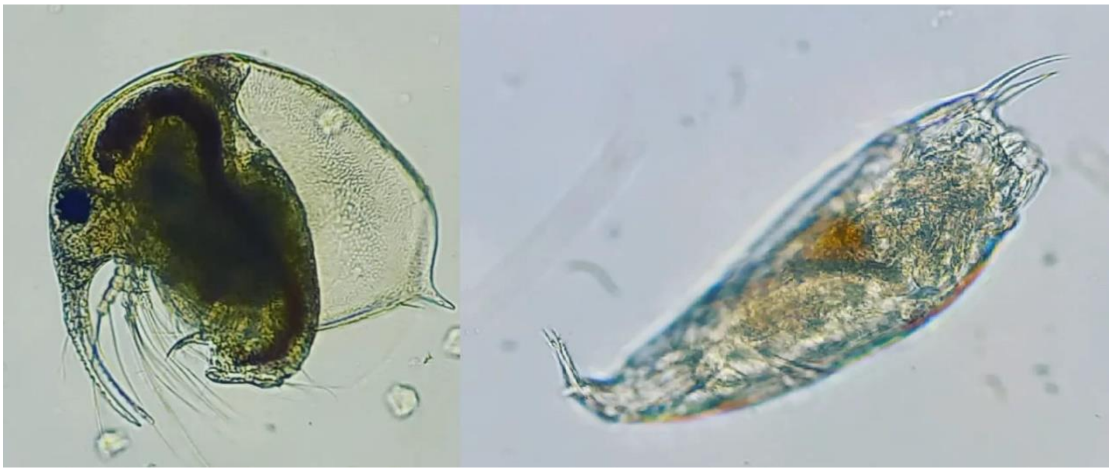
ISSN 2463-6029 (Print)

ISSN 2350-3432 (Online)

Assessment of Trophic State Change and Lake Health in Selected Lakes of the Auckland Region based on Zooplankton Assemblages: 2012-2019



ERI Report Number 155

by

Ian C. Duggan[1] & Ebrahim Hussain[2]

Client report prepared for

Auckland Council

December 2021

Email: i.duggan@waikato.ac.nz

[1] Environmental Research Institute
School of Science, Division of Health, Engineering, Computing and Science,
University of Waikato, Private Bag 3105
Hamilton 3240, New Zealand

[2] Auckland Council, Private Bag 92300, Victoria Street West, Auckland 1142, New Zealand

Cite report as:

Duggan IC and Hussain E. 2021. Assessment of Trophic State Change and Lake Health in Selected Lakes of the Auckland Region based on Zooplankton Assemblages: 2012-2019. *Environmental Research Institute Report No. 155*. Client report prepared for Auckland Council. Environmental Research Institute, School of Science, Division of Health, Engineering, Computing and Science, The University of Waikato, Hamilton. 17pp + appendices. ISSN 2463-6029 (Print), ISSN 2350-3432 (Online)

Disclaimer:

The information and opinions provided in the Report have been prepared for the Client and its specified purposes. Accordingly, any person other than the Client, uses the information and opinions in this report entirely at their own risk. The Report has been provided in good faith and on the basis that reasonable endeavours have been made to be accurate and not misleading and to exercise reasonable care, skill and judgment in providing such information and opinions.

Neither The University of Waikato, nor any of its employees, officers, contractors, agents or other persons acting on its behalf or under its control accepts any responsibility or liability to third parties in respect of any information or opinions provided in this Report.

Cover picture: Left: The cladoceran *Bosmina* sp.; right: the rotifer *Trichocerca similis*. Photos: Ian Duggan.

Reviewed by:

Jane Groom

Auckland Council

Approved for release by

Charles Lee

University of Waikato

Executive summary

This report provides an assessment of eight natural lakes in the Auckland region, from zooplankton samples collected between 2012 and late 2019 at a frequency of six to eight samples per year. From these samples, the lakes have been assessed to establish their trophic state, the proportion of non-native zooplankton species, and the proportion of crustacean zooplankton relative to rotifers.

Inferred trophic states of the lakes based on zooplankton composition has been generally ranked in a similar manner over time; of the lakes sampled over the entire period, Lake Tomarata typically had the best inferred water quality (generally as mesotrophic, though late in the study it sat near the eutrophic boundary). The median Trophic Level Index (TLI) based on zooplankton for this lake was 3.5 between 2015 and 2019. Lake Whatihua, only sampled from late-2017, was also assessed to contain species typical of mesotrophic conditions (median TLI = 3.4). For the remaining lakes, median TLI values based on zooplankton composition between 2015 and 2019 were; Rototoa 3.5 (mesotrophic), Wainamu 4.0, Pupuke 4.3 (both eutrophic) and Kuwakatai 5.2 (supertrophic; sampling ceased in August 2017). Lakes Kereta and Spectacle were not assessed during the 2015-2019 time period.

Lake Pupuke rapidly declined in water quality in 2019, to have hypertrophic assessments at the end of the study; this is consistent with reported high chlorophyll *a* concentrations at this time. Lake Tomarata was assessed to have declining water quality based on zooplankton composition, in common with traditional TLI assessments. However, this lake was assessed to have higher water quality overall, and to diverge in assessments by 1.2 TLI units; this may in part be due to elevated TN concentrations in this lake, not reflected in concentrations of TP or chlorophyll *a*, which may unduly affect traditional TLI assessments for this lake. The other long-term lakes, Waimanu, Pupuke and Rototoa, all has assessments within 0.5 TLI units when comparing the traditional and rotifer inferred TLI systems.

The proportion of non-native species and the proportion of crustacean zooplankton relative to rotifers both showed promise as monitoring tools for the Auckland lakes. Two non-native species were recorded in the lakes, with various levels of dominance. *Daphnia galeata* was recorded in all of the monitored lakes, while *Skistopiaptomus pallidus* was recorded in Lake Kereta only. For the proportions of non-native species, Lake Tomarata was least affected, with samples comprising 4.9% non-native species on average. Data from 2012 and 2013 indicated that the overall relative abundances of the calanoid copepod *Skistodiaptomus pallidus* in Lake Kereta were far lower than they were in the year's immediately following invasion in late 2008. No new non-native species were recognised in the monitored lakes during this survey, although an unusual occurrence of the copepod *Boeckella propinqua* was recorded in Lake Whatihua; this species has otherwise been found from natural lakes only in the central North Island, although has been recorded previously in Auckland dams.

On average, larger crustaceans dominated over the smaller rotifers in all of the Auckland lakes monitored. Lake Rototoa was the least crustacean dominated (53%), followed by lakes Tomarata (58%), Kereta (68%), Spectacle (78%), Whatihua (79%), Wainamu (81%), Pupuke (88%), and Kuwakatai (95%) was the most crustacean dominated. Lake Wainamu appears to have reduced proportions of crustaceans between 2018 and 2019 relative to the 2012 to 2017 period, which may indicate this lake is undergoing a change in its trophic ecology; control of pest fish ceased in this lake in 2015, including of European perch (*Perca fluviatilis*), which may be reducing the importance of larger, more visible crustaceans.

Table of contents

1. Introduction

In New Zealand, lake trophic state is typically assessed by monthly sampling of a variety of physical and chemical indicators – Secchi depth, and concentrations of total phosphorus, total nitrogen and chlorophyll *a* – combined to provide a single Trophic Level Index (TLI) number (Burns et al. 1999). Often neglected are bioindicator approaches, using the responses of organisms to aid in evaluations of trophic state and other aspects of lake health. Such bioindicators integrate biological, physical and chemical properties in the environment over time.

Trophic state was found to be a major determinant of rotifer distribution among North Island lakes by Duggan et al. (2001a, b), and a quantitative bioindicator index was developed using rotifer community composition to infer Trophic Level Index (TLI) values (*sensu* Burns et al. 1999). This method is increasingly being used in North Island lakes, particularly to infer trophic state in situations where lakes cannot be sampled regularly (e.g., Environment Waikato lakes; Duggan 2007; Duggan 2008). Rotifers appear to be particularly useful indicators as they are species rich, they are often the numerically dominant zooplankton, and are sensitive to environmental change (e.g., Duggan et al. 2001b).

Beyond nutrients, zooplankton may provide further measures of ecosystem health, in particular with respect to non-native species. For example, lake health is compromised when non-native species are present or dominating biotic assemblages. In New Zealand, invasions of zooplankton are becoming more frequent and widespread, with a number of non-native cladocerans and copepods increasing in number and distribution over the last 20 years (e.g., Duggan et al. 2006; Duggan et al. 2012; Duggan et al. 2014), and can commonly dominate the invaded communities (Balvert et al. 2009; Duggan et al. 2014). For example, during regular monitoring of zooplankton in the Auckland lakes, the North American calanoid copepod *Skistodiaptomus pallidus* was found to establish in Lake Kereta in late-2008, coincidently with the release of domestically cultured grass carp (*Ctenopharyngodon idella*); this species was commonly found to numerically dominate zooplankton assemblages following this time (Duggan et al. 2014). Due to these findings, the Department of Conservation and Biosecurity New Zealand developed new regulations[1] regarding the treatment and transportation of grass carp to reduce the invasion rate of zooplankton species carried incidentally. These regulations would not have been developed if it were not for the Auckland Council including zooplankton in their long-term State of the Environment (SOE) monitoring programme. Furthermore, zooplankton community composition can also be altered by the presence of non-native fish. For example, the removal of brown trout from Upper Karori Reservoir, Wellington, shifted community composition dominance from large crustaceans to small rotifers (Duggan et al. 2015). As such, changes in the proportions of these major groups may indicate changes occurring in lake ecosystems beyond water quality changes. Between 2005 and 2011, Auckland Council had requested zooplankton data only for the inference of the rotifer inferred TLI, and the additional potential ecosystem health indicators were not examined.

Between 2012 and 2019, Auckland Council has conducted routine water quality monitoring of eight lakes in the Auckland region; Lakes Rototoa, Spectacle, Tomarata, Wainamu, Pupuke, Kuwakatai, Kereta and Whatihua. This monitoring has included zooplankton sample collection, which have been examined for both crustacean and rotifer community composition.

---

[1] see the 'Standard for Managing Exotic Hitchhiker Copepods when moving, transferring or Releasing Grass Carp and Silver Carp"; https://www.mpi.govt.nz/dmsdocument/32257/direct

This report aims to:

1. Use the Rotifer Community Index of Duggan et al. (2001b) to infer trophic state changes from zooplankton samples collected from the Auckland monitored lakes between January 2012 and December 2019.
2. Examine the changes in the proportions of native versus non-native species, and crustacean versus rotifers, in the dataset during this time, to assess whether these provide additional information on lake health for the Auckland lakes.

2. Methods

Eight lakes were monitored by Auckland Council during this period. Four were sampled approximately six times per year between January 2012 and December 2019; Lakes Rototoa, Tomarata, Wainamu and Pupuke. There were no samples collected between mid-2013 and late 2014 due to a pause on the monitoring programme. For Lakes Kereta and Spectacle, sampling ceased in May 2013, and for Lake Kuwakatai the final sampling was in August 2017. Lake Whatihua was sampled between August 2017 and September 2019. Zooplankton were sampled using a 72 µm mesh net (0.2 m diameter) through the top 5 m of the water column. Samples were preserved with >70% isopropyl alcohol (see ARC (2005) for further description of sampling methods).

For the assessment of the proportion of non-native zooplankton species, and the proportions of crustaceans (i.e., cladocerans, copepods and ostracods) relative to rotifers, samples were enumerated until at least 300 individuals were counted. As trophic state monitoring is best assessed by rotifers, this taxon continued to be enumerated and identified until at least 300 individuals of rotifer indicator taxa were counted, or until the whole sample was completed if fewer individuals were found.

Trophic state was assessed using the bioindicator scheme of Duggan et al. (2001b), where it was recommended that four quarterly samples should be taken in a year and averaged to obtain trophic state. As in previous reports, TLI values were calculated for samples if they had any rotifer indicator taxa present in the samples. TLI values were inferred for any one date as an average of data collected on that sampling date, and from the previous data taken up to one year before. TLI values are therefore provided as a moving average of inferred TLI for each lake over time. For the first sampling dates of the current study (2012 onwards), we used data from 2011 sampling in calculations.

3. Results and discussion

3.1. Overall trends in inferred Trophic Level Index among lakes

Examining median values of data collected between 2015 and 2019 (*sensu* Groom 2021), zooplankton assessed TLI values were (from lowest to highest); Whatihua 3.4 (sampled since November 2017 only), Tomarata 3.5, Rototoa 3.5 (all mesotrophic), Wainamu 4.0, Pupuke 4.3 (both eutrophic) and Kuwakatai 5.2 (supertrophic; sampling ceased in August 2017). Lakes Kereta and Spectacle were not assessed during the 2015-2019 time period.

Lake Tomarata typically presented assessments that were on the oligotrophic-mesotrophic boundary early in the study (2012-2016), though water quality has gradually declined since this time to sit at the mesotrophic-eutrophic boundary in 2019 (Figure 1; Appendix 1a). This declining trend is consistent with other parameters in the lake. For example, assessments using the Lake Submerged Plant Index (LakeSPI) indicated that since 2012, populations of native macrophyte species have collapsed (with the lake classified as 'non-vegetated' in 2017 and 2019[2]), while surface chlorophyll *a*, TP and TN concentrations have also shown indications of declining water quality over this time (Groom 2021). Despite showing similar declining trends, the assessed TLI values using rotifers were consistently lower for this lake using rotifers relative to the traditional TLI method; median TLI values of 4.7 were recorded between 2015 and 2019 using traditional methods (Groom 2021), while using zooplankton communities the median TLI value was assessed as 3.5 over the same period. The ranking and patterns for this lake as being the least productive were mostly consistent using zooplankton assessments since 2012 (Appendix 1a). However, this ranking differed from that using traditional methods; across the four lakes assessed long-term, Lake Rototoa was considered to have the best water quality (3.8; mesotrophic), with lakes Wainamu (4.5), Pupuke (4.5) and Tomarata (4.7) all very similar (all eutrophic; Groom 2021). Lake Tomarata, despite sharing a eutrophic assessment with Wainamu and Pupuke, is commonly considered to have the worst water quality, ranking last among these. Interestingly, Lake Tomarata was included in the training set for the development of the rotifer inferred TLI system, and at that time was one of the three lakes to deviate furthest from the observed versus expected 1:1 line across the 33 lakes examined in the late 1990s (Lake Wainamu, being another; Duggan et al. 2001). At that time, Lake Tomarata was assessed as eutrophic using traditional methods, but mesotrophic using rotifers (Duggan et al. 2001), with the lower value using zooplankton communities consistent with that observed now. Nevertheless, the TLI value derived using traditional methods for this lake may be unduly high, driven by elevated TN concentrations relative to other variables used in calculations; for example, in the 2015-2019 period, TN concentrations were around two times higher in Lake Tomarata than in lakes Pupuke, Wainamu and Rototoa, while chlorophyll *a* and TP were all similar among the lakes. As phosphorus will be the limiting nutrient in Lake Tomarata, TN will likely be elevating the calculated TLI values without contributing to productivity (i.e., trophic status). Low visual clarity readings could also drive higher TLI scores using the traditional method, as the lake is dystrophic and the tannin staining becomes more pronounced periodically throughout the year, resulting in lower Secchi depth values.

---

[2] LakeSPI surveys are taken over transects, not a large spatial scale. Extensive mature beds of *Chara australis* as well as *Nitella* species have been documented along majority of the western and north-eastern littoral margins (pers. comm. Hussain, 2021), and the LakeSPI score for 2020 is "moderate", showing recovery from the transect points being non-vegetated.

In the short period of monitoring of Lake Whatihua, since late-2017, the lake has been dominated by species indicative of mesotrophic conditions. As such, this lake has also been assessed as having among the best water quality in this study. The extremely low values at the start of the monitoring of this lake, in the oligotrophic range, may be due to the limited number of samples assessments were made from during this time.

Lake Rototoa typically had zooplankton based TLI assessments around the mesotrophic to eutrophic boundary (median TLI 3.5 in the 2015-2019 time period). This is very similar to the median inferred TLI of 3.8 based on traditional methods between 2015 and 2019 (Groom 2021). The assessments of Lake Rototoa using zooplankton became highly unstable from late-2017, being assessed to have improved in water quality from mid-2017 to mid-2018 into the oligotrophic range, when it became dominated by species typical of oligotrophic conditions (in particular *Conochilus dossuarius*, a species common in, for example, Lake Taupō). However, the lake then declined rapidly to be assessed as eutrophic at the end of the study. Over the longer term, the classifications for Lake Rototoa based on rotifer communities have generally declined from its oligotrophic assessments in 2002 (Appendix 1b). LakeSPI classes this lake as being of 'high' condition, with >50% native vegetation and 11% non-native in 2019. Nevertheless, this lake has experienced large shifts in LakeSPI assessments through time. Included in this was a peak and then rapid decline of non-native vegetation between 2017 and 2019, including a collapse in the hornwort population. These vegetation changes, which are only monitored coarsely, may be related to the instability of rotifer inferred TLI during this time. The overall decline in water quality based on zooplankton composition is consistent with declines in TP and chlorophyll *a* in the lake in recent years (though TN concentrations are increasing; Groom 2021)

Lake Wainamu was typically assessed as being in the mesotrophic range using zooplankton, though this varied through time, and bordered on the mesotrophic-eutrophic boundary at both the start and end of this study; these assessments have been fairly consistent since 2002 (Appendix 1a,b). Using traditional methods, median TLI was assessed as 4.5 over the 2015-2019 period (Groom 2021); the zooplankton inferred values over the same time period were slightly lower, at 4.0 (on the mesotrophic/eutrophic boundary). Again, Lake Wainamu was used in the development of the rotifer inferred TLI in the late 1990s, and was one of the lakes that diverged most greatly from the 1:1 observed versus inferred line most greatly at that time; with traditional methods Lake Wainamu was assessed as eutrophic at that time, while using the zooplankton TLI this lake was assessed as mesotrophic. As such, and similar to Lake Tomarata, this lake appears to be consistently assessed lower using the zooplankton TLI than traditional methods. Nevertheless, the reasons are less clear for this lake, as TN values are not anomalously high. Water quality declines observed in water clarity and surface chlorophyll *a*, TP and TN concentrations were seemingly not reflected in changes in the zooplankton community; the lake has consistently been assessed as unvegetated since 2012.

Lake Pupuke, while being in the eutrophic range between 2014 and 2018, rapidly declined into the hypertrophic range over the last year of the study (2019) based on zooplankton assessments. Over the period 2015 to 2019, the median assessed TLI using zooplankton was 4.3 (eutrophic), though it began this period well below this and ended it well above it. The median trophic state during this period using traditional methods was very similar, at 4.5 (Groom 2021). Similarly, surface TP, TN and chlorophyll *a* concentrations, and water clarity, have all been assessed to be in decline during this period. Further, similar to the trends in zooplankton inferred data, Waters & Kelly (2019) reported a seven-fold increase in surface water chlorophyll *a* concentrations between 2017 and 2019. As such, the zooplankton data reflect similar rapid declines in the water quality of this lake late in this sampling period.

Sampling ceased in Lake Kuwakatai in August 2017. Median assessments in the 2015-2017 period using zooplankton were 5.2 (supertrophic). Similar to the 2009 to 2011 period, Lake Kuwakatai had assessments based on zooplankton that wavered between eutrophic and supertrophic (Figure 1; Appendix 1a). However, on average, the assessments for Lake Kuwakatai were worse in 2015-2017 than they were in 2012-2013. Lake Spectacle and Kereta were only sampled during the first 1.5 years of this study (2012-2013), but continued trends seen previously. Lake Spectacle was primarily assessed in the hypertrophic range, but finished the study assessed as supertrophic. Lake Kereta was inferred based on zooplankton composition to consistently have poor water quality, assessed as hypertrophic throughout (Figure 1). Over the longer term, the assessments for Lake Kereta appeared to be declining, with this lake having been assessed as mesotrophic to eutrophic between 2001 and 2010 (Appendix 1a, b); these changes may be associated with the introduction of grass carp into the lake in 2008 (Duggan et al. 2014), which is likely to have moved the lakes production from the benthos to the pelagic.

Overall, the TLI inferred from rotifer communities suggested a better trophic state for Lake Tomarata than what would be calculated using traditional water quality parameters, with a difference in assessment of 1.2; this may be explained partially by unduly high TN concentrations in this lake relative to other water quality variables, and low visual clarity due to its dystrophic nature. Median values were more similar in the other lakes, with Wainamu having the next greatest difference (0.5), while the assessed values in Lakes Rototoa (0.3) and Pupuke (0.2) were fairly similar (cf. Groom 2021). Nevertheless, despite the difference in assessed values for Lake Tomarata, the declining trend in trophic state was similar between the methods. Overall, it appears uncommon for rotifer inferred trophic state to differ from traditionally measured TLI by over one TLI unit in the Auckland lakes.

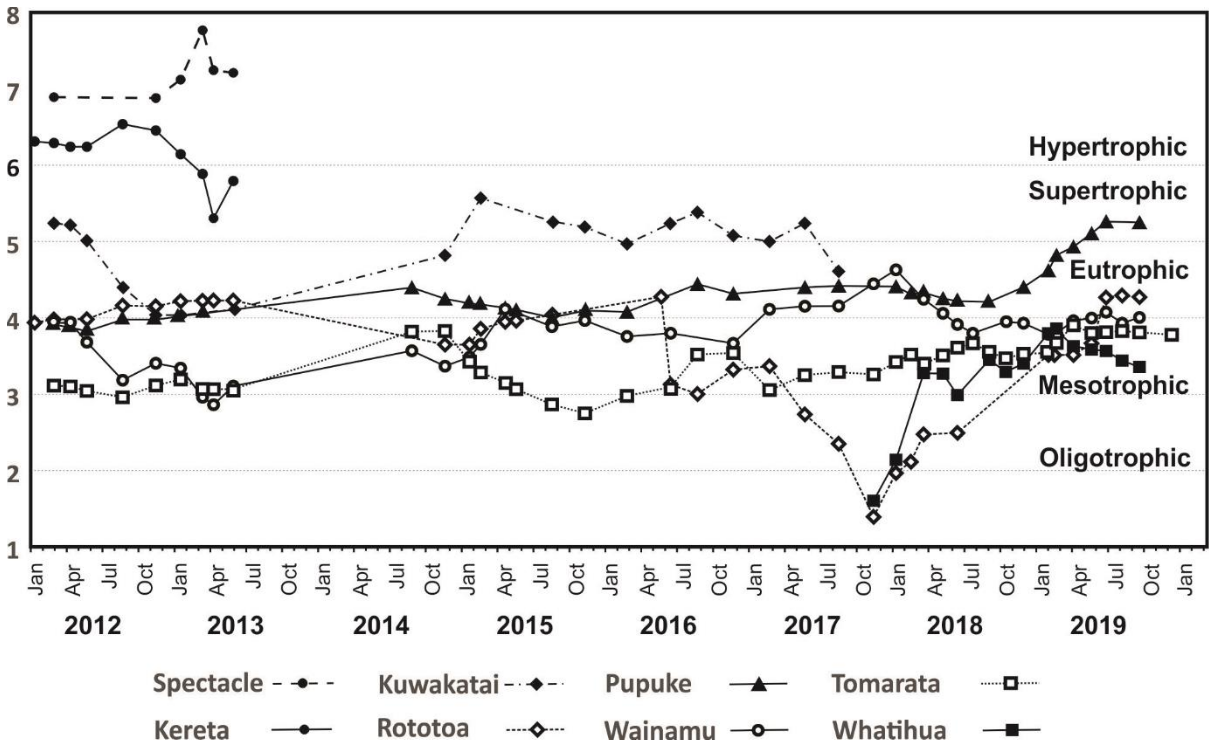


Figure 1: Assessed trophic state (TLI) of eight lakes in the Auckland region between 2012 and 2019. Data points represent a moving average TLI assessment for each lake, using the average of samples collected from that month and from samples collected within the year prior to that sample.

3.2. Overall trends in proportions of non-native species among lakes

Two non-native zooplankton species were recorded from the Auckland lakes. The Holarctic *Daphnia galeata* has been recorded in all of the lakes, while the North American *Skistodiaptomus pallidus* has been recorded only from Lake Kereta (Appendix 2).

Lake Tomarata was least affected by non-native zooplankton species, with typically very low proportions found at any time (an average of 4.9% of non-native individuals across samples; Figure 2). Nevertheless, this has increased through the study, with the highest recorded proportion (34.8%) being recorded in June 2018. This may be related to the decline in water quality in Lake Tomarata through this time, providing more suitable food resources for the non-native *Daphnia galeata*; *Daphnia* numbers have been observed to increase with increasing trophic state elsewhere (e.g., Straile & Geller 1998). Lake Spectacle was the only other lake to average less than 10% non-native species (8.8%). On average, the remaining lakes were from least to most affected by non-native species; Lake Whatihua (12.1%), Lake Wainamu (13.3%), Lake Kereta (18.2%) and Lake Kuwakatai (25.5%), with Lake Pupuke (30.3%) and Lake Rototoa (30.3%) the most affected.

Lake Rototoa, despite having the highest equal average, was highly variable, with dominance of non-native species ranging up to 88.2% non-native; the highest maxima for any of the other lakes was from Lake Pupuke, the most urbanised lake, with 84.5%. Only one other lake, Lake Kuwakatai, reached 50% on any occasion. The high variability in the proportions of invaders in Lake Rototoa appeared to vary seasonally, being lowest from December to April and highest from July to September. In winter in Lake Rototoa, large populations of perch hibernate in the deeper waters (Banda 2014), which would reduce the predation pressure on non-native *Daphnia* at this time, and would greatly increase in the warmer months.

All lakes had the presence of *Daphnia galeata*, which first invaded New Zealand around 1990 (Duggan et al. 2006). Lake Kereta had the further presence of the calanoid *Skistodiaptomus pallidus*, known from New Zealand since 2000, but which invaded Lake Kereta in conjunction with grass carp releases in late 2008 (Duggan et al. 2014). *Skistodiaptomus* commonly dominated the Lake Kereta community between January 2010 and July 2011; it was found to comprise >50% of the community in 6 of the 7 samples during this time, while it was twice found to encompass greater than 90% of the community (Duggan et al. 2014). During 2012 and 2013, *Skistodiaptomus* averaged only 6.3% of the community, with one peak of 27% in March 2013. Although still present when this lake ceased to be monitored, the overall relative abundances of this species at that time appeared to be reduced.

No new non-native species were recognised in the monitored lakes during this survey. However, an unusual occurrence of the native copepod *Boeckella propinqua* was recorded from Lake Whatihua. Although found in constructed reservoirs in the Auckland region, the range of this species in natural lakes is limited to the central North Island (Banks & Duggan 2009). As such, this lake is outside of its natural range in New Zealand. It is possible it has been introduced to this lake associated with regular stockings of rainbow trout, or it has spread naturally from the already invaded Auckland reservoirs.

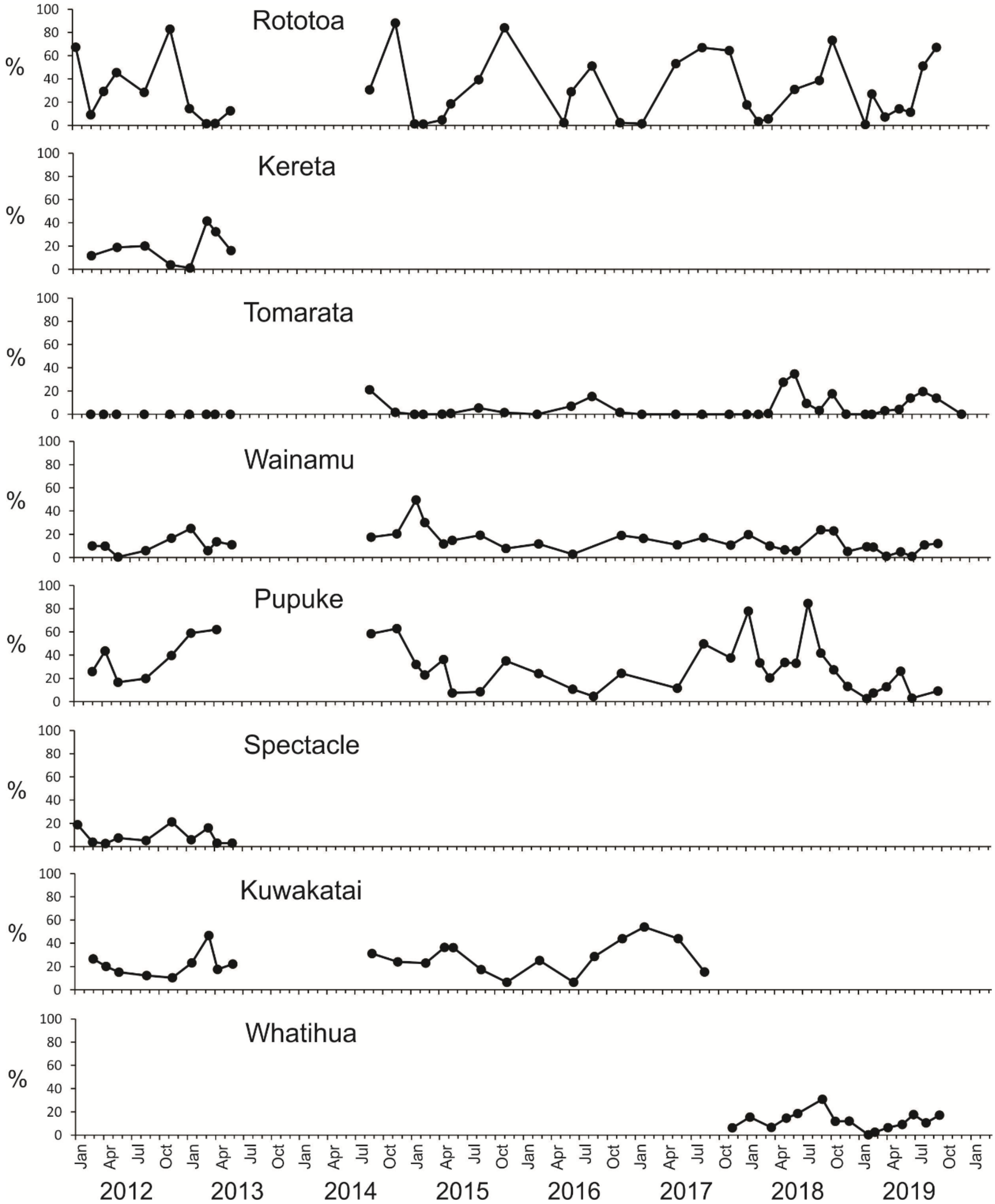


Figure 2: Trends in the proportions of non-native zooplankton abundances in Auckland lakes between 2012 and 2019. The remaining zooplankton considered native.

3.3. Overall trends in proportions of crustaceans and rotifers among lakes

Larger crustaceans, rather than the smaller rotifers, typically dominated the community composition of all of the Auckland lakes (Figure 3). Lake Rototoa was highly variable, switching regularly between small and large zooplankton dominance, but across the study averaged 54.7% crustacean dominance, the lowest proportion of all the lakes; this, again, is likely due to the high and seasonally variable predation pressure from perch in this lake.

Lake Tomarata averaged 58.0% crustacean dominance over the study but has become more frequently rotifer dominated over the last year of study (2019), while similar trends were also apparent in Lake Wainamu and Lake Whatihua. This may indicate a change in the trophic ecology of these lakes, possibly resulting from a greater predation pressure on larger crustacean zooplankton. This appears a likely explanation for Wainamu, at least, as pest fish were regularly removed from the lake between 2004 and 2015; nearly 25,000 pest fish were removed from the lake during this time, with 88% of those being European perch (*Perca fluviatilis*; Rowe & Verberg, 2015). An increase in perch numbers since the cessation of fish control in 2015 may be lowering the numbers of larger, more visible crustaceans, allowing a greater importance of the smaller, less visible rotifers.

The remaining lakes were crustacean dominated with, in order, Lake Kereta (67.7%), Spectacle (77.9%), Whatihua (79.1), Wainamu (80.6), Pupuke (87.6), and Kuwakatai (95.3) having the highest. The lack of rotifer dominance in any of the Auckland lakes across the study is unusual when compared to lakes in the Waikato region (Duggan 2021); this may indicate that the Auckland lakes are under less pressure from non-native zooplanktivorous fish than the Waikato lakes, or they are under reduced pressure due to predation on zooplanktivorous fish by piscivores such as trout (i.e., a trophic cascade). Nevertheless, it is unclear why lakes such as Lake Pupuke should be heavily crustacean dominated, despite perch being abundant there (Champion & de Winton 2005). However, it may be due to the unusual bathymetry of the lake, being deep relative to the surface area relative to other Auckland lakes. For example, in spring and summer, when this species is most likely to be planktivorous, *Perca fluviatilis* showed a strong preference for the littoral zone and complex habitats in a deep reservoir in France (Westrelin et al. 2018). As such, planktivorous life stages of perch may avoid the open water, where the plankton were collected, in this lake.

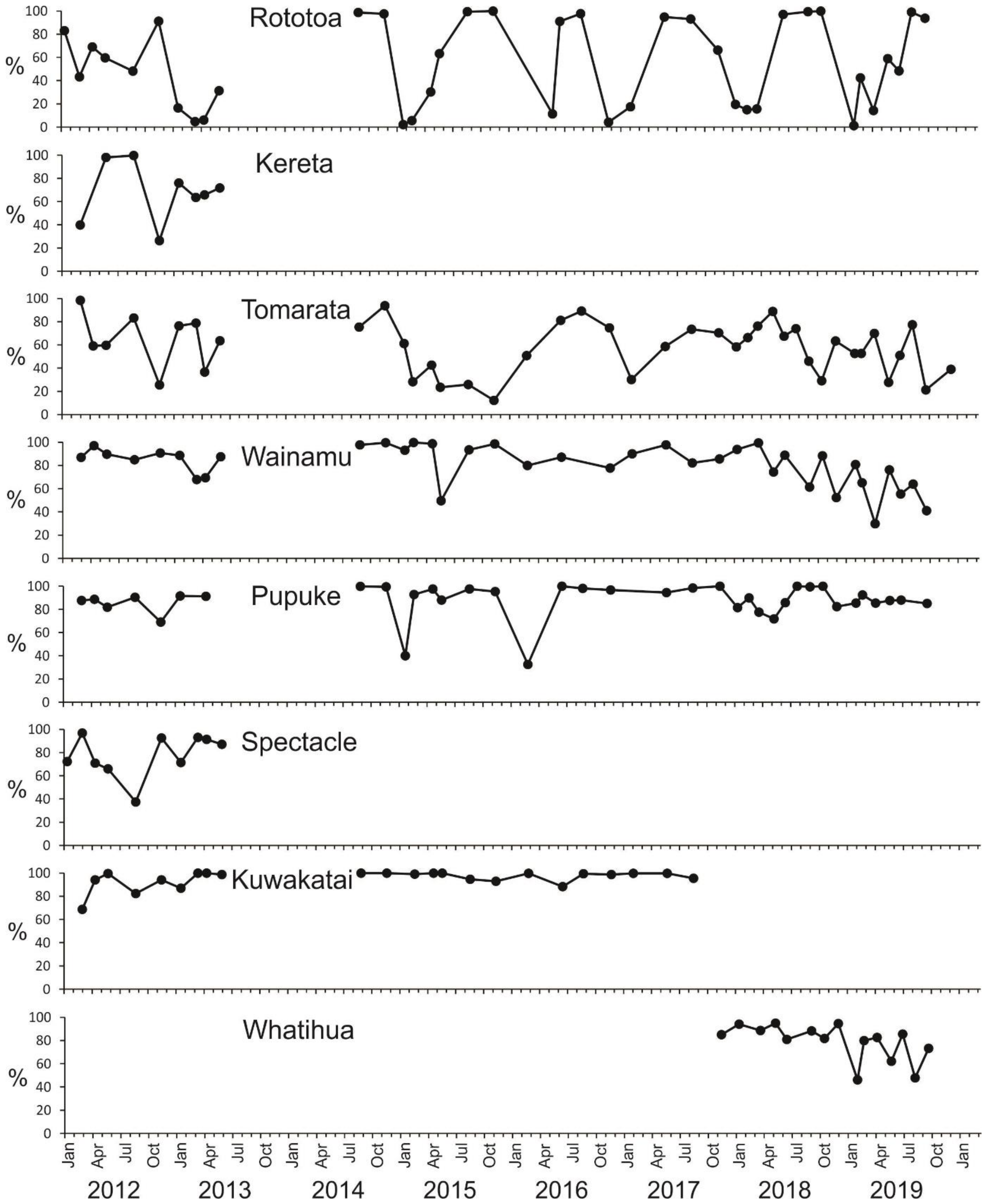


Figure 3: Trends in the proportions of crustacean zooplankton abundances in Auckland lakes between 2012 and 2019. The remaining zooplankton are smaller rotifers.

4. General Conclusions

The rotifer inferred trophic states of the monitored lakes in this study were ranked in a broadly similar manner as they were in the previous studies. Median values of data collected between 2015 and 2019 ranked lakes based on TLI values as follows: Whatihua 3.4, Tomarata 3.5, Rototoa 3.5 (all mesotrophic), Wainamu 4.0, Pupuke 4.3 (both eutrophic) and Kuwakatai 5.2 (supertrophic; sampling ceased in August 2017). TLI values were broadly similar (<1 TLI unit different) between that calculated using traditional monitoring and inferred using rotifers for the long-term lakes (Rototoa, Wainamu and Pupuke). Only Lake Tomarata varied more widely, and traditional TLI values may be overinflated in this lake by disproportionately high TN values (which will likely not affect the productivity). However, the general trend of a decline in water quality in Lake Tomarata was observed across both traditional and rotifer inferred TLI. Lake Pupuke was assessed to have experienced a recent rapid decline in water quality in 2019, in line with reported chlorophyll *a* trends during this time.

The proportions of non-native zooplankton species had not been assessed for the Auckland lakes prior to 2012, but shows promise as an assessment metric of the ecological state of the Auckland lakes, with some clear trends apparent among lakes during this time period. Lake Tomarata had the lowest proportions of non-native species, with samples comprising 4.8% non-native species on average. Nevertheless, this is increasing, perhaps in conjunction with the increasing trophic state. The remaining lakes, from least to most affected by non-native species were; Lake Spectacle (8.8%), Lake Whatihua (12.1%), Lake Wainamu (13.3%), Lake Kereta (18.3%), Lake Kuwakatai (25.5%), with Lake Rototoa (30.3%) and the most urban Lake Pupuke (30.3%) the most affected.

All lakes had the Holarctic cladoceran *Daphnia galeata* present, while Lake Kereta had the further presence of the North American calanoid copepod *Skistodiaptomus pallidus*. Following the establishment of *Skistodiatomus* in Lake Kereta in conjunction with grass carp releases in late 2008, the overall relative abundances of this species in 2012 and 2013 appeared to be lower than they were in the years immediately following invasion. No new non-native species were recognised in the monitored lakes during this survey, although the occurrence of the native *Boeckella propinqua* in Lake Whatihua – naturally distributed among lakes the central North Island – is interesting.

Lake Pupuke was assessed using zooplankton to have the poorest trophic state assessment and also commonly had the greatest proportions of non-native species, providing a combined assessment that this lake was among those with the poorest health. In contrast, lakes with the best rotifer trophic state assessments were also among those with the lowest proportions or non-native species (e.g., Tomarata), providing a combined assessment that this lake had the greatest health. Nevertheless, it must be acknowledged that the rankings of trophic state differed between the two methods, although except for Lake Tomarata the overall assessments were broadly similar. Invasions of new species may affect the bioindicator scheme over time, as they have elsewhere. New Zealand has been subject to a number of new zooplankton invaders, including the discovery and spread of several large crustacean species since the development of the bioindicator scheme (e.g., Duggan et al. 2001b; 2006; 2012; 2014). The effects of invaders on community bioindices has been noted elsewhere. For example, for the Biological Monitoring Working Party (BMWP) score system using stream macroinvertebrate in the British Isles, scores are reduced in sites invaded with the non-native amphipods *Gammarus pulex* and *Crangonyx pseudogracilis*, with taxa more tolerant of organic pollution being found in invaded sites (MacNeil & Briffa 2009; MacNeil et al. 2012; MacNeil et al. 2013). These authors argued that with invasion pressures increasing, the ability of biotic indices to reliably reflect changes in water quality in being undermined. For zooplankton, in long term studies in the Great Lakes, invasions by predatory cladocerans have been shown to shift the composition of rotifers independent of changes resulting from trophic state (Barbiero & Warren 2011), further suggesting bioindicator schemes using zooplankton are similarly vulnerable. Nevertheless, one of the least invaded lakes here, Lake Tomarata, had an assessed trophic state furthest from the traditional assessment, while Lake Pupuke, the most invaded, was assessed similarly between the two methods. Again, high levels of TN relative to other traditional measures that make up the TLI may be over-inflating the TLI value for Lake Tomarata using traditional measurements.

The proportion of crustaceans to rotifers also showed promise as an indicator within the lakes, with each lake differing in the degree of crustacean dominance from the others. On average, crustaceans dominated over rotifers in all of the Auckland lakes monitored, but Lake Rototoa was the least crustacean dominated (54.7%) and Kuwakatai (95.3%) was the most. Importantly, changes towards the end of the study were observed for Lake Tomarata and Lake Wainamu, which were becoming rotifer dominated over the last year of the study (2019), which may be early indicators of a change in the trophic ecology of the lakes; in the former this may be related to declines in water quality, whereas for the latter, it appears a reduction in control measures on perch could be responsible.

5. Acknowledgements

The authors wish to thank Auckland Council field staff for collection of the samples during regular monitoring.

6. References

ARC (2005). Assessment of Trophic State Change in Selected Lakes of the Auckland Region based on Rotifer Assemblages. Auckland Regional Council Technical Publication No. 269, June 2005.

Balvert, S.F., Duggan, I.C. & Hogg, I.D. (2009). Zooplankton seasonal dynamics in a recently filled mine pit lake: the effect of non-indigenous Daphnia establishment. *Aquatic Ecology* 43: 403–413.

Banda, F. (2014). A comparative analysis of *Perca fluviatilis* population dynamics from two lakes in New Zealand. Unpublished MSc thesis, Auckland University of Technology.

Banks, C.M. & Duggan, I.C. (2009). Lake construction has facilitated calanoid copepod invasions in New Zealand. *Diversity and Distributions* 15: 80-87.

Barbiero, R.P. & Warren. G.J. (2011). Rotifer communities in the Laurentian Great Lakes, 1983–2006 and factors affecting their composition. *Journal of Great Lakes Research* 37: 528–540.

Burns, N.M., Rutherford, J.C. & Clayton J.S. (1999). A monitoring and classification system for New Zealand lakes and reservoirs. *Journal of Lake and Reservoir Management* 15: 255-271.

Champion, P.D. & de Winton, M.D. (2005). Recommendations for management of Auckland Region's freshwater pests. NIWA Client Report: HAM2005-137.

Duggan, I.C. (2007). An assessment of the water quality of ten Waikato lakes based on zooplankton community composition. Environment Waikato Technical Report 2007/34, Hamilton.

Duggan I.C. (2008). Zooplankton Composition and a Water Quality Assessment of Seventeen Waikato Lakes Using Rotifer Community Composition. Environment Waikato Technical Report 2008/26, Hamilton.

Duggan, I.C. (2009). Assessment of Trophic State Change in Selected Lakes of the Auckland Region based on Rotifer Assemblages, 2008-2011. Auckland Regional Council.

Duggan, I.C. (2016). Review of Zooplankton Monitoring for TLI and Lake Health Assessment of the Waikato Lakes: 2007-2015. Waikato Regional Council.

Duggan, I.C., Green, J.D. & Thomasson, K. (2001a). Do rotifers have potential as bio-indicators of lake trophic state? *Verhandlungen – Internationale Vereinigung für Theoretische und Angewandte Limnologie* 27: 3497-3502.

Duggan, I.C., Green, J.D. & Sheil, R.J. (2001b). Distribution of rotifers in North Island, New Zealand, and their potential use as bioindicators of lake trophic state. *Hydrobiologia* 446/447: 155-164.

Duggan, I.C., Green, J.D. & Burger, D.F. (2006). First New Zealand records of three non-indigenous zooplankton species: *Skistodiaptomus pallidus*, *Sinodiaptomus valkanovi* and *Daphnia dentifera*. *New Zealand Journal of Marine and Freshwater Research* 40: 561-569.

Duggan, I.C., Neale, M.W., Robinson, K.V., Verburg, P. & Watson, N.T.N. (2014). *Skistodiaptomus pallidus* (Copepoda: Diaptomidae) establishment in New Zealand natural lakes, and its effects on zooplankton community composition. *Aquatic Invasions* 9: 195-202.

Duggan, I.C., Özkundakci, D. & David, B.O. (2021). Long-term zooplankton composition data reveal impacts of invasions on community composition in the Waikato lakes, New Zealand. *Aquatic Ecology* 55: 1127-1142.

Duggan, I.C., Robinson K.V., Burns, C.W., Banks, J.C. & Hogg, I.D. (2012). Identifying invertebrate invasions using morphological and molecular analyses: North American *Daphnia ‘pulex’* in New Zealand fresh waters. *Aquatic Invasions* 7: 585-590.

Duggan, I.C., Wood, S.A. & West, D.W. (2015). Brown trout (*Salmo trutta*) removal by rotenone alters zooplankton and phytoplankton community composition in a shallow mesotrophic reservoir. *New Zealand Journal of Marine and Freshwater Research* 49: 356-365.

Fowler, E.C. and Duggan, I.C. (2008). Assessment of Trophic State Change in Selected Lakes of the Auckland Region based on Rotifer Assemblages: 2005-2008. Prepared by the Centre for Biodiversity and Ecology Research, University of Waikato, for Auckland Regional Council. Auckland Regional Council Document TR 2009/001

Groom, J (2021). Lake water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting. Auckland Council technical report, TR2021/04.

MacNeil, C. & Briffa, M. (2009). Replacement of a native freshwater macroinvertebrate species by an invader: implications for biological water quality monitoring. *Hydrobiologia* 635: 321-327

MacNeil, C., Boets, P. & Platvoet, D. (2012). ‘Killer Shrimps’, Dangerous Experiments and Misguided Introductions: How Freshwater Shrimp (Crustacea: Amphipoda) Invasions Threaten Biological Water Quality Monitoring in the British Isles. *Freshwater Reviews* 5: 21-35.

MacNeil, C., Boets, P., Lock, K. & Goethals, P.L.M. (2013). Potential effects of the invasive ‘killer shrimp’ (*Dikerogammarus villosus*) on macroinvertebrate assemblages and biomonitoring indices. *Freshwater Biology* 58: 171–182.

Straile, D., & Geller, W. (1998). The response of *Daphnia* to changes in trophic status and weather patterns: a case study from Lake Constance. *ICES Journal of Marine Science* 55: 775-782.

Waters, S. and Kelly, D. (2019). Lake Pupuke: Nutrient recycling and management of legacy nutrients. Report prepared for Auckland Council. Cawthron Report No. 3349. P 49.

Westrelin, S, Roy, R., Tissot-Rey, L, Bergès, L. & Argillier, C. (2018). Habitat use and preference of adult perch (*Perca fluviatilis* L.) in a deep reservoir: variations with seasons, water levels and individuals. *Hydrobiologia* 809: 121–139.

Appendix 1a

Rotifer inferred TLI values for each of the long-term monitored Auckland lakes for the current study and from ARC (2005) and Fowler & Duggan (2008). Blank areas indicate that no sample was collected and/or received for that month.

	Ototoa	Kereta	Tomarata	Wainamu	Pupuke	Spectacle	Kuwakatai	Whatihua
Jan-12	3.94					6.31		
Feb-12	3.98	6.89	3.11	3.93	3.91	6.29	5.24	
Apr-12	3.93		3.10	3.94	3.86	6.24	5.22	
May-12	3.98		3.04	3.68	3.83	6.24	5.01	
Aug-12	4.16		2.96	3.18	3.98	6.54	4.40	
Nov-12	4.15	6.88	3.11	3.41	3.98	6.45	4.05	
Jan-13	4.22	7.12	3.19	3.34	4.02	6.14	4.03	
Mar-13	4.22	7.77	3.07	2.96	4.06	5.89		
Apr-13	4.23	7.24	3.07	2.86		5.30		
May-13	4.23	7.21	3.07	3.11		5.79	4.11	
Aug-14			3.82	3.57	4.40			
Nov-14	3.65		3.83	3.37	4.25		4.82	
Jan-15	3.65		3.43	3.48	4.19			
Feb-15	3.86		3.28	3.65	4.17		5.57	
Apr-15	3.95		3.15	4.11	4.13			
May-15	3.96		3.07	4.07	4.11			
Aug-15	4.02		2.87	3.89	4.00		5.27	
Nov-15			2.75	3.97	4.09		5.19	
Feb-16			2.98	3.76	4.08		4.97	
May-16	4.28							
Jun-16	3.13		3.10	3.80			5.24	
Aug-16	3.00		3.52		4.44		5.38	
Nov-16	3.32		3.54	3.67	4.32		5.08	
Feb-17	3.37		3.06	4.11			5.00	
May-17	2.74		3.25	4.15	4.40		5.24	
Aug-17	2.35		3.29	4.15	4.42		4.61	
Nov-17	1.39		3.26	4.44				1.60
Jan-18	1.97		3.42	4.63	4.41			2.14
Feb-18	2.11		3.52		4.31			
Mar-18	2.47		3.40	4.25	4.33			3.28
May-18			3.51	4.06	4.26			3.27
Jun-18	2.50		3.61	3.91	4.22			2.99
Jul-18			3.67	3.80				
Sep-18			3.55		4.21			3.45
Oct-18			3.47	3.95				3.29
Nov-18			3.53	3.93	4.40			3.40
Jan-19	3.52		3.54	3.79	4.62			3.80
Feb-19	3.52		3.67	3.80	4.82			3.84
Apr-19	3.51		3.91	3.96	4.93			3.63
May-19	3.67		3.80	4.00	5.11			3.59
Jun-19	4.27		3.81	4.08	5.26			3.57
Aug-19	4.29		3.83	3.93				3.44
Sep-19	4.27		3.81	4.00	5.25			3.36
Dec-19			3.78					

Appendix 1b

Rotifer inferred TLI values for each of the long-term monitored Auckland lakes for the current study and from ARC (2005) and Fowler & Duggan (2008). Blank areas indicate that no sample was collected and/or received for that month.

	Ototoa	Kereta	Tomarata	Wainamu	Pupuke	Spectacle	Kuwakatai	Whatihua
Jan-05	2.61	2.88	4.29	4.34	4.71	7.58	3.87	
Mar-05	2.77	3.04	4.73		4.38	7.75	4.07	
May-05	2.80	3.19	4.76	4.29	4.19	7.75	3.89	
Aug-05	2.86	3.35	4.63	4.40	4.05	7.22	4.17	
Nov-05	2.85	3.40	4.19	4.59	4.10	7.15		
Jan-06	2.66	3.62	3.75	4.51	4.08	6.35	3.97	
Feb-06	2.48	3.63	3.79	4.31	3.99	6.57	3.85	
Apr-06	2.51	3.92	3.68		4.12	6.05		
May-06	2.49	3.72	3.32	4.25	4.08	5.91	3.98	
Sep-06	2.39	3.52	3.19	4.05	3.86	5.82		
Nov-06	2.45	3.76	3.47	3.88	4.00	5.82	3.99	
Jan-07				4.12				
Feb-07	2.83	3.77	3.69	4.15	4.11	6.17		
May-07	3.00	3.98	3.97	4.13	4.40	7.41	5.23	
Aug-07	2.95	3.98	4.06	4.25	4.34	7.55	5.04	
Oct-07	2.91	4.22	4.06	4.25	4.62	7.22	4.91	
Dec-07	2.88	4.15	3.78	4.25	4.36	6.97	4.82	
Jan-08	2.97	4.12	3.81	4.06	4.29	6.64	4.82	
Feb-08	2.98	4.08	3.76	4.16		6.12	4.77	
Apr-08	2.95	3.94	3.70	4.20	4.24	5.54	4.94	
May-08	2.93		3.64	4.19				
Aug-08	2.93	3.83	3.48	4.15	4.14	5.09	5.03	
Feb-09	3.21	5.12		3.29	4.25	5.82	4.23	
Apr-09	3.21	4.48		3.85	4.32	6.32	4.67	
May-09	3.89	4.29		3.74	4.34	6.32	4.79	
Aug-09		4.62	4.11	3.70	4.41	6.46	5.26	
Nov-09	4.25							
Jan-10	4.69	4.52	3.31	4.13	4.44	6.44	5.15	
Mar-10	5.03	4.34		4.24	4.48	6.27	5.07	
Apr-10	4.41		3.20	4.43		6.60	4.82	
May-10	4.34		3.07	4.67		7.10	4.69	
Jun-10					4.41			
Aug-10	4.20	3.58	2.65	4.87	4.36	7.04	4.48	
Nov-10	3.99	4.10	2.87	4.65	4.31	6.63	4.42	
Jan-11		5.20	2.99	4.20	4.19	6.53	4.43	
Mar-11	3.59	7.32	2.93	4.07	3.89	6.59	4.65	
Apr-11	3.81	6.55	3.00	3.79	3.80	6.22	4.64	
Jun-11	3.68		3.14	3.62	3.74	5.59	4.85	
Aug-11	3.77		3.16	3.59		5.37	5.05	
Nov-11	3.95	6.57	2.99	3.66	3.73	5.79	5.36	

Appendix 2

List of zooplankton species recorded during the study.

	Ototoa	Kereta	Tomarata	Wainamu	Pupuke	Spectacle	Kuwakatai	Whatihua
Rotifera								
Anuraeopsis navicula			x					
Ascomorpha ecaudis				x				
Ascomorpha ovalis	x		x	x				
Ascomorpha saltans	x		x		x			
Ascomorphella volvocicola								x
Asplanchna brightwelli	x	x	x			x		
Asplanchna priodonta	x	x	x	x	x	x	x	
Asplanchna seiboldi								
Bdelloid rotifers	x	x	x	x	x		x	x
Brachionus calyciflous			x			x		
Brachionus caudatus		x						
Cephalodella gibba				x				
Collotheca sp.	x		x	x	x	x	x	x
Conochilus coenobasis			x	x	x			
Conochilus unicornis			x	x				
Conochilus dossuarius	x		x					
Epiphanes macrourus			x					
Euchlanis dilatata					x			
Euchlanis meneta		x						
Filinia longiseta	x	x				x		
Filinia novaezealandiae		x	x	x	x	x		x
Filinia terminalis	x		x	x		x		
Gastropus hyptopus				x				
Hexarthra intermedia		x			x	x		
Hexarthra mira	x		x	x	x			x
Keratella cochlearis	x	x	x	x	x	x		x
Keratella procurva		x		x	x	x	x	x
Keratella tecta		x		x		x		x
Keratella tropica	x	x				x		
Lecane bulla	x	x	x	x	x	x		x
Lecane closterocerca								x
Lecane hornemanni	x							
Lecane luna					x			
Lecane lunaris	x		x		x			
Monommata cf. *diaphna*								x
Platyais quadricornis			x					
Polyarthra dolichoptera	x		x	x	x	x	x	x
Pompholyx complanata	x	x		x	x	x	x	x
Synchaeta longipes	x							
Synchaeta oblonga				x	x		x	x
Synchaeta pectinata	x		x	x	x	x		x
Synchaeta stylata			x					
Testudinella parva			x					
Trichocerca longiseta					x			
Trichocerca porcellus				x	x			
Trichocerca pusilla		x	x		x	x		
Trichocerca similis	x	x	x	x	x	x	x	x
Trichocerca stylata						x		
Cladocera								
Alona sp.	x	x	x		x		x	x
Bosmina meridionalis	x	x	x	x	x	x	x	x
Ceriodaphnia dubia			x		x		x	
Chydorus sp.	x	x	x			x	x	x
Daphnia galeata	x	x	x	x	x	x	x	x
Ilyocryptus sordidus			x					
Copepoda								
Boeckella propinqua								x
Calamoecia lucasi	x	x	x	x	x	x	x	x
Macrocyclops albidus							x	
Mesocyclops australiensis	x	x	x	x	x	x	x	x
Skistodiaptomus pallidus		x						
Tropocyclops prasinus			x					
Copepod nauplii	x	x	x	x	x	x	x	x
Ostracod	x		x		x	x		