Lake Water Quality State and Trends in Tāmaki Makaurau / Auckland 2010-2019. State of the Environment Reporting

J Groom

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Research and Evaluation Unit RIMU

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Cover photograph of Lake Tomarata. Taken from Gravitas consultancy presentation. (Gravitas 2020)

Executive summary

Auckland Council undertakes long-term monitoring of lake water quality as part of its State of the Environment monitoring. There are four lakes within the Tāmaki Makaurau that have been monitored consistently over time. These are Lake Pupuke, Lake Wainamu, Lake Tomarata and Lake Rototoa, all of which have different land cover types in the surrounding catchment and are publicly accessible.

This monitoring is necessary so that we can assess the life supporting capacity of the lakes, assess the quality of the lakes for recreational use, detect trends in water quality, and to subsequently assess the efficiency of council initiatives, policies and lake management strategies. The last State of the Environment reporting for the region's lakes was published in 2015, utilising data collected to the end of 2012.

This report provides an overview of the current state of lake water quality and identifies trends in water quality over the most recent 10-year period (2010-2019). Data were analysed for the surface and bottom waters in each of the four lakes. The state of the lakes was assessed using water quality parameters, human contact attributes, ecological indicators, and graded according to the National Policy Statement for Freshwater Management (NPS-FM 2020).

Three of the monitored lakes were in a eutrophic state, where elevated nutrients result in changes to algal biomass, and/or are in a poor or non-vegetated ecological condition. All four lakes were above the national bottom lines for all water quality attributes as per the NPS-FM National Objectives Framework assessment for the first time.

There were degrading trends in total nitrogen, water clarity and sediment attributes, and improvements in total phosphorus concentrations across the region. The confidence of these trend directions was determined using a scale of very likely, likely, and indeterminate.

Lake Pupuke had degrading trends in parameters in the surface waters, Lake Wainamu had mainly likely improving trends and Lake Tomarata was in poor condition with very likely degrading trends in most water quality parameters, with the biggest magnitude of change in several water quality parameters. Lake Rototoa was in the best state for water quality and ecological condition compared to other monitored lakes in the Auckland region. However, this lake had degrading trends in sediment attributes and total nitrogen, suggesting vulnerability to changes in lake health within the next decade.

Several key pressures were identified as potential drivers of changes in water quality in these lakes including, but not limited to, catchment land cover type, pest fish, invasive plant species, internal nutrient loading, and a changing climate. Previous management of these lakes has included pest fish management, invasive weed management and restoration work in the riparian zone.

To better understand the state and vulnerability of Auckland's lakes, and to enable the setting of robust future management priorities, this report clearly identifies that additional lakes should be monitored and with increased frequency. As a result, Auckland Council amended its lake water quality programme in early 2020 to include most lakes identified in the natural lakes management area overlay of the Auckland Unitary Plan.

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1.0 Introduction

The Auckland region covers a land area of approximately 4894km^2 and encompasses a range of surface freshwater ecosystems, including lakes, rivers, streams, springs and wetlands. There are approximately 72 waterbodies within the Auckland region that are over one hectare in area (Department of Conservation, 2019), including small farm ponds and large water supply reservoirs. The majority of naturally formed lakes in the region are dune lakes, except for Lake Pupuke which is a deep volcanic lake.

The characteristics of lake condition across the Auckland region are in part regulated by natural environmental variability (i.e. geology, seasonal variation in rainfall and temperature); however, they are also influenced by anthropogenic pressures (e.g. changes in surrounding land cover). The monitoring of these lakes is necessary to understand natural variability so that we can detect trends that may be attributed to multiple drivers and to help inform council initiatives, policies and lake management strategies.

Collecting information on lake water quality and ecological health is important to provide an integrated overview of the physical, chemical, and biological condition of the region's lakes. This is used to assess the life supporting capacity of these lakes, as well as the quality of the lakes for recreational use.

1.1 National and regional directives

Auckland Council's lake water quality programme is designed to meet the following national and regional objectives:

- Satisfy Auckland Council's obligations under section 35 of the Resource Management Act 1991 to monitor and report on the state of the region's lake environments.
- Contribute to Auckland Council's ability to maintain and enhance the quality of the environment (Local Government Act 2002).
- Meet Auckland Council's obligations under the National Policy Statement for Freshwater Management (NPS-FM), including monitoring of key attributes aimed at evidencing improving lake health (MfE, 2020).
- Support Māori in their role as kaitiaki to protect and enhance te mauri o te wai (the life supporting capacity of water).
- Help inform the efficacy and efficiency of regional policy initiatives and strategies.

- Assist with the identification of large scale and/or cumulative impacts of land use activities and disturbance on lake health.
- Provide baseline and regionally representative data to support the resource consent process and associated compliance monitoring for lake environments.
- Continuously increase the knowledge base for Aucklanders and promote awareness of lake water quality issues in the region and how these might be managed.
- Provision of lake health data to national environmental reporting initiatives.

These objectives are provided for under the Auckland Unitary Plan (AUP) (Operative in Part) and fit under the "Environment and Cultural Heritage" component of the Auckland Plan 2050. A key challenge identified for the region is managing the effects of growth and development on our natural environment and ensuring environmental values are maintained or improved for the benefit of future generations. These documents provide direction and specific policies and rules for minimising and managing the adverse effects of present and future urban and rural intensification and population growth across the region and seek to ensure that the values of Auckland's freshwater resources are restored, maintained and enhanced.

The lake water quality monitoring programme provides information on the condition of the region's lake environments, helps to track council's progress in achieving environmental goals, and provides feedback on the performance of management actions. The programme forms part of the feedback loop necessary to confirm management strategies implemented under the Unitary Plan are effective in sustaining ecosystem function and opportunities for future use.

1.2 Report purpose and objectives

The purpose of this report is to assess the current condition of the four consistently monitored lakes across the Auckland region, identify changes in water quality over time and understand the pressures influencing overall lake health. This information helps decision makers to assess the performance of existing management strategies and informs the direction of effective resource management and environmental policy.

The primary objectives of this report are to:

- Describe the current state of lake health in the region through the assessment of water quality, human contact indicators, trophic state and ecological indicators.

- Identify temporal trends in key indicators and descriptors where there is robust long-term data.

Previous reporting of lake water quality state and trends in seven lakes in the Auckland region was completed in 2005 (Barnes & Burns, 2005), covering the period 1992-2005, and a subsequent report in 2015 (Hamill & Lockie, 2015). The most recent report analysed data from 1993 through to 2012 (covering a total of 27 years) for seven lakes. Due to changes in the lake water quality programme (discussed in Appendix A), this report focuses on state and trends for four lakes that have a consistent dataset covering the period between 2010-2019.

1.3 Supporting information

This report has been produced alongside several others pertaining to the freshwater and marine environments in the Auckland region, including:

- *Auckland river water quality: annual reporting and National Policy Statement for Freshwater Management current state assessment, 2019* – TR2021/11
- *Coastal and estuarine water quality 2019 annual report* – TR2020/016
- *Coastal and estuarine water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/02
- *Groundwater quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/03
- *Marine ecology state and trends in Tāmaki Makaurau / Auckland to 2019. State of the environment reporting* – TR2021/09[1]
- *Marine sediment contaminant state and trends in Tāmaki Makaurau / Auckland 2004-2019. State of the environment reporting* – TR2021/10[1]
- *Rainfall, river flow, and groundwater level state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/06
- *River ecology state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/05
- *River water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/07

The authors in this series have worked collectively to analyse current state and trend data over the same time period (2010-2019). This is a new approach adopted by the Research and Evaluation Unit (RIMU) and aims to better identify linkages between environmental

[1] Analyses for coastal benthic ecology and coastal sediment contaminants were completed for all data on record.

domains and inform the overall State of the Environment five-yearly report in a more consistent manner.

Supplementary data files of the trend analysis outputs presented in this report are available on Auckland Council's Knowledge Auckland website: www.knowledgeauckland.org.nz. All related reports (past and present) are also available on the Knowledge Auckland website.

Further enquiries or data requests in relation to this or any other reports can be directed to environmentaldata@aucklandcouncil.govt.nz.

2.0 Methods

2.1 Programme overview

Auckland Council has monitored water quality in the seven largest lakes in the Auckland region since 1988. These lakes are: Kereta, Kuwakatai, Rototoa, Spectacle, Tomarata, Pupuke and Wainamu. Lake Pupuke has some water quality data available from as early as 1977. The lake water quality monitoring programme has evolved over time, with sites added or removed according to varying management priorities. Further details of changes to the programme, including data collection and laboratory analytical methods can be found in Appendix A.

The seven lakes were initially chosen to be representative of the region because they are the largest naturally formed lakes in Auckland, they represent different lake types, had a range in water quality state at programme inception and are located in catchments with different land cover types.

Four lakes have been consistently monitored over time, either quarterly or every six weeks, they are: Pupuke, Rototoa, Tomarata and Wainamu. These four lakes are the focus of this report. Further to water quality monitoring, there are periodic assessments of the submerged aquatic plants (macrophytes) which provide an indication of the ecological health of each lake.

2.2 Monitored lakes

The locations of the four lakes that have been monitored consistently over the past 10 years are shown in Figure 2-1.

The geophysical characteristics of monitored lakes are provided in Table 2-1. All are dune lakes, except Lake Pupuke which is volcanic. Lakes Rototoa and Pupuke are the largest and deepest lakes monitored. Lake Tomarata is the only polymictic lake of the four reported on, meaning the bottom and surface waters are generally well mixed.

Figure 2-1 Lakes monitored for water quality within the Auckland region (to the end 2019).

Table 2-1 Characteristics of the four lakes monitored for water quality across the Auckland region (2010-2019). Source for area information: LCDB5 (Manaaki Whenua – Landcare Research, 2020).

	Pupuke	Wainamu	Tomarata	Rototoa
Lake type	Volcanic	Dune	Dune	Dune
Lake area (ha)	5.1	3.0	0.2	10.5
Max. depth (m)	57	15	5	29
Catchment area (ha)	89.8	489.3	104.1	422.8

2.2.1 Catchment land cover

Current catchment-scale land cover for each lake was calculated using geospatial data obtained from the Land Cover Database V5.0 (Manaaki Whenua – Landcare Research, 2020), whereby land cover descriptors were assessed and grouped according to seven broad land cover types: native forest, exotic forest, rural, urban, wetland, waterbody and other (Figure 2-2). A further breakdown of land cover categories is provided in Appendix B.

The dominant land cover categories in this report were determined according to the following decision criteria:

- Native forest – comprised of greater than 95 per cent native forest cover.
- Exotic forest – comprised of greater than 80 per cent exotic forest cover.
- Urban – comprised of greater than 7 per cent urban land cover.

Sites not meeting the above criteria were classified as having predominantly rural land cover under the following categories:

- Rural low – rural catchment with 50 per cent forest cover (native and exotic) or greater.
- Rural high – rural catchment with less than 50 per cent forest cover.

Accordingly, the dominant land cover category for each lake can be classed as:

- Lake Pupuke – Urban.
- Lake Wainamu – Native forest.
- Lake Tomarata – Exotic forest.
- Lake Rototoa – Rural low.

Additionally, changes in land cover between 1996 and 2018 were assessed through changes to dominant land cover over time. There were no changes in dominant land cover within the catchments surrounding the four monitored lakes across the 22 years available for analysis. However, there were slight changes to the harvested forest composition (in the exotic forest category) between 2001 and 2008 in the Lake Rototoa catchment, as discussed in Section 4.4.

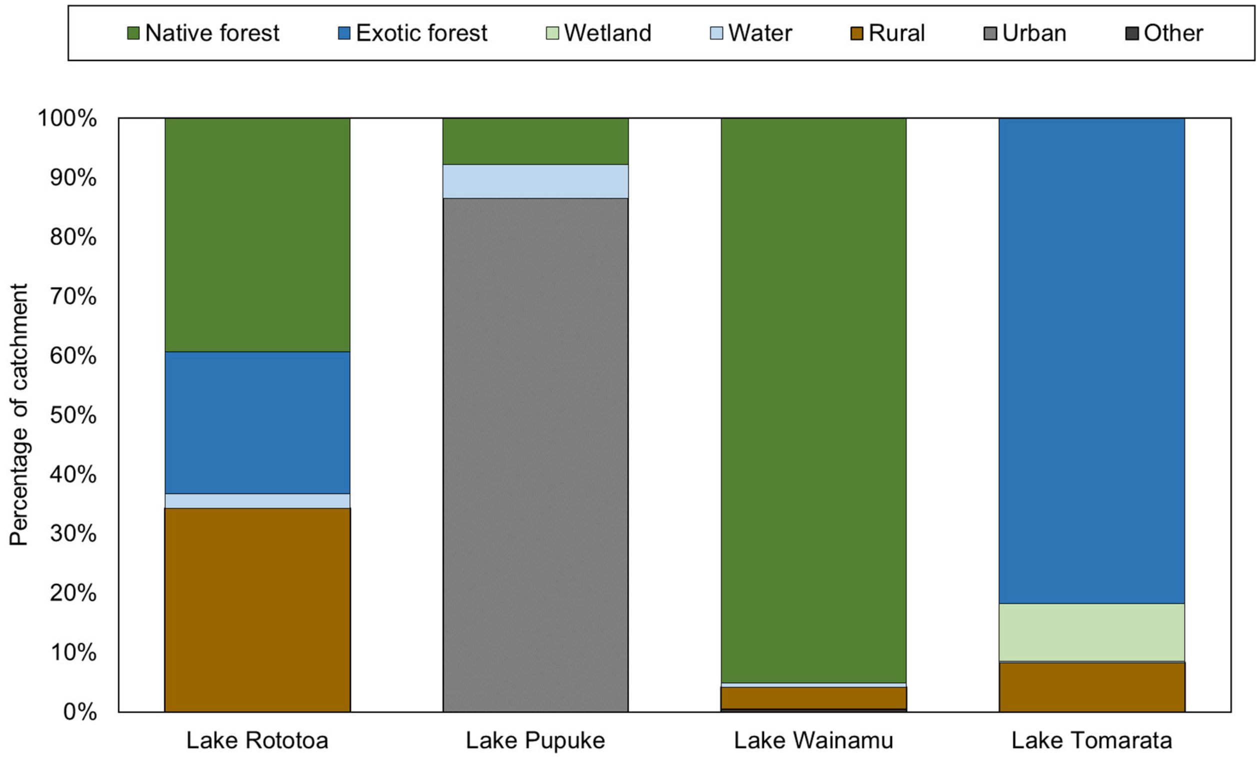

Figure 2-2 Land cover for monitored lakes across the Auckland region. Sourced from LCDB5, as of 2018.

2.3 Data collection

Over the 10-year period (2010-2019), lake water quality monitoring frequency varied between quarterly and six times per year. The majority of sampling took place in January or February, April or May, August and November (more detailed breakdown provided in Appendix A). However, there are data discontinuities due to changes in the monitoring programme, particularly during 2013 and 2014 (as discussed in Appendix A). Due to the limited sample events each year, it is important to consider that any subsequent analysis or calculations could be skewed by a single event (e.g. an algal bloom) and seasonal patterns may not be adequately captured.

Monitoring methods were generally consistent with the New Zealand lake water quality monitoring protocols (Burns et. al. 2000), whereby each lake was sampled at the deepest point, as marked by a permanent buoy. Profiles were collected through the water column every metre to the maximum depth for temperature, dissolved oxygen, salinity, conductivity, and pH. Water clarity from the surface of the lake was recorded using the Secchi disc method.

In the field, the temperature profile was used to determine whether the lake was stratified or isothermal. A lake is stratified when the difference between the surface temperature and the bottom water temperature is greater than 3°C (Burns et. al. 2000). If the temperature difference is less than 3°C, the lake is classified as isothermal. The classification of the lake on the day of sampling determines the depth of the water samples and for certain attributes in the NPS-FM (e.g. TN), the NOF guideline values for each band are different dependent on the lake type (i.e. polymictic or seasonally stratified).

All lakes had a sample taken from the epilimnion (herein referred to as the surface sample), and some of the deeper lakes had a sample collected from the hypolimnion (herein referred to as the bottom sample), all taken using a Van Dorn sampler at the appropriate depth according to Burns et al. (2000) protocol. Surface water samples were collected to assess potential catchment inputs and bottom water samples were collected to assess the resuspension of nutrients from lakebed sediments. As Lake Pupuke is deeper than the other monitored lakes, a third mid-layer sample was sometimes taken, however this has not been completed consistently over time and therefore data is not reported here.

Human health samples included *E. coli* and cyanobacteria, both of which were taken from the centre of the lake rather than any primary access points. The *E. coli* sample was taken from the surface of the lake (e.g. 0m depth) using a sterile bottle. The cyanobacteria sample was taken using a 5m tube to collect a composite sample of the upper five metres of surface water.

Samples were collected for laboratory analysis of nutrients, metals, suspended sediment, and other chemical properties of water (Appendix C, with a detailed description of the importance of each parameter in Table C.2). All samples were analysed by Watercare Services Ltd prior to June 2017 and by RJ Hills Laboratories Ltd (Hills), from July 2017 onwards.

2.4 Data processing

Prior to analysis of data, the dataset was processed, and outliers removed where there was good reason to believe them to be measurement errors (i.e. issues with sensors identified from sampling comments) that could lead to skewing the dataset.

Values that were less than the detection limit for any water quality parameter are referred to as 'left censored' values. Censored values were replaced by imputation for the purposes of calculating the five-year state statistics. Left censored values were replaced with imputed values generated using ROS (Regression on Order Statistics; Helsel 2012), following the procedure described in Larned et al*.* (2018). The ROS procedure produces estimated values for the censored data that are consistent with the distribution of the uncensored values, and it can accommodate multiple censoring limits.

For trend analysis, censored values were replaced with a value half the detection limit. This ensures that any measured value that is equal to the detection limit is treated as being larger than any value that is less than the detection limit (i.e., a measured concentration of 0.2 mg/L is larger than a value recorded as <0.2 mg/L), and that the difference between the two censored values is not measurable and treated as zero.

The face value of all detection limits was used for this analysis where there were differences in detection limits over time, rather than replacing all lower detection limit values with the highest detection limit. This ensures that observations obtained with more sensitive laboratory analytical measurements are not lost under an 'umbrella' of water quality observations with poor resolution. However, this can induce 'improving' trends where observations are lower than were able to be recorded previously, or alternatively induce 'degrading' trends where observations were historically lower than current detection limits. Where there is a risk of induced trends influencing results reported here, they have been clearly identified.

2.5 Data analysis

2.5.1 State analysis

The overall current state and function of lakes within the region was assessed for a five-year period (2015-2019) and visualised using boxplots separated into surface and bottom water groupings, using NPS-FM grading for water quality and human contact indicators (MfE, 2020 Appendix 2A), annual Trophic Level Index (TLI, Burns et al., 2005) for each of the five years and the most recent Lake Submerged Plant Index (LakeSPI) ecological assessments (de Winton and Burton, 2017). More details of these methods are outlined in Appendix C.

To meet Auckland Council's obligations under the National Policy Statement for Freshwater Management (NPS-FM), the state assessment focuses on the best available lake surface water quality recorded over the preceding five years (2015-2019 inclusive) in accordance with the National Objectives Framework (NOF, MfE 2020, Appendix 2A attributes). Currently there are no lake water quality guidelines in the AUP, therefore we rely on the national level guidelines in the NPS-FM for the assessment of the state of lake water quality at this point in time.

The NOF identifies a core group of attributes which councils must use to grade the quality of lake surface water. The state of each attribute is graded into specific bands (using various statistical metrics). Each band (A – best, B, C, D/E – worst) is associated with a narrative description which describes the expected ecological or human contact outcome of interest. The '*National Bottom Line'* refers to the minimum state for each attribute that councils must meet, or work towards meeting over time. The overall band for the attribute is defined by the lowest (worst) band of the contributing metrics for that attribute state assessment.

At this time, we have not derived NOF bands for the new lake attributes in the 2020 NPS-FM including submerged plants (native), submerged plants (invasive), lake-bottom dissolved oxygen and the mid-hypolimnetic dissolved oxygen for seasonally stratifying lakes. Attributes that have been graded in this report are all of those that were in the previous version of the NPS-FM (2017), using the attribute tables for banding outlined in the 2020 NPS-FM.

Total ammoniacal nitrogen refers to two chemical species that are in equilibrium in water – toxic ammonia (NH_3) and the relatively non-toxic ammonium ion (NH_4^+). The proportion of the two varies, particularly in response to pH and temperature. The NOF toxicity guidelines for ammoniacal nitrogen are standardised to a pH of 8.0. Total ammoniacal nitrogen results are adjusted for pH following a conversion table, as prescribed by the Ministry for the Environment (MfE, 2017a) for comparison to NOF guidelines only.

2.5.2 Trend analysis

Analyses were undertaken using purpose-written script designed for water quality trend analysis as described in Larned et al. (2018) using the R statistical package (R Core Team, 2020). The script was obtained from Land Water People (LWP) and is readily available at https://landwaterpeople.co.nz/pdf-reports/.

Trends in lake water quality data were analysed by grouping data into quarters for every year, over the most recent 10-year monitoring period (2010-2019). Some years had six samples, therefore the median value for the quarter is used for the trend analysis.

The Land Air Water Aotearoa (LAWA) reporting requires data be available for 90 per cent of the years being analysed (Cawthron Institute, 2019), however for this report, data requirements deviated from this to enable reporting on lakes that had data available for 80 per cent of the years (i.e., the maximum possible number of quarters over the 10-year period of analysis is 40, therefore a minimum of 32 quarters is required for this analysis). Any sites or parameters that did not meet these data requirements were not analysed and therefore no trends were reported.

As a first step, data was assessed for seasonality using the Kruskal-Wallis test which determined the type of test used in subsequent trend analysis. Seasonal tests compare observations within each quarter over time while non seasonal tests compare all observations over time.

Monotonic trends across sites were analysed by assessing the direction of a trend (i.e., what is the likelihood the parameter is increasing or decreasing?). The confidence in the trend direction is calculated using the Kendall (or seasonal Mann-Kendall) test based on the probability that the trend was decreasing. An overarching assumption of the first step of the trend analysis is that there are always differences between observations (McBride, 2019). The calculated probability was interpreted based on the categories used by the Intergovernmental Panel on Climate Change (Snelder & Fraser, 2018) and further aggregated to five categories for simplicity as per LAWA (Cawthron Institute, 2019) (see Table 2-2).

For most parameters, a decreasing trend is interpreted as an improvement in lake water quality, and an increasing trend is a degradation in lake water quality. For physical parameters such as temperature and pH, we have referred to the likelihood of the direction of the trend as increasing or decreasing and have not assigned this as either improving or degrading. A trend is classified as indeterminate when there is insufficient evidence to determine if the data is trending in a particular direction.

Table 2-2 Trend confidence category levels used to determine the direction of water quality trends (Cawthron Institute, 2019).

Trend categories		Probability (%)
Very likely improving	Very likely decreasing	90-100
Likely improving	Likely decreasing	67-90
Indeterminate	Indeterminate	33-67
Likely degrading	Likely increasing	10-33
Very likely degrading	Very likely increasing	0-10

Where water quality is found to be degrading further assessment is critical to understand what actions may be necessary to improve water quality. This includes assessment of the likelihood of the trend, the magnitude of the trend, the risk of adverse ecological outcomes (in relation to the known current state), and consideration of whether the current state is a reflection of naturally occurring processes.

The magnitude of the trend is characterised by the slope of the trend line using the Sen slope estimator (SSE) (or the seasonal version (SSSE)). The SSE is the median of all possible inter-observation slopes. The 90 per cent confidence intervals of this median estimate are also calculated.

While a trend may be very likely improving or degrading, the smaller the Sen slope, or rate of change, the longer it would take to be reflected in assessments of the current state, assuming a linear rate of change. Trend magnitude was considered in this report relative to the limit of precision (i.e., the measurement resolution) for each parameter following the approach in Fraser and Snelder (2018). Trend magnitude can only be estimated for very likely trends.

However, the estimation of the magnitude of the trend decreases in reliability as the proportion of censored values increases. The LWP script specifically identifies where the slope was calculated from data with censored observations. In these instances, the magnitude of the trend is considered to be imprecise and was not reported here. Only magnitudes of change that meet all of the above criteria (i.e., very likely trend, exceeding the measurement resolution, and are not calculated from censored observations) are presented in the report.

3.0 Results

3.1 Current state of lakes

3.1.1 Nutrients and chlorophyll α

The state of each water quality parameter is presented via boxplots to enable inter-lake comparisons and assess the variability in the data across the five-year period used. In the surface waters, Lake Tomarata had the highest median value for chlorophyll α and the nitrogen parameters (ammoniacal N, total kjeldahl nitrogen (TKN), total nitrogen (TN) and total oxidised nitrogen (TON)) (Figure 3-1). While Lake Tomarata had the highest median value of chlorophyll α, Lake Pupuke had the greatest spread in the data with values up to 0.06 mg/L. In the bottom waters, Lake Rototoa had the highest ammoniacal N median value with the greatest range in ammoniacal N, while Lake Tomarata had the highest TKN and TN values for both surface and bottom waters. Both lakes Pupuke and Rototoa had the greatest range in ammoniacal N and TON in the bottom waters (Figure 3-1).

Lake Wainamu had the highest total phosphorus (TP) median value in both surface and bottom waters. Dissolved reactive phosphorus (DRP) displayed the greatest variability in Lake Wainamu and Lake Tomarata for both the surface and bottom waters, however the median values were similar across all lakes, largely due to values being close to, or below, the detection limit (Figure 3-1).

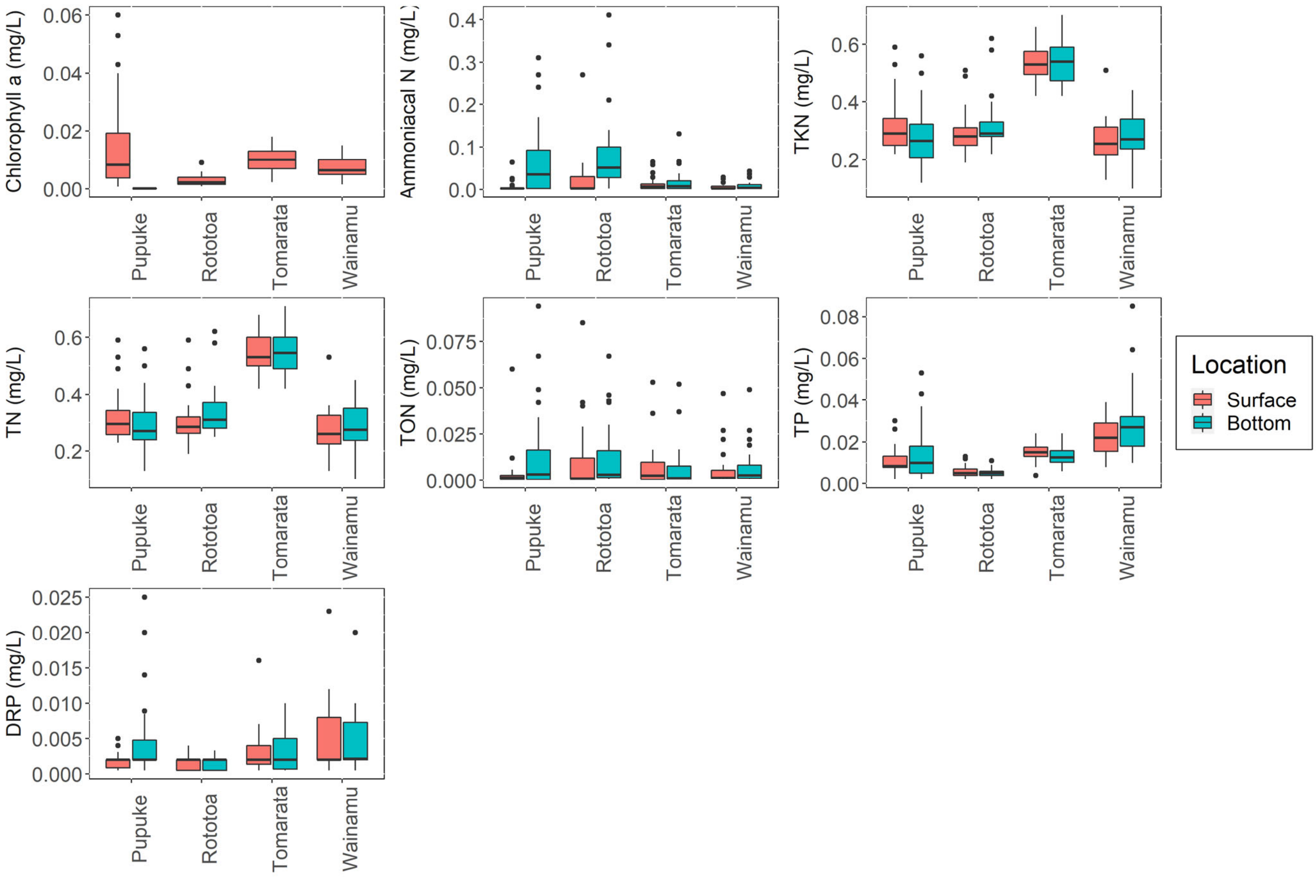

Figure 3-1 Boxplots of nutrient parameters in the surface and bottom waters for monitored lakes across the Auckland region (2015-2019). The boxes represent the median and upper and lower quartiles, while whiskers of the boxplot indicate the 10^{th} and 90^{th} percentiles of the data.

3.1.2 Suspended sediment and water clarity

Lake Wainamu had the highest median turbidity in both the surface and bottom waters, as well as the largest variability in values, and Lake Pupuke had higher turbidity in surface waters compared to the bottom waters, while the other lakes all had higher bottom water turbidity (Figure 3-2).

Lake Wainamu and Lake Tomarata had similar median values for total suspended sediments (TSS), with Lake Wainamu having the highest TSS in the bottom waters. Lake Pupuke had the lowest bottom water TSS with small variability in the data, however there was larger variability in the surface waters (Figure 3-2).

In line with these results, Lake Wainamu had the lowest median water clarity, and Lake Rototoa had the highest median water clarity. Lake Pupuke had a large spread in the water clarity data, with the second highest median water clarity (Figure 3-2).

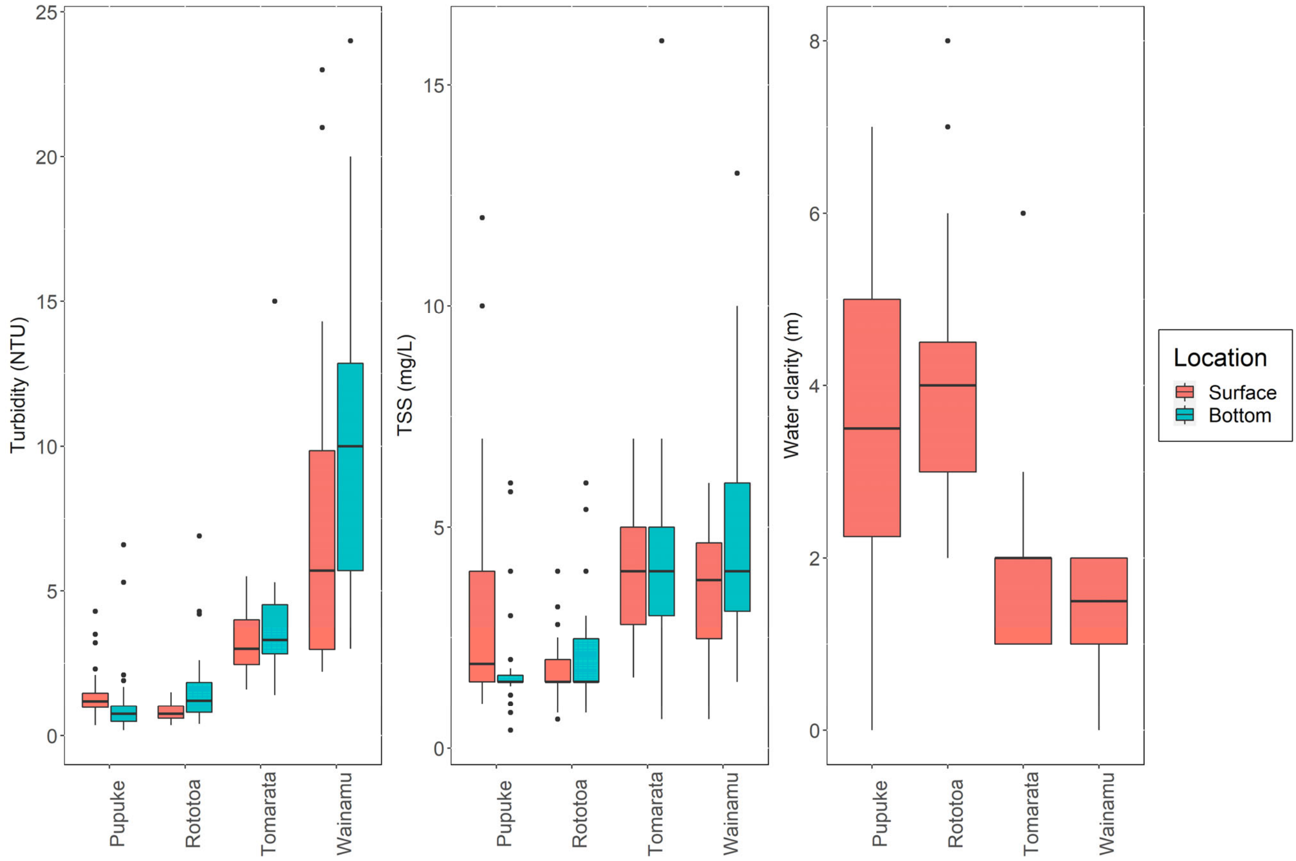

Figure 3-2 Boxplots of sediment parameters and water clarity in the surface and bottom waters for monitored lakes across the Auckland region (2015-2019). The boxes represent the median and upper and lower quartiles, while whiskers of the boxplot indicate the 10th and 90th percentiles of the data.

3.1.3 Physical water quality parameters

Surface waters and bottom waters had similar within lake conductivity and salinity, with Lake Tomarata having the lowest median conductivity and salinity.

The differences between surface waters and bottom waters were evident in the other physical parameters (Figure 3-3). Lake Pupuke had the highest median pH, and Lake Tomarata had the lowest pH in the bottom waters. Dissolved oxygen (DO) was lowest in Lake Pupuke bottom waters with the median value a magnitude of difference lower than the others, but Lake Wainamu bottom waters had the largest variability. There was smaller variability in surface water DO, with Lake Rototoa having the highest median DO (Figure 3-3). The surface water median temperature was the highest in Lake Rototoa, and the lowest in Lake Pupuke. There was a similar amount of variability in the surface water temperatures across all four lakes. Lake Pupuke also had the lowest bottom water temperature (due to the depth of the lake), and Lake Tomarata had the highest, with a median value similar to the surface waters due to the shallow depth of the lake and mixing of waters (Figure 3-3).

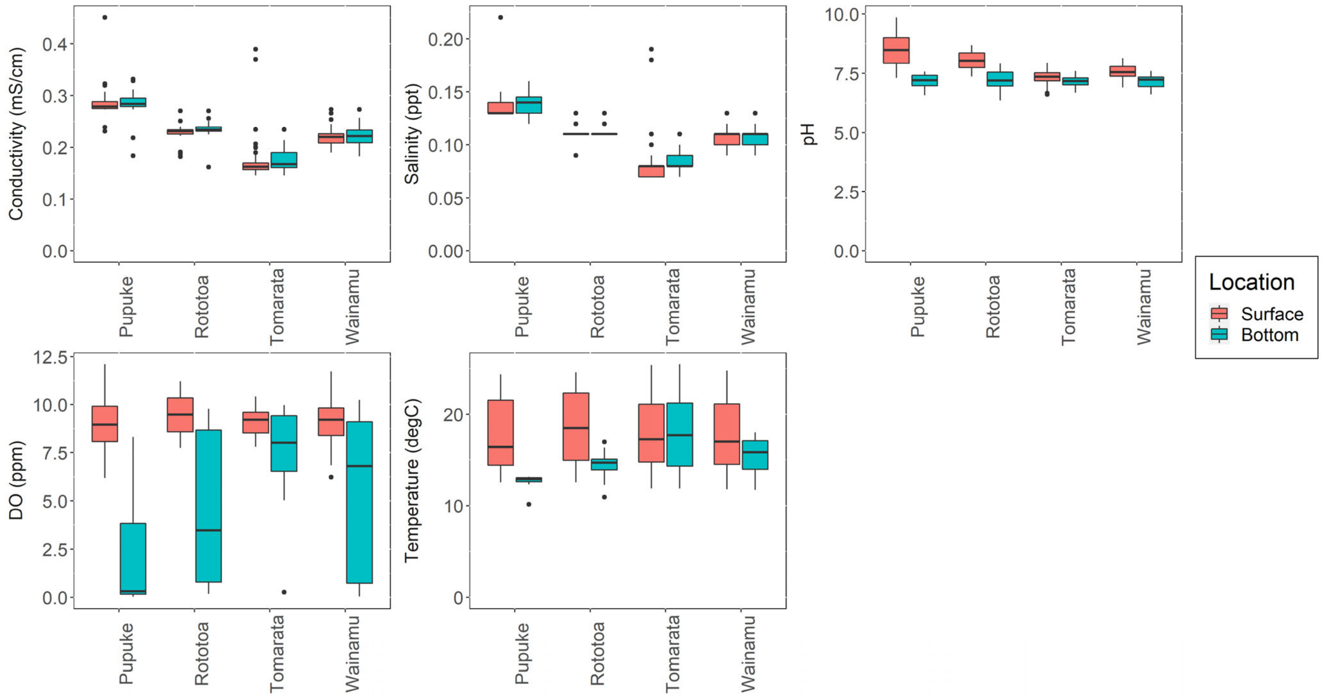

Figure 3-3 Boxplots of physical water quality parameters in the surface and bottom waters for monitored lakes across the Auckland region (2015-2019). The boxes represent the median and upper and lower quartiles, while whiskers of the boxplot indicate the 10th and 90th percentiles of the data.

3.1.4 NPS-FM – Lake ecosystem health

The following sections provide an overview of the bands for all lakes as per the NPS-FM, with further discussion on each individual lake provided in Section 4.0.

Key trophic state attributes relating to ecosystem health include total nitrogen (TN) and total phosphorus (TP), which alter the trophic state of lakes and contribute to plant growth. Additionally, phytoplankton biomass (using the proxy chlorophyll α) is a measure of plant growth derived from elevated nutrients. Further, the ammonia attribute assesses the risk of toxicity to lake aquatic life (e.g., sensitive fish species).

Those lakes with trophic state attributes in band A are expected to have healthy and resilient ecological communities, while those in band B are slightly impacted by algal and plant growth arising from elevated nutrient concentrations, with subsequent reduced water clarity. Band C suggests lake ecological communities are moderately impacted by algal and plant growth arising from elevated nutrient concentrations.

None of the lakes were below the national bottom line for any of the trophic state or toxicity attributes assessed. The state of key attributes are presented in Table 3-1, and all attribute bands (including median, 80th and 95th percentiles and maximum metrics) are presented in Appendix E.

For TN, all lakes were graded B, except for Lake Tomarata which was graded C (Table 3-1). Lake Pupuke and Lake Rototoa were graded A for TP, and Lake Wainamu had the lowest grading of C. This is supported by an assessment of potential nutrient limitation for the past five years, by calculating the ratio of TN:TP and comparing with the Redfield ratio (Abell et al*.,* 2010). Three of the lakes were potentially P limited (ratio exceeding 15:1), except Lake Wainamu which was in the range of potential N- and P co-limitation (between 7:1 and 15:1).

Three lakes were graded A for ammonia toxicity, meaning 99 per cent of all species are protected. Lake Rototoa was graded B (95 per cent species protection), due to a single high five-year maximum value (in January 2019), compared to the use of the median metric alone that would have placed it in the A band.

Gradings for chlorophyll α were in band C, suggesting ecological communities are moderately impacted by algal and plant growth arising from elevated nutrient concentrations, with subsequent reduced water clarity. The exception was Lake Rototoa which was graded B, suggesting ecological communities are only slightly impacted by additional algal growth. Lake Rototoa had the best gradings across trophic state attributes suggesting this has the best water quality of the monitored lakes based on the NPS-FM assessment criteria.

Table 3-1 NPS-FM (2020, Appendix 2A attributes) bands for key attributes in the surface water of the four monitored lakes in the Auckland region (2015-2019).

	TN	**TP**	**Ammonia (toxicity)**	**Chlorophyll α**
Pupuke	B	A	A	C
Wainamu	B	C	A	C
Tomarata	C	B	A	C
Rototoa	B	A	B	B

3.1.5 NPS-FM – Human contact

Human contact attributes described in the NOF include *E. coli* and cyanobacteria, which are measures of risk to human health. These two attributes are used to assess improvement through time of freshwater for recreational activities and human contact. All four lakes were graded A for *E. coli* (Table 3-2), although samples were taken from the centre of the lake rather than at any identified primary contact area (e.g., where people might likely access the lake) which would be required for lake surveillance purposes. The *E. coli* grading is an interim grade based on three years of data (2017-2019), with between 18 and 22 samples for each lake. A finalised attribute grade cannot be determined until after five years of consistent monthly data collection at each monitored lake.

Blue-green algae (cyanobacteria) are commonly found in lakes, however under certain conditions there are some species that produce toxins. Monitoring of cyanobacteria assesses the levels of potentially toxin producing species, not the actual level of any toxins present. All lakes were graded A for cyanobacteria (Table 3-2). Avoidance of contact with freshwater that contains high amounts of toxin producing species of cyanobacteria is recommended by public health authorities (Wood et al., 2009).

Table 3-2 NPS-FM grades for human contact attributes in the surface water of the four monitored lakes across the Auckland region (2015-2019).

	E. coli*	**Cyanobacteria**
Pupuke	A	A
Wainamu	A	A
Tomarata	A	A
Rototoa	A	A

**E. coli grading is an interim grade based on only three years of available data (2017-2019).*

3.1.6 Trophic Level Index

The state of lakes can be summarised using four water quality parameters (TN, TP, chlorophyll α and water clarity) that assess the trophic state of the lake presented as the

Trophic Level Index (TLI, Burns et al*.,* 2005). Figure 3-4 shows the variability in annual TLI for the past five years (2015-2019). Three of the four lakes had a TLI of greater than 4 for each of the five years and were classed as eutrophic, meaning all lakes were enriched in nutrients.

Lake Rototoa had the lowest TLI median for the five years and was classed as mesotrophic (TLI score between 3 and 4), suggesting this was the lake with the best water quality of those monitored in the Auckland region. In contrast, Lake Tomarata had the highest median TLI score for the five years and is considered to have the poorest water quality.

Lake Pupuke had one year (2018) where the annual TLI score was 4, suggesting the lake was on the border of mesotrophic and eutrophic, however for the rest of the years it was eutrophic. This highlights a caution on assigning a single annual TLI score and basing planning targets on this value; therefore looking at the TLI across a number of years, as well as taking monthly samples, is beneficial for assessing the state of the lake.

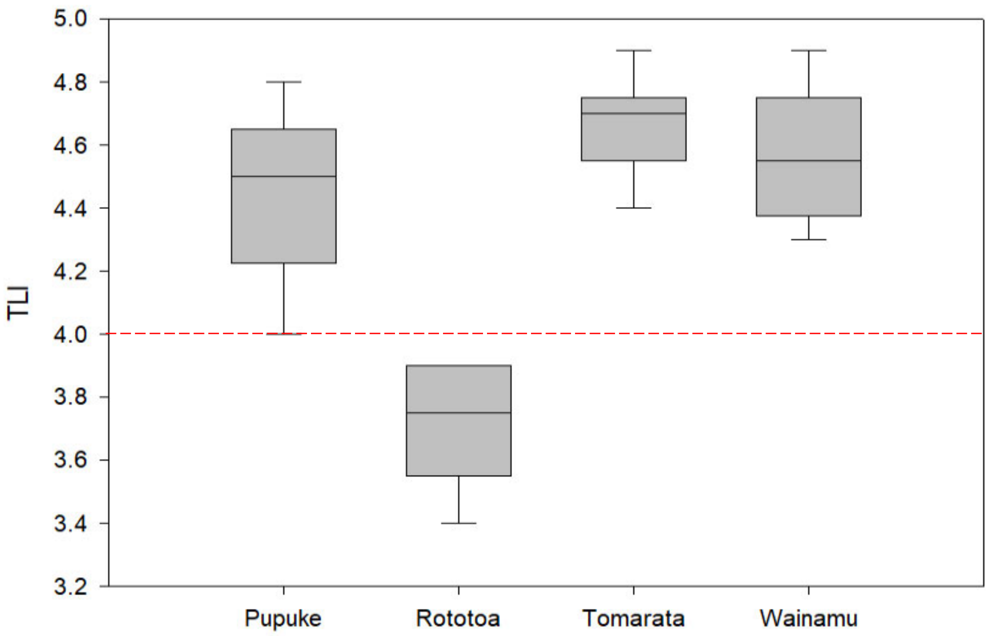

Figure 3-4 Distribution of mean annual TLI for the period 2015-2019 for the four monitored lakes across the Auckland region. The red dashed line indicates the TLI score that is needed to be exceeded for a lake to be classified as eutrophic. The boxes represent the median and upper and lower quartiles, while whiskers of the boxplot indicate the 10^{th} and 90^{th} percentiles of the mean annual TLI scores.

3.1.7 Lake ecology

To provide an indication to the state of lake ecology, the submerged plants in the lake were assessed, looking at the balance of native and invasive plant species and assigning a LakeSPI score (details of calculation in Appendix D).

In a pristine state, lakes within the Auckland region would contain a diverse range of native macrophytes (submerged plant species) growing from the lake edge towards the centre of the lake. Their extent is determined by the water clarity or the maximum depth of the lake. In shallow lakes, the macrophytes would have probably once grown across the entire lake bed (de Winton and Burton, 2017). Today, relatively few lakes remain in a pristine condition because invasive plant species and reduced water clarity have limited the quality and extent of native macrophytes in most lakes.

Only three lakes have been surveyed between 2015 and 2019, as Lake Wainamu has been classed as non-vegetated since 2012 and has not subsequently been surveyed. The Lake Submerged Plant Index (LakeSPI) scores for two of the lakes were poor or non-vegetated (Table 3-3).

Table 3-3 LakeSPI results for the monitored lakes across the Auckland region (2015- 2019).

Lake	LakeSPI (%)	Most recent year of survey	Native condition index (%)	Invasive condition index (%)	LakeSPI class
Pupuke	18	2017	11	84	Poor
Tomarata	0	2019	0	0	Non-vegetated
Rototoa	67	2019	54	11	High

Lake Rototoa was classed as high condition, as it has been consistently since surveys began in 1988 (Figure 3-5). However, the invasive condition index proportion has been slowly increasing throughout the years largely due to a threat of Hornwort invasion (invasive macrophyte). However, during the 2019 survey there was no Hornwort reported at the survey sites (de Winton, 2019) and the invasive index reduced, resulting in an increase in the overall LakeSPI result (Figure 3-5). Within Lake Rototoa there are predominantly native plant communities and the depth extent of submerged vegetation is up to 11m (de Winton, 2019).

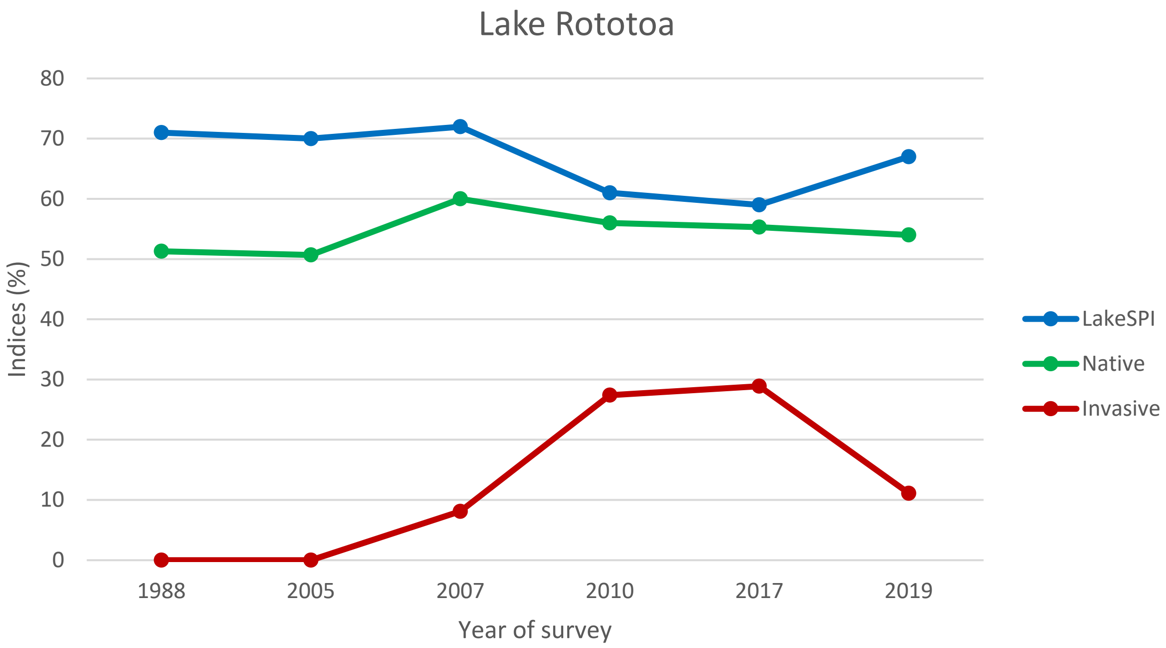

Figure 3-5 LakeSPI results for Lake Rototoa over time.

Lake Tomarata has seen the greatest change in the LakeSPI over time (Figure 3-6). Between 1988 and 2012 it was classed as excellent condition with a high native index; however this has reduced over time, with the invasive index being the highest in the first survey in 1988. Between 2012 and 2017 it was classed as being in high condition, however since the survey in 2017 the lake has been classified as non-vegetated, which was the same state for the 2019 survey (Figure 3-6).

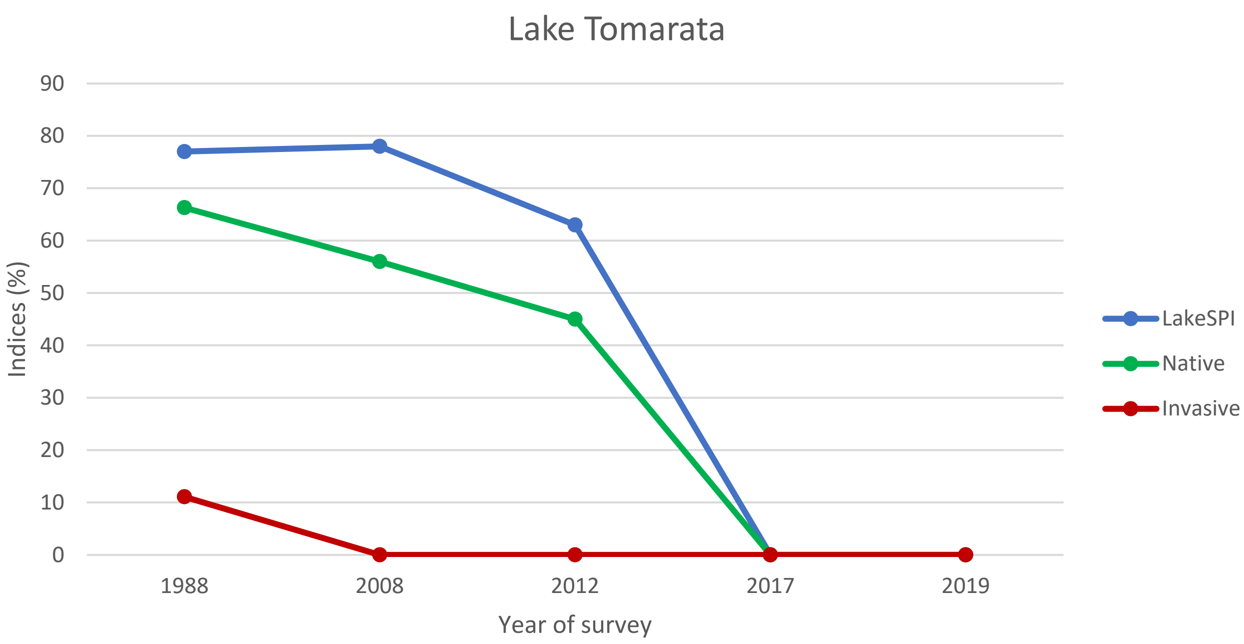

Figure 3-6 LakeSPI results for Lake Tomarata over time.

3.2 Trends in lake water quality

Trends in surface and bottom water quality were initially assessed from a regional perspective to decipher if trends followed similar patterns across the four monitored lakes in the Auckland region. Trends in *E. coli* and cyanobacteria have not been analysed due to inconsistent data available for the 10-year period of analysis.

High level regional patterns are outlined below, and within lake patterns are discussed further in Section 4.0. Any presentation of trend magnitudes are only for those that were very likely and exceeded the measurement resolution, as explained in Section 2.5.2. The time series plots for the very likely trends that exceeded the measurement resolution are presented in Appendix F.

3.2.1 Nutrients and chlorophyll α

Two lakes had degrading chlorophyll trends and the other two had improving trends (Figure 3-7). A similar pattern is shown in bottom water ammoniacal N, as two lakes had very likely degrading trends, and the other two had likely improving trends. Surface ammoniacal N trends could not be completed in Lake Pupuke due to not meeting the data requirements (see

Section 2.5.2). Out of the three lakes that had trends, one was indeterminate, one improving and one degrading (Figure 3-7).

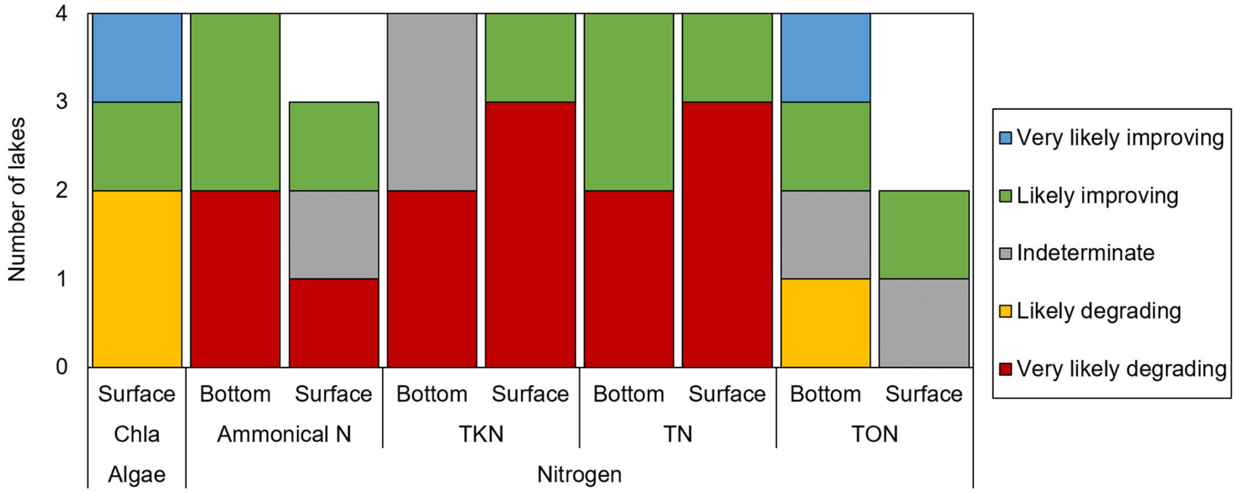

Figure 3-7 Trends for bottom and surface waters, showing the number of sites per trend category for algae and nitrogen parameters for monitored lakes across the Auckland region (2010-2019).

Three lakes had very likely degrading trends for surface water total nitrogen (TN), only one lake (Lake Wainamu) had an improving trend for this parameter (Figure 3-7). The magnitude of the very likely trends was assessed relative to the limit of precision (i.e., the measurement resolution) to ascertain how much a trend is increasing or decreasing. For TN (Figure 3-7), out of the three lakes that had very likely degrading trends, two lakes had magnitudes of change that exceeded the measurement resolution for the surface waters (Lake Tomarata and Lake Rototoa). Figure 3-8 shows that Lake Tomarata had the greatest magnitude of change in TN, followed by Lake Rototoa. Both lakes also had very likely degrading trends in lake bottom waters for TN, with the magnitude of change exceeding the measurement resolution (Figure 3-8). The magnitude of change in the bottom waters was higher than the magnitude of change in the surface waters in both lakes. Lake Tomarata is already in a degraded state (highest median value and NPS-FM band C, Figure 3-1 and Table 3-1) and is degrading at the fastest rate.

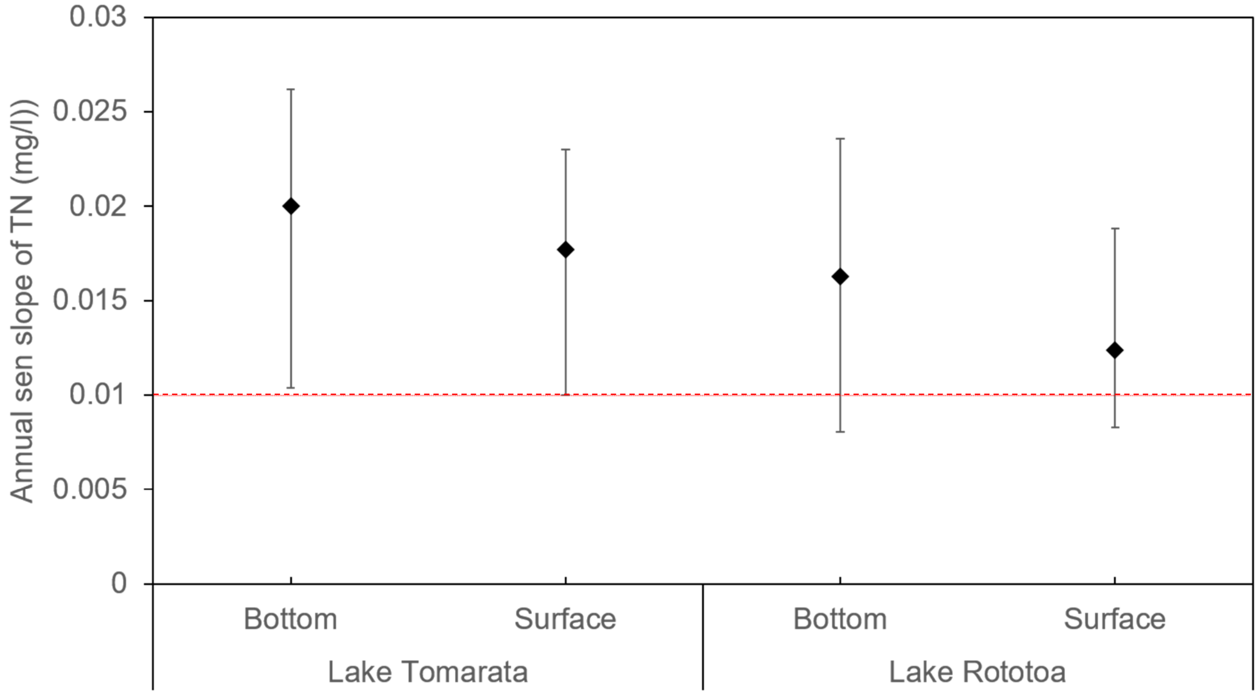

Figure 3-8 The annual sen slope (in units of parameter) for total nitrogen (TN) for monitored lakes with very likely trends that have a magnitude of change greater than the measurement precision limit (red lines). Error bars are 90% confidence intervals of the slope estimate.

Total oxidised nitrogen (TON) had half improving trends for the bottom waters, and one lake likely degrading. However, the surface TON trends could not be calculated for Lake Wainamu and Lake Tomarata due to not meeting the data requirements (see Section 2.5.2). Only Lake Pupuke had a likely improving trend in the surface TON (Figure 3-7).

Most trends for total phosphorus (TP) were improving (Figure 3-9), which reflects a similar pattern to the analysis of lakes nationally (Larned et al*.,* 2018). Dissolved reactive phosphorus (DRP) had very likely improving trends for all four lakes in the bottom waters, and improving trends for the surface waters (Figure 3-9). It is worth noting these trends are likely an artefact of multiple step changes in reporting for this parameter due to changes in the laboratory detection limits over time (initially starting at 0.005 and reducing to 0.001 mg/L through time) and therefore are ignored for reporting purposes, and no assessment of the magnitude of these trends has been considered for this reason.

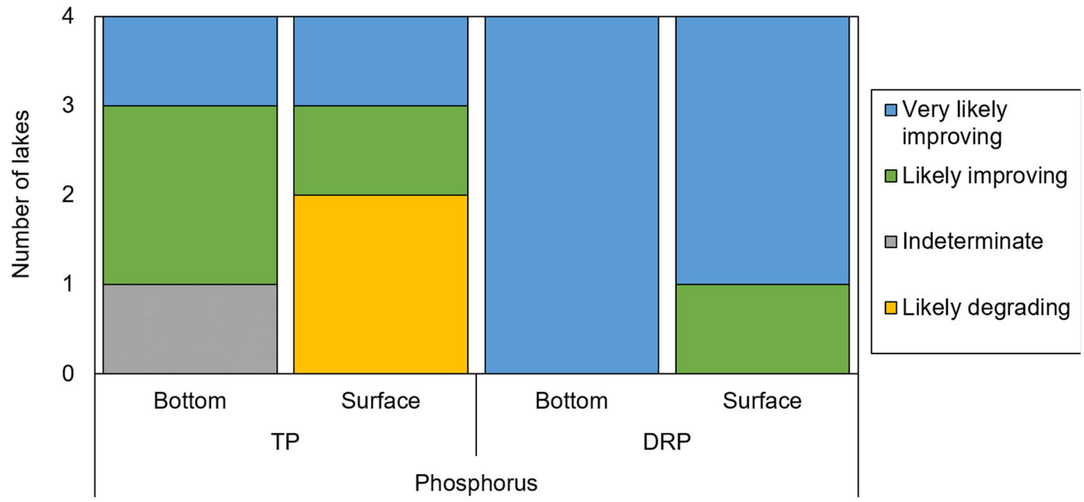

Figure 3-9 Trends for bottom and surface waters, showing the number of sites per trend category for phosphorus parameters for monitored lakes across the Auckland region (2010-2019).

3.2.2 Suspended sediment and water clarity

Trends for turbidity included both very likely degrading trends in surface waters (for three of the lakes), but also very likely improving trends in Lake Wainamu and Lake Pupuke bottom waters (Figure 3-10). For the very likely trends that exceed the precision limit (i.e., measurement resolution), it is clear the biggest magnitude of change was an improvement in the turbidity in the bottom waters in Lake Wainamu (Figure 3-11), which had the highest turbidity across the four monitored lakes, with a median bottom water turbidity of 10.4 NTU (Figure 3-2.)

For the very likely degrading trends in turbidity, Lake Tomarata had the greatest magnitude of change, above the precision limit, in both the surface and bottom waters. Lake Tomarata had the second highest turbidity for both surface and bottom waters across the four monitored lakes, with a median value of 3.0 NTU and 3.3 NTU for the surface and bottom waters, respectively (Figure 3-2).

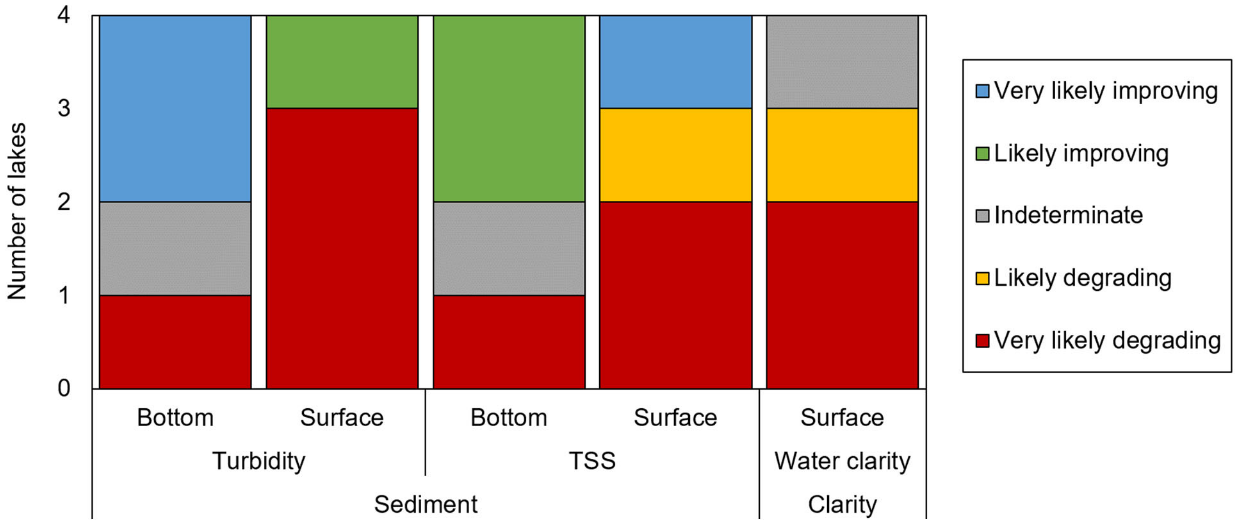

Figure 3-10 Trends for bottom and surface waters, showing the number of sites per trend category for suspended sediment and water clarity for monitored lakes across the Auckland region (2010-2019).

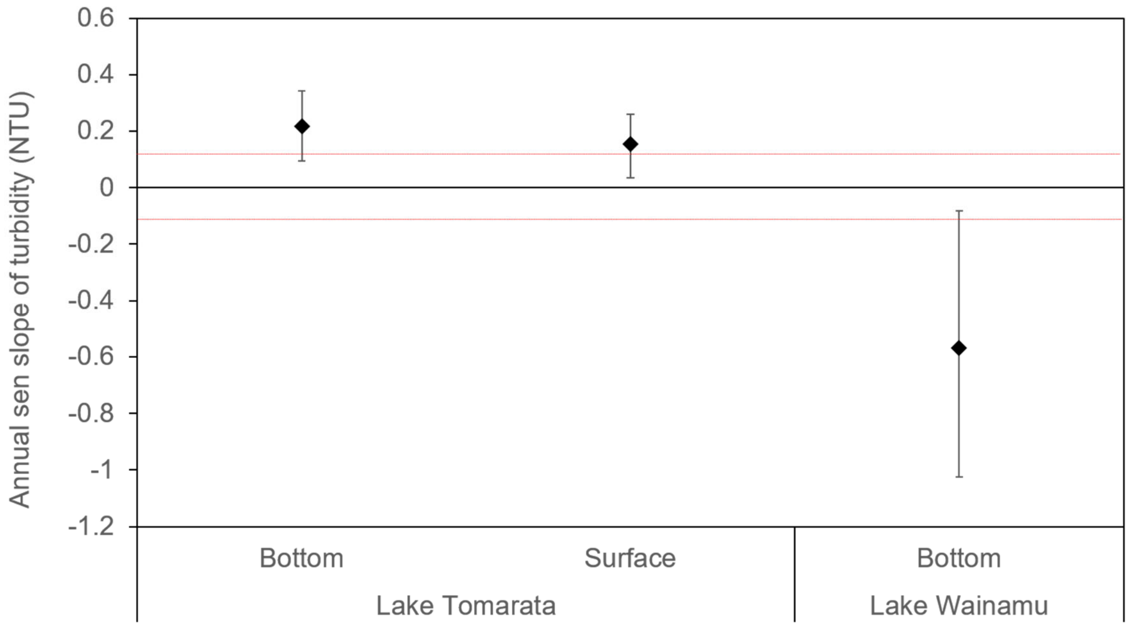

Figure 3-11 The annual sen slope (in units of parameter) for turbidity, for monitored lakes with very likely trends that have a magnitude of change greater than the measurement precision limit (red lines). Error bars are 90% confidence intervals of the slope estimate.

There were degrading trends in surface total suspended sediments (TSS) in three lakes, compared to two lakes that had improving bottom water TSS. There were both very likely degrading and improving trends in total suspended solids (TSS) that were greater than the precision limit (Figure 3-12). Lake Tomarata had the greatest magnitude of change in degrading TSS, in surface waters, which was approximately three times greater than the magnitude of the change in the surface waters of Lake Pupuke, which only just exceeds the measurement resolution limit (Figure 3-12). Lake Tomarata is the lake across the four monitored lakes that had the highest five-year median for TSS in the surface waters (Figure 3-2). Lake Wainamu is the only lake that has improving TSS trends that exceed the measurement resolution, from having the second highest TSS state concentrations in surface water across the five-year period (Figure 3-2).

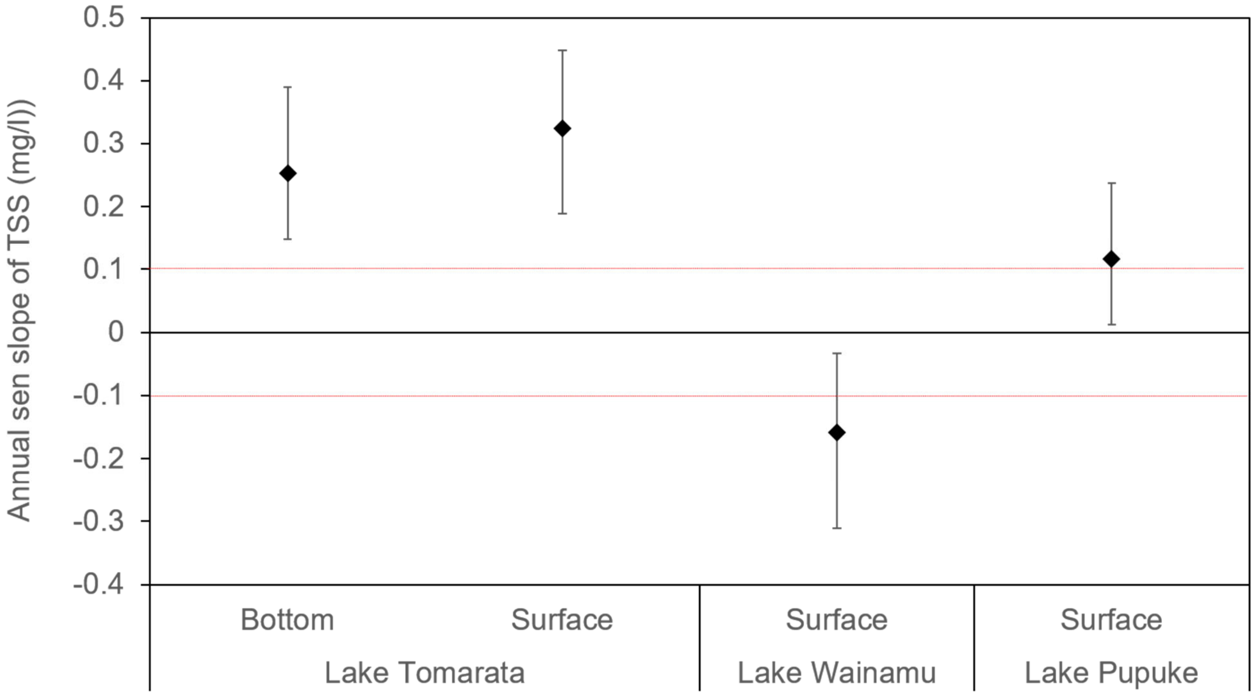

Figure 3-12 The annual sen slope (in units of parameter) for TSS, for monitored lakes with very likely trends that have a magnitude of change greater than the measurement precision limit (red lines). Error bars are 90% confidence intervals of the slope estimate.

Surface water clarity displayed degrading trends in three lakes, with one lake (Lake Tomarata) having an indeterminate trend (Figure 3-10). It is important to consider that surface water clarity experiences natural fluctuations driven by unpredictable atmospheric drivers that control catchment runoff, sediment resuspension, algal growth and sedimentation (Özkundakci & Lehmann, 2019), therefore may not display a clear trend over a short time period (10 years), although three of the lakes did have a trend evident.

Further, the data for water clarity can display a cyclic trend oscillating between high and low water clarity, in correspondence with the El Niño Southern Oscillation (Barnes & Burns, 2005). New Zealand's climate varies significantly from year to year and long-term, associated with decadal circulation and climate variations such as the Interdecadal Pacific Oscillation (IPO) and El Niño Southern Oscillation (ENSO). These climatic cycles affect temperature, prevailing wind and rainfall patterns. During the 10-year period assessed in this report, the climate was mainly in a neutral phase of the ENSO cycle, with a La Niña event during the start of the time period (2011), and an El Niño event in the middle of the time period (2015/2016) (MfE, 2017b). However, to understand the effect of these inter-decadal cycles on water quality, a longer period of record for analysis is required.

3.2.3 Physical water quality parameters

For physical parameters (i.e. conductivity, salinity, pH, temperature, and dissolved oxygen (DO)), the trends were classified as increasing or decreasing, rather than improving or degrading (Figure 3-13).

For conductivity and salinity, there was no clear pattern across all lakes or lake depth sampled. There were many indeterminate trends in conductivity, particularly in the bottom waters. Salinity trends could not be calculated for surface waters in Lake Pupuke due to not meeting the data requirements (see Section 2.5.2). The state assessment for conductivity and salinity showed Lake Pupuke had the highest five-year median values for both surface and bottom waters (Figure 3-2) and there was little variability between surface and bottom waters for all lakes.

All lakes had increasing pH in surface waters, and most lakes had increasing pH in the bottom waters (Figure 3-13), which can have effects on the trophic state of a lake. Lake Pupuke had the highest surface pH, while bottom water pH was similar across all lakes (Figure 3-2). Increases in pH can increase the solubility of phosphorus and other nutrients, making them more accessible for plant growth. This triggers a chain reaction, as plants and algae increase the pH and also increase the demand for dissolved oxygen (DO) in the lake, resulting in potential reductions in DO concentrations in the water column (Graham et al*.,* 2020).

Three lakes had increasing DO in the bottom waters. National reporting has observed decreasing bottom water DO in lakes (Larned et al*.,* 2015). Three lakes had decreasing trends in DO in surface waters, which supports the increasing pH and degrading chlorophyll α in surface waters. However, it also could be influenced by the sampling time shifting to earlier in the morning from 2014. Therefore, these DO trends should be interpreted with caution due to the natural diurnal variation in lake DO concentrations (Milne et al*.,* 2019). The one lake with increasing DO in the surface waters was Lake Tomarata, where the sampling time shifted to later in the morning since 2014.

Half of the lakes had increasing temperatures in the surface waters, and the same for bottom waters, with one lake that had decreasing bottom water temperatures. Lake Rototoa had the highest median surface water temperature (Figure 3-2), and this showed a very likely increasing temperature. Lake Pupuke had the lowest median bottom water temperature (Figure 3-2) and showed an increasing trend. The rest of the temperature trends were indeterminate (Figure 3-13).

Calculations of the difference between the surface and bottom temperature of the lake, for each sampling occasion, allowed for the assessment of stratification in lakes (Figure 3-13). The difference in temperature showed an increasing trend for two lakes (i.e., the range in temperature of the lake is getting bigger), while one lake displayed a decreasing trend which could imply an increase in the mixing of surface and bottom waters.

An increase in the temperature range in these lakes suggests that surface waters were warming faster than the bottom waters, supported by larger magnitudes of change in surface waters than bottom waters (approximately 1.5 times higher magnitude of change in Lake Tomarata and Lake Pupuke). Increased surface water temperatures reduce the replenishment of oxygen in bottom waters by reducing vertical mixing (Verberg et al., 2010). This can increase the intensification of stratification in lakes, which has been observed across New Zealand lakes in recent decades (Verberg et al., 2010). National reporting has suggested New Zealand lakes are expected to suffer increasing frequency and duration of bottom water anoxia as a result of a changing climate, which in turn can increase the vulnerability of lakes to eutrophication and reduced water clarity by enhancing internal loading of nutrients from lakebed sediments. Further, lakes that stratify may resist recovery attempts due to the anoxic bottom water that could lead to settled nutrients being recycled into the upper water column, driving the growth of phytoplankton which then settles back into the bottom water (Graham et al*.,* 2020).

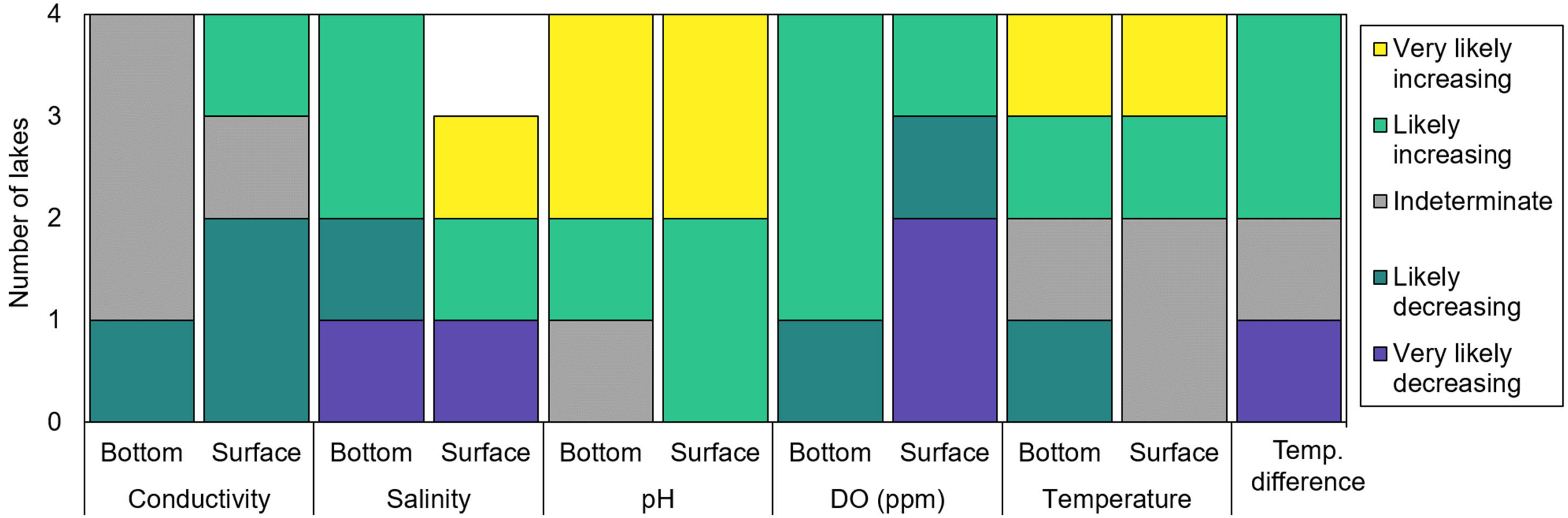

Figure 3-13 Trends for each physical parameter for surface and bottom waters, showing the number of sites per trend category for monitored lakes across the Auckland region (2010-2019).

4.0 Discussion

4.1 Lake Pupuke

Lake Pupuke is a deep, volcanic lake that regularly stratifies outside of winter months, with anoxic bottom waters even during non-stratified periods (Hamill & Lockie, 2015). During the 10-year period of this analysis, the lake was stratified for 75 per cent of sampling events (between November and June), with corresponding anoxic bottom waters for 87 per cent of these occasions. In comparison, for all of the sample events, the bottom waters were anoxic 53 per cent of the time. For the years 2015 to 2019 the state was eutrophic with median TLI score of 4.5

A summary of 10-year trends for surface water and bottom water for Lake Pupuke are presented in Figure 4-1 and Figure 4-2. Note that there are no trends for surface water ammoniacal N due to not meeting the data requirements (see Section 2.5.2).

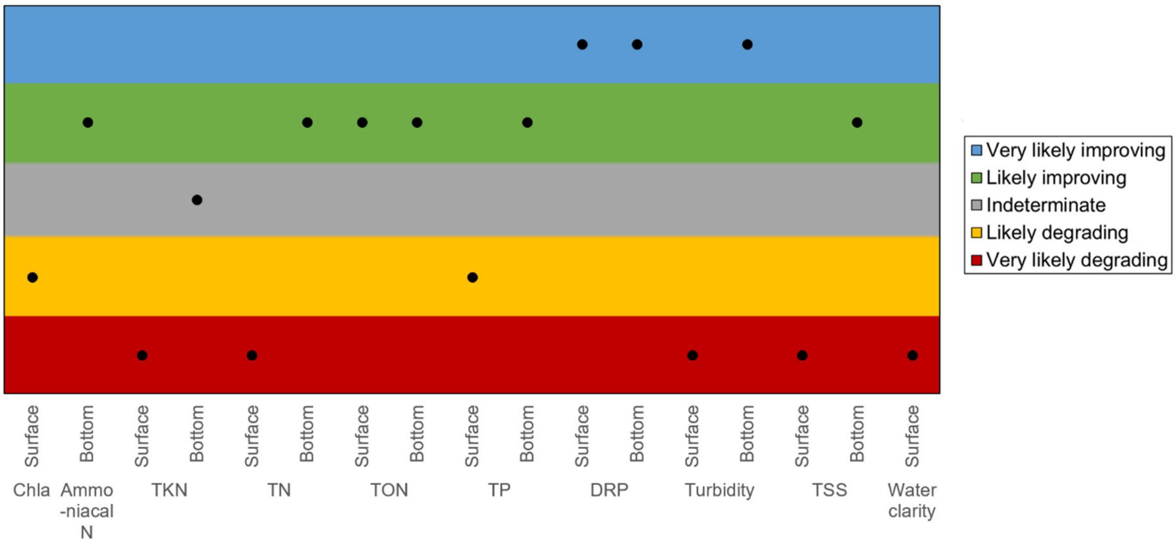

Figure 4-1 Ten-year trends (2010-2019) in microalgae (Chl a), nutrient concentrations (N and P), and sediment attributes in the surface and bottom waters of Lake Pupuke.

Nutrient (including TN and TP) and sediment concentrations (turbidity and TSS) in bottom waters had improving trends (Figure 4-1). Note DRP trends are likely an artefact of step changes in detection limits as discussed in Section 3.2.1. Surface waters had predominantly degrading trends for nutrient and sediment concentrations. This included degrading trends over the 10 years in chlorophyll α (i.e., increasing concentrations) which could suggest an increase in algae in the surface waters and subsequently a reduction in light penetration through the water column. Using the same water quality data used in this report, recent research reported a seven-fold increase in surface water chlorophyll α concentrations between 2017 and 2019 (Waters & Kelly, 2019), which could be driving the likely degrading trend observed over the 10-year period (Figure 4-1).

Recent research into nutrient cycling in Lake Pupuke found that there was a high phosphorus content present in both deep and shallow lake sediments, meaning that a large amount of legacy phosphorus is contained within them, so that along with anoxic bottom waters, particularly during thermal stratification, there is a very high potential for phosphorus release that can trigger algal bloom events (Waters & Kelly, 2019). The primary productivity in Lake Pupuke may largely be driven by these within-lake nutrient sources, although external nutrient loads have not been quantified (Waters & Kelly, 2019). Therefore, changes in nutrient concentrations in the lake over time, such as the degrading surface water trends in TP reported here, should be carefully monitored to prevent any further degradation of water quality.

Previous Auckland Council reporting noted an increase in TN and TP concentrations in summer periods between 1992 to 2005, particularly during the stratified season of 1998/1999, suggesting there was a release of nitrogen and phosphorus from anoxic sediments on the lake bottom (Barnes & Burns, 2005). However, this did not correspond to a subsequent increase in phosphorus concentrations in the surface waters of the lake, suggesting rapid sedimentation of the released phosphorus (Barnes & Burns, 2005). It has previously been argued that further improvements to water quality in Lake Pupuke will be hindered by internal nutrient recycling, particularly of phosphorus (Barnes & Burns, 2005). While there was a likely improving trend in TP for bottom waters suggesting there could have been a reduction in internal loading over the recent monitoring period, the surface waters showed a likely degrading trend in TP (Figure 4-1) which could be an effect of activities in the surrounding catchment.

Degrading trends in surface water sediment parameters (TSS and turbidity), were supported by a very likely decreasing trend in water clarity (Figure 4-1). Surface water TSS was the only very likely trend for Lake Pupuke that was degrading at a magnitude of change exceeding the measurement precision limit, with an annual sen slope of -0.12 mg/L, although it should be noted there were a high proportion of censored values for TSS (23 per cent of data), meaning the concentrations were below the detection limit, and therefore we have less confidence in the magnitude of change compared to others.

Previously, reducing water clarity in the lake has been attributed to the presence of coarse fish (Rowe et al., 2003 in Hamill & Lockie, 2015). Historic improvements in water clarity were observed from the 1960s up to the 1990s before a decline in water clarity from 2000 (Barnes & Burns, 2005), this decline was still evident in the most recent trends in water clarity reported here (Figure 4-2).

Recent experimental work investigating nutrient cycling from lakebed sediments in Lake Pupuke found that in elevated pH conditions (up to 9.8 pH) the release rates of phosphorus from shallow sediments were high (Waters & Kelly, 2019). Over the 10-year period of trend analysis in this report, the surface water median was higher than the bottom waters, with 19 per cent of surface samples exceeding 9.2 pH, which is the critical threshold above which the release of phosphorus in bioavailable form from sedimentary particulates to the water column is likely to occur (Waters & Kelly, 2019). Therefore, increasing trends in both surface and bottom water pH (Figure 4-2) could result in increased internal nutrient loading, although there were no degrading nutrient trends in the bottom waters (Figure 3-7). Also, increased pH can increase the toxicity of pollutants, such as ammonia. The ammonia toxicity NPS-FM grade was A (Table 3-1), however it was on the border of the B band for the annual maximum attribute.

There was also a very likely increasing trend in temperature of bottom waters (Figure 4-2), which had a magnitude of change that exceeds the measurement precision limit, with an annual sen slope of 0.06°C. An increasing trend was also observed in bottom water DO, however there was a very likely decreasing trend in the surface waters, which had a magnitude of change that exceeds the measurement precision limit, with an annual sen slope of -0.085 (ppm).

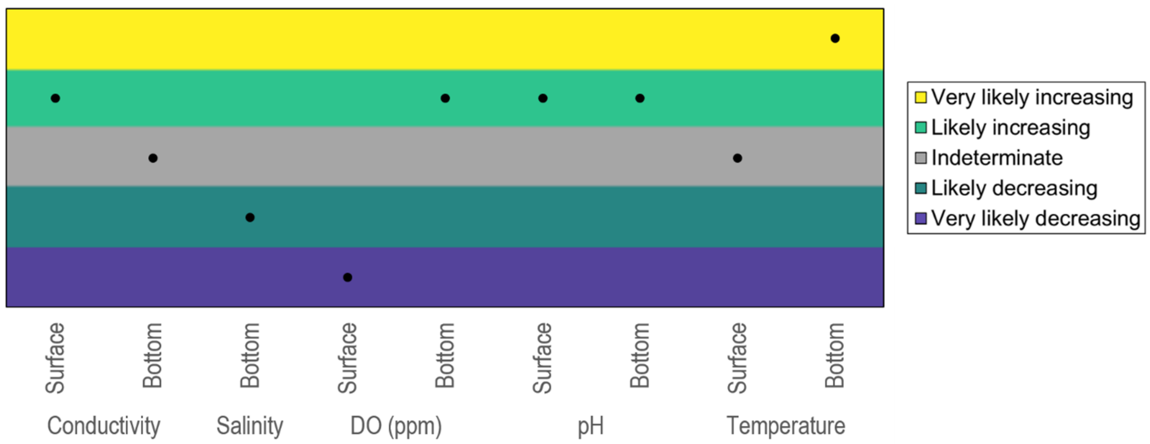

Figure 4-2 Trends in physical parameters in the surface and bottom waters of Lake Pupuke.

4.2 Lake Wainamu

Lake Wainamu is the only monitored lake with a catchment dominated by native forest land cover. Previous reporting identified that the lake stratifies seasonally, with anoxic bottom waters and has relatively poor water clarity (Hamill & Lockie, 2015), as was the case in the most recent 10 years. During the current 10-year period of analysis, the lake was stratified for 50 per cent of sampling events (between November and April), with anoxic bottom waters for 75 per cent of these occasions. In comparison, for all sample events, the bottom waters were anoxic 38 per cent of the time, and there were no cases of anoxic bottom waters when the lake was isothermal.

For the years 2015 to 2019 the state was eutrophic with median TLI score of 4.5. The 10-year trends for surface water and bottom water are presented in Figure 4-3 and Figure 4-4 below.

Generally, all water quality variables were improving in Lake Wainamu over the 10-year period. The surface waters and bottom waters displayed similar improving trends for each parameter. The exceptions were TKN and TSS which had indeterminate trends for the bottom waters, and water clarity which had a likely degrading trend.

There were two very likely trends where the magnitude of change exceeded the measurement precision limit; TSS in the surface waters and turbidity in the bottom waters (Figure 3-11 and Figure 3-12). TSS in the surface waters was improving at a magnitude of change exceeding the measurement precision limit, with an annual sen slope of -0.16 mg/L. Turbidity was the highest in Lake Wainamu, with the bottom waters having the highest median values across the region (Figure 3-2). Improving trends in turbidity in the bottom waters were at a magnitude of change exceeding the measurement precision limit, with an annual sen slope of -0.57 NTU.

Previously, Lake Wainamu had low water clarity, thought to be due to a high suspended sediment concentration (Barnes & Burns, 2005). Between 2004 and 2015, nearly 25,000 pest fish were removed from the lake (88 per cent of these were perch) as a management strategy for improving water clarity (Rowe & Verberg, 2015). A review of the programme determined that the pest fish reduction resulted in an improvement in water clarity, with increases in water clarity from one metre to up to four metres in 2008 (Rowe & Verberg, 2015). However, the introduction of grass carp in 2009 to remove vegetation (submerged macrophytes) is thought to have caused a reduction in water clarity and an increase in suspended sediments over the subsequent years (Hamill & Lockie, 2015).

Figure 4-3 shows that while water clarity was likely decreasing over the most recent 10-year period, TSS and turbidity were both improving in the surface and bottom waters, and chlorophyll α concentrations were also improving, therefore the drivers of declining water clarity are uncertain.

Lake Wainamu was the worst monitored lake in the Auckland region for TP concentrations, just falling into band C (Table 3-1). A likely improving trend in TP concentrations over time suggests the current state will be at least maintained for this attribute, however, there was insufficient evidence to suggest it is improving at a rate that could result in the lake moving up into the B band.

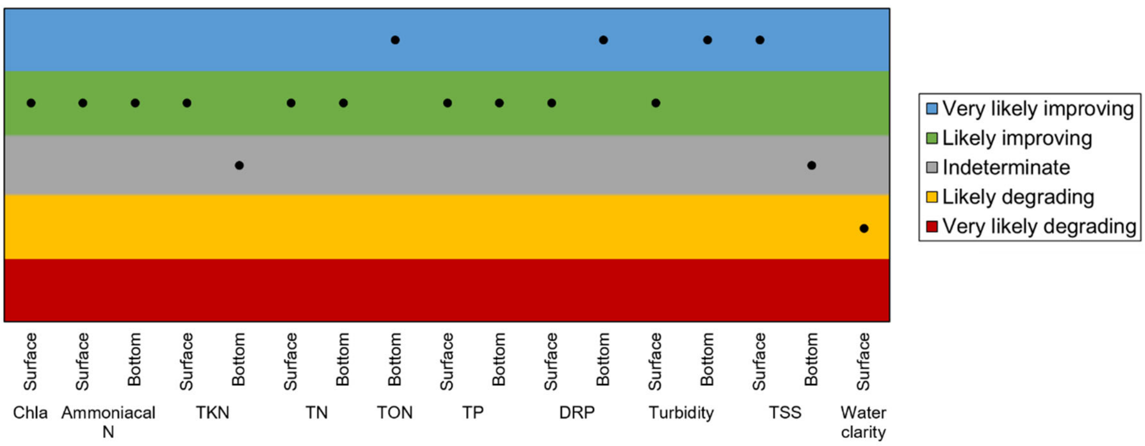

Figure 4-3 Trends in algae, nutrient concentrations, and sediment attributes in the surface and bottom waters of Lake Wainamu.

Physical parameters did not see the same consistent pattern as for nutrients and chlorophyll α. The pH in both surface water and bottom water was increasing, which is an opposite trend from that seen between 2006-2012 where pH was observed to be decreasing (Hamill & Lockie, 2015). As discussed in Section 3.2.3, increases in pH can have effects on the trophic state of a lake by making nutrients accessible for plant growth, causing changes in the DO concentrations in the water column, and increasing the toxicity of pollutants.

The bottom water temperature and DO had likely increasing trends, while surface temperature trends were indeterminate, and surface DO was decreasing.

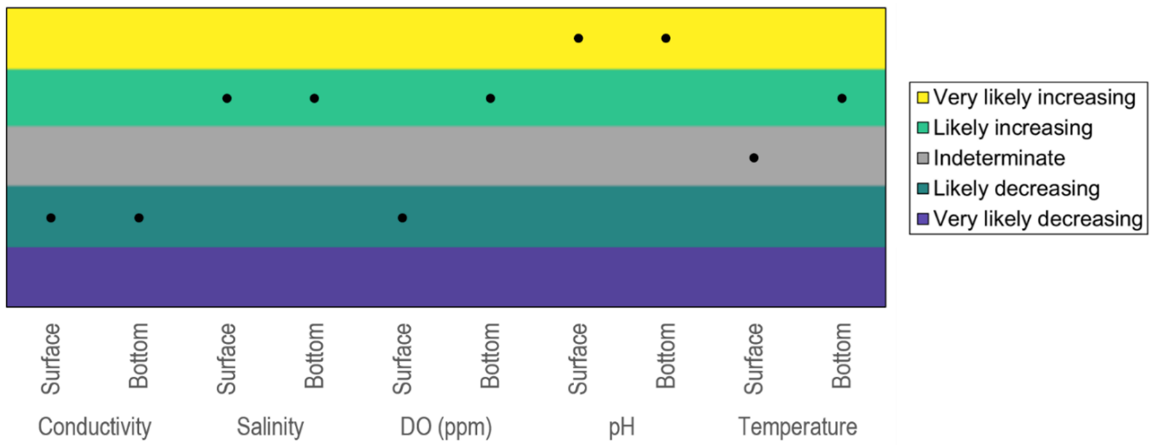

Figure 4-4 Trends in physical parameters in the surface and bottom waters of Lake Wainamu.

4.3 Lake Tomarata

Lake Tomarata is one of the three dune lakes in the Te Arai area, which make up the Ngāroto Lakes complex. All three lakes are within the Ngāti Manuhiri rohe, holding significant ecological, cultural, spiritual, and recreational values.

Lake Tomarata is the only polymictic lake of the four discussed in this report, meaning the bottom and surface waters are generally well mixed. Previous reports have shown bottom water and surface water have similar water quality and trends over time (Hamill & Lockie, 2015), which is true for the most recent 10-year trends presented here, except for dissolved oxygen.

Lake Tomarata was the most degraded lake monitored in the Auckland region, as it had the highest TLI (median TLI for the five years (2015-2019) was 4.7) and became de-vegetated sometime between 2012 and 2017 (Section 3.1.7). It has been implied that lakes that are in a degraded state can be very difficult to restore, and the most pragmatic and effective way to manage these ecosystems is to maintain the lake resilience at the desired state (Özkundakci & Lehmann, 2019), and not let further degradation occur. However, with a changing climate, polymictic lakes are vulnerable to enhanced eutrophication due to increased internal loading, which can lead to a biological response of increased algae biomass, while changes in external loads will have a lesser relative impact (Me et al., 2018). This could be true for Lake Tomarata, as there are limited direct external loads, as the lake has an extensive wetland margin that filters nutrients before they can enter the lake (Barnes & Burns, 2005).

Drastic changes in submerged vegetation have been reported in Northland dune lakes from the mobilisation of organic matter from the harvesting of plantation forest (de Winton and Burton, 2017). However, there was no harvested forest land cover apparent in either 2012 or 2018 in the immediate surrounding lake catchment (Appendix C) suggesting this is an unlikely cause of the de-vegetated state of the lake since 2012-2017; although harvesting of forestry in the wider Te Arai catchment has occurred during this time.

There has been recent work in Lake Tomarata as part of freshwater biosecurity projects, which are funded by Auckland Council's Natural Environment Targeted Rate (NETR) which has been in place since July 2018. This work has involved a survey of fish communities in the lake, which found three native species (shortfin eel, longfin eel and common bully), and two exotic species (rudd and tench) (Ling et al*.,* 2019a). A relatively abundant population of herbivorous adult rudd will have significantly contributed to macrophyte loss and prevented any subsequent re-establishment of the native plant community from a sediment seed bank (Ling et al*.,* 2019a).

Previously, macrophyte cover was absent in the lake throughout the 1990s, but it did recover to the extent that native charophyte vegetation extended to a depth of 3.9m in 2008, corresponding to improvements in water clarity (Hamill & Lockie, 2015), before reducing to 2.6m in 2012 (de Winton and Burton, 2017). This is promising in that the re-emergence of macrophytes could happen in the future and the re-establishment of submerged macrophytes may result in improvements to water clarity. In the 2019 LakeSPI survey, although the overall LakeSPI class was de-vegetated, there were isolated germlings and young plants of native chrophytes identified (de Winton, 2019). However, these had a low germination response suggesting recruitment is low and/or germinating plants are being frequently removed or disturbed (de Winton, 2019). Currently, there is ongoing research by Auckland Council using fish exclusion cages to assess the impact of fish grazing on possible charophyte restoration in the lake.

It is also possible that the restoration of submerged vegetation could be hindered by the high volume of recreational activities on the lake (Wells, 2016). Further, the high volume of recreational use at the lake increases the risk of introduction of invasive weeds. A recent recreational use survey conducted at both Lake Tomarata and Lake Rototoa (Gravitas, 2020) showed only 47 per cent of survey participants knew about the Check Clean Dry Campaign (MPI, 2020), suggesting further work can be done to improve the education around freshwater biosecurity in the region.

Previous reports on trends between 1992 and 2005 showed the lake became less eutrophic, with improvements in water clarity, chlorophyll α and TSS concentrations (Barnes & Burns, 2005). However, there were no observed significant changes in TN and TP (Barnes & Burns, 2005). This was not found in more recent trend reporting for the period between 2006-2012, where both surface water and bottom waters were found to have decreasing TP, water clarity and pH, and increasing turbidity (Hamill & Lockie, 2015). The 10-year trends for surface water and bottom water between 2010-2019 are presented in Figure 4-5 and Figure 4-6 below.

All water quality variables were generally degrading in Lake Tomarata over the 10-year period. The surface waters and bottom waters had similar degrading trends for each parameter, likely due to the polymictic nature of the lake. Aside from DRP, which had very likely trends likely as an artefact of step changes in detection limits (see Section 3.2.1), the exceptions were TON and TP which had indeterminate trends for the bottom waters and ammonia and water clarity which had an indeterminate trend for the surface waters.

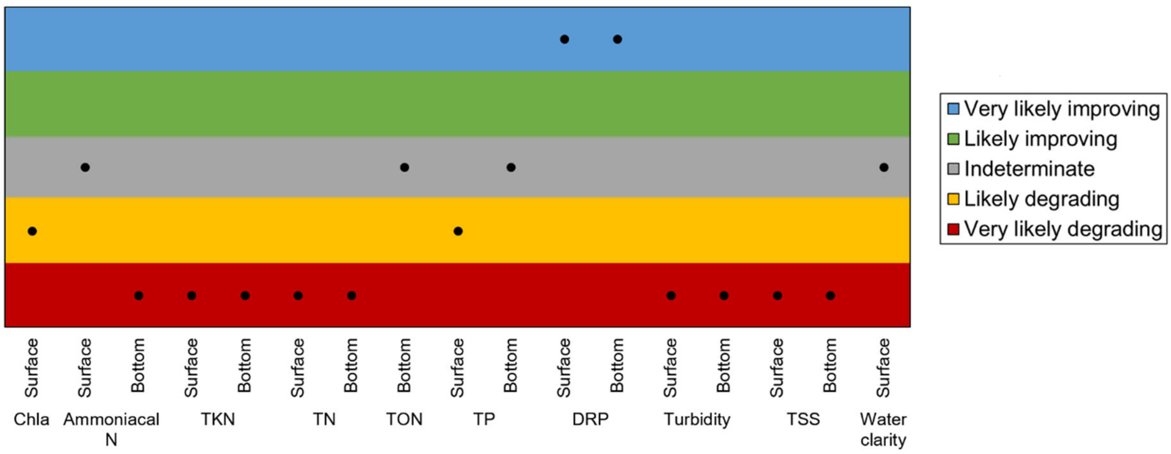

Figure 4-5 Trends in algae, nutrient concentrations, and sediment attributes in the surface and bottom waters of Lake Tomarata.

There were several very likely trends where the magnitude of change exceeded the measurement precision limit, presented in Table 4-1. As with the surface water TSS in the other lakes, the magnitude of change presented here should be treated with caution due to the high proportion of censored values (16 per cent).

As TN is an attribute in the NPS-FM, the trend magnitude can be linked to the existing state of the lake, which is currently in the C band (Table 3-1). The five-year median concentration of TN was only just over the limit for the C band, but the trends in Figure 4-5 showed a very likely degrading trend in TN with an annual magnitude of change at approximately 0.018 mg/L (Table 4-1). Therefore, at this rate of change it could take between 10 and 30 years (i.e., several decades) before the lake would fall into the D band, and below the national bottom line for this attribute.

Despite degrading trends in TSS, turbidity and chlorophyll, there was an indeterminate trend in water clarity (Figure 4-5). Water clarity and suspended sediment concentrations undergo natural fluctuations driven by atmospheric drivers that are difficult to predict, particularly for shallow, polymictic lakes where wind is a driver of the resuspension of sediments. This can result in naturally occurring higher TSS concentrations, which has been observed in de-vegetated lakes in the Waikato region (Özkundakci & Allan, 2019).

Table 4-1 Trend magnitudes of annual change for very likely trends in Lake Tomarata that exceed the measurement precision limit (i.e. measurement resolution). Upper and lower confidence intervals are in brackets.

Parameter	**TKN (mg/L)**	**TN (mg/L)**	**TSS (mg/L)**	**Turbidity (NTU)**
Precision limit	0.01	0.01	0.1	0.1
Surface water				
Annual change	0.016 (-0.009, +0.021)	0.018 (-0.010, +0.023)	0.325 (-0.189, +0.448)	0.155 (-0.034, +0.259)
Bottom waters				
Annual change	0.019 (-0.009, +0.025)	0.020 (-0.010, +0.026)	0.253 (-0.148, +0.390)	0.216 (-0.094, +0.342)

Salinity showed a decreasing trend in both the surface and bottom waters, while temperature and DO did not have consistent trends for either the surface or bottom waters (Figure 4-6), despite the mixing nature of the polymictic lake. However, there was a slight shift in the sampling time to later in the morning since 2014 that could have influenced surface temperature and DO.

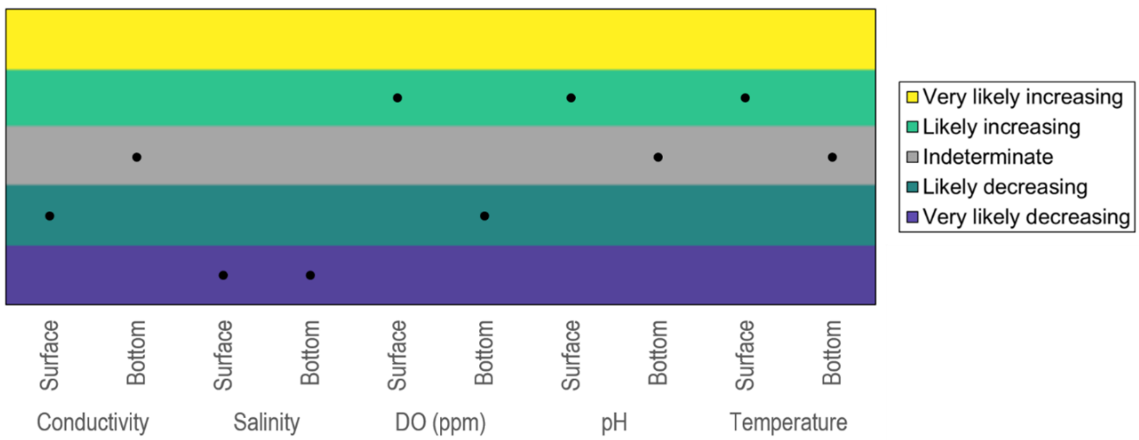

Figure 4-6 Trends in physical parameters in the surface and bottom waters of Lake Tomarata.

Recently, between 2017 and 2020, Lake Tomarata, along with the other two lakes in the Ngāroto complex (Lake Slipper and Lake Spectacle) have had restoration work completed around them as part of a Ministry for the Environment (MfE) funded initiative. The type of works included stock exclusion, riparian management, restoration planting, weed control, pest control and a wider catchment management plan. Water quality monitoring was completed more frequently by Auckland Council and members of a Ngāti Manuhiri. It is likely too soon to assess the effects of any of these restoration strategies on lake water quality, but an effect could potentially be observed in future reporting, with continued monitoring.

4.4 Lake Rototoa

In the last lake state and trends report, Lake Rototoa was described as mesotrophic, with the best water quality of any monitored lake in the Auckland region (Hamill & Lockie, 2015). During the 10-year period of analysis for this report, the lake was stratified for 60 per cent of the sample events (between November and April), with anoxic bottom waters for 86 per cent of these occasions. In comparison, for all sample events, the bottom waters were anoxic 53 per cent of the time. Under isothermal conditions, the bottom waters did not become anoxic. For the years 2015 to 2019 the state was mesotrophic with median TLI score of 3.8. The 10-year trends for surface water and bottom water between 2010 and 2019 are presented in Figure 4-7 and Figure 4-8 below.

Both surface waters and bottom waters had very likely improving trends in DRP and TP, however DRP trends are likely an artefact of step changes in detection limits as discussed in Section 3.2.1. Most other water quality variables showed degrading trends for both the surface and bottom waters, except TSS which was improving in bottom waters and chlorophyll α which was improving in surface waters, at a magnitude of change that exceeded the measurement precision limit (Table 4-2).

Most of the very likely degrading trends were in the nitrogen parameters, with TN degrading at a magnitude that exceeded the measurement precision limit in both the surface and bottom waters (Table 4-2). The catchment surrounding Lake Rototoa is classed as rural low (Section 2.2.1), so there could be agricultural discharge of nutrients due to livestock urine and waste, and the application of fertiliser containing nutrients (MfE, 2017c).

As TN is a reporting attribute for lakes in the NPS-FM, the trend magnitude can be linked to the existing current state of the lake, which was in the B band based on the five-year median concentration of TN (Table 3-1). Trends in Figure 4-7 showed a very likely degrading trend in TN with an annual magnitude of change at approximately 0.012 mg/L (Table 4-2). For context, based on the assumption that the degrading trend continues linearly at this rate in consecutive years, it could take less than a decade to reach TN concentrations high enough for the lake to fall into the C band.

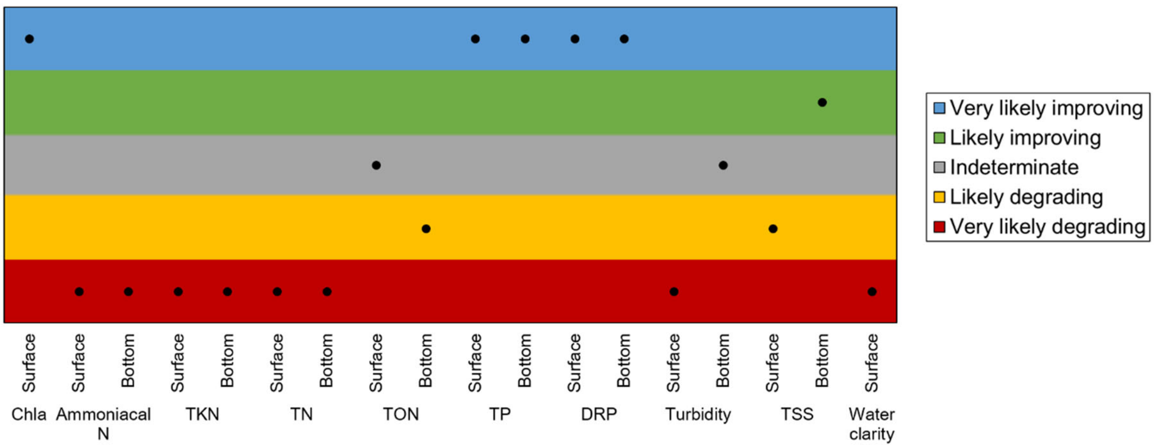

Figure 4-7 Trends in algae, nutrient concentrations, and sediment attributes in the surface and bottom waters of Lake Rototoa.

A very likely decreasing trend in water clarity corresponded with degrading trends in surface TSS and turbidity (Figure 4-7). It is possible the decrease in water clarity is being driven by increased sediment concentrations in the lake, as chlorophyll α concentrations were improving (i.e. decreasing) suggesting the trend in water clarity is not being driven by increases in phytoplankton.

Pressures that could be driving increases in sediment and resulting decreases in water clarity include catchment land practices, pest fish disturbance and climatic cycles (i.e. ENSO cycle). Lake Rototoa has exotic forest within its catchment (Appendix B), with pine forest appearing to be planted around the late 1970s or early 1980s (based on historic aerial photographs). The mobilisation of organic matter from the harvesting of plantation forest has been considered to influence the drastic changes in submerged vegetation in Northland dune lakes (de Winton and Burton, 2017). According to the LCDB5, in 2001, two per cent of the Lake Rototoa catchment was classed as harvested forest, compared to five per cent in 2008, however during the 10-year period of this analysis there were no changes in land cover and there was no harvested forest (Appendix B).

There has been evidence of pest fish including rudd, tench and perch reducing the water clarity in this lake (Hamill & Lockie, 2015). There were no exotic species recorded prior to the introduction of perch in 1999 (Ling et al*.,* 2019b). A recent survey of fish communities in the lake, as part of the Auckland Council's Natural Environment Targeted Rate (NETR) work, found increases in tench, perch and gambusia, reductions in goldfish and declines in native species such as common bully and dwarf inanga, and there were no reports of the presence of rudd in the lake. Increases in tench numbers and biomass are likely to contribute to a decline in water quality (Ling et al*.,* 2019b). The population of kōura (freshwater crayfish) appears to have stabilised, however at a lower population density than prior to the introduction of perch. Kākahi (freshwater mussels) have suffered a recent mortality event involving the death of approximately 80 per cent of the adult population (Ling et al*.,* 2019b). This recent reduction in the kākahi population could contribute to declining water quality because of the release of stored nutrients in their biomass and the lost capacity for biofiltration (Ling et al*.,* 2019b). Monitoring of kōura and kākahi is currently ongoing by Auckland Council.

There was previously a threat of Hornwort (invasive macrophyte) in the lake, identified from the 2010 LakeSPI survey. However, this does not seem to have eventuated as in the 2019 survey there was no Hornwort reported at the survey sites (de Winton, 2019). There is evidence that elevated nutrient concentrations fuel the growth of invasive macrophytes (Perrie & Milne, 2012), so it is something that could occur in the future with the degrading trends in nitrogen parameters.

There were very likely increasing trends in pH in both surface and bottom waters, with the surface water pH having increased at a magnitude of 0.059 (pH units) annually, and the bottom waters increased at a magnitude of 0.048 (pH units) (Table 4-2). Increases in pH can have effects on the trophic state of a lake, suggesting Lake Rototoa could be vulnerable to eutrophication. Also, increased pH can increase the toxicity of pollutants, such as ammonia, which shows a very likely degrading trend in both the surface and bottom waters (Figure 4-7). The ammonia toxicity NPS-FM grade was B (Table 3-1), largely due to a single high maximum value in January 2019, however the median concentration of ammonia toxicity is the highest out of the four lakes in the region. Therefore, increased pH, along with higher ammonia concentrations, could have subsequent implications for ammonia toxicity, potentially causing a decline in grading of Lake Rototoa for this attribute.

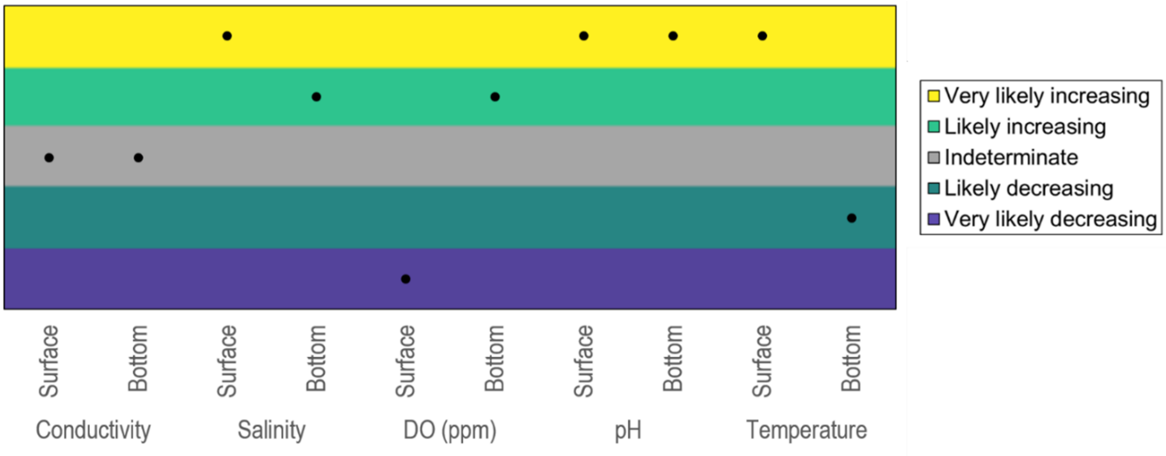

Figure 4-8 Trends in physical parameters in the surface and bottom waters of Lake Rototoa.

Another very likely trend with a magnitude that exceeded the precision limit was the surface water DO, which was decreasing at a magnitude of -0.036 (ppm) (Table 4-2). Despite a decreasing trend in the DO of surface waters, the DO in bottom waters was increasing (Figure 4-8). As discussed, it is possible that the surface water DO was decreasing as a result of the sampling time shifting earlier in the morning from 2014. The increasing trend in bottom water DO could have been because of decreasing bottom water temperatures, as cold water can hold more dissolved oxygen. This would assume that the biological matter in the bottom waters is not depleting dissolved oxygen to decompose dead algae sinking through the water column.

Table 4-2 Trend magnitudes of annual change for trends in Lake Rototoa that exceed the precision limit (i.e. measurement resolution). Upper and lower confidence intervals are in brackets.

Parameter	Chlorophyll (mg/L)	TKN (mg/L)	TN (mg/L)	DO (ppm)	pH (pH units)
Precision limit	0.0001	0.01	0.01	0.01	0.01
Surface water					
Annual change	-0.0002 (--0.0004, +0.0000)	0.012 (-0.008, +0.018)	0.012 (-0.008, +0.019)	-0.036 (--0.078, +-0.012)	0.037 (-0.012, +0.062)
Bottom water					
Annual change		0.013 (-0.006, +0.020)	0.016 (-0.008, +0.024)	-	0.048 (-0.008, +0.072)

Overall, these trends in water quality show further declines may result in adverse changes to the high ecological values of the lake. The improved monthly monitoring regime for Lake Rototoa as part of council’s expanded lake water quality programme in 2020 should help to provide finer spatial scale understanding of changes occurring in this lake.

5.0 Summary

Lake water quality has been monitored at seven lakes across the Auckland region since 1988, although only four publicly accessible lakes are reported on here due to the consistent dataset across the 10-year monitoring period (2010-2019). The monitoring of these lakes is necessary to understand natural variability so that we can detect trends that may be attributed to multiple drivers and to subsequently help inform council initiatives, policies and management strategies.

This state and trends report focuses on trends occurring between 2010 and 2019 for four lakes in the Auckland region (Lake Pupuke, Lake Wainamu, Lake Tomarata and Lake Rototoa), across a variety of land cover classes, and the National Policy Statement for Freshwater Management (NPS-FM) state was determined for the period 2015-2019. Three of the lakes were in a eutrophic state with poor or non-vegetated ecological condition, with only one lake classed as mesotrophic with high ecological condition (Lake Rototoa), however, none of the monitored lakes were below the national bottom line for any of the national objectives attributes for trophic state assessment.

Grading of surface water quality attributes including total nitrogen, total phosphorus and ammonia (toxicity) as per the NPS-FM placed the lakes predominantly in the A bands and some were in the B bands (particularly for total nitrogen). There were three C bands for chlorophyll α, and also Lake Tomarata for total nitrogen and Lake Wainamu for total phosphorus. Gradings for human contact attributes (*E. coli* and cyanobacteria) were all in the A band, however *E. coli* is only an interim grade based on three years of data and was measured in the centre of the lake, rather than primary access locations. Overall, the state assessment of lake water quality, trophic state, ecology and human contact attributes suggest Lake Rototoa remains the lake with the least impacted state in the Auckland region.

Across the four lakes, there were mainly degrading trends in total nitrogen, water clarity and sediment parameters, and improvements in total phosphorus concentrations. Lake Tomarata and Lake Rototoa had the greatest magnitude of change in total nitrogen in the bottom waters. Lake Tomarata also had the greatest magnitude of change in turbidity in the surface and bottom waters, as well as total suspended sediment in the surface waters, with a magnitude of change approximately three times greater than the magnitude of the change in the surface waters of Lake Pupuke.

Lake Pupuke had a mix of trends, with some improvements in certain parameters, particularly in the bottom waters, but degrading trends were present in the surface waters supporting anecdotal reports of more frequent algal blooms in the lake.

Generally, Lake Wainamu had improving trends suggesting an improvement in lake condition. This is a promising sign, particularly for total phosphorus, as this was the lake in the Auckland region that had the lowest grading for total phosphorus concentrations. An improvement in total phosphorus concentrations over time may avoid this lake falling below the national bottom line or could result in the lake moving up into a higher band in the NPS-FM.

Lake Tomarata was in poor ecological condition already (de-vegetated) and in the lowest band for total nitrogen of the monitored lakes in Auckland. This lake had degrading trends in most water quality parameters, and for total nitrogen, total suspended sediment and turbidity, the lake was degrading at the greatest magnitude of change in the region, a degradation from currently some of the highest values of multiple water quality parameters.

Lake Rototoa was the lake that was in the best state in terms of both water quality and ecological condition. However, the lake showed degrading trends in surface sediment parameters and both the bottom waters and surface waters had degrading trends in total nitrogen. Total nitrogen was degrading at a rate that suggests the lake is vulnerable to greater impacts on lake ecological communities in the near future and could fall into the C band in the NPS-FM within the next 10 years.

Several key pressures have been suggested as potential drivers of changes in water quality in these lakes including, but not limited to, land cover change, pest fish, encroachment by invasive species, historic internal nutrient loading and a changing climate, which can also hinder recovery of any restoration due to changes in lake stratification. There was no apparent land cover change in the immediate surrounding lake catchments during the period of analysis.

Management in these lakes over recent times have included pest fish management including; over-fishing to improve water clarity, and fish community surveys, and invasive weed management through the introduction of grass carp. Some lakes have had restoration work including stock exclusion and planting of the riparian margins (e.g. Ngāroto catchment restoration around Lake Tomarata). Further work to guide management strategies has included an assessment of the recreational use and public knowledge around freshwater biosecurity, and exploratory research into nutrient loading (Lake Pupuke), and the effect of fish grazing on native charophyte restoration (Lake Tomarata). Future management is anticipated in Lake Rototoa and Lake Tomarata as part of council's NETR work programme.

Due to the limited number of lakes monitored consistently over the last 10 years it is difficult to get a detailed understanding of the common drivers of change in water quality in Auckland lakes. This shows there is a need for more frequent and consistent monitoring, including: more frequent sampling (monthly); water level monitoring; and biological monitoring (macrophyte and/or fish surveys). Additional lakes will need to be monitored before future planning targets can be determined, due to the potentially unique responses of individual lakes.

As a result of this clear need for enhanced monitoring, Auckland Council expanded its lake water quality monitoring programme, from 2020. Sampling is now undertaken monthly, and an increased number of lakes are now monitored, to largely cover those identified in the natural lakes management area overlay of the Auckland Unitary Plan (AUP) and to support management of these valued resources over the coming decades.

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7.0 Acknowledgements

Auckland Council's lake water quality monitoring programme has benefitted from the efforts of numerous people since its inception. We acknowledge the efforts from members of the environmental teams within RIMU for their help with undertaking the sampling.

Thanks to both Hills and Watercare Laboratories for their services in laboratory analysis of these samples.

Thank you to Rhian Ingley, Tarn Drylie Coral Grant (Auckland Council), and an anonymous reviewer for providing comments that improved this report.

Appendix A Lake Water Quality programme design and changes

Site changes

The lake water quality monitoring programme was paused from mid-2013 until late 2014, when it was reinstated with a reduced site list (removal of Lake Kereta and Lake Spectacle). Then, in late 2017, Lake Kuwakatai was removed from the monitoring programme and replaced with Lake Whatihua. Lake Kuwakatai was removed from the programme because it had been in a relatively stable, albeit impacted, state for a long time and it is not publicly accessible.

Lake Whatihua was added because the network at the time had no perched lake sites and no representative sites from the Awhitu Peninsula coastal dune lakes series. As there is only three years of data for Lake Whatihua, it will not be reported on until 2022, once there has been five years of data collected.

The depth at which surface and bottom water samples were collected changed in late 2004 to 2005 – with samples being collected at deeper depths for most lakes (except Pupuke and Spectacle). From previous reporting (Hamill & Lockie, 2015), this change had a significant influence on the water quality of bottom water samples. This is an important consideration for any long-term data analysis comparisons, however, was not an issue for the trend analysis in this report, which covered 10 years from 2009 onwards.

Table A.1 Duration of monitoring for each lake in the Auckland Council monitoring programme.

Lake	Duration of monitoring
Kereta	1988-2013
Kuwakatai	1988-2017
Rototoa	1988-2019
Spectacle	1988-2013
Tomarata	1988-2019
Pupuke	1977-2019 (Some water clarity data available for 1966 and 1967)
Wainamu	1988-2019
Whatihua	2017-2019

Detection limit changes

Baseline monitoring aims to build a consistent dataset to improve the confidence in state and trend assessments over time, to better assist our understanding of management outcomes. Due to logistical requirements, changing priorities, and improvements to laboratory analysis methodologies, some discontinuities exist within the dataset. Changes in analytical procedures during the monitoring programme resulted in changes in detection limits at different times, as shown in Table A.2.

Table A.2 Detection limit changes in Auckland Council's lake water quality programme. All units are mg/L.

Variable	Time period	Detection limit (mg/L)
Total nitrogen (TN) Pre-2007 TN was derived from TKN	1993-Nov 2006 2007-Jan 2008 Aug 2007-2012 2012-present	0.2 0.1 0.02 0.01
Total oxidised nitrogen (TON)	1993-1998 Nov 1999-2012 2012-present	0.05 0.002 0.001
Total ammoniacal nitrogen	1993-1996 1997-March 2005 Aug 2005-present	0.005 0.01 0.005
Total phosphorus (TP)	1993-Nov 2008 Feb 2009-2013 2013-present	0.01 0.005 0.004
Dissolved reactive phosphorus (DRP)	1993-March 2005 Nov 2007-2013 2013-2017 2017-present	0.01 0.005 0.002 0.001
Chlorophyll α	1993-2017 (except for 1995/06 where detection limit was 70-200) 2017-2019 2019-present	0.0006 0.003 0.0002

Data collection changes

Over the 10-year period (2010-2019), lake water quality monitoring frequency varied between quarterly and six times per year, with Lake Pupuke monitored 11 times in one year (2018). Due to the programme pause in 2013-2014, there were only two samples for 2014 across all four lakes. Lake Wainamu only had three samples in 2016. More recently, in 2018, Lake Tomarata and Lake Pupuke had a higher number of samples than other lakes.

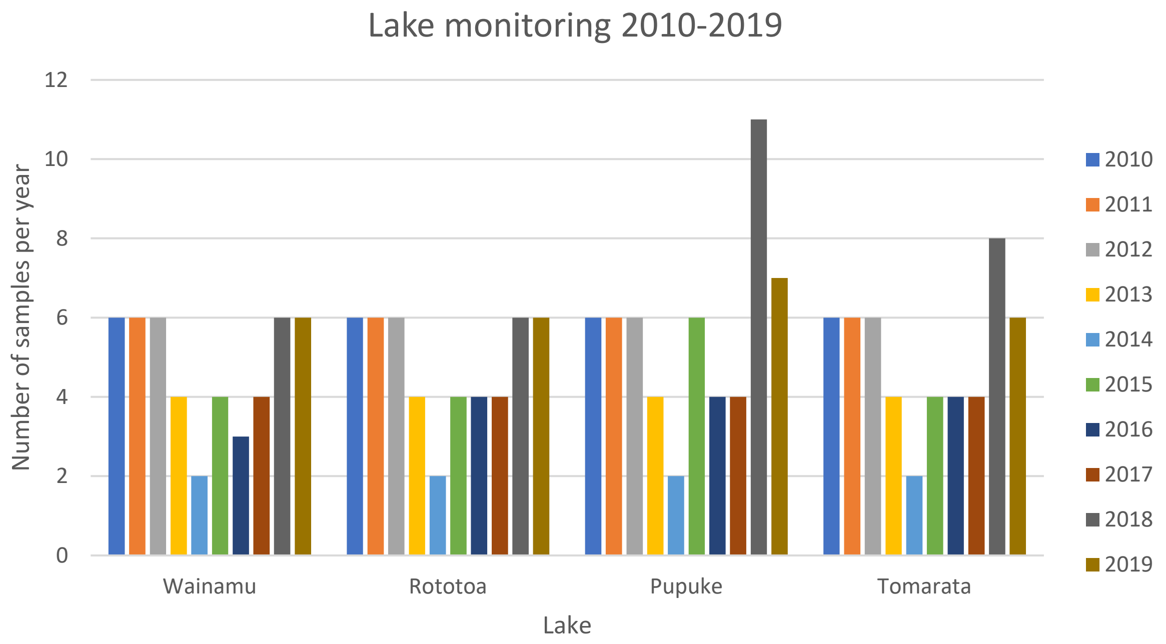

Figure 7-1 Number of samples per year for each lake for the monitoring period 2010-2019.

The majority of sampling for all lakes took place in January or February, April or May, August and November of each year. The months July, October and December were only sampled once in Lake Pupuke, and one sample in July in Lake Tomarata.

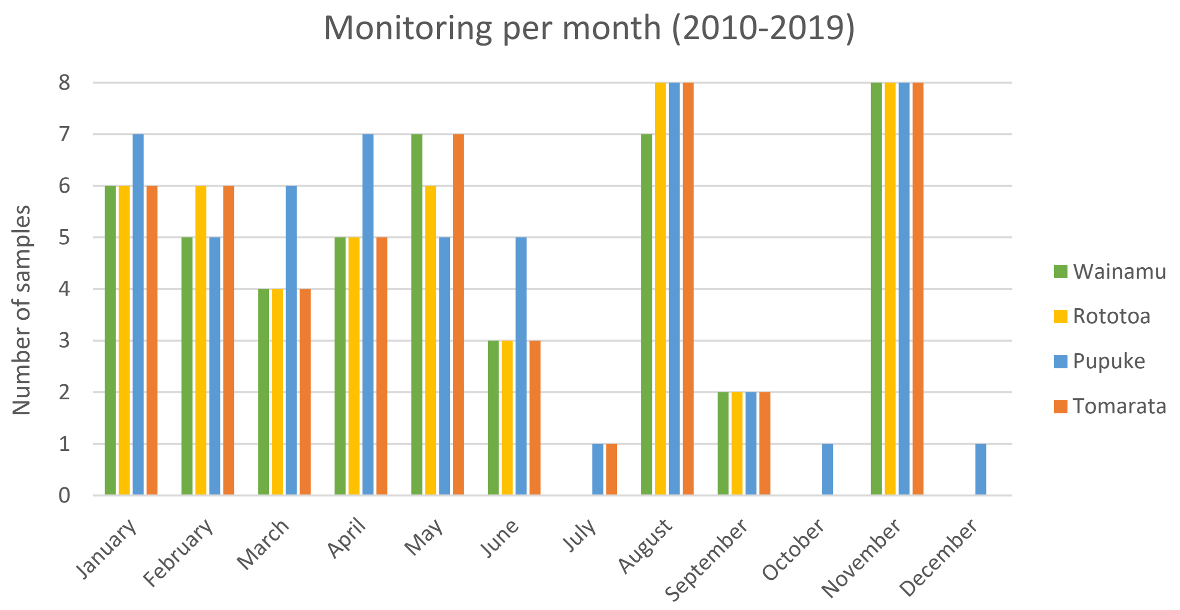

Figure 7-2 Number of samples per month during the monitoring period 2010-2019 for each lake.

Appendix B Land cover breakdown

Land cover from LCDB5 at 2018 (Manaaki Whenua – Landcare Research, 2020). All values are rounded to the nearest whole number.

Table B.1 Land cover breakdown for each lake, as a percentage of the catchment.

	Native forest (% cover)			Exotic forest (% cover)		Rural (% cover)		Urban (% cover)		Wetland (% cover)		Other (% cover)	Water (% cover)
Site name	Indige-nous forest	Broad-leaved indigenous hardwoods	Manuka/ kanuka	Exotic forest	Forest – harvested	High producing exotic grassland	Low producing grassland	Urban park/ open space	Built-up area	Herbaceous freshwater vegetation	Flaxland	Sand or Gravel	Lake or pond
Lake Pupuke	2	6	0	0	0	0	0	11	76	0	0	0	6
Lake Wainamu	70	0	25	0	0	4	0	0	0	0	0	1	1
Lake Rototoa	1	17	21	24	0	34	1	0	0	0	0	0	2
Lake Tomarata	0	0	0	82	0	8	0	0	0	10	0	0	0

Appendix C Physical-chemical parameters

Table C.1 Summary of measured water quality parameters, current detection limits (2019), analytical methods and two sources of data collection

Parameter	Unit	Detection Limit	Method	Source	Surface Water	Bottom Water
Water clarity	metres	0	Secchi disk	Field	X	-
Dissolved oxygen	ppm	0.1	EXO2 Sonde (Xylem Analytics)	Field	X	X
Dissolved oxygen saturation	% sat	0.01	EXO2 Sonde (Xylem Analytics)	Field	X	X
Temperature	°C	0.01	EXO2 Sonde (Xylem Analytics)	Field	X	X
Conductivity	mS cm	0.01	EXO2 Sonde (Xylem Analytics)	Field	X	X
Salinity	ppt	0.2	EXO2 Sonde (Xylem Analytics)	Field	X	X
pH	pH units	0.01	EXO2 Sonde (Xylem Analytics)	Field	X	X
Total suspended solids (TSS)	mg/L	3	APHA (2012) 2540 D	Lab	X	X
Turbidity	NTU	0.05	APHA (2012) 2130 B (modified)	Lab	X	X
Chlorophyll α	mg/L	0.0002	APHA (2012) 10200 H (modified)	Lab	X	-
Total oxidised nitrogen (NO_2N + NO_3N)	mg/L	0.001	APHA (2012) 4500-NO_3 I (modified)	Lab	X	X
Ammoniacal nitrogen (NH_4-N)	mg/L	0.005	APHA (2012) 4500-NH_3 H (modified)	Lab	X	X

Total Kjedahl nitrogen (TKN)	mg N/L	0.01	Calculation: TN – (NO_3N + NO_2N)	Lab	X	X
Total nitrogen (TN)	mg N/L	0.01	APHA (2012) 4500-N C & 4500 NO_3 I (modified)	Lab	X	X
Dissolved reactive phosphorus (DRP)	mg/L	0.001	APHA (2012) 4500-P G	Lab	X	X
Total phosphorus (TP)	mg/L	0.004	APHA (2012) 4500-P B & E (modified)	Lab	X	X

Table C.2 Narrative summary of water quality parameters assessed

Parameter	Description
Salinity and Chloride	Salinity and chloride levels decrease as the influence of freshwater increases. Salinity levels affect the toxicity of some contaminants.
Temperature	Surface temperature is driven by seasonal changes in solar radiation and climatic conditions (e.g. El Niño or La Niña weather patterns). Temperature affects biological processes and moderates the toxicity of contaminants. Temperature differences in the water column of lakes result in stratification during certain periods of time, where cool, dense water remains at the bottom of the lake and there is no mixing with the warmer surface waters.
pH	pH is a measure of acidity/alkalinity. Changes in pH affect the toxicity of some contaminants.
Dissolved Oxygen (DO)	Oxygen is released by plants during photosynthesis and taken up by plants, animals and bacteria for respiration. Oxygen-scavenging compounds associated with organic matter also affect DO levels. High DO values can reflect high primary production while low DO values can reflect high rates of decomposition of organic matter. In extreme cases low DO levels (i.e. anoxia) due to respiration and/or chemical uptake can stress or kill aquatic organisms i.e. reduce the life-supporting capacity of the water. DO levels are diurnally and seasonally variable. DO is typically higher during the day and decreases at night. Colder waters also typically hold more oxygen than warmer water.
Turbidity Suspended solids	Turbidity is a measure of the degree to which light is scattered in water by particles, such as sediment and algae. Total suspended solids are a measure of the amount of suspended material in the water column such as plankton, non-living organic material, silica, clay and silt.

Parameter	Description
Total Oxidised Nitrogen (TON, NO_2 +NO_3-N)	Ammonium-N and nitrate-nitrite-N are dissolved forms of nitrogen that are immediately available for phytoplankton and macroalgae uptake and growth, and are used as key indicators for that nutrient.
Ammoniacal Nitrogen (NH_3 + NH_4-N)	Ammonia is reported as a combination of un-ionised ammonia (NH_3) and the ammonium ion (NH_4), at normal pH values ammonium (NH_4) dominates. Un-ionised ammonia is the more toxic form to aquatic life and is highly dependent on water temperature, salinity and pH.
Total Kjedahl Nitrogen (TKN)	Total Kjedahl Nitrogen is the sum of ammoniacal nitrogen and organic nitrogen (amino acids and proteins).
Total Nitrogen (TN)	Total Nitrogen includes all forms of dissolved and particulate nitrogen (TKN + TON). Particulate nitrogen consists of plants and animals, and their remains, as well as ammonia adsorbed onto mineral particles. Particulate nitrogen can be found in suspension or in the sediment. High nutrient levels cause algal blooms, nuisance plant growth and eutrophication. High concentrations of some nutrients are also toxic to aquatic organisms (e.g. ammonia).
Dissolved Reactive Phosphorus (DRP) Total Phosphorus (TP)	Phosphorus is found in water as dissolved and particulate forms. Dissolved Reactive Phosphorus is immediately available for uptake and growth by phytoplankton and macroalgae. Particulate phosphorus consists of plants and animals and their remains, as well as phosphorus in minerals and adsorbed onto mineral surfaces. Total Phosphorus is a measure of both dissolved and particulate forms in a water sample. Sources of phosphorus include sewage and animal effluent, cleaning products, fertilisers, and industrial discharges. Earthworks and forestry can also release phosphorus through soil erosion. In lakes, there is internal nutrient loading from buried nutrients in the lakebed sediment.

Parameter	Description
Chlorophyll α	Chlorophyll α is used as an indicator of phytoplankton concentration which can indicate trophic status. Chlorophyll α levels vary naturally according to seasonal cycles and climatic conditions. However, excess nutrients caused by human activity can increase chlorophyll α levels to the point where water quality is affected. Effects include altered water colour and clarity, unpleasant odours, altered pH levels and lowered oxygen concentrations.

Appendix D Methods of calculation for state analysis

Trophic Level Index

The state of lakes can be summarised using four water quality parameters that assess the life supporting capacity of the lake. These are:

- Chlorophyll α
- Water clarity
- Total phosphorus
- Total nitrogen

The results of each of these parameters together produce a lake water quality index called the Trophic Level Index (TLI) that provides a quality state for each lake, as shown in Table D.1. The TLI generates a number between 0 and 7, with a lower number indicating better water quality.

Table D.1 Trophic Level Index descriptions (Burns et al. 2005).

TLI	Trophic Level State	Description
< 2	Microtrophic	Very low nutrient levels and algae, with very high water clarity.
2-3	Oligotrophic	Low levels of nutrients and algae, with high water clarity.
3-4	Mesotrophic	Moderate levels of nutrients and algae.
4-5	Eutrophic	Elevated levels of nutrients and algae, with low water clarity.
5-6	Supertrophic	Saturated with nutrients, high algae growth with blooms possible in summer. Very low water clarity.
>6	Hypertrophic	Super-saturated with nutrients, very high algae growth with blooms common in summer. Very low water quality.

Trophic Level Index (TLI) is calculated using the annual mean of each variable for each of the five years of data (2015-2019), from the surface water samples only. Previous reporting used three years of data, however we opted to analyse five years of data to provide a consistent dataset for all of the state assessments in this reporting.

The following regression equations were used to calculate the TLI (Burns et al. 2005):

$$\mathrm{TL_N} = -3.61 + 3.01 \log(\mathrm{TN})$$

$$\mathrm{TL_P} = 0.218 + 2.92 \log(\mathrm{TP})$$

$$\mathrm{TL_S} = 5.10 + 2.6 \log\left(\frac{1}{\mathrm{SD}} - \frac{1}{40}\right)$$

$$\mathrm{TL_C} = 2.22 + 2.54 \log(\mathrm{Chl}\ a)$$

$$\mathrm{TLI} = \frac{(\mathrm{TL_N} + \mathrm{TL_P} + \mathrm{TL_S} + \mathrm{TL_C})}{4}$$

Where:

TN = total nitrogen (mg/m^3)

TP = total phosphorus (mg/m^3)

SD = Secchi depth (m)

Chl *α* = chlorophyll *α* (mg/m^3)

Lake ecology

To assess the ecological condition of lakes based on their macrophyte communities, surveys were undertaken at the lakes during several years. Key features of the macrophyte community structure and composition were used to produce a series of indices using the LakeSPI (Submerged Plant Indicators) tool (de Winton and Burton, 2017). Macrophytes are useful indicators of ecological condition because of their size, ease of identification and perennial nature.

Results from the macrophyte survey and subsequent LakeSPI analysis produced three indices:

- LakeSPI index – This is an overall index of the plant community (the higher the score, the better the ecological condition of the lake)
- Native condition index – This index is based on the diversity and quality of native submerged plants (the higher the score, the better)
- Invasive condition index – This index is based on the degree of impact of invasive weed species (the lower the score, the better)

The LakeSPI index enables each lake to be assigned an overall quality class using the ranges shown in Table D.2.

Table D.2 Descriptions of LakeSPI scores (de Winton and Burton, 2017).

LakeSPI	Quality
> 75	Excellent
50-75	Good
20-50	Fair
1-20	Poor
0	Non-vegetated

Appendix E NPS-FM (2020) attribute bands

	Lake Pupuke		Lake Wainamu		Lake Tomarata		Lake Rototoa	
	Band	Five-year value	Band	Five-year value	Band	Five-year value	Band	Five-year value
Ecosystem health								
Chlorophyll α (median) (mg chl-*α*/m^3)	C	8	C	6	C	10	B	3
Chlorophyll α (maximum) (mg chl-*α*/m^3)	C	60	B	15	B	18	A	9
Total nitrogen (median)* (mg/m^3)	B	295	B	260	C	530	B	285
Total phosphorus (median) (mg/m^3)	A	9	C	22	B	15	A	5
Ammonia toxicity (median) (mg NH_4-N/L)	A	0.003	A	0.002	A	0.003	A	0.007
Ammonia toxicity (maximum) (mg NH_4-N/L)	A	0.050	A	0.015	A	0.034	B	0.116
Human contact								
E. coli (median) (*E. coli*/100 mL)	A	3	A	10	A	10	A	3
E. coli (Hazen 95th percentile) (*E. coli*/100 mL)	A	10	A	200	A	53	A	10
E. coli % exceedances over 540/100 mL	A	0	A	0	A	0	A	0
E. coli % exceedances over 260/100 mL	A	0	A	0	A	0	A	0
Cyanobacteria (80th percentile) Biovolume (mm^3/L)	A	0.002	A	0.003	A	0.007	A	0.016

*total nitrogen annual median has different grading for seasonally stratified and polymictic lakes (e.g., Lake Tomarata).

Appendix F Selected time series plots

Time series plots of the very likely trends are presented. Note that Y axes vary between plots to best fit the data for the specific site and parameter.

Lake Pupuke

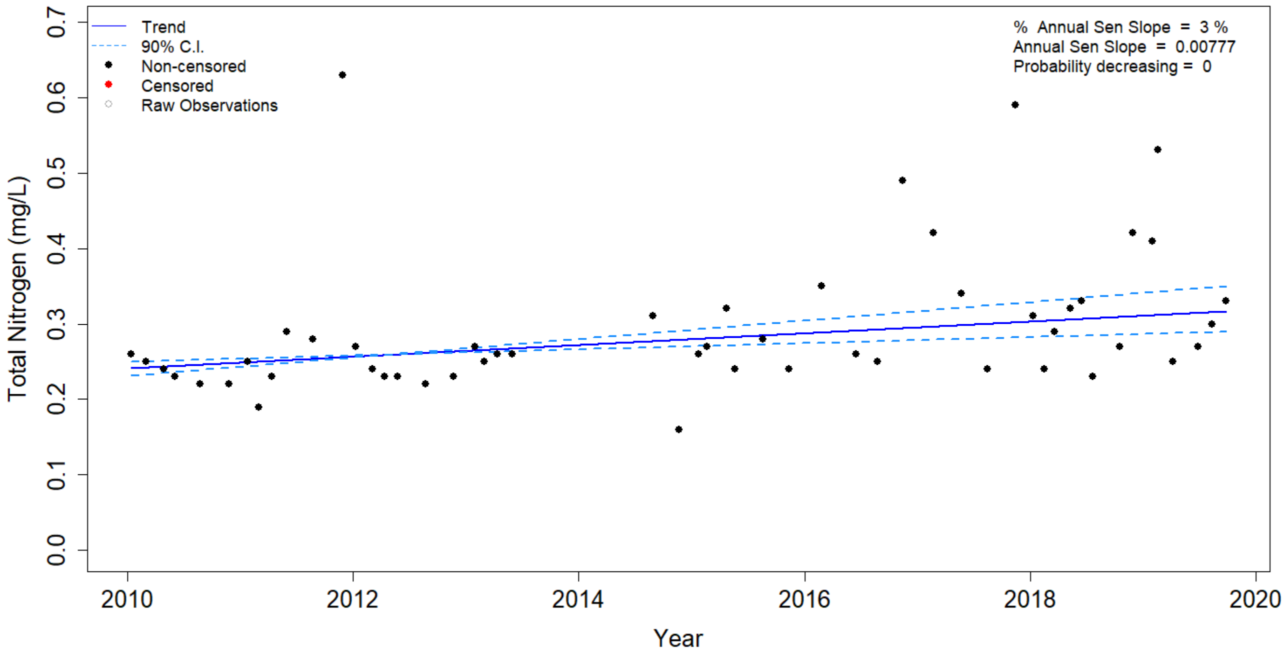

Figure 7-3 Observations of total nitrogen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke surface waters.

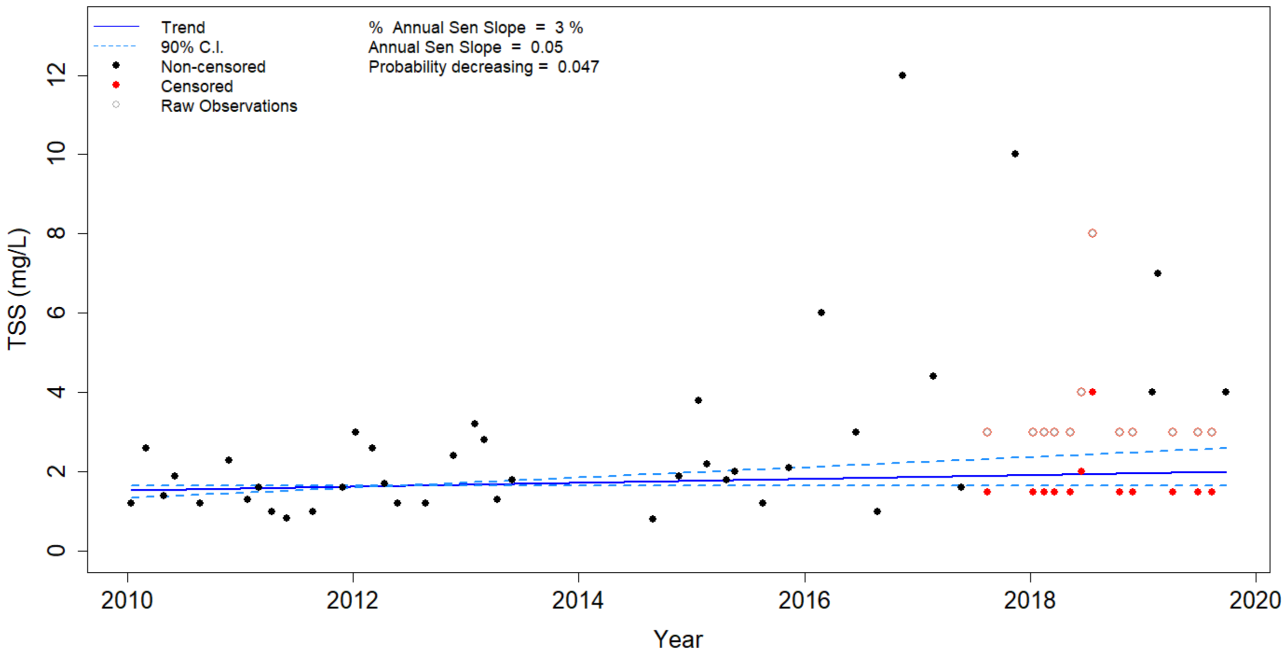

Figure 7-4 Observations of total suspended solids (TSS) over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke surface waters.

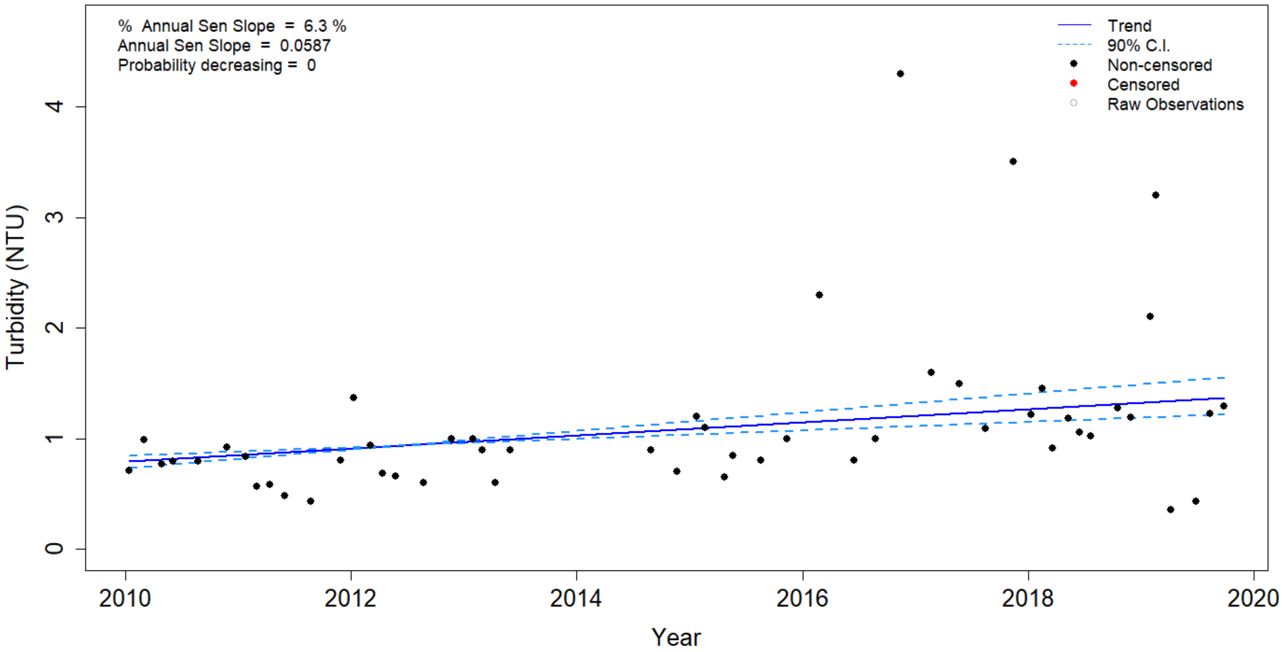

Figure 7-5 Observations of turbidity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke surface waters.

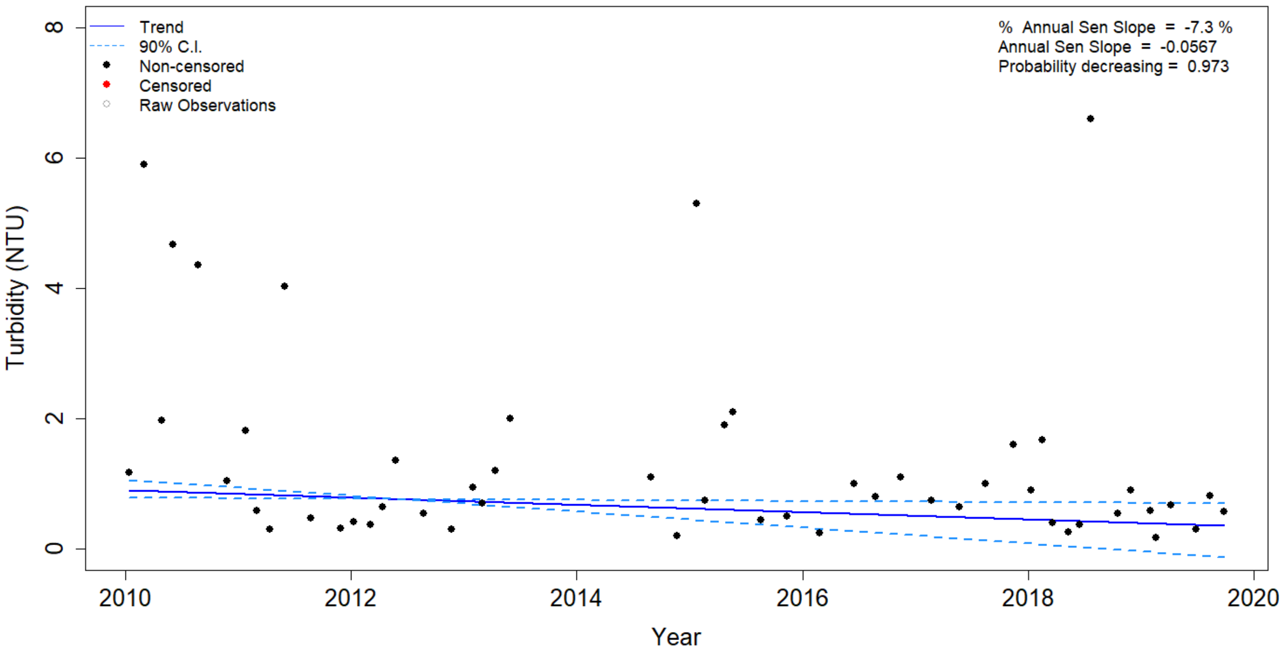

Figure 7-6 Observations of turbidity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke bottom waters.

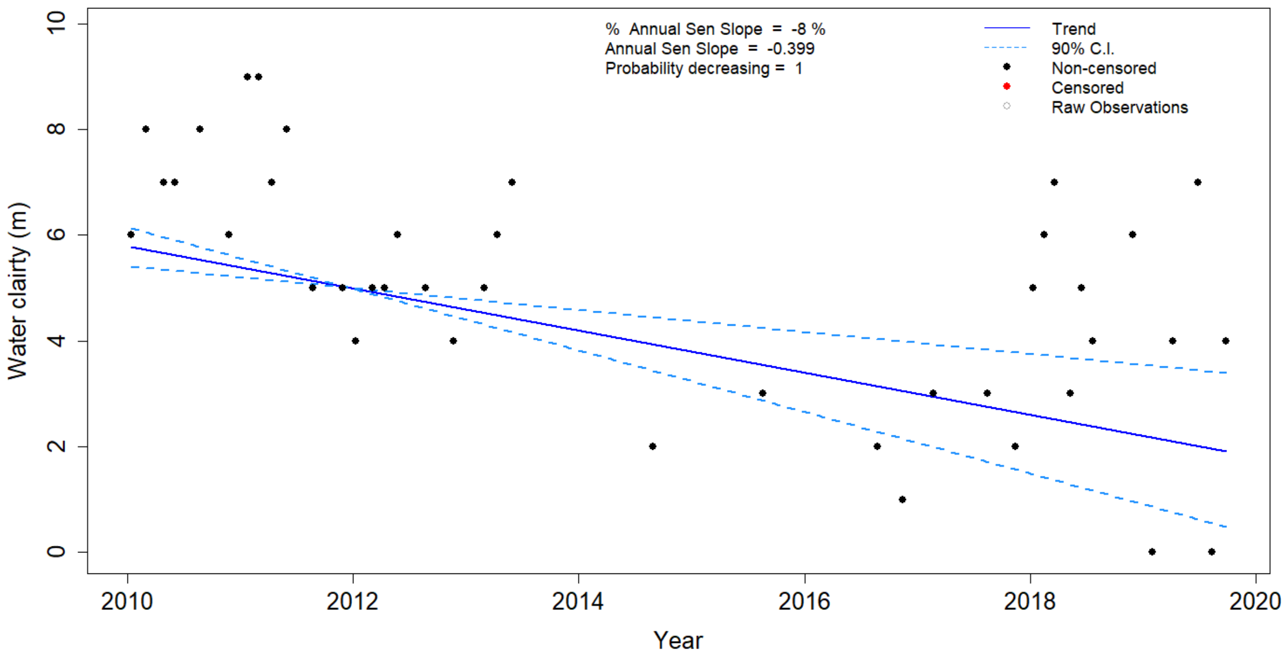

Figure 7-7 Observations of water clarity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke surface waters.

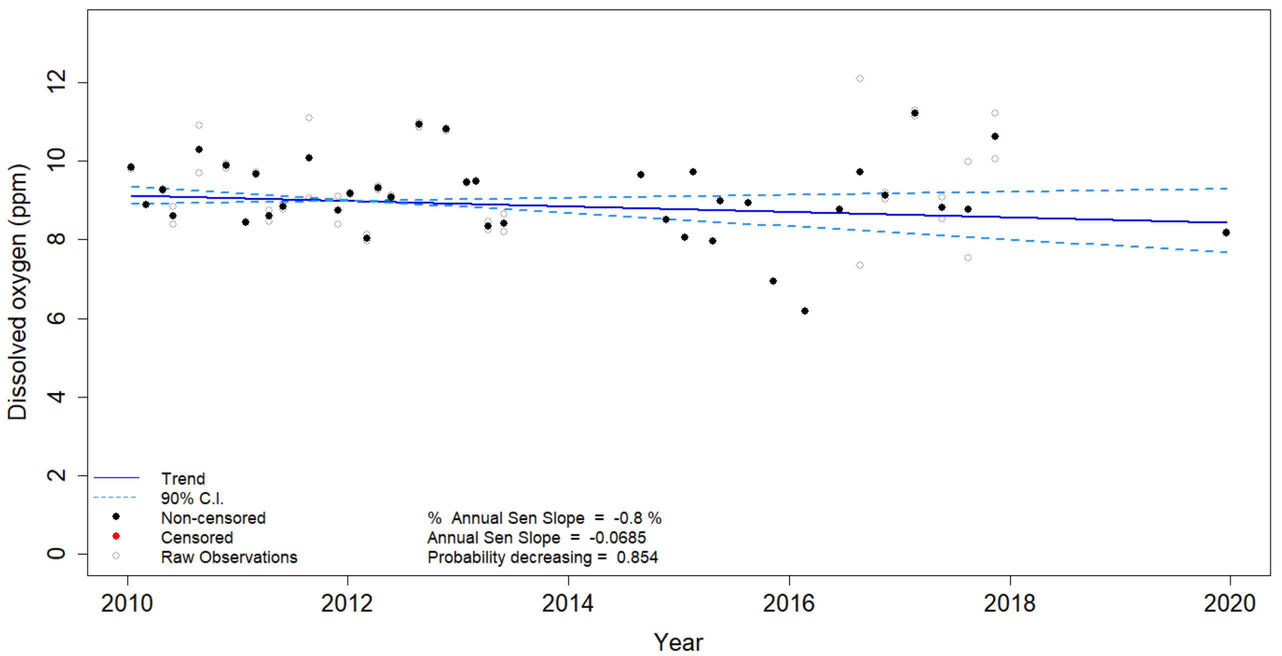

Figure 7-8 Observations of dissolved oxygen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke surface waters.

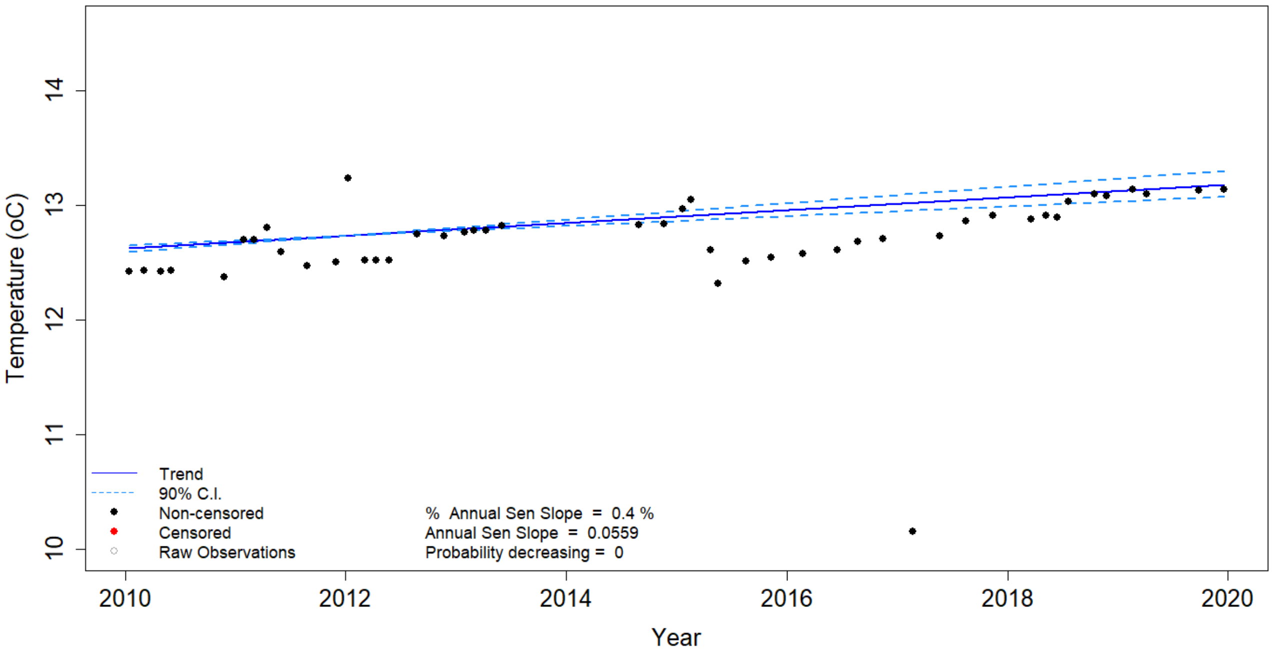

Figure 7-9 Observations of temperature over time fitted with annual Sen Slope and 90% confidence intervals for Lake Pupuke bottom waters.

Lake Wainamu

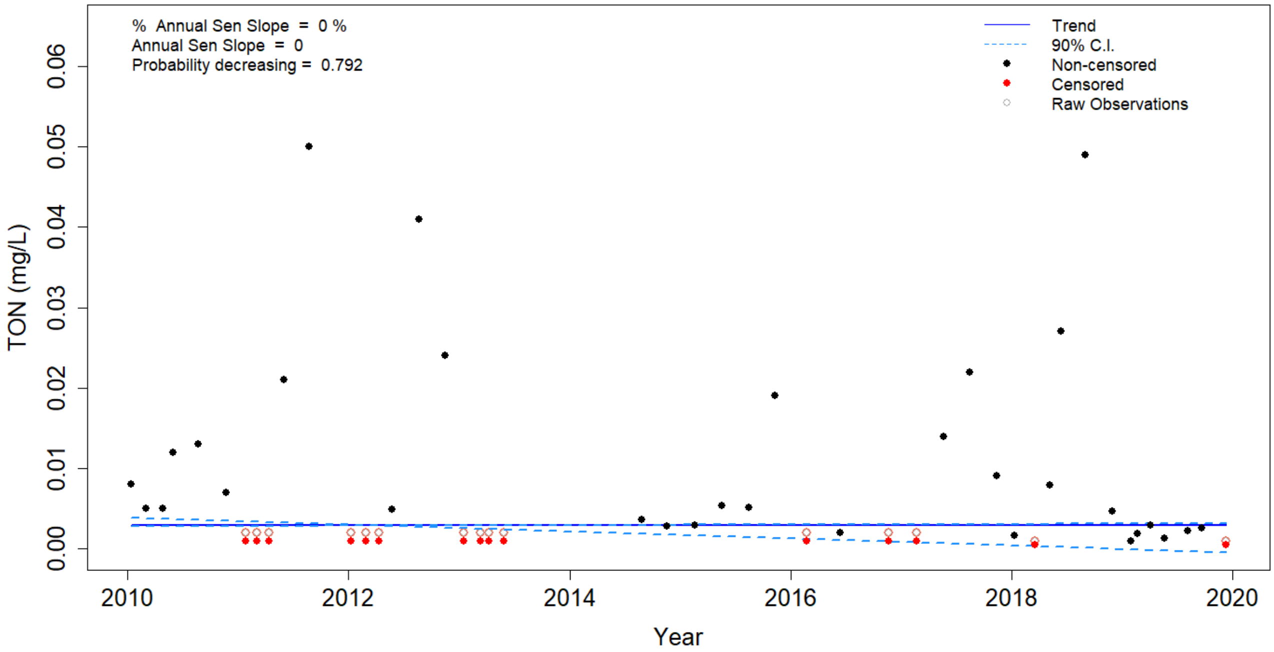

Figure 7-10 Observations of TON over time fitted with annual Sen Slope and 90% confidence intervals for Lake Wainamu bottom waters.

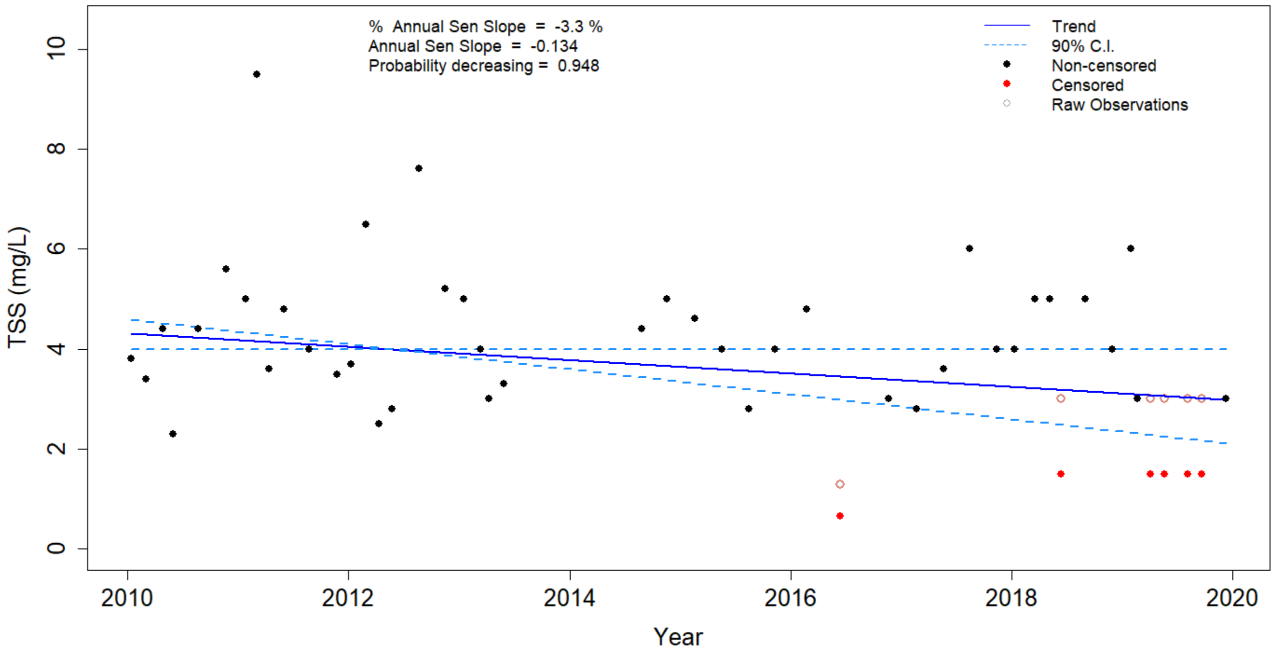

Figure 7-11 Observations of TSS over time fitted with annual Sen Slope and 90% confidence intervals for Lake Wainamu surface waters.

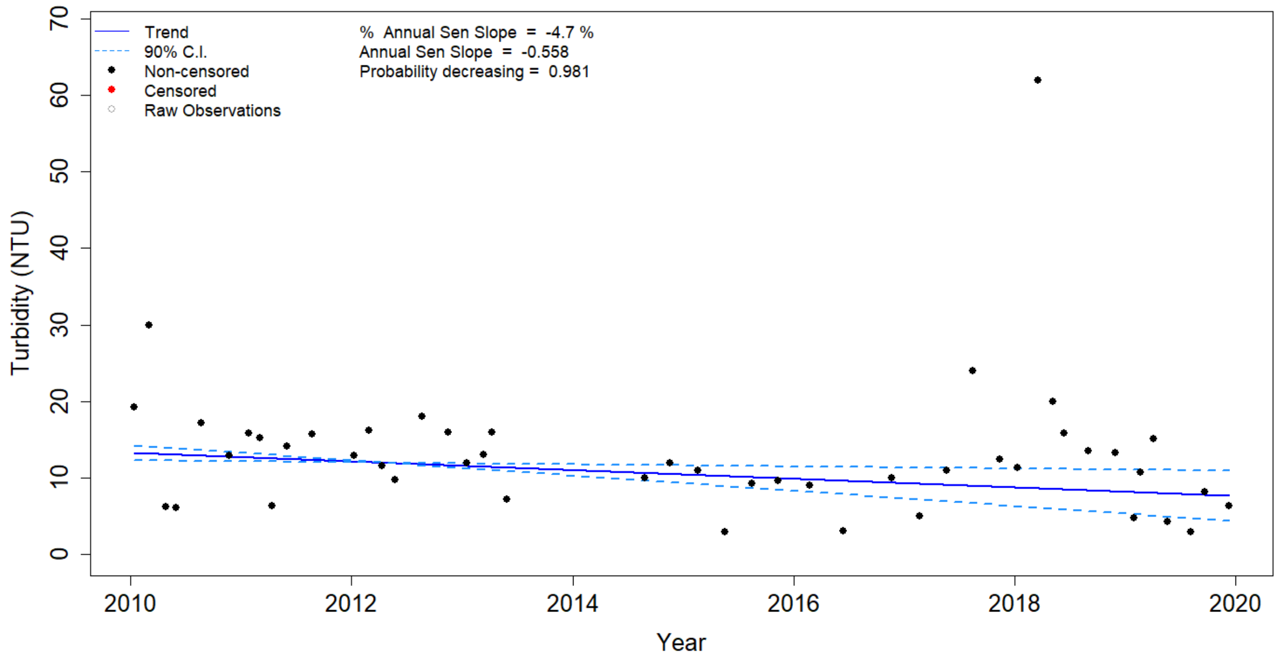

Figure 7-12 Observations of turbidity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Wainamu bottom waters.

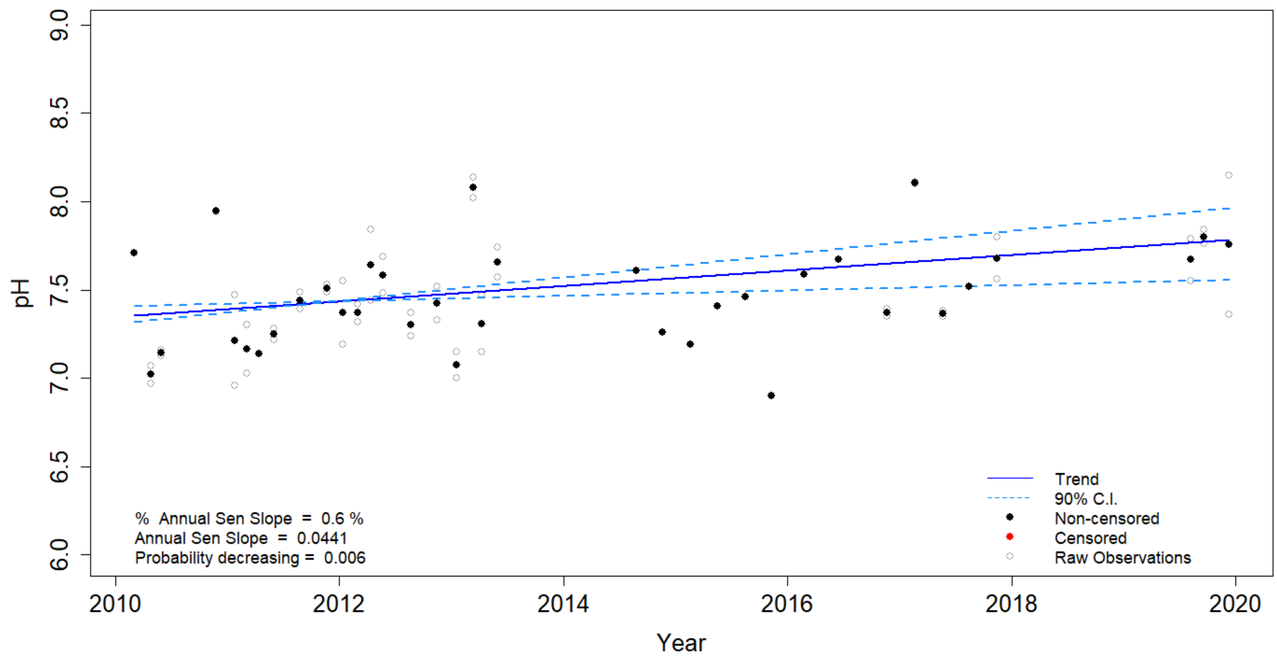

Figure 7-13 Observations of pH over time fitted with annual Sen Slope and 90% confidence intervals for Lake Wainamu surface waters.

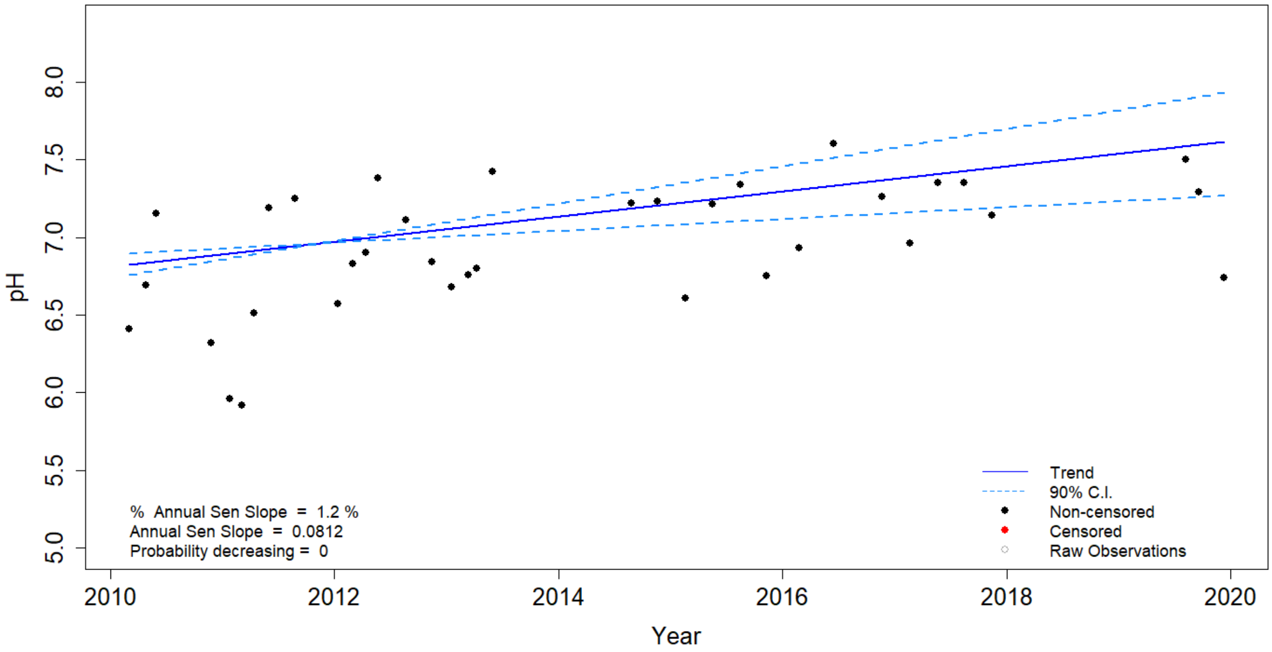

Figure 7-14 Observations of pH over time fitted with annual Sen Slope and 90% confidence intervals for Lake Wainamu bottom waters.

Lake Tomarata

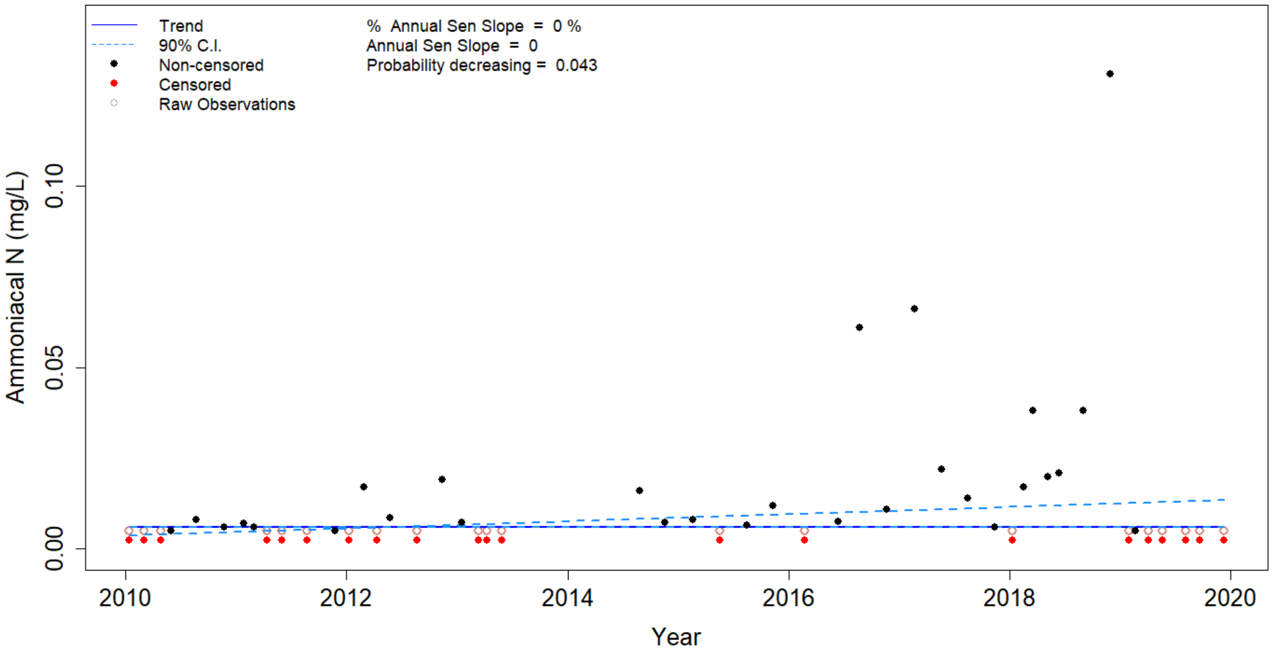

Figure 7-15 Observations of ammonia over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata bottom waters.

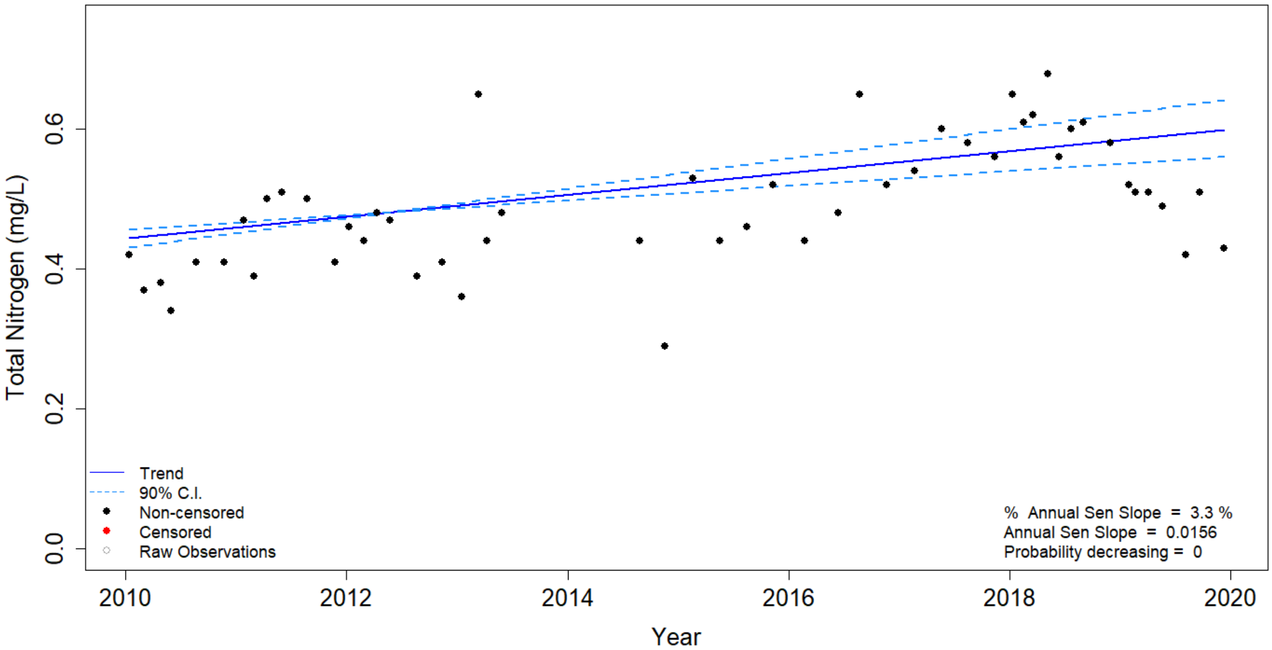

Figure 7-16 Observations of total nitrogen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata surface waters.

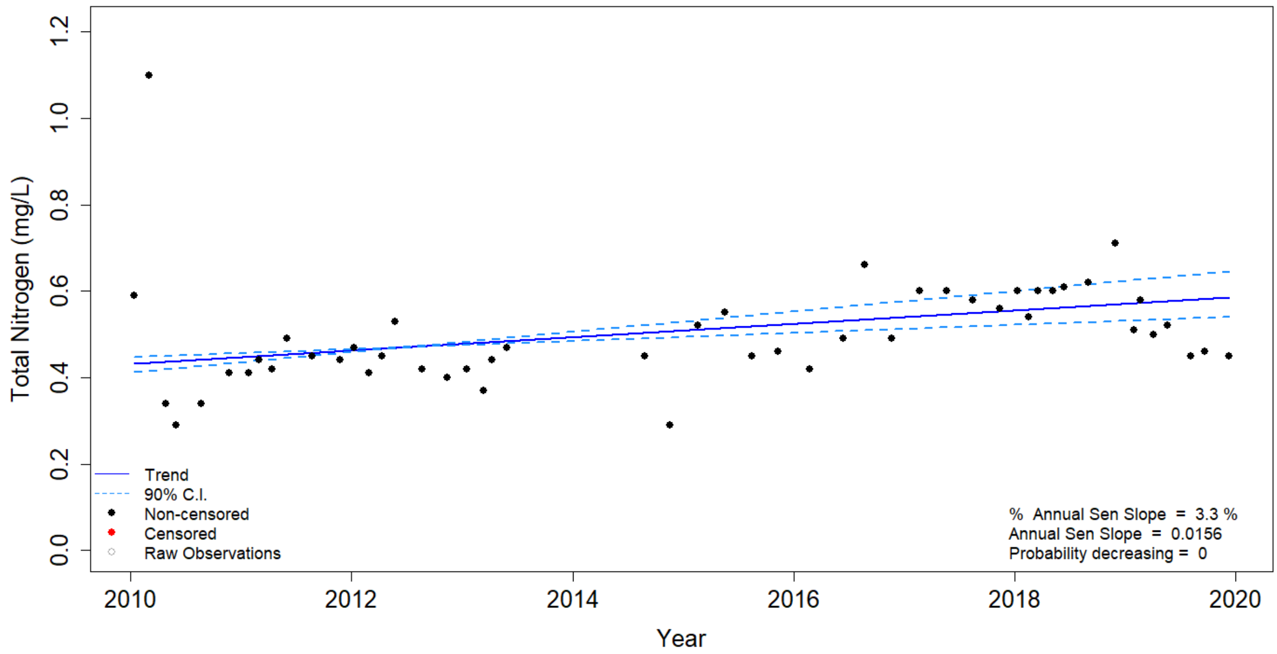

Figure 7-17 Observations of total nitrogen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata bottom waters.

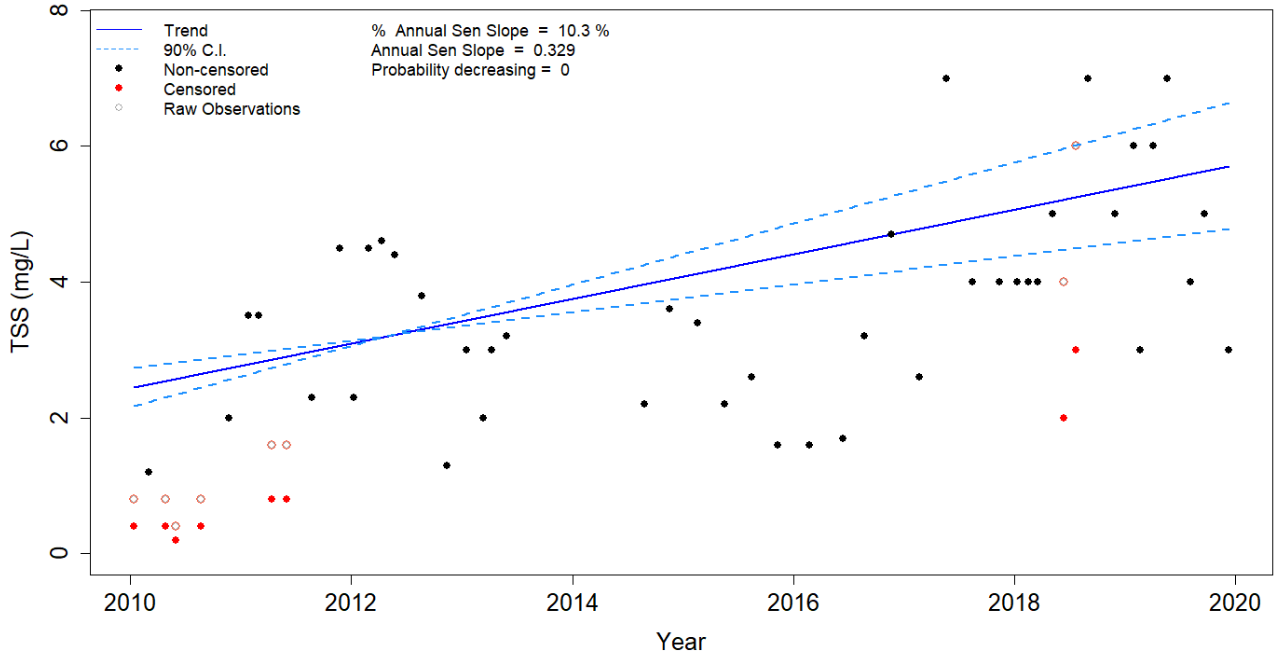

Figure 7-18 Observations of total suspended sediment (TSS) over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata surface waters.

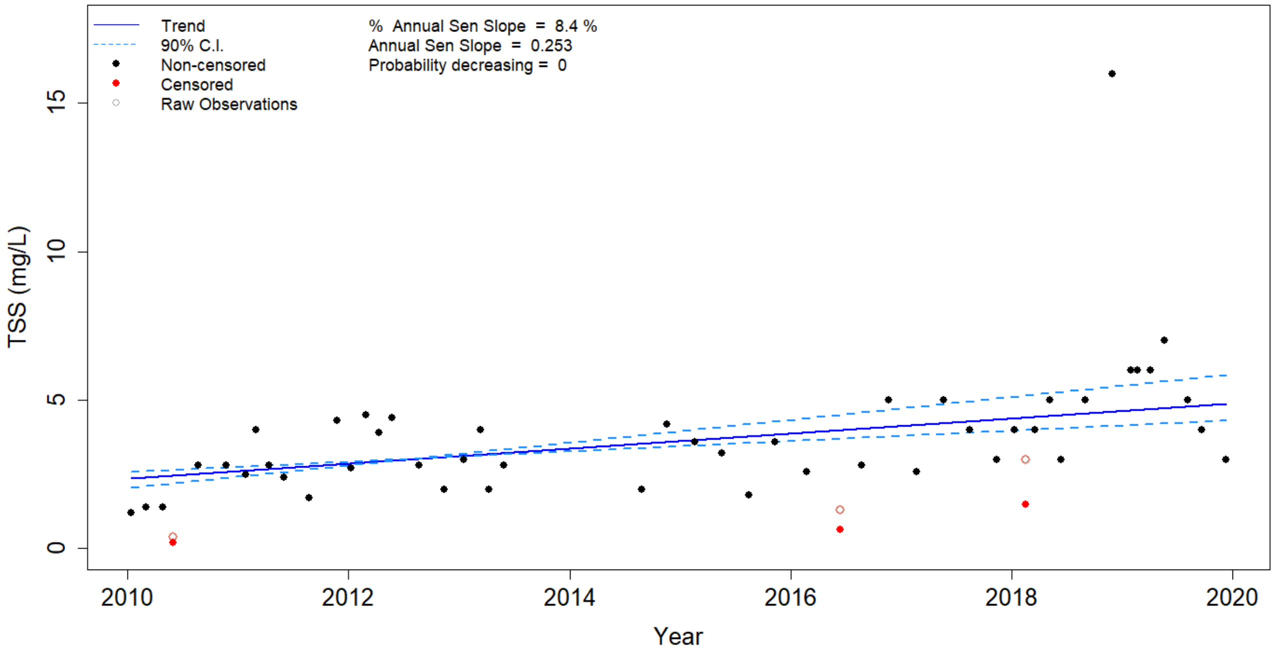

Figure 7-19 Observations of total suspended sediment (TSS) over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata bottom waters.

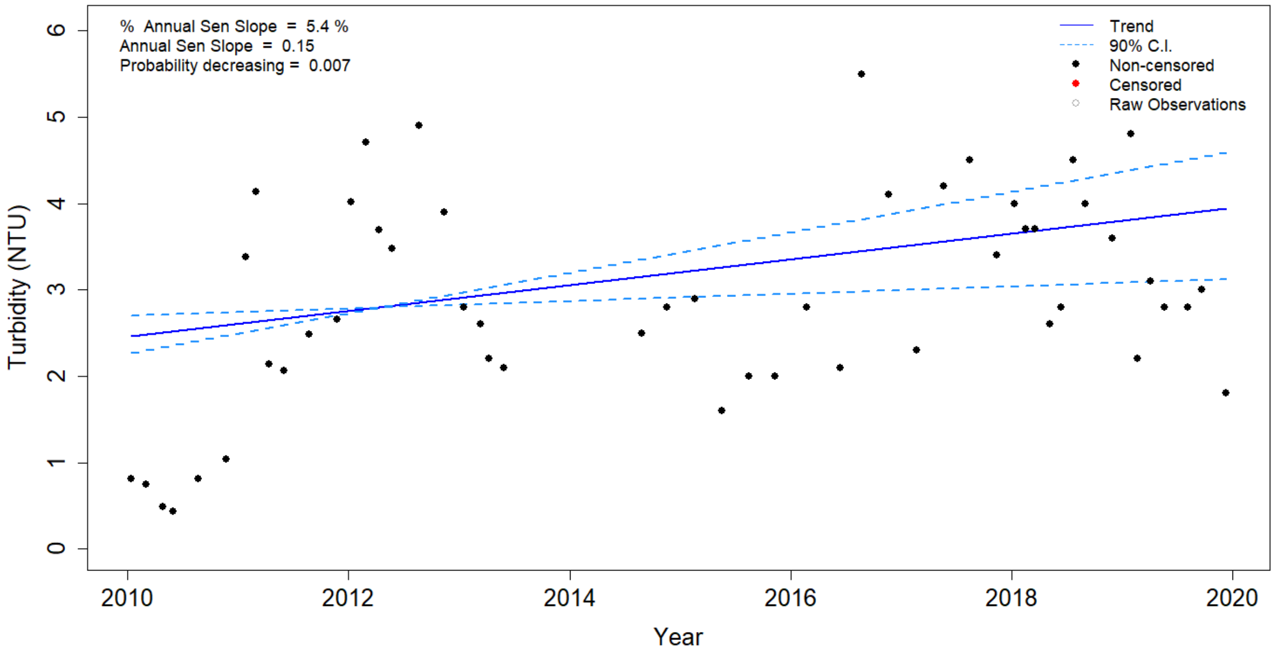

Figure 7-20 Observations of turbidity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata surface waters.

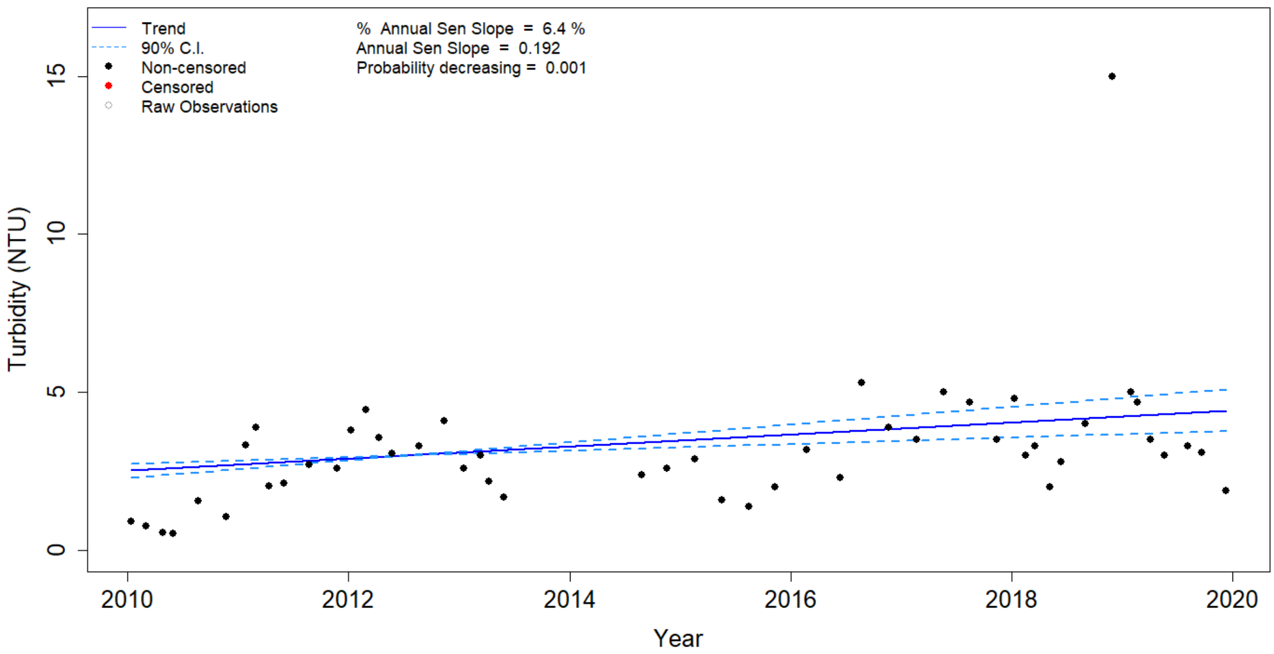

Figure 7-21 Observations of turbidity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Tomarata bottom waters.

Lake Rototoa

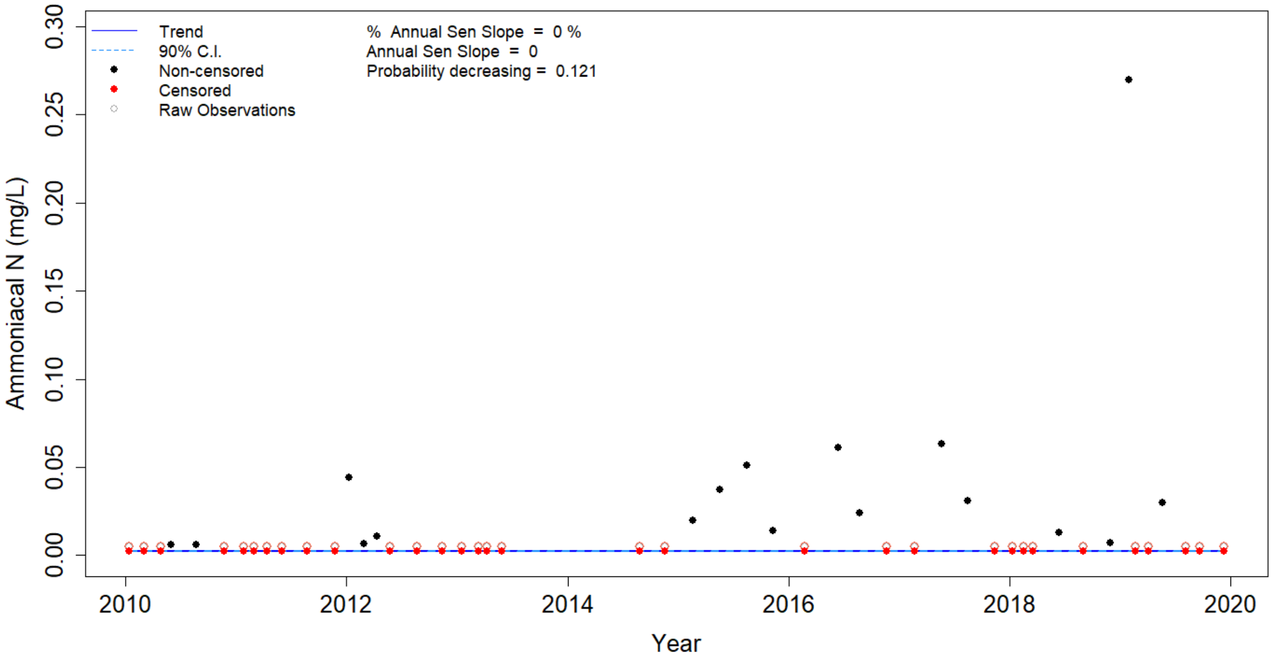

Figure 7-22 Observations of ammonia over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

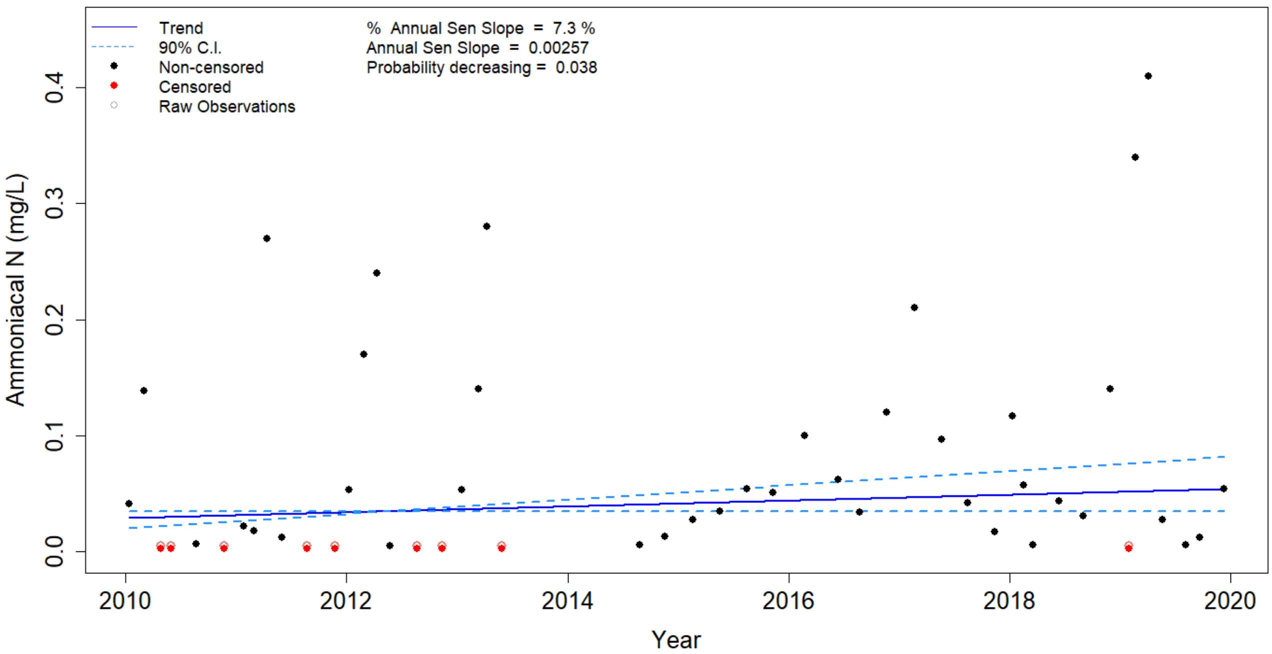

Figure 7-23 Observations of ammonia over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa bottom waters.

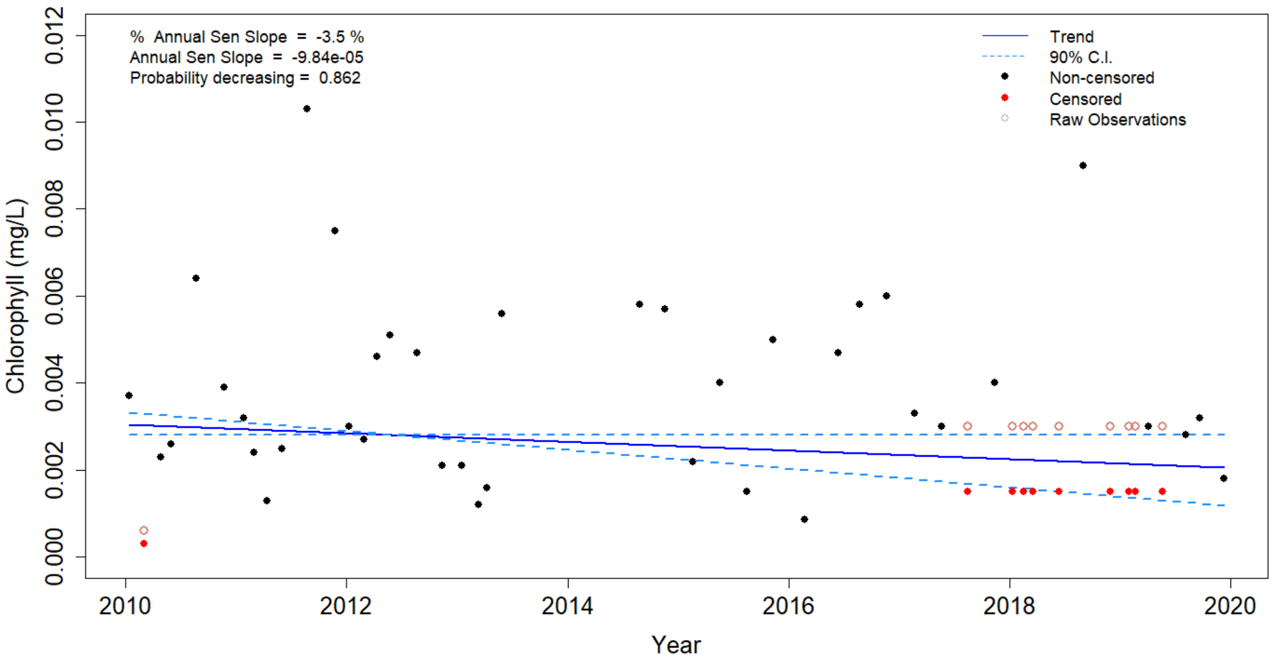

Figure 7-24 Observations of chlorophyll over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

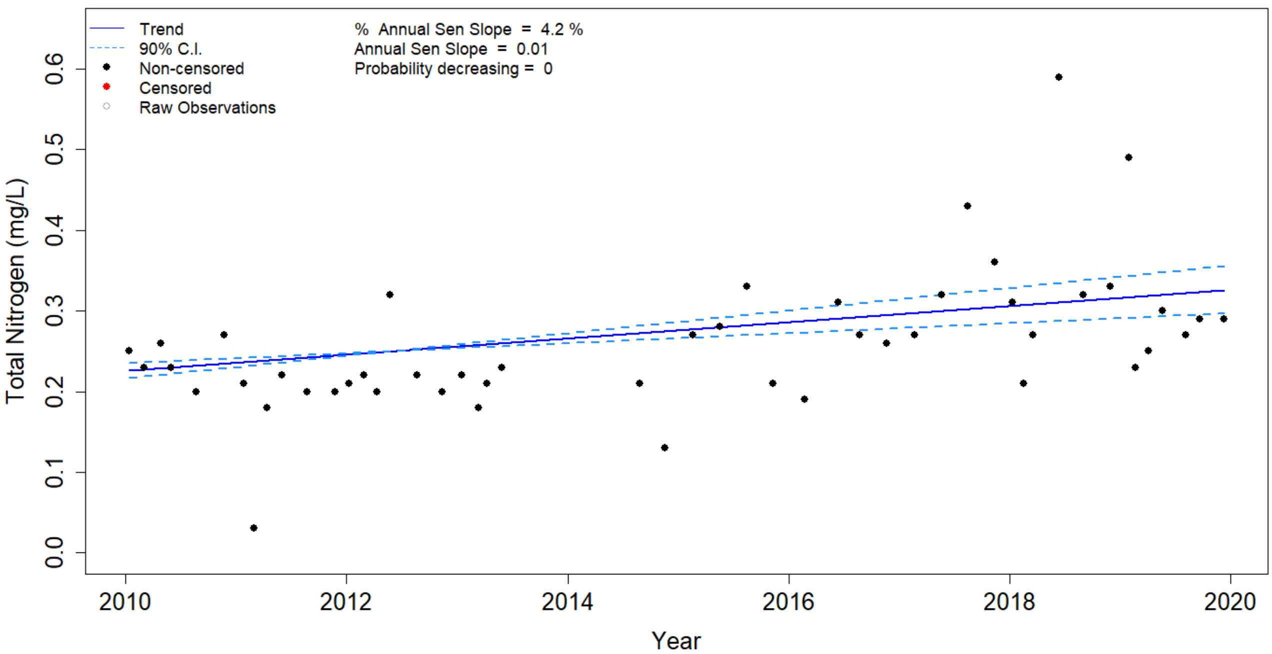

Figure 7-25 Observations of total nitrogen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

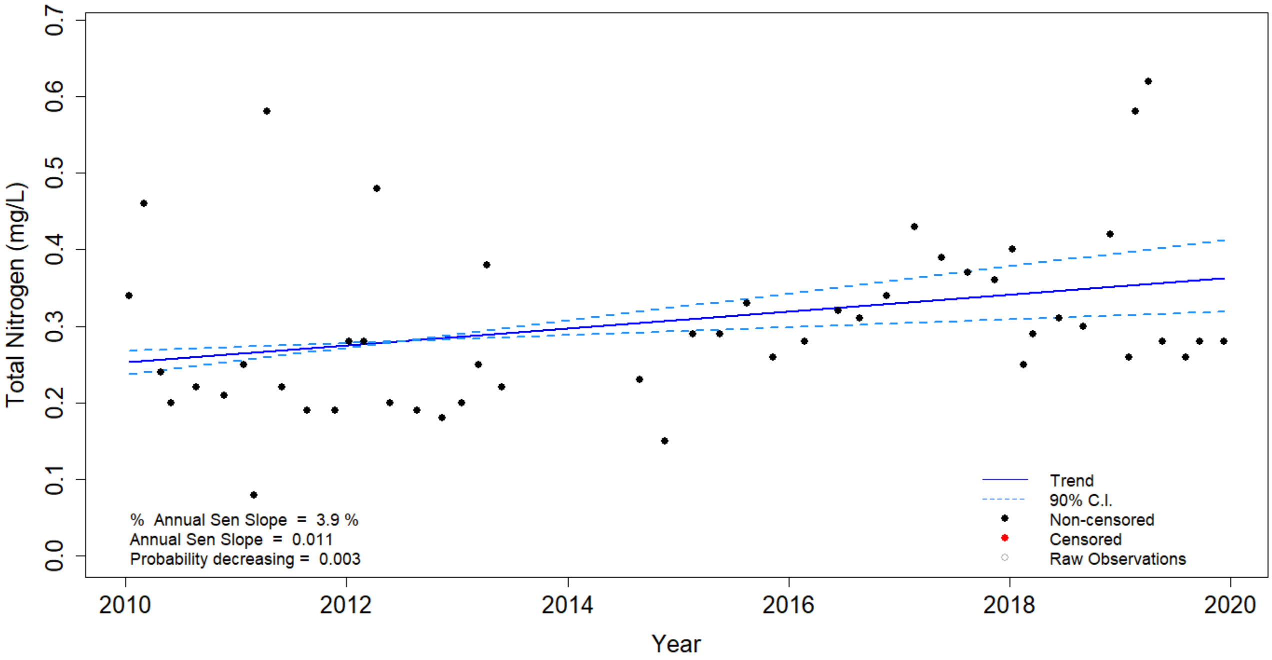

Figure 7-26 Observations of total nitrogen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa bottom waters.

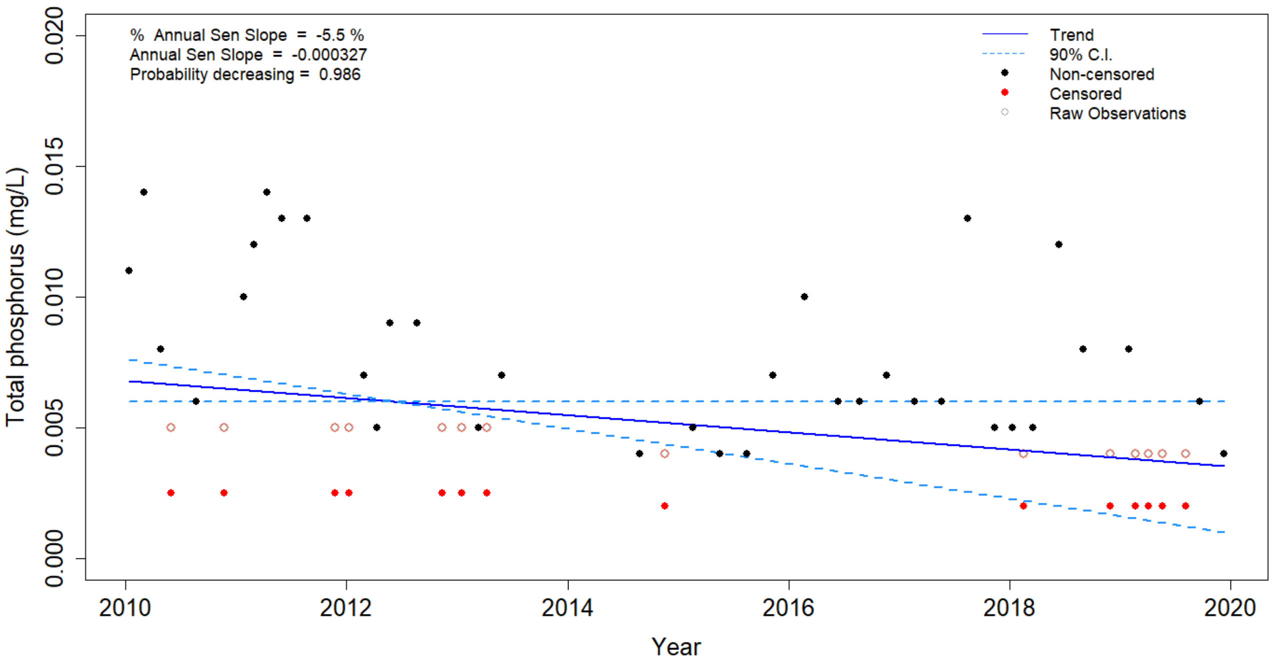

Figure 7-27 Observations of total phosphorus over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

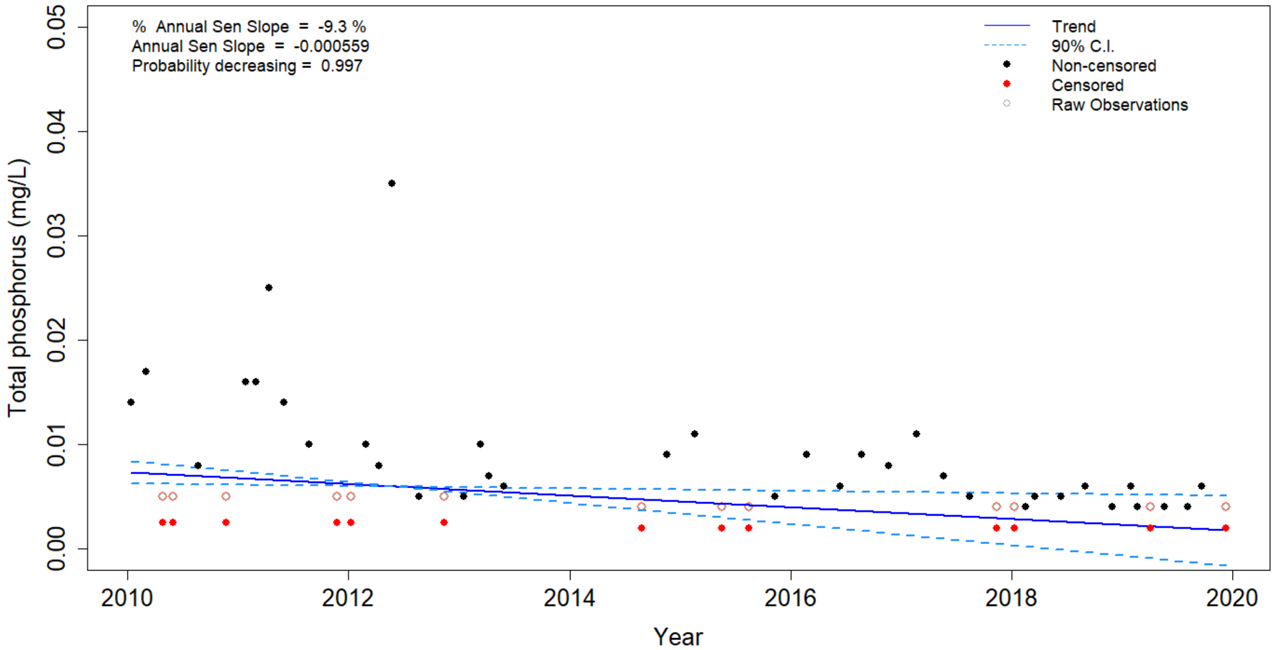

Figure 7-28 Observations of total phosphorus over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa bottom waters.

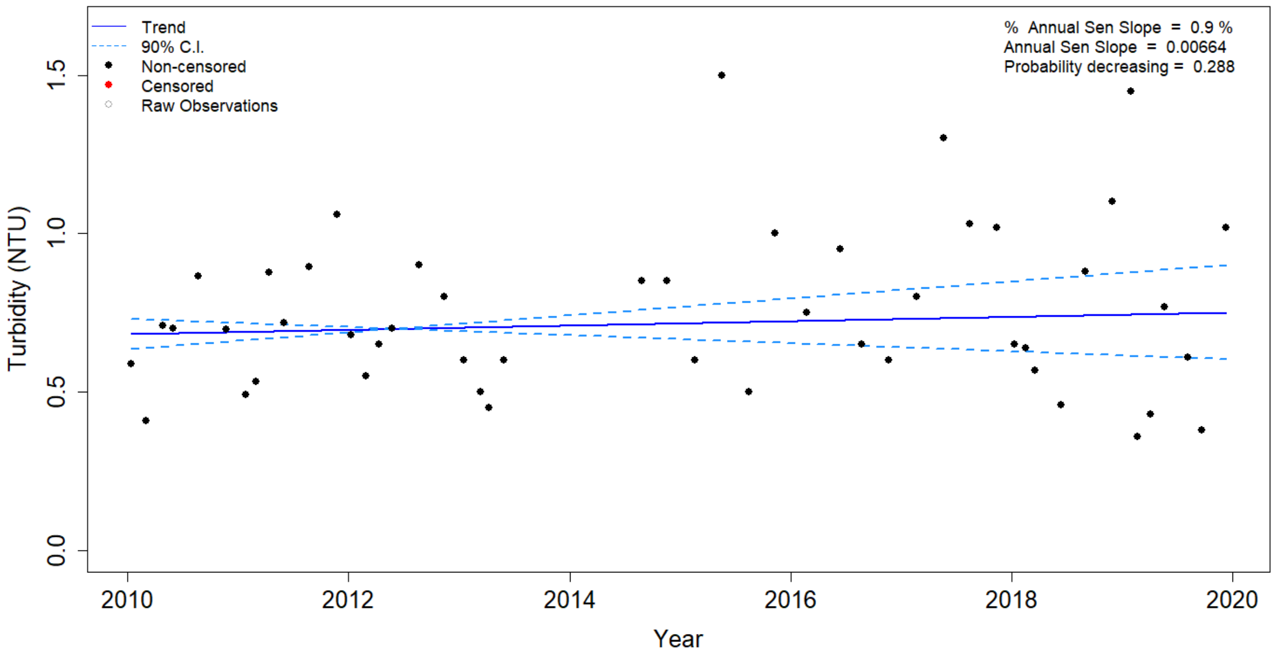

Figure 7-29 Observations of turbidity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

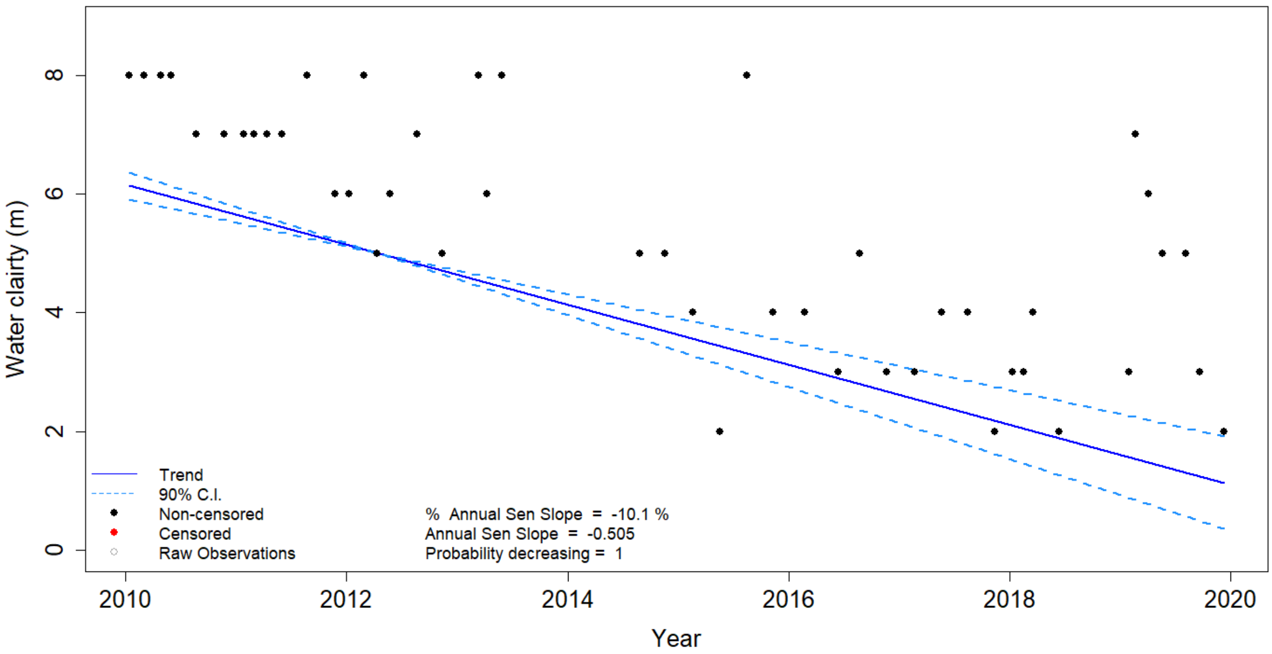

Figure 7-30 Observations of water clarity over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

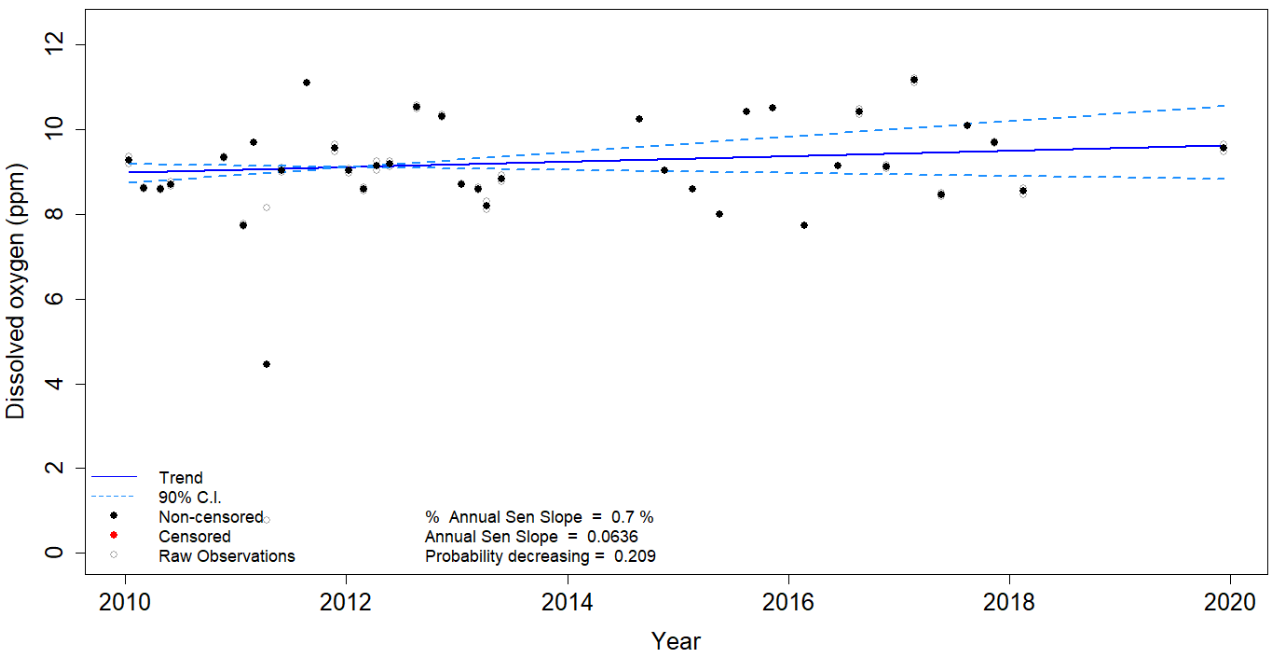

Figure 7-31 Observations of dissolved oxygen over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

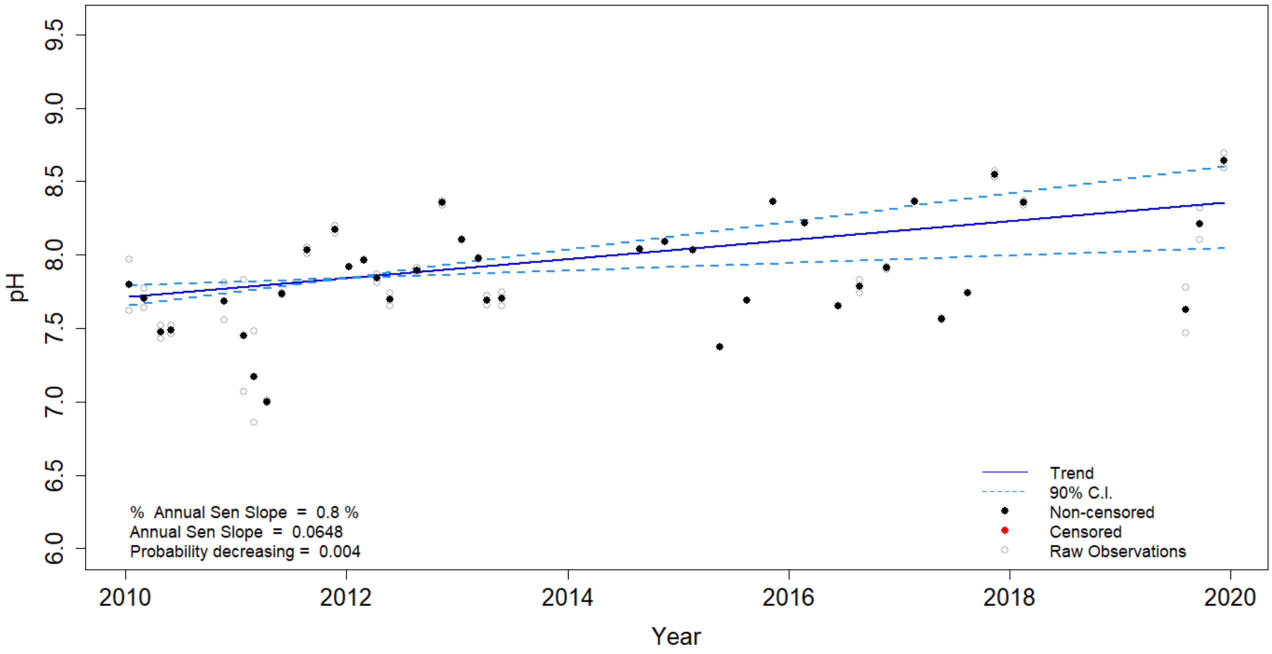

Figure 7-32 Observations of pH over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

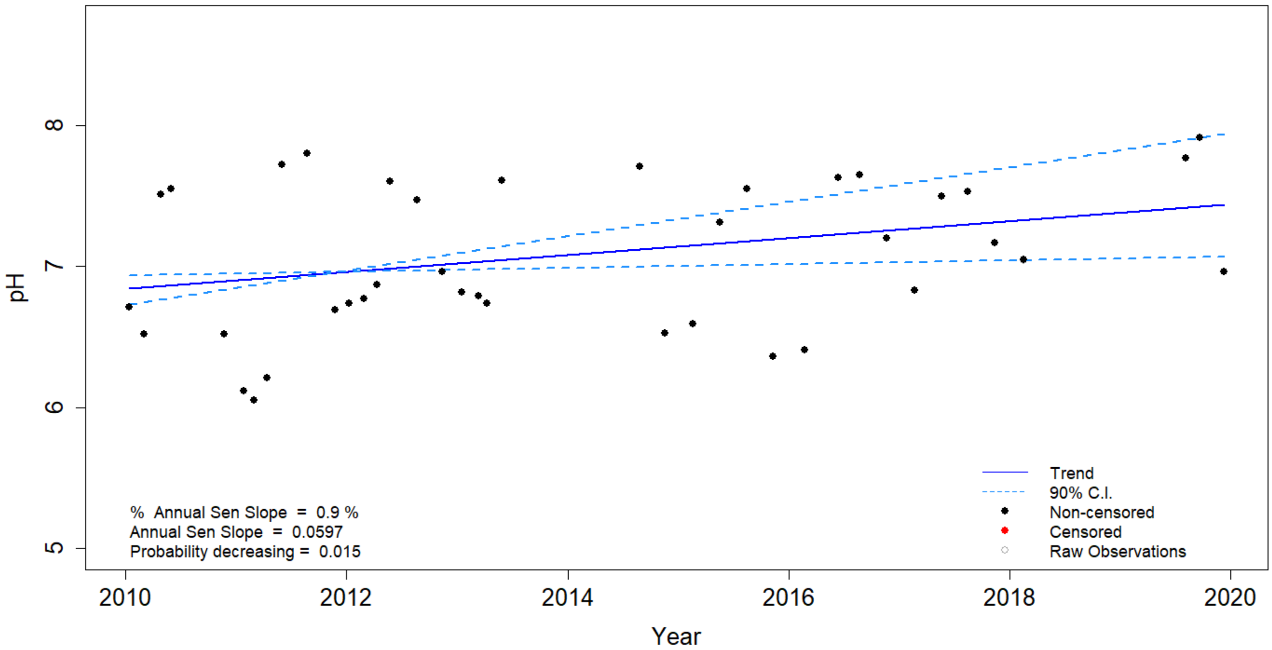

Figure 7-33 Observations of pH over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa bottom waters.

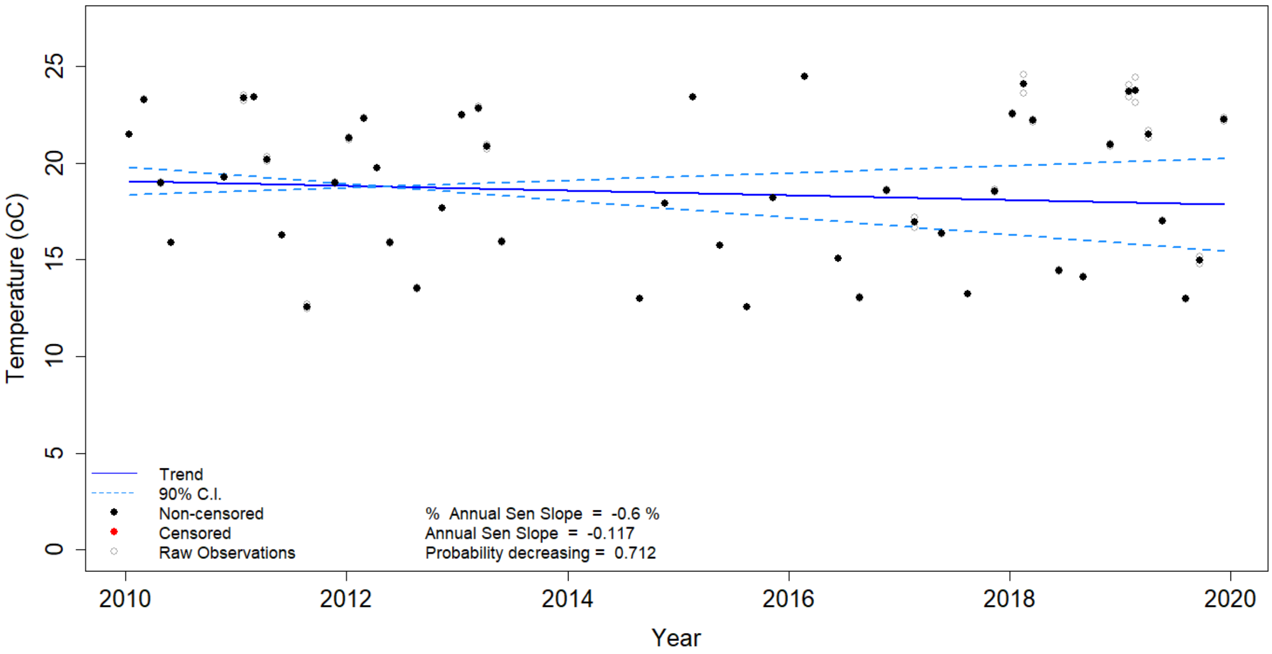

Figure 7-34 Observations of temperature over time fitted with annual Sen Slope and 90% confidence intervals for Lake Rototoa surface waters.

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