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The impact of climate change on New Zealand lakes: A review

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Abstract: Climate change is increasingly impacting natural aquatic ecosystems, altering the hydrology, hydrodynamics and biogeochemical processes that affect ecosystem services, species distributions and ecological function. As atmospheric CO_2 levels rise, the temperature will get warmer and the climate is expected to become more variable and unpredictable, including more frequent occurrences of extreme rainfall events. It is critical that water managers begin to factor these changes into future management of lake ecosystems so that mitigation actions to maintain or improve the ecological status of lakes do not fall short of expectations. The urgency of these measures relates to the potential for climate change to shift the baseline lake trophic state to a higher state. We examine possible implications for New Zealand (NZ) lakes from climate change using a perspective based on historical, contemporary and future climate. Our review includes detailed considerations using specific examples of how climate change might affect geochemical engineering operations to improve lake trophic state, dynamics of cyanobacteria (specifically blooms), evaporation from lakes, and lake food webs, as well as how remote sensing can help to address some of the monitoring challenges. The implications of recently introduced water policies in NZ that seek to maintain or improve water quality and ecological health of lakes may require more stringent nutrient control measures than originally anticipated due to a shifting baseline of increasing trophic state with climate change.

Keywords: climate change, climate projections, lakes, rainfall, cyanobacteria, temperature

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1. Introduction

The climate of the Earth has never been stable and historical glacial periods of the Quaternary period were some 4-5 °C cooler than present, while some interglacial periods were up to 1-2 °C warmer (Hulme, Declan, & Xianfu, 2003). Over the past 600,000 years the frequency of major climatic changes has been about 100,000 years, characterised by significant excursions on time scales from multi-millennia to multi-decadal (Hays, Imbrie, and Shackleton, 1976; Imbrie and Imbrie, 1979). Emiliani (1966), for example, identified multi-millennial climatic changes using variations in oxygen isotope ratios of foraminifera in marine sediments. The most recent of the interglacial periods signalled by these isotopic ratios is known as the stage 1 period from ~10 000 years ago to present. The rate of temperature increase over the past century is unprecedented, however, attributable mostly to anthropogenic greenhouse gas emissions. Our understanding of trajectories of climate is underpinned by global climate models coordinated by the Intergovernmental Panel on Climate Change (IPCC). The assessments undertaken periodically by IPCC set the framework for determining the likely scale of impact of climate change on water resources and infrastructure. Successive iterations of future climate provided by IPCC will challenge organisations to continuously adapt and develop evolving environmental management strategies reflective of a continuously evolving understanding of climate change science.

A challenge in predicting future climate is that climate variables, such as temperature, precipitation and wind, do not function independently and their interactions may work synergistically to exacerbate climate change, or antagonistically to negate change. This interconnectivity adds to the complexity of climate model projections. The greatest certainty in predictions is for temperature, followed by rainfall, humidity, and wind patterns. Annual rainfall projections show wide variation among climate models, but most projections indicate that there will be greater variability in rainfall in time and space. One of the most pronounced effects of climate change in terms of catchment water yields will be from evaporative losses associated with higher temperatures. Downscaling from global to regional levels is also important, especially for variables such as rainfall, due to differential impacts on water yields. Further

New Zealand is located over a wide, mid-latitudinal band (34° to 47 °S) in the southern hemisphere. The climate is temperate maritime and is characterized by modest seasonal temperature oscillations and strong westerly winds (Maunder, 1971; Sturman and Tapper, 2006). Annual mean air temperature varies from about 9 °C in the far south to 16 °C in the far north. The interaction of westerly winds with the perpendicularly aligned land mass results in marked variations in rainfall across the land mass. Rainfall across the mid part of the South Island may vary from 3–4 m yr^{-1} on the west coast to >12 yr^{-1} in the Southern Alps and < 0.4 m yr^{-1} in the arid interior (Wratt et al., 1996). Climate change is expected to alter wind and ocean-current patterns, the occurrence of droughts and frosts and the frequency of heavy rainfall events, as well as resulting in increased air temperature.

The impacts of global warming and regional climate variability provide a strong rationale for adapting the management of lakes to account for the effects of climate change. Climate change may indirectly increase exposure of NZ lake ecosystems to exotic species through chance migrations but more importantly, it is likely to alter the probability of naturalization and affect the resilience of resident communities to invaders (Walther et al., 2009, Hamilton et al., 2012). The most immediate threat to lake ecosystems, however, is from the wide range of alien freshwater organisms already present, which has been heavily influenced by the aquarium trade (Champion and Clayton 2001; Duggan recent pub) and the substantial existing populations of naturalized invasive weeds, fish and invertebrates (Champion et al., 2004; Duggan, Green, and Burger, 2006). Johnson, Olden, and Vander Zanden (2008) have observed a positive correlation between presence of water impoundments and alien species. Opportunities for spread and establishment of alien aquatic species may therefore be facilitated by climate change-driven increases in water storages and distribution infrastructure in NZ (Rahel and Olden 2008), particularly associated with the rapid increase in storages to support irrigated pastoral agriculture (ref). Droughts in the arid eastern and interior regions of the South Island and the mid-latitudes of eastern North Island are likely to increase are also the regions where water resources are being most intensively used for irrigation. It is also notable that invasion of non-indigenous calanoid copepods in NZ has been associated with new waterbody construction and the low inherent biotic resistance of these systems in their early filling and establishment phases (Banks and Duggan, 2009). With an expected increase in the frequency of extreme rainfall events, increased flood-mediated connectivity of water bodies could provide another mechanism for proliferation of invasive species (Walther et al., 2009). The impacts of climate change on invasive species in lakes can also be indirect, through changes in lake trophic status, habitat availability, and the resulting species interactions and structuring (Christie, 2016).

Nutrient concentrations have increased in many NZ lakes to well above natural reference levels (Abell et al. 2019) and this change is likely to be linked to the widespread occurrence of potentially toxic cyanobacteria blooms (Wood…). Climate change may exert symptoms in lakes that are similar to eutrophication (Paerl & Huisman, 2009), mostly associated with temperature-sensitive internal processes (e.g., increased stratification and anoxia-driven bottom-sediment nutrient releases). Hence there will need to be increased emphasis on constraining nutrient inputs in order to avoid amplifying eutrophication (Visconti et al., 2008). Studies has also shown than these internal processes may be more sensitive to climate change than catchment discharge and nutrient loading (Me et al. 2019). An additional stressor of substantial increases in internal loading has the potential to push lakes to critical thresholds where there can be serious deleterious ecological shifts that can be hard to reverse (Schffer…; Sorrell and Schallenberg).

Climate change directly affects important characteristics of lake systems including lake level, thermal stratification, water temperature, water and sediment biogeochemistry, biodiversity, and productivity. Increases in lake water temperature are likely to enhance the growth, distribution and abundance of emergent aquatic macrophytes. There is a high level of certainty that increased temperature will favour the invasive emergent aquatic macrophytes, which poses a risk for native macrophyte species which are sensitive to overtopping and being outcompeted for light by invasive species.

Warming climate will affect the environment supporting freshwater fish in NZ lakes and is likely to act synergistically with substantial existing and proposed freshwater habitat and flow modifications. McDowall (1992) provides an early synopsis of the potential for climate change to affect fish species distributions in NZ. He considered that some diadromous species may move further south, depending on the availability of habitat, some species with restricted ranges could become extinct, while others may have sufficient behavioural or genetic plasticity to adapt be able to survive rapidly warming. In NZ the spread of some fish species is climate and location dependent (McDowall, 1992). High water temperatures could facilitate the spread of different fish species such as common carp (*Cyprinus carpio*) and brown bullhead catfish (*Ameiurus nebulosus*), which are widespread in lakes and rivers in the upper North Island (Hicks, Ling and Wilson 2010). Other smaller fish species such as western mosquitofish (*Gambusia affinis*) and goldfish (*Carassius auratus*) are already widespread throughout NZ and are likely to benefit from increased water temperature. Experimental studies suggest that an increase in temperature can impact whole-system metabolism in alpine tarns as well as changing the dynamics between insects and their predators through changes in timing of insect emergence (Greig et al., 2012).

Table 1 shows predicted climate variables and the predicted effects of anthropogenic climate change in NZ and key limnological impacts. The temperature, precipitation, and wind datasets are estimated from statistically downscaled global circulation models.

Table 1. Predicted effects of anthropogenic climate change in NZ and key limnological impacts; predicted changes in key climatic drivers.

Effect	Predicted magnitude of effect	Reference	Limnological impact	Reference
Warming	).1- 1.4 ^{0}C by 2030s	Wratt et al. (2004)	Eutrophication	Visconti et al. (2008), Trolle et al. (2011))
	0.2- 4.0 ^{O}C by 2080s	Wratt et al. (2004)	Phenology	Winder and Schindler (2004a, b)
Precipitation	Increase except eastern North Island and northern South Island	Hennessey et al. (2007)	Decreased water residence times Increased external nutrient loading	Hamilton et al. (2012)
wind	Midrange projections by 2080: 60% increase in mean westerly component of wind speed	Wratt et al. (2004))	Increased turbulence /resuspension	Hamilton and Mitchell (1997)
			Deeper mixing	Davies-Colley (1984
			Increased aeolian dust (phosphorus)	McGowan et al. (1996)
Sea level	By 2100: 0.18-0.59 m increase relative to year 2000	Hennessey et al. (2007	Salinization of coastal lakes and lagoons and disappearance of some	Schallenberg et al. (2003), Duggan and White (2010)

The main aim of this review is to provide a perspective on how climate change may affect physical, chemical and biological processes in NZ lakes, and how these changes may impact lake management measures. On the one hand lakes are known to be sentinels of climate change (Adrian…;Williamson), but we also want pre-emptive actions that can help to mitigate the effects of climate change and reduce the potential for eutrophication, disruptions in biodiversity and spread of invasive species.

2. Lake stratification responses to climate change and effects on geoengineering treatments: case study of Lake Rotorua

Climate change will affect lake stratification, with consequences for water quality and ecosystem services (Schallenberg et al. 2014). Intensification of thermal stratification is likely to enhance the growth of planktonic, bloom-forming cyanobacteria and cause changes in internal nutrient loading, with consequences for lake water quality and productivity (Ozkundakci et al. 2014; Me et al. 2018). Most shallow lakes in NZ are polymictic with frequently alternating periods of mixing and stratification (Hamilton, Hawes, and Davies-Colley, 2004). Deep NZ lakes are almost uniformly monomictic with the exception of some high-altitude lakes in the central South Island which freeze over in winter (Hamilton, Hawes, and Davies-Colley, 2004; Hamilton et al., 2010). According to the classification scheme of Lewis (2000), lakes at >40^{o} latitude (i.e., encompassing the South Island and lower part of the North Island) should be dimictic. The anomaly of mixing patterns in NZ lakes compared with Lewis' (2000) classification reflects the temperate windy climate in NZ in which lakes mix more deeply than those of large continental land masses and are not subject to calm cold winters or especially hot summers (Davies-Colley, 1988).

Lake Rotorua is a large (80.8 km^2), relatively shallow (mean depth 10.8 m), polymictic lake of volcanic origin. Water quality declined rapidly between the 1960s and mid-2000s (Rutherford et al. 1996; Burger et al. 2008) in response to treated effluent discharges to the lake from the city of Rotorua (up until 1991) and land development for agriculture within the lake catchment. Several large inflows to Lake Rotorua are enriched in dissolved P (Timperly 1983, Morgenstern et al. 2015) from natural geological sources, however, anthropogenic sources have been estimated to contribute at present approximately 50% of the total catchment load (Tempero et al. 2016). The treated effluent discharged to the lake has also created a legacy of highly enriched lake sediment, which has been shown by several studies to contribute substantial internally recycled loads of N and P (White et al. 1978, Burger et al. 2007). Sediment nutrient release is enhanced as dissolved oxygen is consumed within the hypolimnion when the water column stratifies. An automated monitoring buoy has measured water column temperature at 15-minute resolution since 2007, recording frequent periods of stratification ranging from a few days to a several weeks (Figure 1a).

Lake Rotorua is the focus of a multi-million dollar program of management encompassing land use change, geochemical engineering, riparian management, wetland development, and improved wastewater treatment (Burns 2005; Hamilton and Dada 2016). Alum dosing of a surface inflow to the lake commenced in 2006, with the dosing rate increased substantially with dosing of a second inflow commencing in 2010 (Figure 1b). Water quality in Lake Rotorua has improved since alum dosing commenced, with water column total P (Figure 1) and dissolved P (data not shown) varying with the total aluminium dose (Smith et al. 2016). The strong seasonal pattern of elevated total P during warmer months was suppressed during years with high dose rates (Figure 1b).

In the summer of 2014 to 2015 there was a prolonged period of stratification. Forty-six consecutive days occurred when the temperature difference between surface and bottom waters exceeded 2 °C; the previous longest period during the buoy deployment had been 24 days. Despite high alum dosing rates at the time (Fig. 1), concentrations of total P in the hypolimnion increased rapidly, indicative of a large release of dissolved P from the lakebed sediments (Figure 1b). As the intensity of stratification declined and became negligible (as indicated by the temperature difference between surface and bottom waters), surface total P concentrations increased and became similar to those of bottom waters. Similar, although less severe, events were also observed the following summer, in 2015 to 2016. These observations clearly illustrate the challenges faced by lake managers adopting geoengineering lake restoration techniques under changing climatic conditions. Increases in the duration and intensity of stratification events are likely to make internal nutrient cycling more resilient to restoration by geochemical methods. Furthermore increased bottom-water temperatures will increase rates of oxygen consumption and nutrient processing, particularly in polymictic lakes where bottom-water temperature more closely aligns with surface-water and air temperatures compared with seasonally stratified lakes. In the absence of addressing external nutrient loads, higher doses of chemicals will be required to achieve a given level of improvement of water quality. Such additions risk unforeseen consequences including possible eco-toxicological effects on lake biota and exceedance of buffering capacity resulting in acidification. The duration of deoxygenation of bottom waters observed in Lake Rotorua in 2014 to 2015 is of the same order as predicted for 2041-2049 and less than 2091-2099 based on simulations of a coupled climate-lake model and using a mid-range increase in air temperature of 2.7 ºC by end of the present century. This combination of high-frequency and routine monitoring results that can be used to assess lake responses interannual variability in climate, together with model simulations, provides strong evidence that there will be major challenges in restoring shallow eutrophic lakes such as Rotorua. It emphasizes the importance of a sustained effort to reduce catchment nutrient loads and steadily decrease the pool of lakebed sediments that contributes to internal release events.

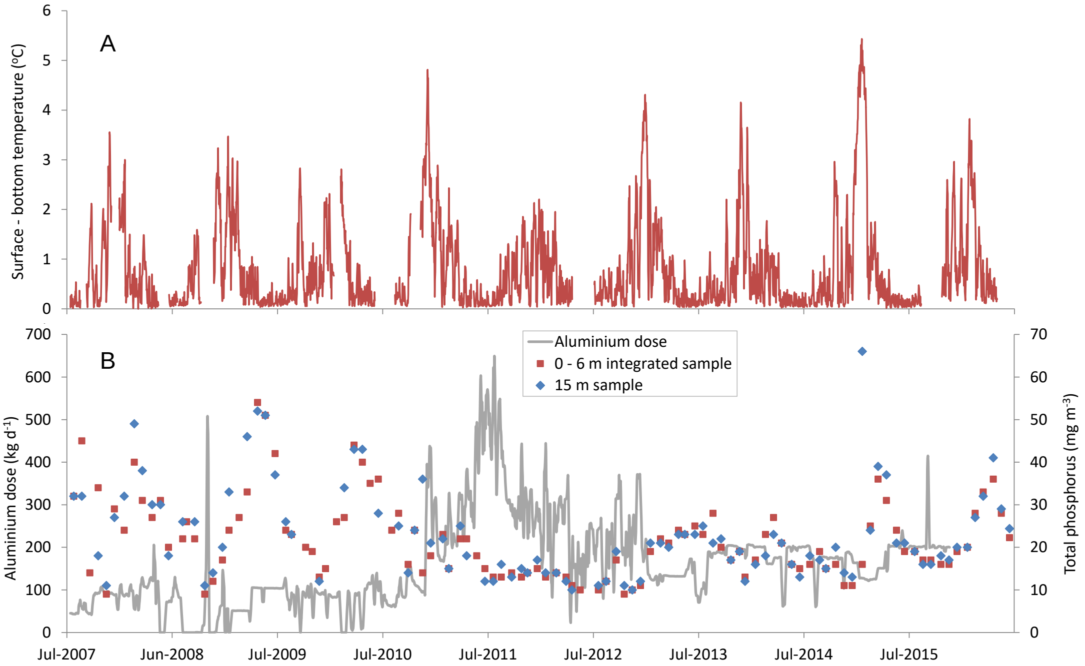

Figure 1. Measurements for Lake Rotorua (North Island, New Zealand) and two tributary streams. A) Daily average difference between surface (0.5 m) and bottom (20.5 m) water temperature. B) Total aluminium dose (grey line) to two stream inflows of the lake and monthly total phosphorus concentrations in surface and bottom waters. Data from Bay of Plenty Regional Council, New Zealand.

3. Effect of climate change on cyanobacteria populations

There is growing evidence that climate change will increase the severity, distribution and longevity of cyanobacterial blooms in lakes (Kosten et al. 2012, Paerl 2014). O'Neil et al. (2012) have identified different genera that are likely to increase in abundance in response to climate warming, and these include the four most common pelagic bloom forming genera in New Zealand**;** *Aphanizomenon, Cylindrospermopsis, Dolichospermum* (basionym *Anabaena*) *and Microcystis* (Wood et al. 2016a).

Cylindrospermopsis blooms are confined to a few large (500-300 ha) shallow (max. 5 m) North Island lakes, where they reach extremely high biomass (Wood et al. 2014). Although drivers of these blooms are complex, two key factors, both expected to increase with climate change, have been identified – temperature and turbidity. Blooms usually occur only when water temperatures are above 20ºC, and peak seasonal abundances correspond to summer thermal maxima (Wood et al. 2014). Low light condition favour *Cylindrospermospsis* (O'Brien et al. 2009). These lakes are highly exposed to wind and extremely turbid due to wind-driven re-suspension of fine sediment.

In a 17 month study of a eutrophic New Zealand lake Wood et al. (2016b) highlighted the complexity of predicting the impacts of climate change on New Zealand other bloom forming genera. The authors investigated bloom formation and species composition in two consecutive summers with contrasting extreme weather; intense precipitation and severe drought. In the first summer moderate levels of nitrate related to high-rainfall events and a wet summer, lead to the dominance of *Aphanizomenon* and *Dolichospermum*, which either lacked or had a very low frequency of heterocytes (Figure 2). *Microcystis* blooms occurred only when ammonium concentrations and water temperature increased. The extended drought in the proceeding summer resulted in prolonged stratification, significantly higher water temperatures, increased dissolved reactive phosphorus and low dissolved inorganic nitrogen concentrations. All *Aphanizomenon* and *Dolichospermum* filaments contained heterocytes (suggest active nitrogen fixation) and *Microcystis* blooms did not occur (Figure 2).

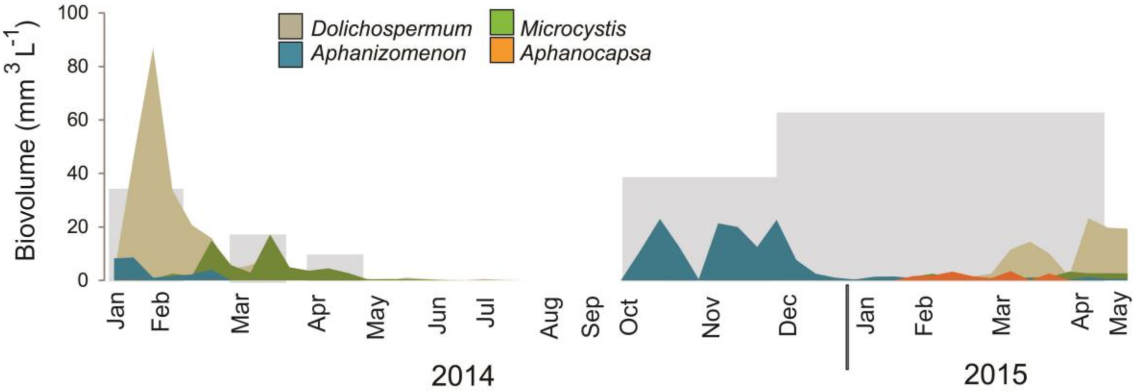

Figure 1. Cyanobacterial biovolumes in Lake Rotorua (South Island, New Zealand) over the 17-month study period (January 2014 to May 2015). Grey shading shows the presence of heterocytes and their approximate frequency (heterocyte per cell). The summer (January to April) of 2014 was characterised by frequent precipitation and two extreme rainfall event, in contrast the summer of 2014 to 2015 (October to April) had the second lowest total rainfall (over the summer period) measured since records began 75 years before present.

Many bloom-forming species overwinter in lake sediment in a dormant vegetative stage or as akinetes. In spring or summer they recruit back into the water column and can provide a substantial inoculum for summer blooms (Torres and Adámek 2013). Despite relatively mild winter water temperature in New Zealand's lowland lakes, benthic recruitment appears important in initiating bloom formation (Faithfull and Burns 2006, Borges et al. 2016). Although factors that promote recruitment are complex and the impacts of climate change rarely considered in this process, temperature has been highlighted as important in shallow New Zealand lakes. Laboratory studies identified temperature as one of the key triggers for *Microcystis* recruitment (Figure 3; Borges et al. 2016). Wood et al. 2014, analysed a 10-year dataset and found that *Cylindrospermopsis* blooms only occurred when bottom water temperatures exceeded 22 °C, which the authors suggest is likely related to akinete germination.

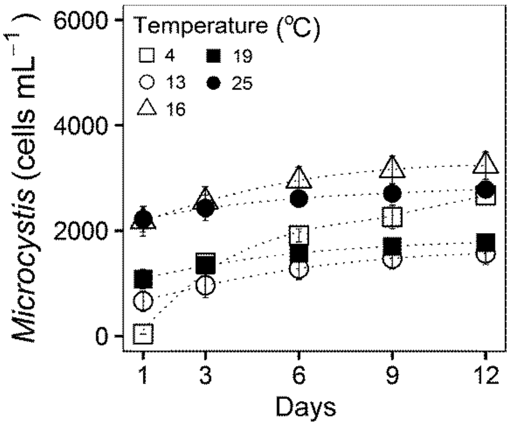

Figure 3. Total cumulative *Microcystis* sp. cell density at the end of a 12-day laboratory-based experiment (data points are an average of triplicates). Surface sediment from Lake Rotorua (South Island, New Zealand) were incubated at five temperatures in Milli-Q water, and recruitment assessed every three days. Recruitment was significantly higher at 16 and 25°C compared to 4, 13 and 19°C (p<0.001; modified from Borges et al. 2016).

Many bloom-forming cyanobacteria produce cyanotoxins, which pose a health risk to humans when lakes are used as drinking water sources or for recreation. Predicting how climate change will impact cyanotoxin production is challenging. Many variables appear to be involved in regulating toxin production, and these differ among species, strains and geographic location (e.g., Kleinteich et al. 2012, Harke and Gobler 2013, Willis et al. 2016). Additionally, cyanobacterial blooms are usually comprised of both toxic and non-toxic genotypes and their relative abundance is spatially and temporally variable (Kurmayer and Kutzenberger 2003). Field studies in New Zealand suggest that within short time frames (up to 6 hours) factors not directly related to climate change cause the most dramatic changes in toxin production in *Microcystis* (Wood et al. 2011). However, a a 17-month study where genotype succession and toxin quota were investigated, showed a statistically significant correlation between water temperature and toxin quotas (of the toxin microcystin; Figure 2; Wood et al. 2016b). These data indicate that predicted global increases in surface water temperature may lead to higher microcystin quotas, or select for toxin-producing strains which produce higher amounts of toxins.

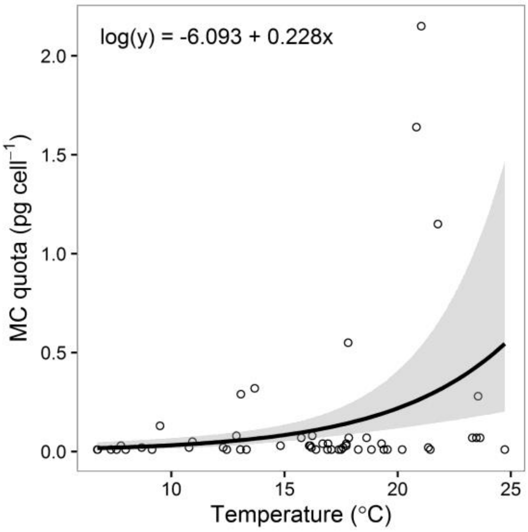

Figure 3. Univariate analysis identified a significant positive relationship (p < 0.001) between surface water temperature and microcystin (MC) quota in a 17-month study (January 2014 to May 2015) at Lake Rotorua (South Island, New Zealand). The shaded area shows the pointwise 95% confidence interval of the fitted values.

While significant attention has focused on the effect of climate change and cyanobacterial bloom formation in eutrophic lakes, less emphasis has been placed on potential shifts in cyanobacterial diversity in lakes of varying trophic status. Wood et al. (2016b) used molecular techniques to study pelagic cyanobacterial diversity in 143 New Zealand lakes that spanned a range of geographic, hydromorphological and trophic gradients. The authors showed that while local conditions were the most important factors in structuring community composition, geographical location (latitude, longitude and altitude) were also significant and their relative importance varied among trophic categories. Their data highlight the need to consider the broad-scale impacts that the dual effects of eutrophication and climate change will have on planktonic cyanobacteria communities.

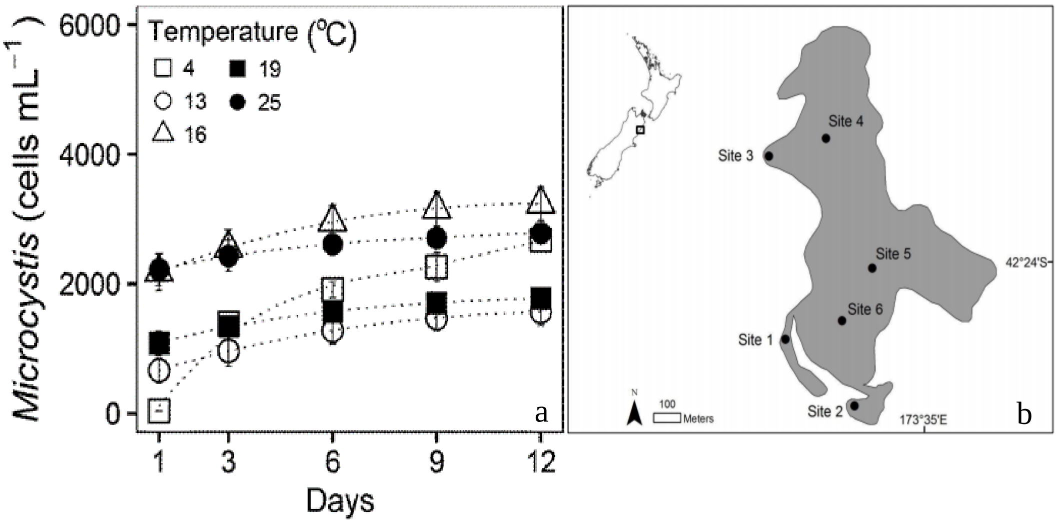

Figure 14. (a) Total cumulative Microcystis sp. cell density at the end of a 12-day laboratory-based experiment (data points are an average of triplicates); (b) Lake Rotorua, a small (0.55 km2), shallow (max. depth 3 m), eutrophic lake in the northeast of the South Island of New Zealand (Flint, 1975); inset: map of NZ showing location of lake Rotorua.

4. **Effects of climate change on lake fish and macroinvertebrates**

Environmental changes induced by a warming climate, altered weather patterns, and rising sea-levels have major implications for lake-dwelling fish and invertebrates, particularly those in northern New Zealand and those inhabiting lowland waterbodies. Climate-induced threats to lake biota include (i) elevated temperatures exceeding tolerance thresholds of cold-adapted species leading to stress, truncated recruitment and the potential for increased parasite loads, (ii) loss of thermal refugia during summer in stratified lakes with anoxic bottom waters, (iii) increases in pest species distribution and abundance due to southward migration as waters warm or as new species establish when temperature thresholds increase above minimum requirements at key times of year, (iv) reduced connectivity and increased salinization, and (v) the potential for trophic and life-cycle mismatches to occur, altering in-lake processes and food web structure.

Lacustrine native fish such as smelt (*Retropinna retropinna*) and larvae of some Galaxiidae, whose larvae may rear in lakes (e.g., banded kokopu *Galaxias fasciatus*; Hicks 2010), have thermal preferences close to current mean summer water temperatures, and key behavioural and developmental characteristics can be affected by much cooler temperatures (Olsen et al. 2014). Water temperature is also a key variable influencing fish parasites, affecting growth rates, time to maturation, mortality rates, the number of generations possible per year, and the duration of the growing and transmission season. Additionally, increased abundance in warmer waters of intermediate hosts such as lymneaid snails may increase transmission of mammalian parasites, while the non-indigenous mosquito *Culex* *quinquefasciatus* is a known vector for avian pox and malaria (*Poxvirus avium* and *Plasmodium relictum*, respectively) (Tompkins & Poulin 2006).

In addition to cold-adapted native species, introduced fish such as salmonids (notably *Salmo trutta*) and perch (*Perca fluviatilis*), which require cool water for spawning and egg development (Collier et al. 2015), could experience reduced distributions in northern New Zealand as suitable habitat in shallow lakes contracts (e.g., Scott & Poynter 1991). These fish are known predators of native species, potentially leading to release of some native biota from predation pressure, and in the case of perch trophic cascades altering food-web interactions (Rowe & Graynoth 2002, Schallenberg & Hamilton 2016). Climate change is also likely to result in the progressive improvement of conditions for pest fish species that already colonise many northern New Zealand lakes, and compete with, or otherwise negatively impact, native species and their habitat. Species of particular concern include common carp (*Cyprinus carpio*) and gambusia (*Gambusia affinis*) which are currently largely absent from the South Island but can be expected to have increased risk of spread in response to elevated water temperatures. These species can adversely affect native biota or, in the case of koi, degrade water quality and contribute to bank erosion when feeding (Parkos et al. 2003).

Change in the timing and/or magnitude of flood-flows, coupled with temperature cues and rising sea levels, will have implications for life cycles of both introduced and some native species. For example, upstream migrations of the dominant whitebait species, inanga (Galaxias maculatus), are typically initiated by large floods in spring, and spawning occurs on certain types of riparian vegetation near the extent of saline intrusion during very high tides in autumn. Rising sea-levels may mean that suitable habitat for spawning is steadily pushed further upstream where vegetation and bank gradients may not be favourable. It has been estimated that 93% of potentially suitable whitebait spawning habitat in the Waikato delta has already been lost due to stop-banking (Jones & Hamilton 2014), and further loss could have significant implications for the whitebait fishery. As noted above, it would be prudent to protect or restore likely future spawning habitats to address this issue.

In addition to invasive fish, there is the potential for introduced invertebrates, particularly snails, to spread more widely or become established. For example, the apple snail *Pomacea diffusa*, although recorded in the wild, may currently be limited by breeding temperature (Collier et al. 2011). There is also the possibility that more subtropical invertebrates (e.g. disease-carrying mosquitoes) could establish. Moreover, if altered wind patterns lead to increased westwind drift, new arrivals of aquatic insects may influence the composition of some northern lake macroinvertebrate communities, particularly if self-introduced species occupy higher trophic levels in lacustrine food-webs. Already, predators including the damselfly *Ischnura aurora*, the dragonflies *Hemianax papuensis*, *Tramea loewii* and *Hemicordulia australiae* (Rowe 1987), the waterboatman *Agraptocorixa hirtifrons* (Young 2010), and the whirligig beetle *Gyrinus convexiusculus* (Wise 1989), have become established from Australia and are spreading amongst northern New Zealand lakes.

Reduced flows caused by altered rainfall patterns in some parts of the country may influence lake ecosystem connectivity with other waterbodies due to lower water levels or reduced flows in outlet streams. Such events could limit colonisation by native diadromous fish if they occur during migration periods, but may also reduce ingress of invasive fish such as common carp which migrate into lakes for spawning (Daniel et al. 2011). There is also potential for reduced flows to contribute to salinization of waterbodies, either through reduced evaporation or greater tidal incursion, particularly on intermittently opening and closing lakes and lagoons. The combined effects of elevated temperature and salinization have been shown to adversely affect lake macroinvertebrate communities elsewhere (Brucet et al. 2012). Change in the timing and/or magnitude of flood-flows, coupled with temperature cues and rising sea levels, will have implications for life cycles of both introduced and some native species. For example, glochiidia release by freshwater mussels (notably *Echryidella menziesii*) is strongly linked to water temperature; if climate change alters the timing of this process and also reduces the abundances of host fish at key times of year then there is the potential for this disconnect to reduce mussel recruitment with implications for in-lake nutrient cycling.

5. Use of satellites to monitor changes in lake properties

The use of surface water temperature measurements obtained from satellites allows near simultaneous monitoring of horizontal variation in water surface temperature. In the case of Landsat thermal data (60 m resolution, 185 km swath) this includes data collected in the same path (path revisit period is 14 days). Landsat 8 path75 captures thermal and visible radiation data encompassing the tip of the North Island (-34.44 degrees) to the bottom of the south Island (-46.66 degrees), capturing much of the Northland, and most of the lower South Island (rows 84, 90, 91 and 92) within a few minutes. Automated scrips were compiled which atmospherically corrected Landsat 8 band 10 thermal infrared data (10.60 - 11.19 micrometers). Conversion from Landsat-scaled radiance (DN) to 32-bit spectral radiance at the sensor aperture ($L(\lambda)$; W m^{-2} sr^{-1} µm^{-1}) was performed:

$$L(\lambda) = G_r \cdot Q_c + B_r \qquad (1)$$

where G_r = rescaled gain (W m^{-2} sr^{-1} µm^{-1}/DN), B_r= rescaled bias (W m^{-2} sr^{-1} µm^{-1}) and Q_c= quantized calibrated pixel value in DN.

Atmospherically corrected water-leaving radiance L_w was calculated according to:

$$L_w = \frac{L_t - L_a}{\varepsilon\tau} - \left(\frac{1}{\varepsilon} - 1\right) L_{sky} \qquad (2)$$

where L_t = at-sensor radiance (W m^{-2} sr^{-1} µm^{-1})
L_a = atmospheric or upwelling radiance emitted by the atmosphere (W m^{-2} sr^{-1} µm^{-1})
ε = emissivity of the water surface
τ = atmospheric transmission
L_{sky} = downwelling or sky radiance reflected from the water surface (W m^{-2} sr^{-1} µm^{-1})

Temperature was then calculated from L_w based on standard formulations specified within the Landsat 8 handbook. An Atmospheric Parameter Calculator (ACPC - using MODTRAN 4.0; NASA) was used to calculate L_a, L_{sky} and τ using National Centres for Environmental Prediction (NCEP) atmospheric profile data including pressure, temperature (*T*) and relative humidity (*RH*) (Barsi et al., 2005). A webscaping script (Python) was called from IDL to automatically retrieve these parameters based on Landsat metadata. Average lake skin surface temperature was then calculated, excluding a 60 m buffer zone from the shoreline. This tool allows estimation of surface temperature to c. ±2 K globally if emissivity is known and the atmosphere is reasonably clear (Barsi et al., 2005). However it has been shown to be capable of accuracy of approximately 1 K if surface measured *T* and *RH* are used within MODTRAN to model transmission, downwelling and upwelling radiance (Allan et al., 2016).

Within the main basin of lakes, Omapere estimated surface water temperature was 20.58 ^{o}C (Fig. 1), and within south island lakes Tekapo, Pukaki and Alexandra (Fig. 2) the estimated surface water temperature ranged from 16.03 ^{o}C in Tekapo to 22.17 ^{o}C in Lake Alexandra. Plumes of colder inflowing waters can be observed in lakes Tekapo and Pukaki (11.67 ^{o}C in Pukaki).

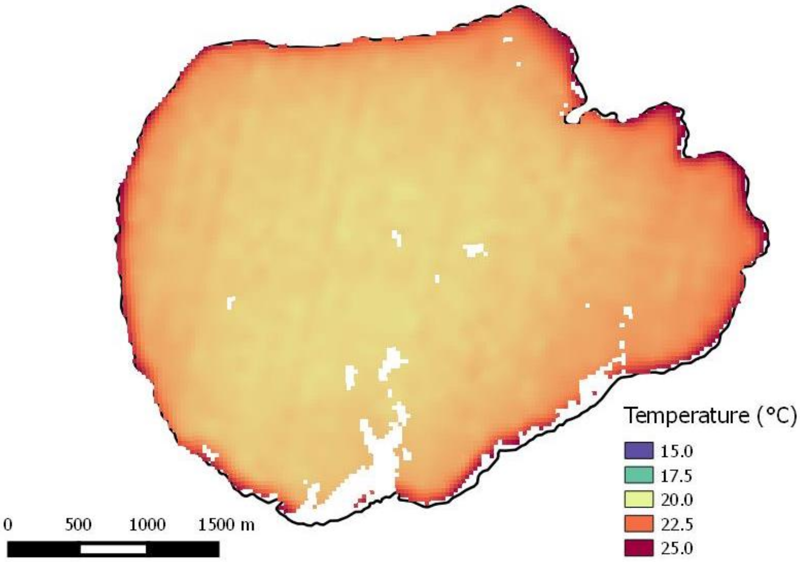

Figure 1. Surface water temperature in Lake Omapere, estimated using Landsat 8 thermal data (band 10), with atmospheric correction parameters generated by the Nasa Atmospheric Correction Parameter calculator (Lat long-35.35, 173.79)

6. Policy and strategy

Climate change is a regionally significant issue because of its potential to have impacts on wellbeing; increased potential for storm damage and weather-related natural hazards, and long-term risks of sea level rise to settlements and infrastructure (Waikato Regional Council, 2013). Climate changing affects the habitat range of animal species and plant creating challenges in managing indigenous biodiversity and biosecurity. In order to mimic the potential adverse effects of climate change-induced weather variability, sea level rise, and indigenous biodiversity, researchers recommended implementation of national adaptation policies to guide river and catchment land use management (Kevin, 2016). Proper actions towards land use management reduces nutrient and sediment loads to lakes and provide greater resilience to storm events, whilst also increasing surveillance, control and eradication efforts for noxious alien freshwater invaders. In addition, there should be an integrated research between policy makers and land use sectors to implement planning and policy measures which protect native biodiversity from the impacts of climate change adaptation (Christie, 2014).

In NZ, integrating climate change threat management is a challenge as the effect of climate change is apparent across all terrestrial and freshwater ecosystems (Waikato Regional Council, 2013); (Christie, 2016). Studies (McGlone & Walker, 2011) revealed that the NZ Department of Conservation (DOC) has gone a step further on the design and application of policy and management strategies through a high-level review of the possible impacts of climate change on native biodiversity. Though the DOC has developed a frame work to manage and monitor the impacts of climate change on native terrestrial biodiversity (Christie, 2014), there is also an indication on the gap and coverage issues. In addition, researches (Christie, 2016) highlighted that the DOC has to give a special consideration on the development of policy strategies and management of freshwater, coastal and alpine ecosystems and certain species as being most vulnerable to the impacts of climate change.

In view of the local and national gaps on ecosystem conservation, Christie (2014) developed a framework to ensure that management and monitoring of climate change impacts is properly integrated into existing DOC research and management systems and processes. According to the author, though researches are carried out on some of the vulnerable ecosystems (McGlone & Walker, 2011), specific research priorities still need to be identified for freshwater and estuarine ecosystems (Jones & Hamilton, 2014).

A review of natural hazard responses to climate change (Environment Waikato, 2008; Christie, 2016) recommends appropriate national climate change adaptation policy and strategies on the specific actions required to avoid or mitigate potential effects. Scientists recommended different approaches to mitigate climate change effects and to integrate specific actions into planning and management activities to increase resilience of freshwater ecosystems, of which Li et al. (2011) made a number of recommendations for local councils and for the nation at large for dealing with climate change. These included: Adopting policies that will accommodate strategies to cope with different thresholds of sea-level rise; managing connectivity between freshwater ecosystems; Integrating climate change projections into biodiversity and biosecurity management, water and land management, and regional planning strategies; enforcing the reduction of non-climate stressors such as nutrient runoff, drainage, sedimentation to off-set the added effects of climate change on existing multiple cumulative stressors, in particular around sensitive wetlands and shallow lakes.

7. Enabling restoration: the policy context in New Zealand

Lake restoration requires an enabling regulatory and social environment. The New Zealand government has recently initiated policies designed to manage diffuse pollution and prevent cumulative degradation of freshwater resources. The National Policy Statement for Freshwater Management (NPS-FM; MfE 2014) is led by the Ministry for the Environment and Ministry for Primary Industries. It was a response to the widespread pressures on, and degradation of freshwater resources identified by the Parliamentary Commissioner for the Environment (PCE 2015), and more generally the articulation of higher expectations for freshwater management in public debate (). For example, earlier trends of agricultural intensification identified in some sectors (e.g., a 160% increase in phosphorus (P) and a 680% increase in nitrogen (N) in the dairy sector from 1996 to 2002) (PCE 2004) have continued, albeit at lower rates from 2000 to 2012 than from 1996 to 2002. Recent (2000 to 2012) agricultural trends include a 5% increase in fertilizer-N, 38% increase in fertilizer-P and 138% increase in livestock densities measured as number of live animals, in sheep equivalents, per hectare of agricultural land. Irrigated land area to support agricultural intensification has also increased rapidly; by 138% from 1990 to 2010, the highest rate of any country in the Organisation for Economic Co-operation and Development (OECD). Irrigation is also being actively supported through investments by the New Zealand Government of NZ $25 million for an Irrigation Acceleration Fund and $400 million by Crown Irrigation Investments Limited as part of a strategy by the Ministry of Primary Industries to double primary industry exports between 2012 and 2025. The investments in irrigation are predicated upon no net degradation of freshwater resources although a recent study (Trolle et al. 2015) related increases in trophic state of one of New Zealand’s most oligotrophic lakes to rapid increases in irrigated area for dairy conversions in a dryland catchment area of the South Island interior. The areas where irrigation is expanding most rapidly are the dry interior of both North and South Islands and lowland areas of the east coast where pressures on water resources have intensified rapidly.

The NPS-FM has two national compulsory values of ‘ecosystem health’ and ‘human health for recreation’. The sixteen regional councils and unitary authorities in New Zealand are directed under the NPS-FM to coordinate community consultative processes which identify suitable values and uses for freshwater within selected areas (freshwater management units) of their regions. Measurable attributes can then be applied to ensure that there is sustainable management to meet the prescribed values and uses of water for each freshwater management unit. The numerical levels of attributes have been aggregated into a National Objectives Framework (NOF) which allocates an attribute into one of four bands (A, B, C or D) ranging from largely un-impacted and in natural or near-reference state (A band), to unacceptable (D band). Under the NPS-FM the latter state activates a policy response in which a plan is required to demonstrate how the freshwater management unit will be improved to move it from a D band to a higher band (i.e., A, B or C). The NPS-FM also uses the NOF to require that there is no net degradation of ecosystem and human health values (i.e., as indicated by a change to a lower band for attributes within a freshwater management unit). The ecosystem health attributes for lakes include proxies for degradation from eutrophication, namely planktonic chlorophyll *a*, total N and total P in surface waters. These attributes are useful in setting restoration goals relating to re-oligotrophication of lake ecosystems and for developing policies to ensure that catchment nutrient loads are appropriate to meet attribute bands.

Two other factors are particularly relevant to supporting the restoration of freshwaters in New Zealand. One of these involves funding mechanisms where Central Government assists regional councils and unitary authorities to restore key freshwater ecosystems, many of which have been lakes: Brunner (West Coast, South Island (SI)), Ellesmere/Te Waihora and Wainono Lagoon (Canterbury, SI), Waituna Lagoon (Southland, SI), Horowhenua (Manawatu-Wanganui Region, North Island (NI)), Taupō (Waikato (NI)), Rotorua Te Arawa Lakes (Bay of Plenty (NI)) and Wairarapa Moana (Greater Wellington (NI)). These lakes are considered to have been affected by legacies of contaminant inputs and past poor management including wastewater inputs, impacts from flood control measures and land management practices which have led to increased trophic state and poor ecological health. The second source of funding support is from settlements between the Crown and Māori for historical breaches by the Crown of the guarantees of access by Māori to natural resources outlined in the Treaty of Waitangi of 1840. The settlements recognise the important role that freshwater resources have for Māori as a source of food and materials (e.g., fibre, building materials), as well as spiritually. A notable settlement case is the 2010 Waikato River Settlement Act between the Crown and Waikato-Tainui and other Māori tribes of the Waikato River. It provides NZ $210 million to support restoration of the Waikato River, including lowland lakes of the Waikato River floodplain (Hamilton et al. 2010) and hydro-dams on the main-stem of the river (Collier et al. 2010).

This description of the policy setting is designed to provide an outline of contentious aspects of current related to recognition of widespread eutrophication of lakes in New Zealand which has been linked to agriculture (Verburg et al. 2010), and recent funding initiatives which concurrently support increased agricultural intensification and lake restoration. New policies (e.g., the NPS-FM) have been designed to arrest and/or support restoration of lakes, and more generally to protect freshwater resources in New Zealand. The NPS-FM has been required to address a failure of existing legislation (the Resource Management Act (1991)) to arrest cumulative degradation arising mostly from diffuse agricultural pollution. Modelling has indicated that it will not be possible for some regional councils and unitary authorities to arrest and halt increases in nutrient loads in freshwater management units under the current trajectory of agricultural intensification (PCE). Meeting the two demands of agricultural growth and freshwater resource protection is reliant upon achieving a level of land and water management that is far beyond what has occurred in contemporary times and historically, and is also likely to also depend on technological advances (e.g., irrigation management, lake geoengineering; MacKay et al. 2014), many of which are at a development stage and have had limited cost-benefit analysis at regional and local levels. Moreover, climate warming is known to exacerbate eutrophication and potentially increase the difficulty to achieve recovery of good ecological status of lakes. Some freshwater management units where attribute bands currently fall above those assigned through the community consultative process, or where there is not an immediate threat of failure to retain the minimum assigned band, are considered to have 'headroom' to allow for agricultural expansion and/or intensification. Such assumptions have generally not built in the dynamic nature of how freshwater systems respond to climatic variations and specifically to climate warming. Therefore while the NPS-FM sets fixed ranges for levels of key attributes of environmental health of lakes (i.e., presently chlorophyll *a*, total P and total N), it is highly likely that arresting lake eutrophication in the presence of climate warming will require an even more advanced level of land and water management than in the absence of warming. Some indication of this is given in Özkundakci et al. (2010) who provide a case study of polymictic Lake Rotorua (North Island) to show how climate warming increases the frequency of occurrence of stratification events, bottom-water anoxia and cyanobacteria blooms. With respect to bottom-water anoxia and cyanobacteria, we demonstrate below expected impacts of climate warming on nutrient levels in bottom waters of lakes and for development of cyanobacteria.

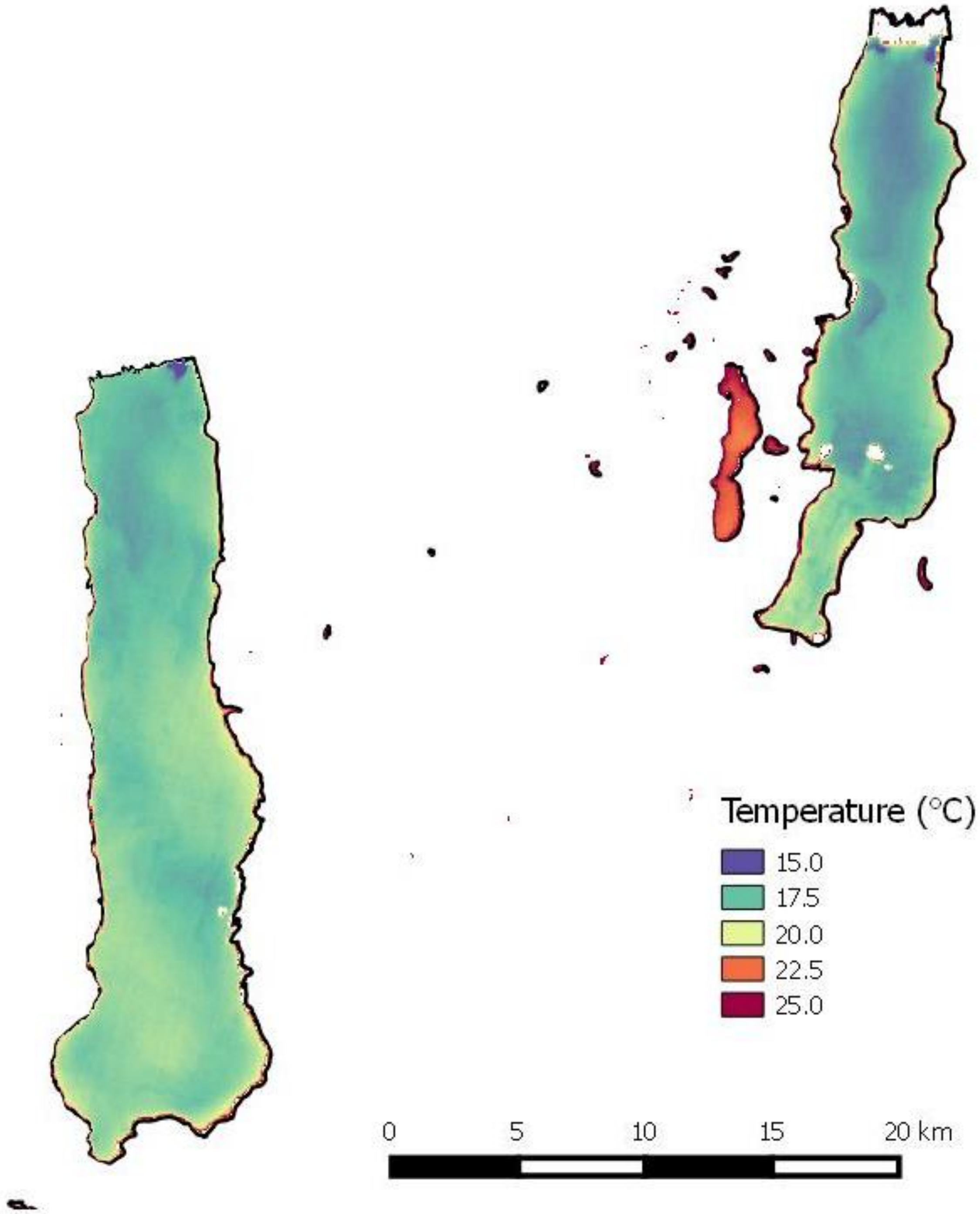

Figure 2. Surface water temperature in Lakes Pukaki (left), Alexandra (middle) and Tekapo (right), estimated using Landsat 8 thermal data (band 10), with atmospheric correction parameters generated by the Nasa Atmospheric Correction Parameter calculator (Lat long-35.35, 173.79).

9. Conclusion

Changes in climate variables such as rainfall and temperature alters the aquatic ecosystem by affecting the growth, reproduction, and physiology of aquatic plants. Research findings have clearly highlighted that climate change has a proportional effect on aquatic ecosystems by altering the production of macroalgae, phytoplanktons, and macrophytes. Climate/bioclimatic envelope models indicated that changes in the distribution and abundance of aquatic vegetation due to climate change is triggered by the increase in lake water temperature and interactive effect of other environmental variables.

To better predict the geographic range and distribution of invasive species on NZ lakes as a result of climate change, it is strongly recommended to use species distribution (bioclimatic envelope) models with reasonable assumptions. Modelling lakes in this regard are based primarily on the use of correlations between observed species distributions and climate variables in order to forecast their future distributions and risk of existence with future climate scenario series.

The effect of climate change has no definite boundary, it affects not only where species are found but also their phenology. Hence addressing the impacts of climate change on freshwater ecosystems requires collective action by local and national government agencies and it remains largely unknown how climate change will influence freshwater ecosystems in NZ. Review of a range of researches described the vulnerability of NZ freshwater ecosystems to climate change impacts and identifies the degree of importance of future researches to underpin an adequate policy response and to inform future management.

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Author Contributions:

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