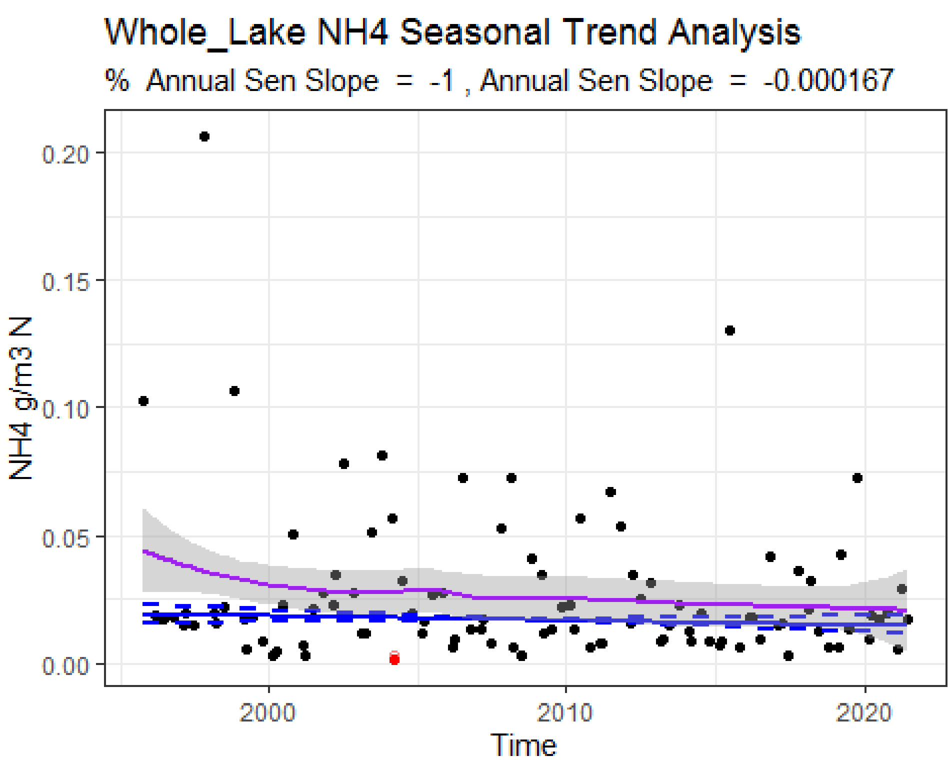
% Annual Sen Slope = 0.8 , Annual Sen Slope = 0.0127

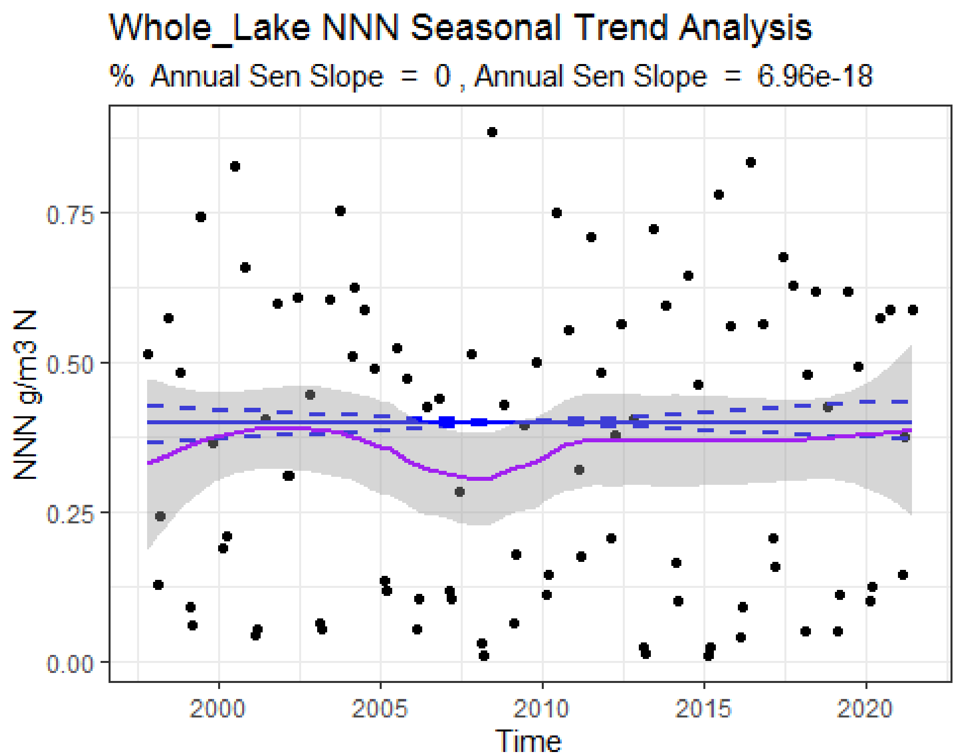


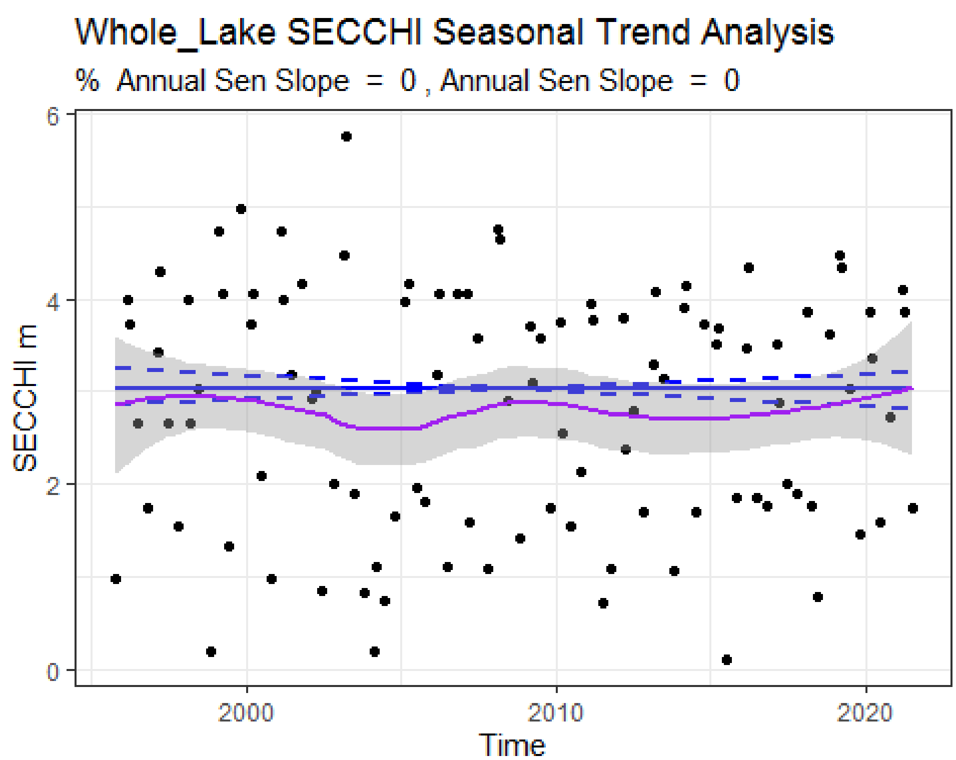

Whole_Lake CHLA Seasonal Trend Analysis
% Annual Sen Slope = 1.7 , Annual Sen Slope = 4.99e-05
CHLA g/m3
0.010
0.005
0.000
2000
2010
2020
Time

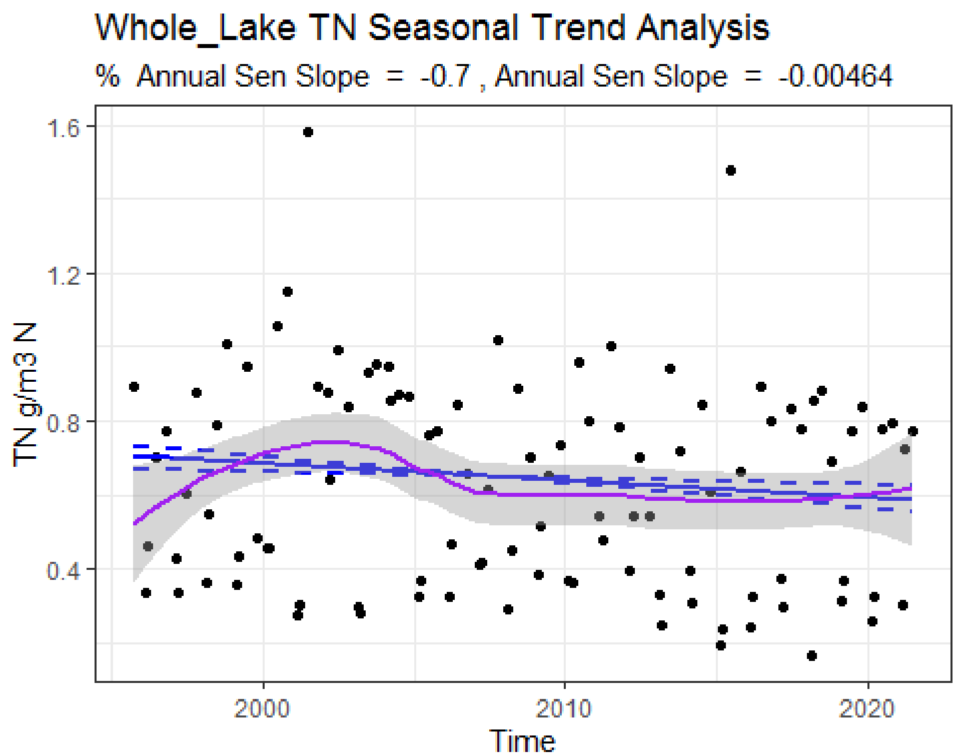

Whole_Lake COND Seasonal Trend Analysis
% Annual Sen Slope = 0.3 , Annual Sen Slope = 0.0332
COND mS/m@25C
15.0
12.5
10.0
7.5
2000
2010
2020
Time


Whole_Lake DRP Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
DRP g/m3 P
0.020
0.015
0.010
0.005
0.000
2000
2010
2020
Time

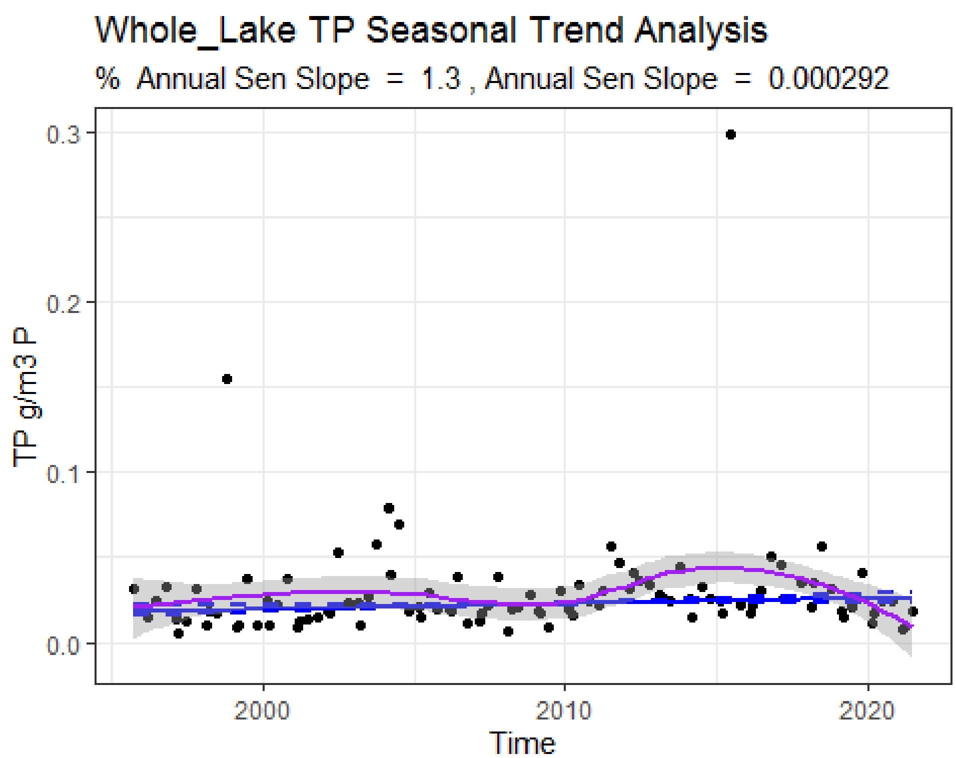

Whole_Lake NH4 Seasonal Trend Analysis
% Annual Sen Slope = -1 , Annual Sen Slope = -0.000167
NH4 g/m3 N
0.20
0.15
0.10
0.05
0.00
2000
2010
2020
Time


Whole_Lake NNN Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 6.96e-18
NNN g/m3 N
0.00
0.25
0.50
0.75
2000
2005
2010
2015
2020
Time

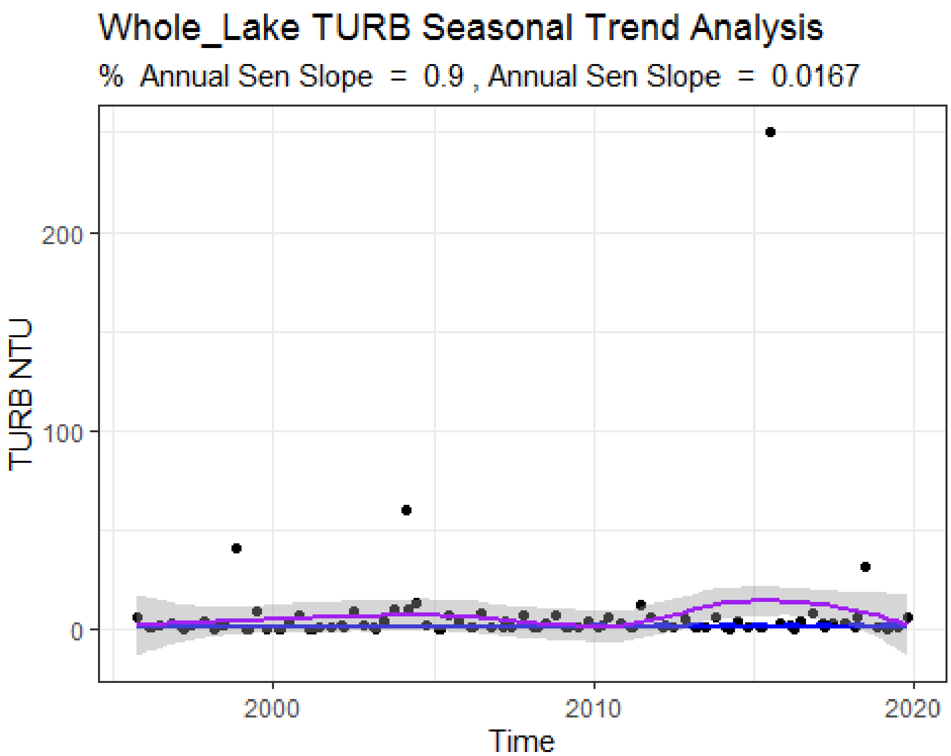

Whole_Lake SECCHI Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
SECCHI m
0
2
4
6
2000
2010
2020
Time

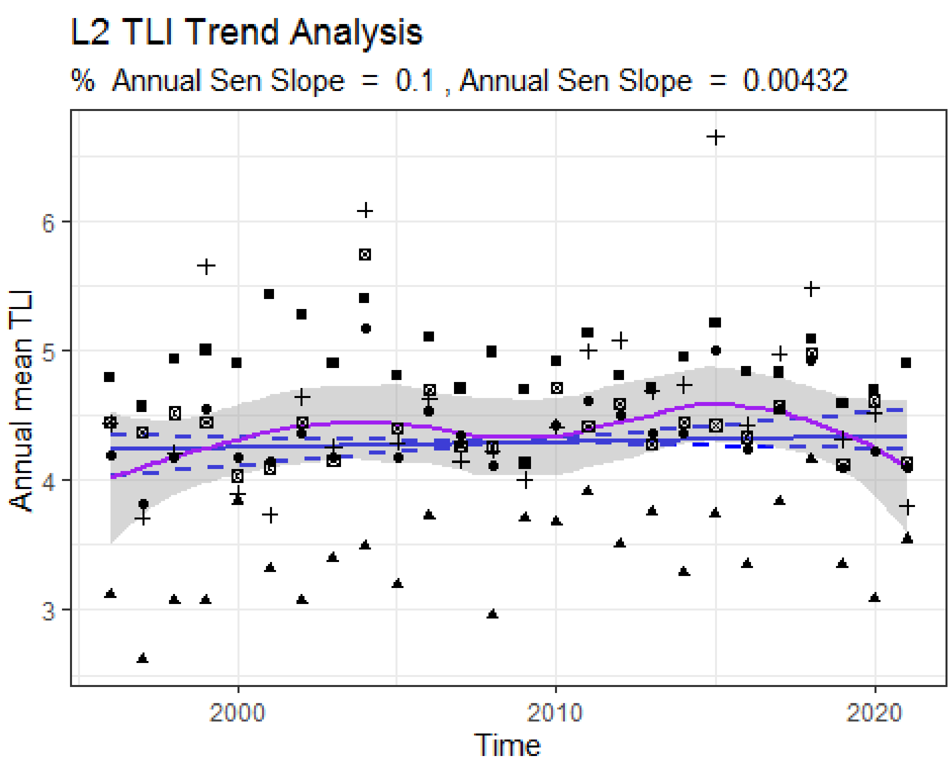


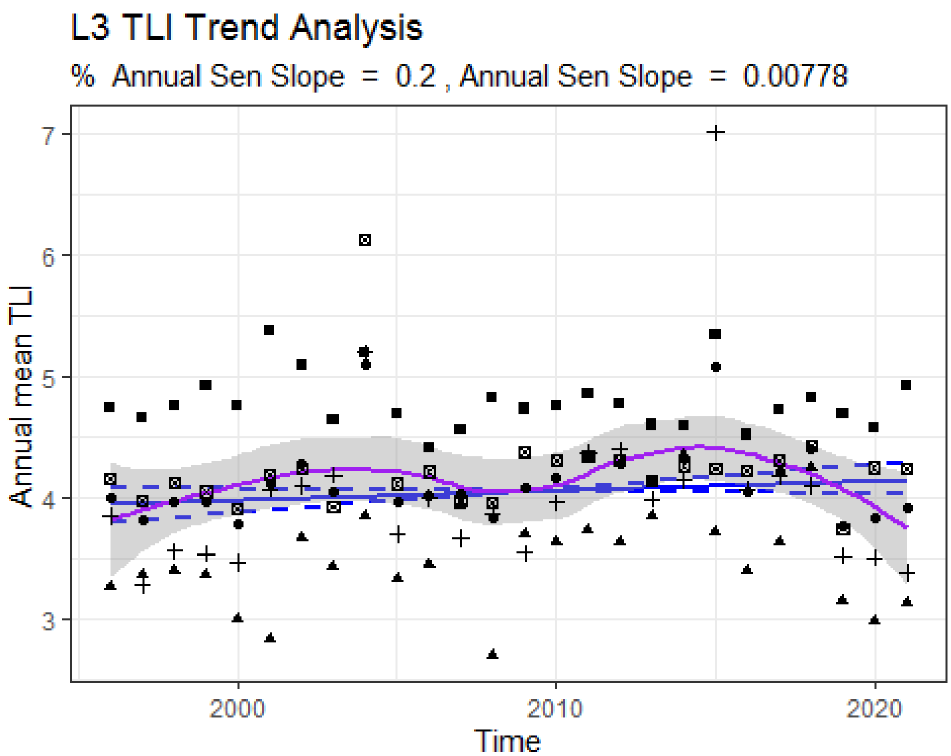
Whole_Lake TN Seasonal Trend Analysis
% Annual Sen Slope = -0.7 , Annual Sen Slope = -0.00464
TN g/m3 N
1.6
1.2
0.8
0.4
2000
2010
2020
Time

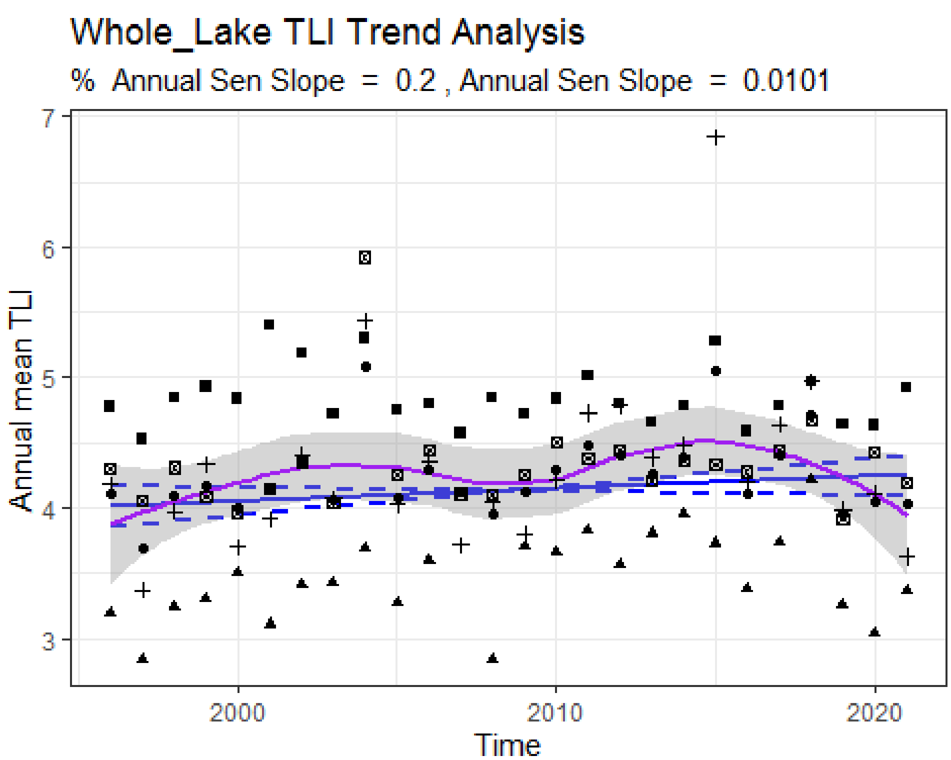


Whole_Lake TP Seasonal Trend Analysis
% Annual Sen Slope = 1.3 , Annual Sen Slope = 0.000292
TP g/m3 P
0.3
0.2
0.1
0.0
2000
2010
2020
Time


Whole_Lake TURB Seasonal Trend Analysis
% Annual Sen Slope = 0.9 , Annual Sen Slope = 0.0167
TURB NTU
200
100
0
2000
2010
2020
Time


L2 TLI Trend Analysis
% Annual Sen Slope = 0.1 , Annual Sen Slope = 0.00432
Annual mean TLI
6
5
4
3
2000
2010
2020
Time

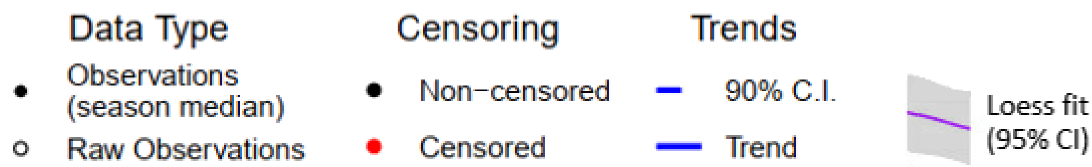

L3 TLI Trend Analysis
% Annual Sen Slope = 0.2 , Annual Sen Slope = 0.00778
Annual mean TLI
7
6
5
4
3
2000
2010
2020
Time

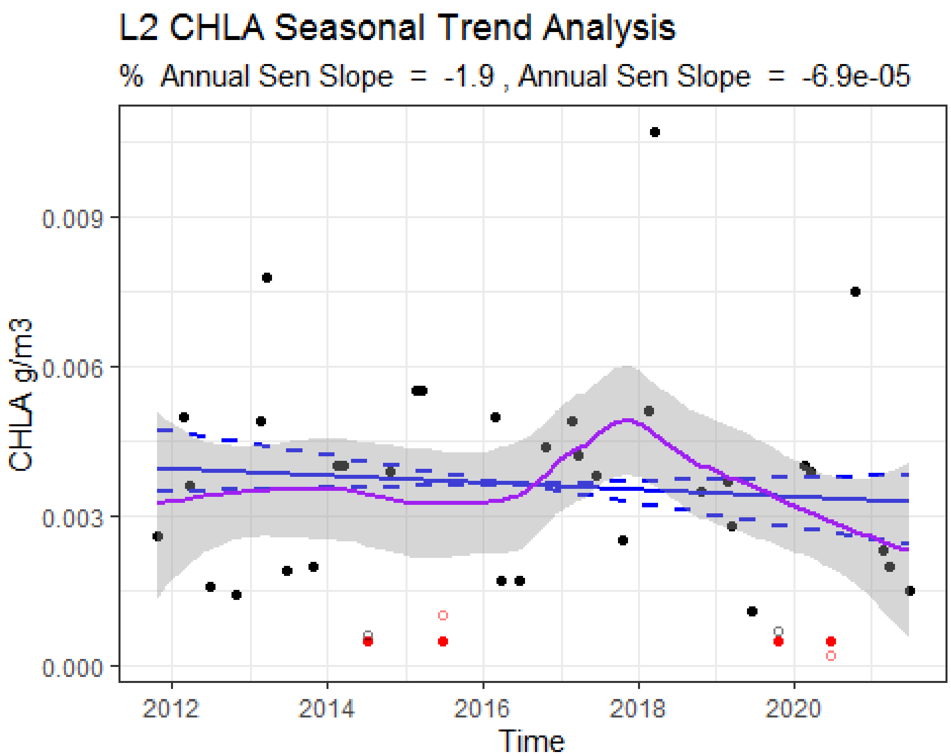

Whole_Lake TLI Trend Analysis
% Annual Sen Slope = 0.2 , Annual Sen Slope = 0.0101
Annual mean TLI
7
6
5
4
3
2000
2010
2020
Time

Appendix VI

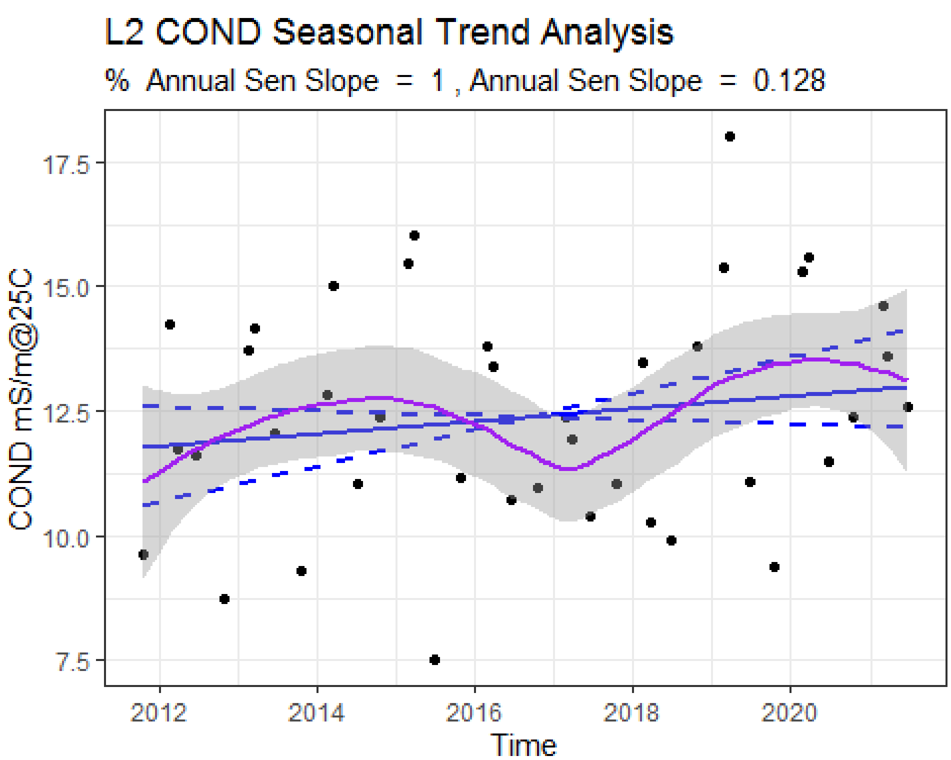
Trend plots for the period 2012-2021

Legend for all trend plots:

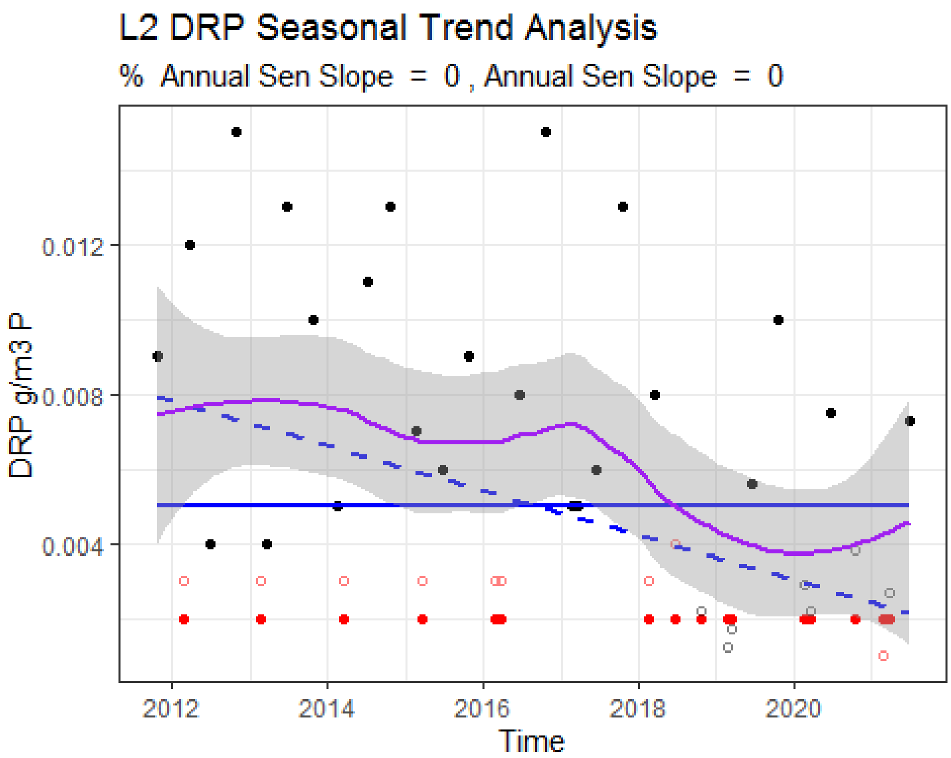


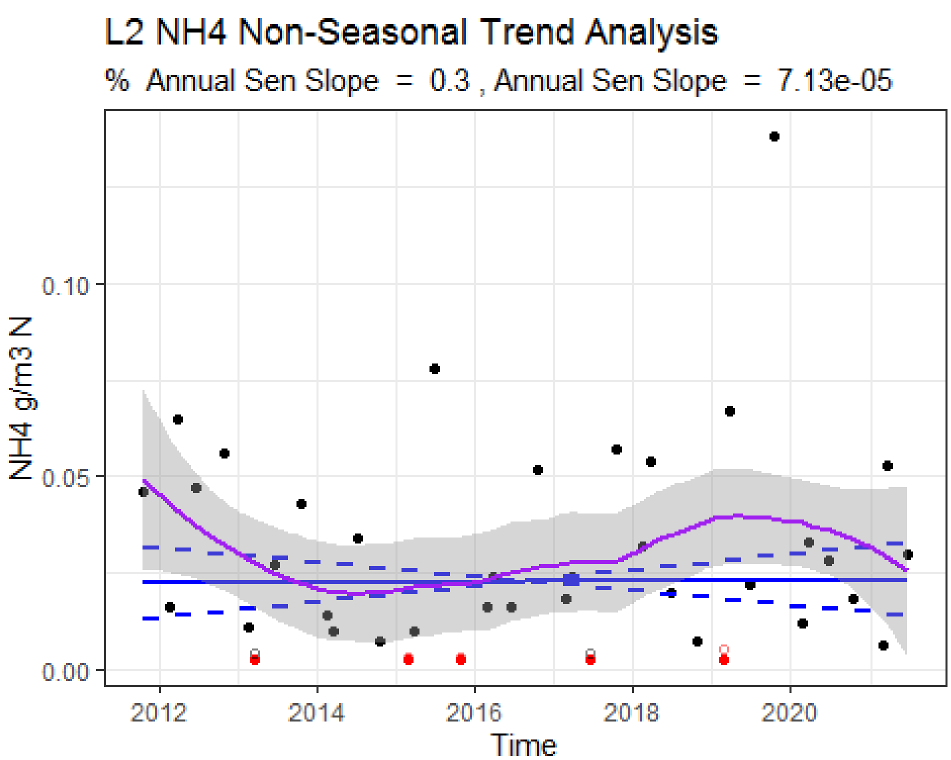


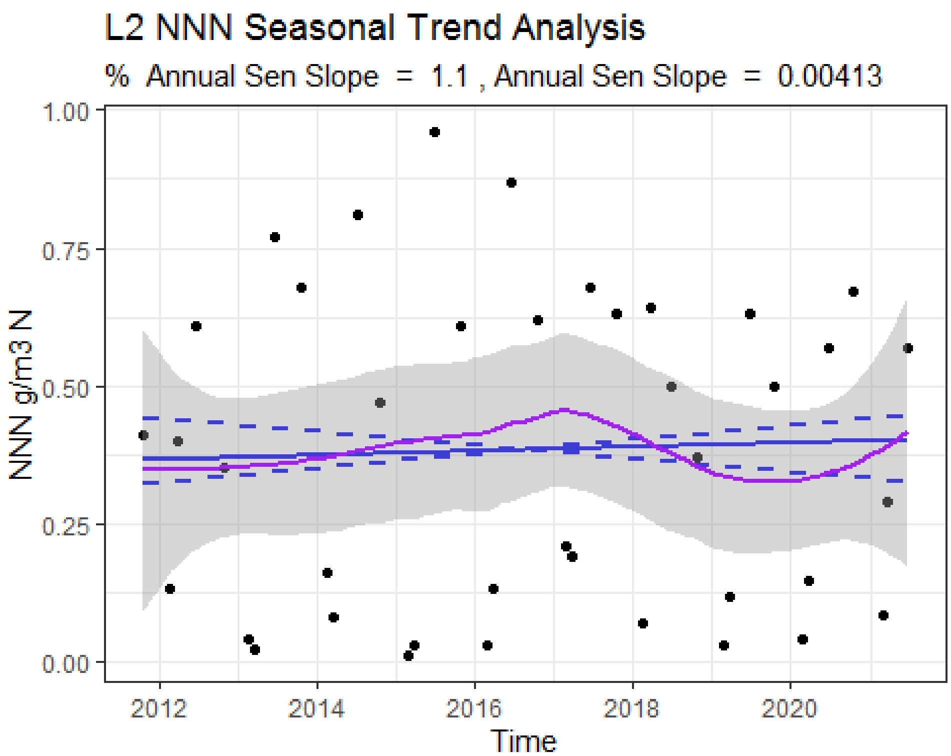
L2 CHLA Seasonal Trend Analysis
% Annual Sen Slope = -1.9 , Annual Sen Slope = -6.9e-05
CHLA g/m3
0.009
0.006
0.003
0.000
2012
2014
2016
2018
2020
Time

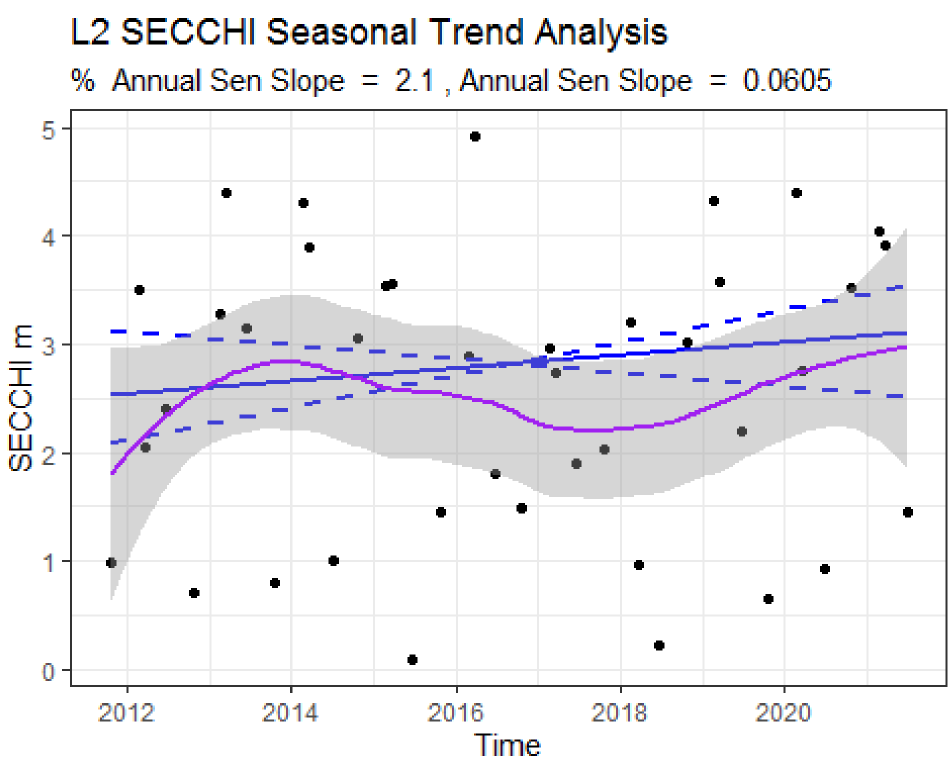


L2 COND Seasonal Trend Analysis
% Annual Sen Slope = 1 , Annual Sen Slope = 0.128
COND mS/m@25C
17.5
15.0
12.5
10.0
7.5
2012
2014
2016
2018
2020
Time


L2 DRP Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
DRP g/m3 P
0.012
0.008
0.004
2012
2014
2016
2018
2020
Time

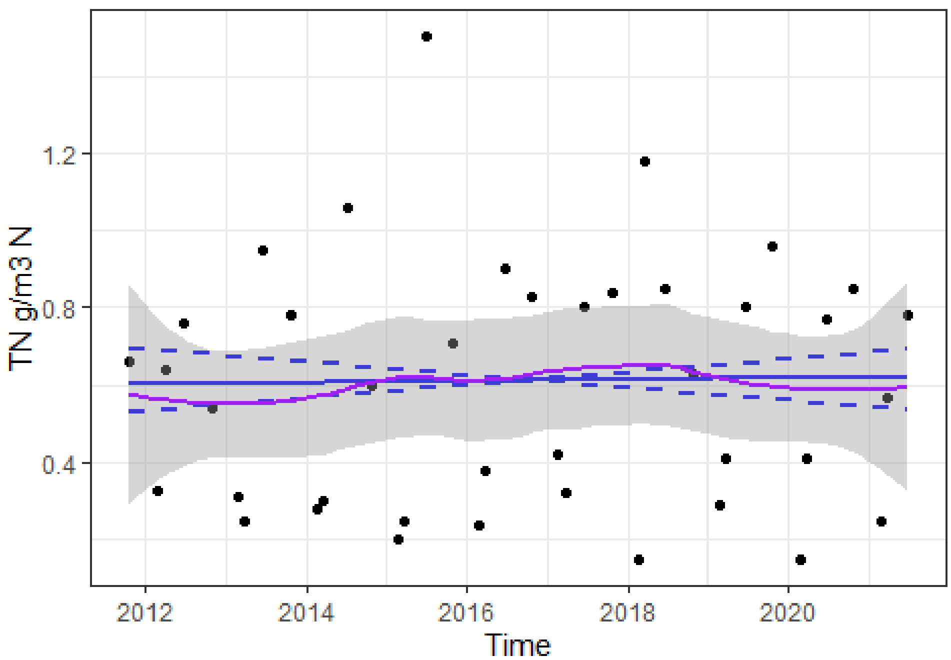

L2 NH4 Non-Seasonal Trend Analysis
% Annual Sen Slope = 0.3 , Annual Sen Slope = 7.13e-05
NH4 g/m3 N
0.10
0.05
0.00
2012
2014
2016
2018
2020
Time


L2 NNN Seasonal Trend Analysis
% Annual Sen Slope = 1.1 , Annual Sen Slope = 0.00413
NNN g/m3 N
1.00
0.75
0.50
0.25
0.00
2012
2014
2016
2018
2020
Time


L2 SECCHI Seasonal Trend Analysis
% Annual Sen Slope = 2.1 , Annual Sen Slope = 0.0605
SECCHI m
5
4
3
2
1
0
2012
2014
2016
2018
2020
Time

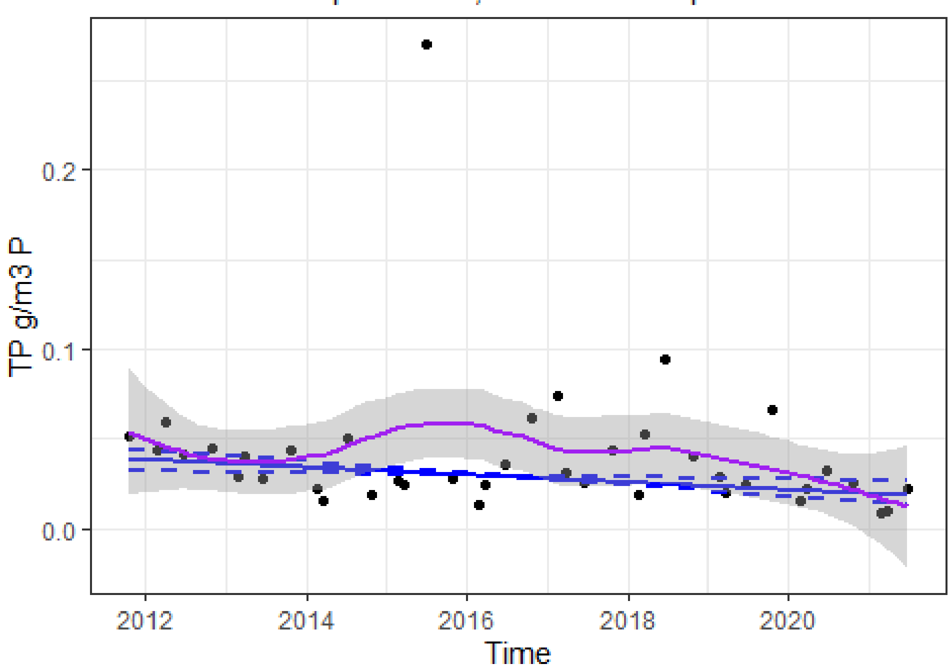
L2 TN Seasonal Trend Analysis

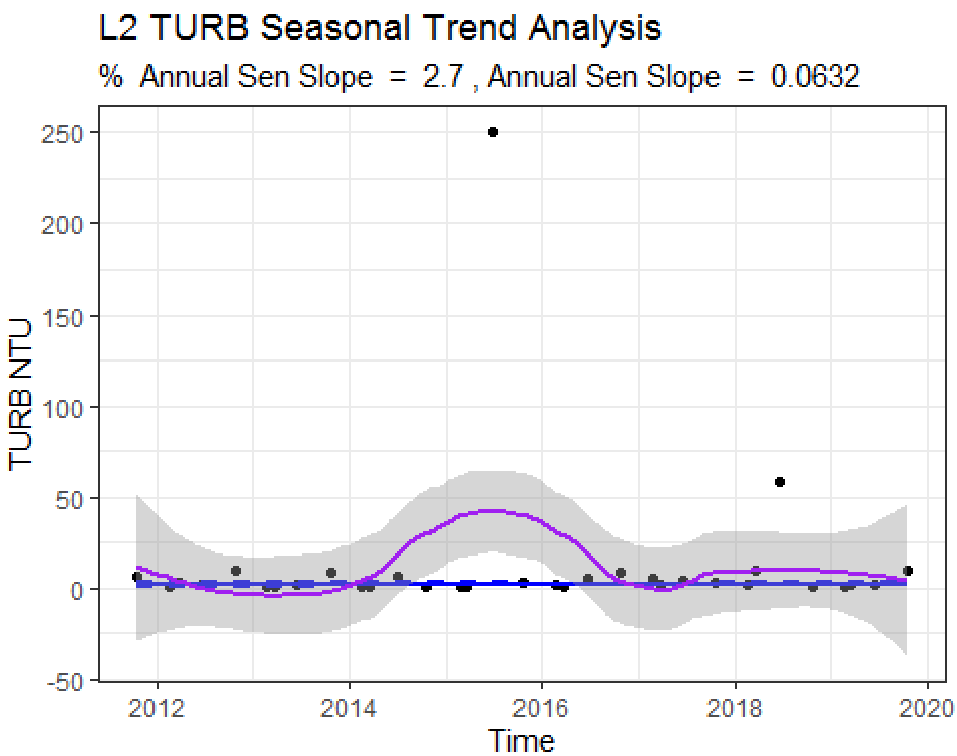
% Annual Sen Slope = 0.3 , Annual Sen Slope = 0.00211

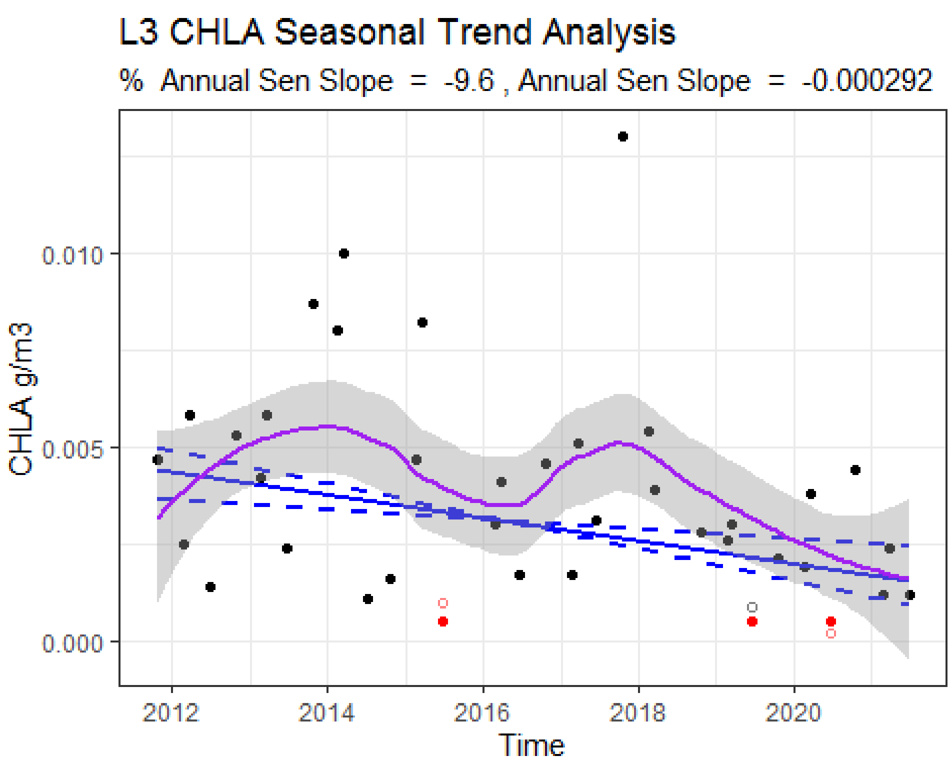


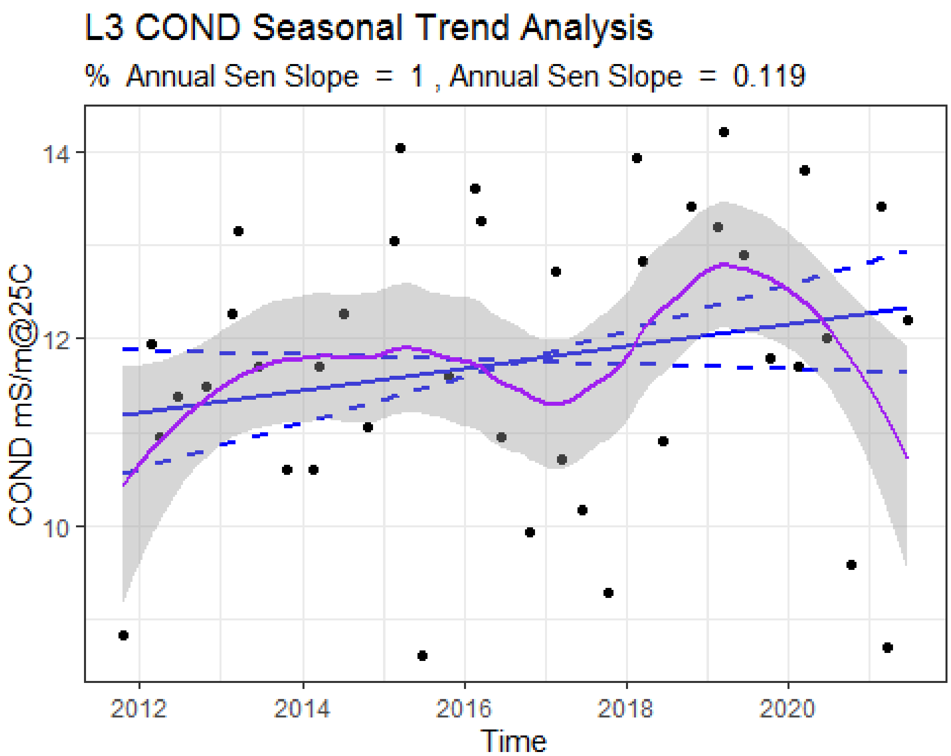
L2 TP Non-Seasonal Trend Analysis

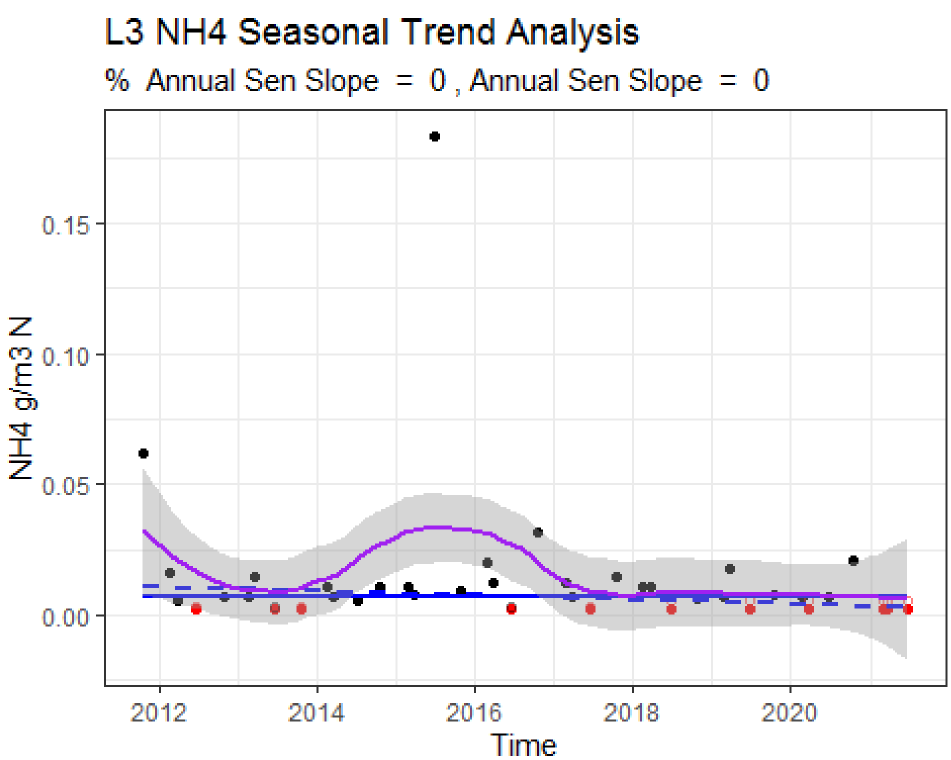
% Annual Sen Slope = -7.2 , Annual Sen Slope = -0.00209




L2 TURB Seasonal Trend Analysis
% Annual Sen Slope = 2.7 , Annual Sen Slope = 0.0632
TURB NTU
250
200
150
100
50
0
-50
2012
2014
2016
2018
2020
Time

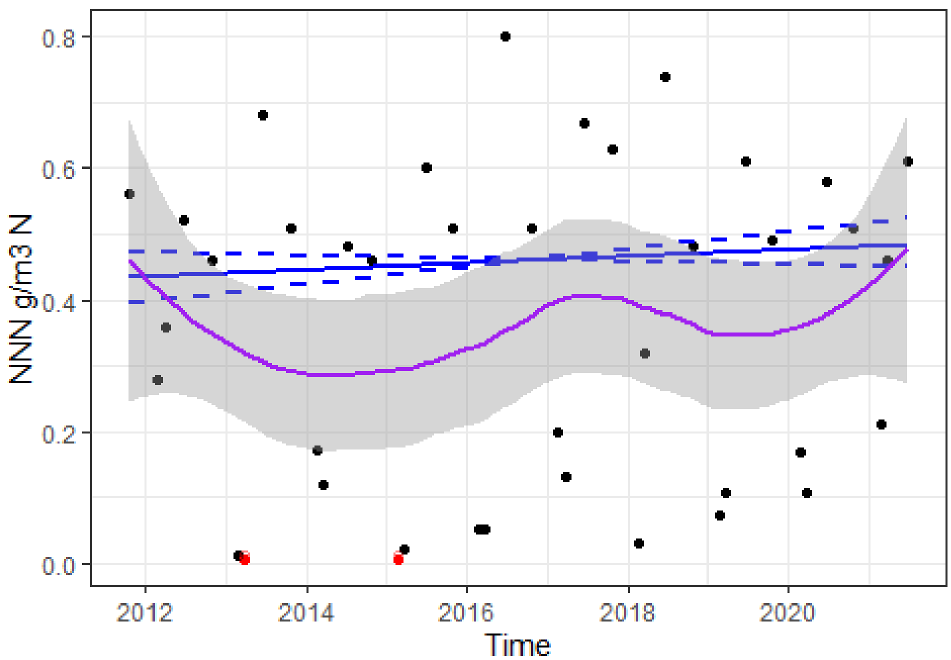

L3 CHLA Seasonal Trend Analysis
% Annual Sen Slope = -9.6 , Annual Sen Slope = -0.000292
CHLA g/m3
0.010
0.005
0.000
2012
2014
2016
2018
2020
Time


L3 COND Seasonal Trend Analysis
% Annual Sen Slope = 1 , Annual Sen Slope = 0.119
COND mS/m@25C
14
12
10
2012
2014
2016
2018
2020
Time


L3 NH4 Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
NH4 g/m3 N
0.15
0.10
0.05
0.00
2012
2014
2016
2018
2020
Time

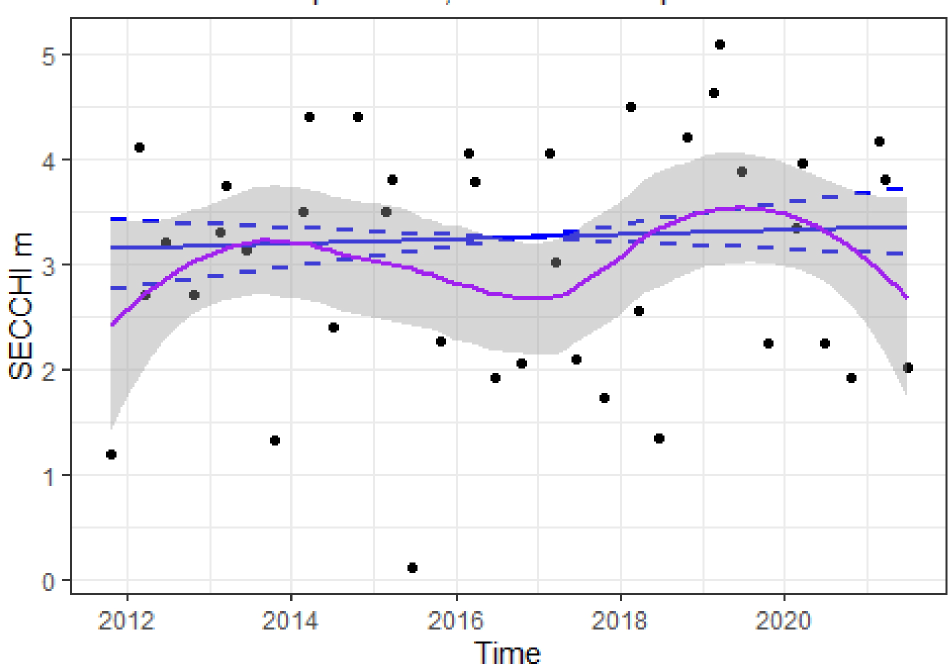
L3 NNN Seasonal Trend Analysis

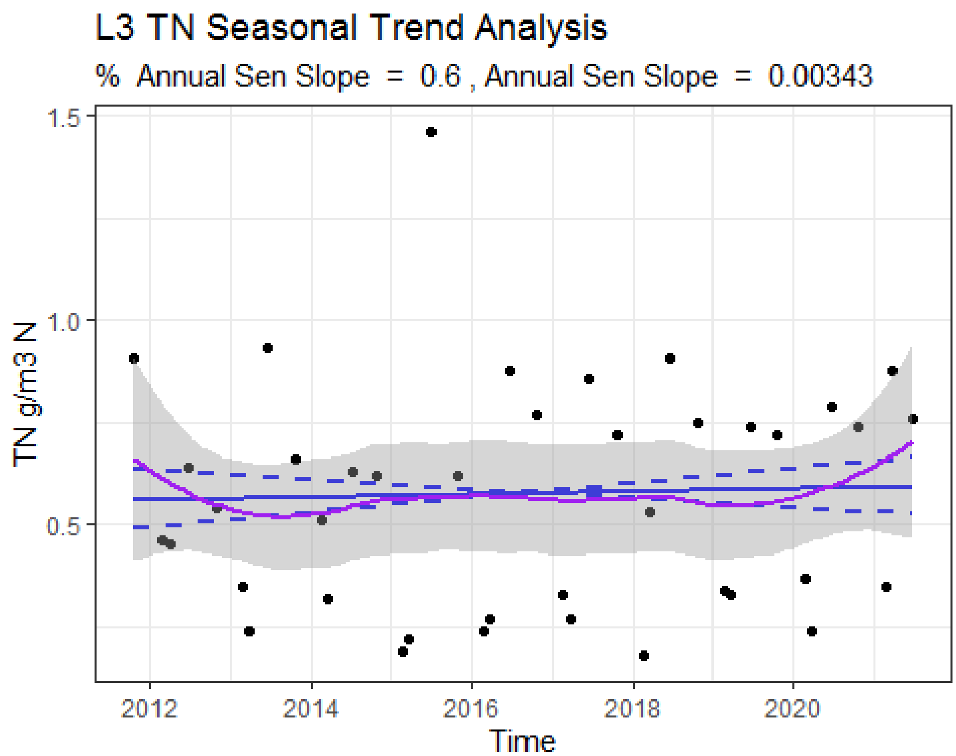
% Annual Sen Slope = 1.2 , Annual Sen Slope = 0.00535



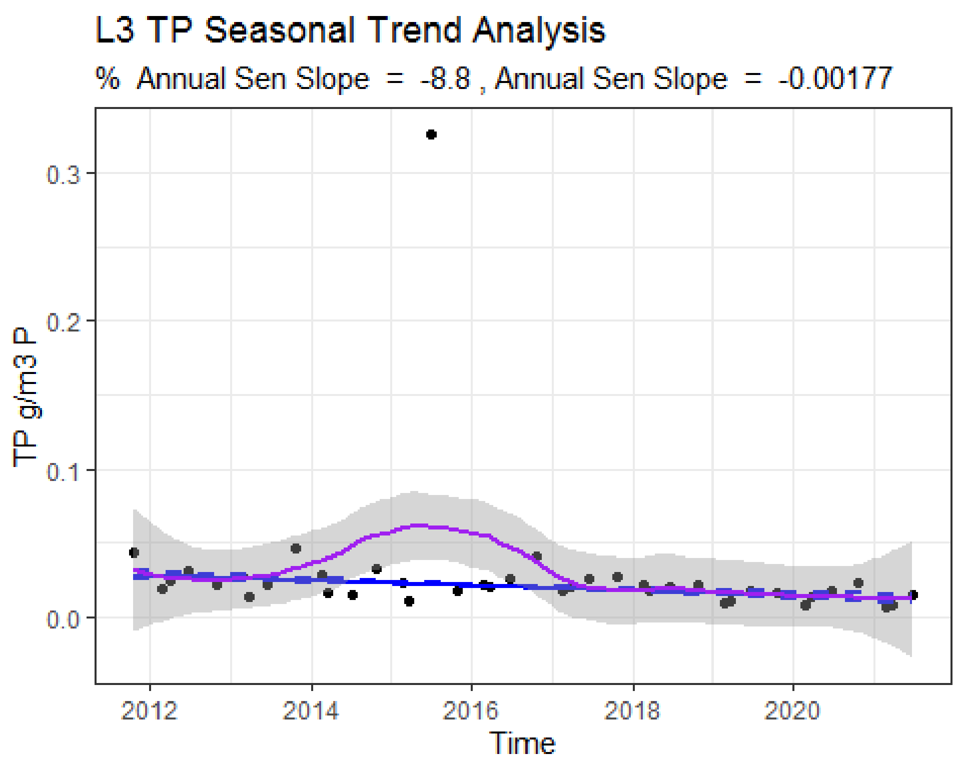
L3 SECCHI Seasonal Trend Analysis

% Annual Sen Slope = 0.7 , Annual Sen Slope = 0.0224





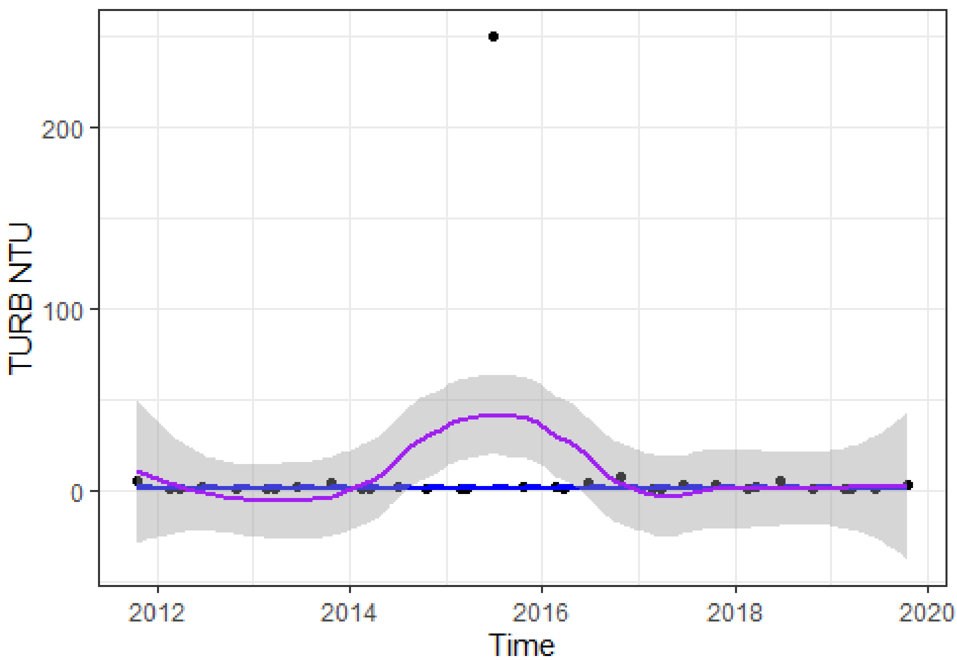
L3 TN Seasonal Trend Analysis
% Annual Sen Slope = 0.6 , Annual Sen Slope = 0.00343
TN g/m3 N
1.5
1.0
0.5
2012
2014
2016
2018
2020
Time



L3 TP Seasonal Trend Analysis
% Annual Sen Slope = -8.8 , Annual Sen Slope = -0.00177
TP g/m3 P
0.3
0.2
0.1
0.0
2012
2014
2016
2018
2020
Time

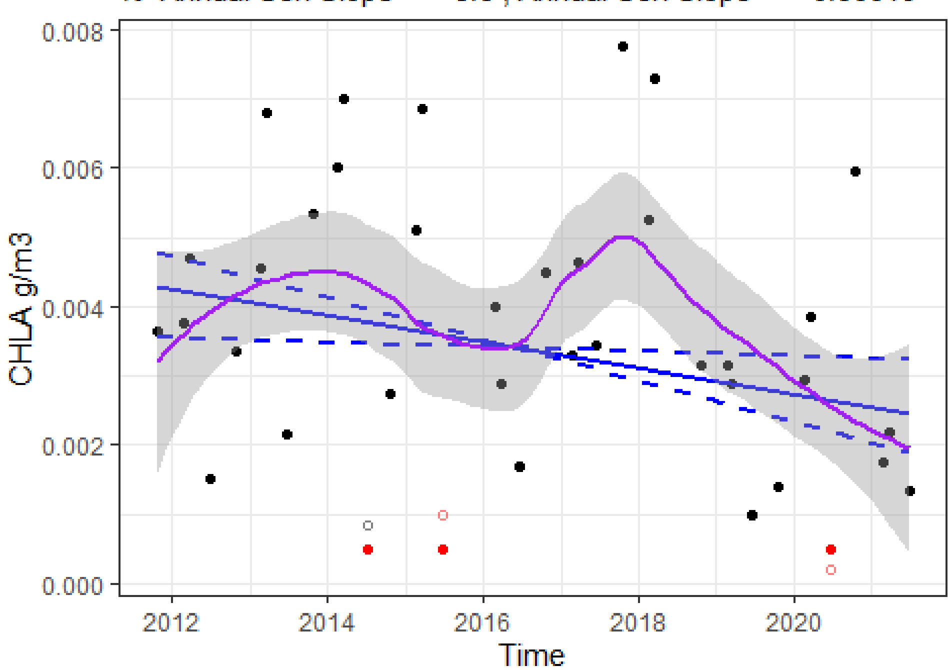
L3 TURB Seasonal Trend Analysis

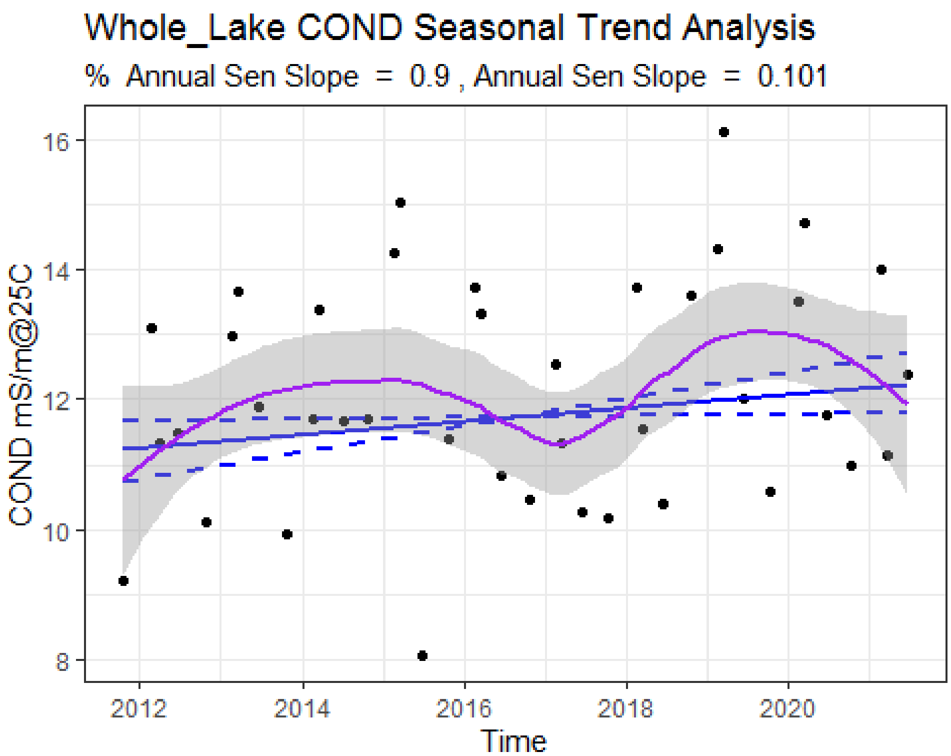
% Annual Sen Slope = -0.5 , Annual Sen Slope = -0.00743

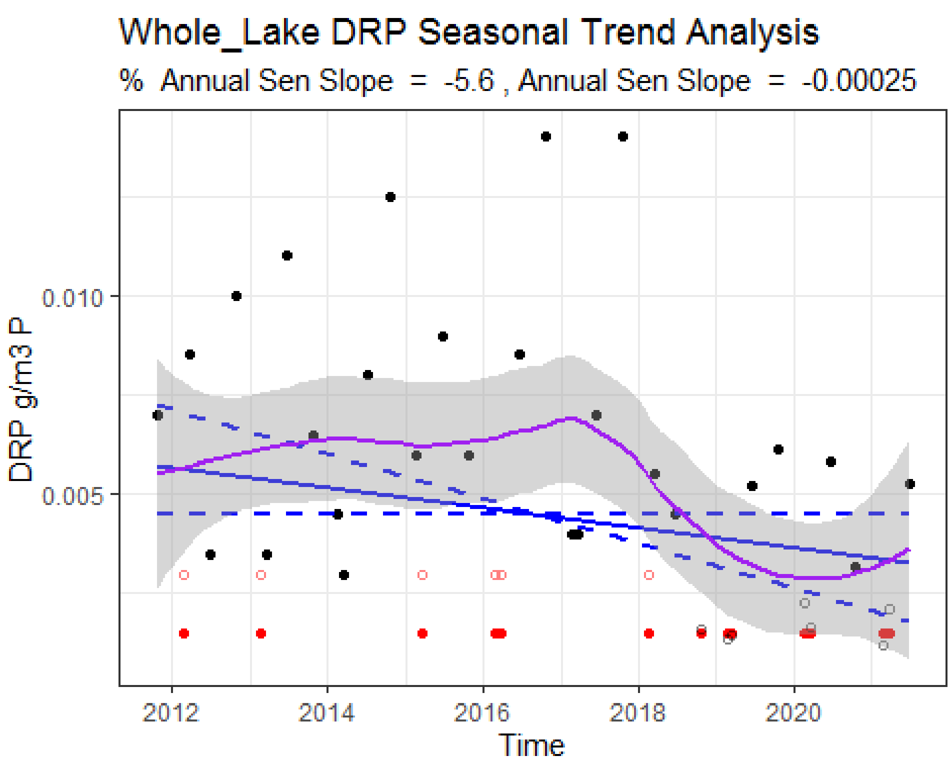


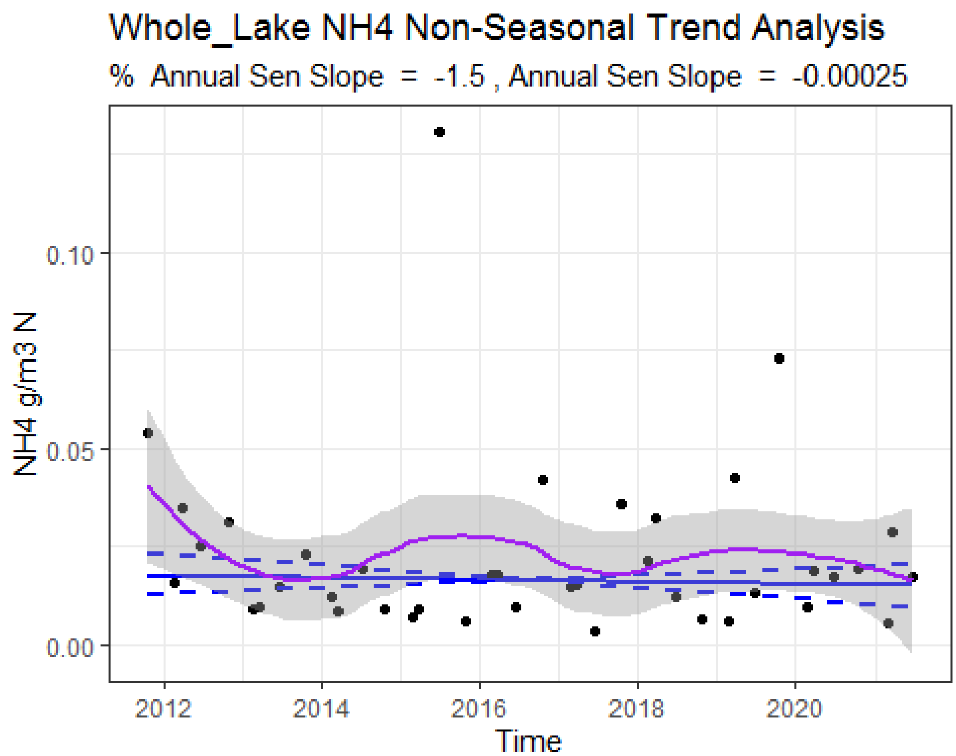
Whole_Lake CHLA Seasonal Trend Analysis

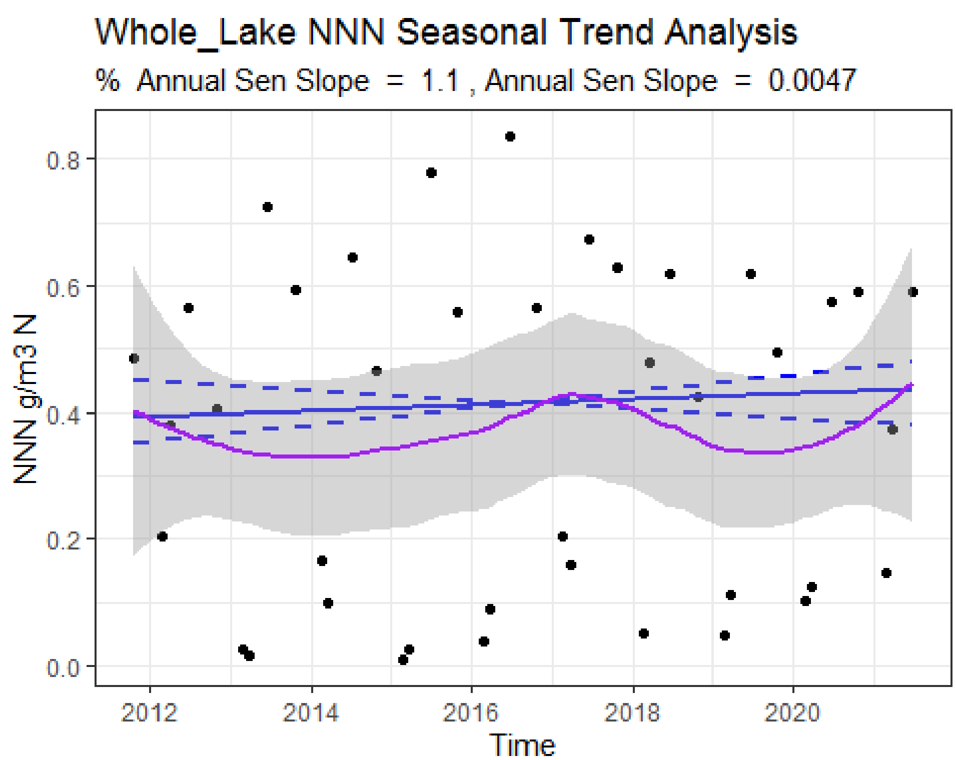
% Annual Sen Slope = -5.6 , Annual Sen Slope = -0.00019

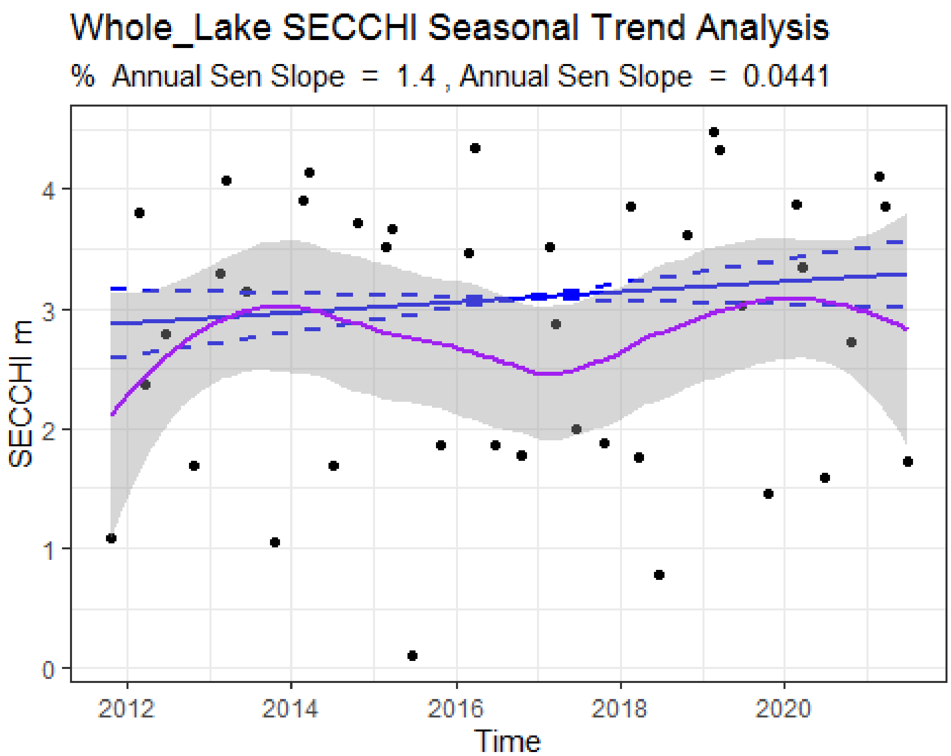


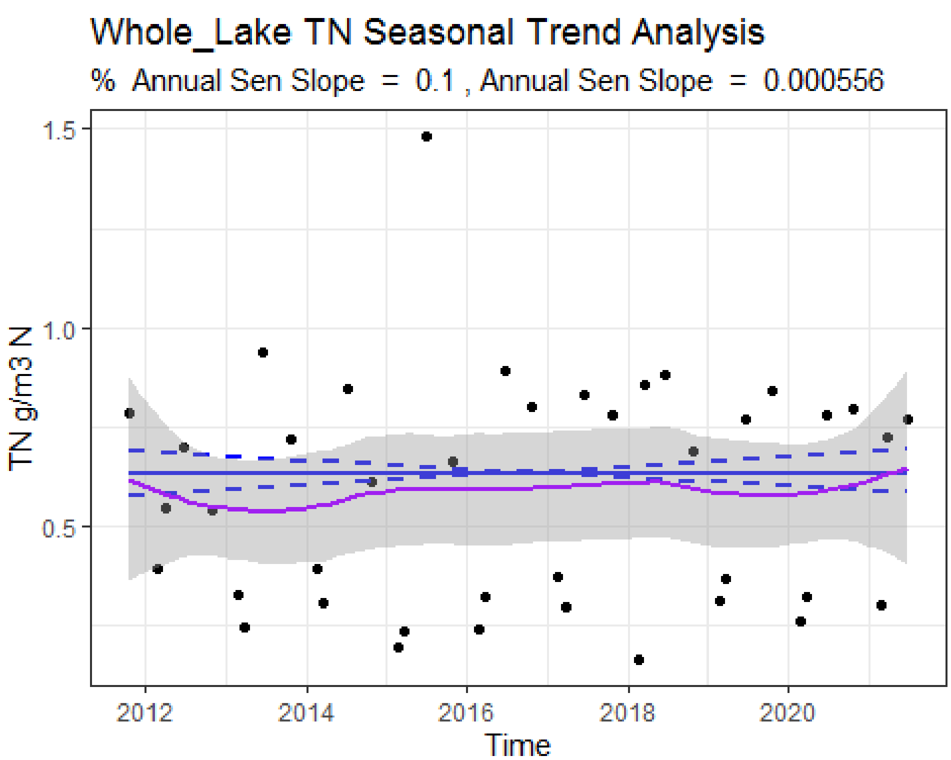

Whole_Lake COND Seasonal Trend Analysis
% Annual Sen Slope = 0.9 , Annual Sen Slope = 0.101
COND mS/m@25C
16
14
12
10
8
2012
2014
2016
2018
2020
Time

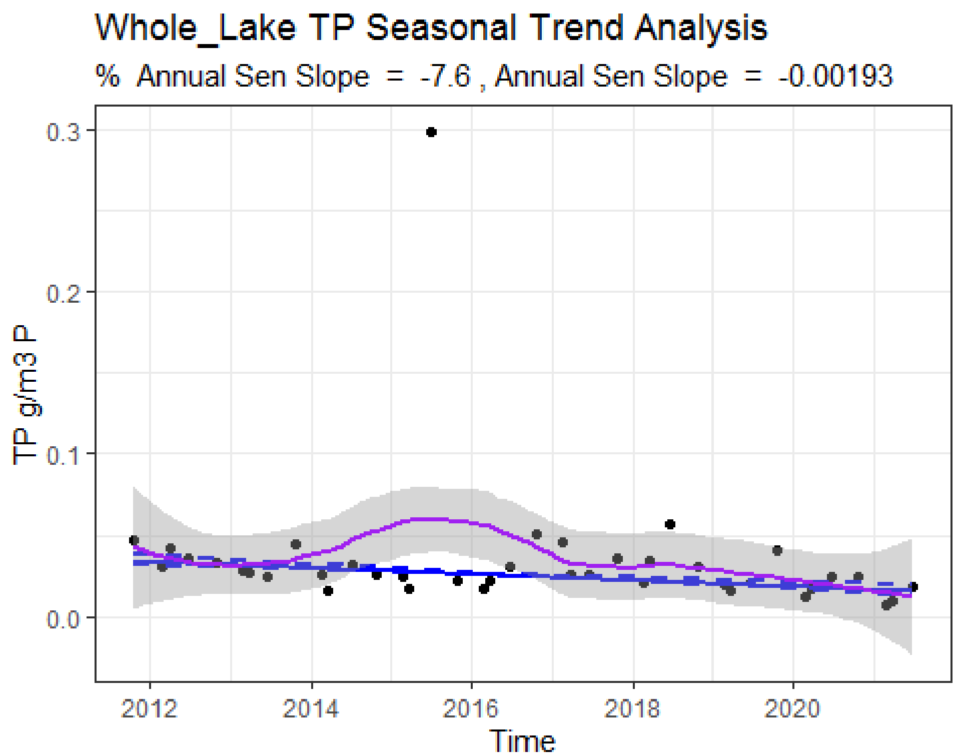

Whole_Lake DRP Seasonal Trend Analysis
% Annual Sen Slope = -5.6 , Annual Sen Slope = -0.00025
DRP g/m3 P
0.010
0.005
2012
2014
2016
2018
2020
Time

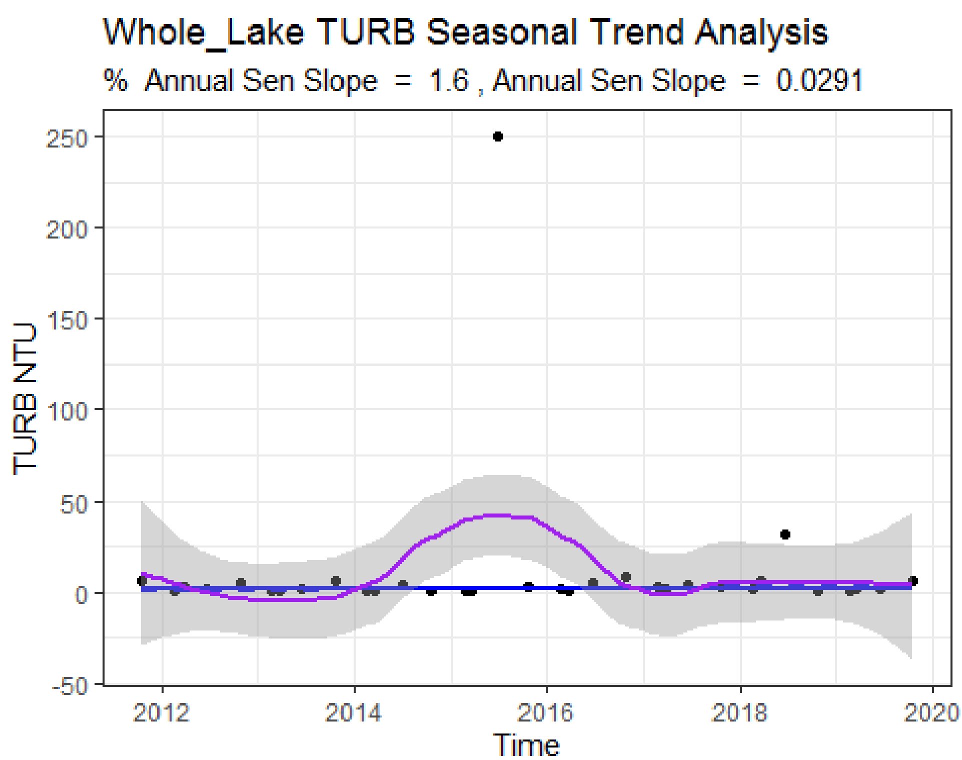

Whole_Lake NH4 Non-Seasonal Trend Analysis
% Annual Sen Slope = -1.5 , Annual Sen Slope = -0.00025
NH4 g/m3 N
0.10
0.05
0.00
2012
2014
2016
2018
2020
Time


Whole_Lake NNN Seasonal Trend Analysis
% Annual Sen Slope = 1.1 , Annual Sen Slope = 0.0047
NNN g/m3 N
0.8
0.6
0.4
0.2
0.0
2012
2014
2016
2018
2020
Time


Whole_Lake SECCHI Seasonal Trend Analysis
% Annual Sen Slope = 1.4 , Annual Sen Slope = 0.0441
SECCHI m
0
1
2
3
4
2012
2014
2016
2018
2020
Time


Whole_Lake TN Seasonal Trend Analysis
% Annual Sen Slope = 0.1 , Annual Sen Slope = 0.000556
TN g/m3 N
0.5
1.0
1.5
2012
2014
2016
2018
2020
Time


Whole_Lake TP Seasonal Trend Analysis
% Annual Sen Slope = -7.6 , Annual Sen Slope = -0.00193
TP g/m3 P
0.3
0.2
0.1
0.0
2012
2014
2016
2018
2020
Time


Whole_Lake TURB Seasonal Trend Analysis
% Annual Sen Slope = 1.6 , Annual Sen Slope = 0.0291
TURB NTU
250
200
150
100
50
0
-50
2012
2014
2016
2018
2020
Time