Climate Change Risk Assessment for Auckland's Marine and Freshwater Ecosystems

Melissa M. Foley and Megan Carbines

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RIMU Research and Evaluation Unit

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Climate Change Risk Assessment series 2019

Climate Change Risk Assessment 2019

As communities across the world set out to plan for climate change mitigation and adaptation, they first seek to understand how climate change will affect their city, region, or country.

The Climate Change Risk Assessment (CCRA) has been produced by Auckland Council's Research and Evaluation Unit (RIMU) in support of the Auckland Climate Action Plan (ACAP) at the request of the Chief Sustainability Office. Its aim is to provide information about the risk and vulnerabilities the Auckland region may face under a changing climate regime, which is already underway. In 2018, national climate change projections were scaled-down to produce a more specific picture of their likely effects within the Auckland region. Based on this, CCRA adopted the Intergovernmental Panel on Climate Change's (IPCC) representative concentration pathway (RCP) 8.5 ("business as usual") scenario as its guiding projection, given the lack of evidence of any meaningful and sustained decreases in emissions that would shift to other projection pathways.

The eight reports in the CCRA consider various components of key risks – that is, hazard, exposure, and vulnerability – across sectors and systems of interest: people (heat vulnerability, climate change and air quality), society (social vulnerability and flooding), and natural environment (terrestrial and marine ecosystems), as well sea level rise at regional and local scales. A summary report has also been produced.

Titles in the Climate Change Risk Assessment series:

An assessment of vulnerability to climate change in Auckland
Fernandez, M. A. and N. E. Golubiewski (2019)

Development of the Auckland Heat Vulnerability Index
Joynt, J. L. R. and N. E. Golubiewski (2019)

Air quality and societal impacts from predicted climate change in Auckland
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Climate change risk assessment for terrestrial species and ecosystems in the Auckland region
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Climate change risk assessment for Auckland's marine and freshwater ecosystems
Foley, M. M. and M. Carbines (2019)

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Auckland's exposure to sea level rise: Part 2 – Local inventory (forthcoming)
Boyle, J., N. E. Golubiewski, K. Balderston and C. Hu (2019)

Summary: *Climate change risks in Auckland*
Auckland Council (2019). Prepared by Arup for Auckland Council

Executive summary

The Climate Change Risk Assessment (CCRA) has been developed in support of the Auckland Climate Action Plan (ACAP). Its aim is to provide information about the risk and vulnerabilities the Auckland region may face under a changing climate regime. This CCRA adopted the Intergovernmental Panel on Climate Change's (IPCC) representative concentration pathway (RCP) 8.5 ("business as usual") scenario as its guiding projection. This report details an assessment of risk for Auckland's aquatic environments informed by published expert surveys and studies both international and from New Zealand.

The NIWA climate change projections for the Auckland region (Pearce et al., 2018) highlight changes that could affect the structure and functioning of aquatic ecosystems, and in turn, affect their ability to provide ecosystem services that we rely on throughout the region. For marine ecosystems, the changes of most concern include increasing air and water temperatures, decreasing ocean pH and nutrient concentrations, alterations to current and wind patterns, and sea level rise. For freshwater ecosystems, increasing air temperature, number of dry days, frequency of extreme rainfall events, as well as decreasing river flows and number of rainy days could all have significant effects. It is important to note that our current understanding of climate change impacts in New Zealand waters is limited by the spatial resolution of available models and there is likely to be regional variations in changes in environmental conditions and ecological impact influenced by local physical and biotic interactions (Law et al., 2017). What is outlined in this report reflects our current state of knowledge applied in a regional context.

In marine ecosystems, intertidal habitats (soft- and hard-bottom), kelp forests, and subtidal rocky reefs are the most sensitive to changing conditions. Marine shellfish are also highly sensitive, mainly due to decreasing pH and increasing extreme rainfall events and water temperature. In freshwater ecosystems, habitats and species are sensitive to increasing extreme rainfall events because they can be scoured or buried due to flooding and additional sediment inputs. Freshwater fish and macroinvertebrates are also particularly sensitive to increasing water temperatures, especially species that are already living close to their maximum thermal threshold.

While climate change impacts alone are enough to drive changes in community structure in aquatic ecosystems, it is important to recognise that these climate-driven changes are occurring within systems that are already heavily affected by other human activities (i.e., altered flow, habitat loss, increased nutrient and sediment discharge). Understanding the ability of species and habitats to adapt to changing conditions is vitally important in the context of recent anthropogenic (human-caused) changes in addition to climate change. In the absence of understanding how multiple stressors cumulatively affect aquatic ecosystems, precautionary and adaptive approaches to decision-making must be used at every step in the process.

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1.0 Introduction

The structure and function of aquatic habitats are tightly linked to changes in environmental conditions, such as temperature, precipitation, and water chemistry (Bornette and Puijalon 2011, Fisher and Likens, 1973, Jackson et al., 2001, McArthuer et al., 2010., Magnuson et al., 1979, Niemi et al., 1990, Dunson and Travis, 1991). Aquatic habitats around the world have been highly impacted by human activities, such as fishing, farming, forestry, and urban development (Airoldi and Beck, 2007, Decamps et al., 1988, Sweeney et al., 2004, Thrush et al., 2008, Wang et al., 2001). These habitats are likely to be further impacted by climate change, affecting the ecological, economic, cultural, and social services they provide (Harley et al., 2006, Hoegh-Guldberg and Bruno, 2010, Mantua et al., 2010, Woodward et al., 2010, Carpenter et al., 1992, Doney et al., 2012).

Predicted changes to environmental conditions in the Auckland region due to climate change were recently outlined for a range of climate change scenarios in a report prepared by NIWA on behalf of Auckland Council (Pearce et al., 2018). These changes in environmental conditions will likely have noticeable impacts on aquatic ecosystems throughout the region. Pearce et al., (2018) provided a high-level overview of potential effects in the marine environment using the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathway (RCP) of 8.5. This scenario is considered the business-as-usual scenario and is used in the absence of any concrete policy change or mitigation measures that would suggest a lower scenario (see Pearce et al., 2018 for full scenario descriptions). Here, we discuss the stressors, risks, and vulnerability of aquatic (marine and freshwater) ecosystems to projected climate change effects, including species and habitats within the Auckland region where possible.

While the NIWA projections illustrate how individual abiotic variables are likely to change over the next century, it is difficult to model how changes in multiple variables (e.g., temperature, extreme storms, and nutrients) will cumulatively affect aquatic ecosystems. In addition, the projected climate-related changes are occurring within the broader context of additional environmental change, such as sedimentation, pollution, disturbance, harvesting and water extraction. Understanding the interplay between climate and other human-induced stressors is paramount to protecting culturally, economically, and ecologically important species (Clark et al., 2016, Halpern et al., 2009).

2.0 Potential climate stressors on aquatic ecosystems

Marine and freshwater ecosystems are vulnerable to a number of climate change-related stressors. For each ecosystem, we review the relevant predictions outlined in the NIWA report (Pearce et al., 2018) and highlight how those changes could directly and indirectly affect ecologically and economically important components of marine and freshwater ecosystems in the Auckland region.

2.1 Marine ecosystems

There are myriad climate change-associated environmental changes that could affect marine ecosystems, including changes in water temperature, chemistry, and circulation. Law et al., (2016, 2017) developed climate change projections for waters surrounding New Zealand using a global Earth System Model which was scaled down to New Zealand because regional models that incorporate hydrodynamics and biogeochemistry do not yet exist for the Southwest Pacific. Due to this downscaling, the resolution of the marine projections is lower than the terrestrial projections in the NIWA report (Pearce et al., 2018) and are at the scale of New Zealand rather than the Auckland region. In addition, the mid-century scenarios in Law et al., (2016) are centred on 2050 and end-of-century projections on 2090 instead of 2060 and 2100 that were used in the NIWA report. In spite of these differences, the Law et al., (2016) projections for climate-related changes in marine ecosystems were directly incorporated into the NIWA report (Pearce et al., 2018).

Law et al., (2016) modelled changes in sea surface temperature (SST), ocean acidification, nutrient concentration, and sea level rise for the waters surrounding New Zealand for mid- and end-of-century timeframes using the RCP 8.5 scenario (Table 1).

- Water temperatures are predicted to increase by ~1^{o}C by mid-century (2050) and ~2.5^{o}C by the end of the century (2090). Increased water temperature can affect growth rates and species survival, and can result in a shift of species distributions, favouring warm-water adapted species (Cheung et al., 2009, Molinos et al., 2016).
- The ocean is expected to continue to acidify, with pH decreasing 0.23 pH units by the end of the century, a 116 per cent increase in acidifying hydrogen ions (Law et al., 2016). This fundamental change in ocean water chemistry affects the condition, reproduction, physiology and survival of marine species, particularly those that have hard, carbonate structures, including shellfish, corals, and plankton (Fabry et al., 2008, Frost 2019, Kroeker et al., 2013, Law et al., 2018).

- Concentrations of the macronutrients nitrate and phosphate, which are necessary for primary production, are projected to decrease by 9.2 and 7.8 per cent respectively, by the end of the century. Lower nutrient concentrations could result in fewer primary producers, such as phytoplankton and macroalgae which form the base of the marine food web and underpin the stability of marine ecosystems (Chavez et al., 2011).
- Sea level rise is predicted to increase an additional 0.5 metres by 2050 and 1 metre by 2090 above a 1986-2005 baseline mean sea level. Increased water height and coastal inundation will decrease the viability of some marine habitats (Hoegh-Guldberg and Bruno, 2010), particularly intertidal and mangrove habitats at the edge of the coastal margin (Swales et al., 2008; McDiarmid et al., 2012).
- Changes to rainfall and storm patterns may cause declines in water quality due to increased sediment and other contaminant/nutrient runoff (Najjar et al., 2000).

Table 1. Projected changes to marine conditions by mid- (2050 to 2060) and end-of-century (2090 to 2100) timelines for representation concentration pathway (RCP) 8.5 (Law et al., 2016; Pearce et al., 2018).

Variable	Mid-century	End-of-century
Water temperature	+1^{o}C	+2.5^{o}C
Ocean pH	-0.16	-0.33
Nitrate	No change	-0.5mmol/m^{3}
Phosphate	No change	-0.04mmol/m^{3}
Sea level	+0.5m	+1.0m

These predicted changes to marine conditions must be considered in conjunction with natural variability. There are three long-term climate cycles that affect sea surface temperature, wind forcing, and oceanic currents around New Zealand: El Niño Southern Oscillation (ENSO), Interdecadal Pacific Oscillation, and the Southern Annular Mode. The combination of climate-driven variability and natural variability may result in fluctuations of conditions that exceed the predictions of the NIWA model. For instance, during the positive phase of the ENSO (i.e., La Niña conditions), sea surface temperatures can be 0.8^{o}C warmer than average (Shears and Bowen, 2017), which may increase SST anomalies beyond the average conditions predicted by the models. In addition, there are likely to be regional differences that are not yet accounted for at the spatial scale of currently available models.

2.2 Freshwater ecosystems

Climate change has the potential to significantly alter freshwater ecosystems, although the effects are likely to differ somewhat from marine ecosystems due to the different physical and biological processes in freshwater habitats. The effects of climate change- and human activity-induced (e.g., water consumption, contaminant discharge) changes to these systems could interact synergistically, leading to a cumulative effect that is greater than the sum of all effects (Jackson et al., 2015; Piggott et al., 2015). In addition, freshwater systems have less of a buffer against some climate effects, especially increases in water temperature because the volume of water is typically small, increasing temperature variability and warming.

The NIWA-modelled changes in air temperature, rainfall frequency, rainfall intensity, and stream flow are of concern for Auckland's freshwater ecosystems (Table 2). In summary:

- Mean air temperature is expected to rise nearly 4^{o}C and the number of hot days (> 25^{o}C) is expected to increase five-fold by 2110 (from 15 days to 70 days). Warming air temperatures result in an increase in stream temperature, particularly in places where there is little riparian vegetation to shade the stream (Kaushal et al., 2010).
- Precipitation is predicted to decrease across the Auckland region, increasing the number of dry days (< 1mm rain) and decreasing the number of rain days (> 1mm rain). Less rain will likely result in a decrease in mean annual stream flow throughout Auckland, reducing the amount of in-water stream habitat available for fish and macroinvertebrates.
- Heavy rain days (> 25mm rain) are predicted to increase by up to five days by 2040. Heavy rain events result in higher mean annual flood flows, increased sediment runoff from the land, stream bank erosion, and stream habitat scouring despite lower baseflow from an overall reduction in rainfall (Poff et al., 1997, Power et al., 1995).
- Annual mean wind speed and the number of windy days (> 10m/s) have significantly decreased across the region since 1966 and are projected to continue to decrease until the next century. Reduced wind speed will affect mixing dynamics in the surface ocean and lakes, altering the physical and chemical conditions of the water column.

Table 2. Projected climatic changes for mid- and end-of-century timelines using RCP 8.5 models that could affect freshwater habitats and species (Pearce et al., 2018).
Projected climatic changes for mid- and end-of-century timelines using RCP 8.5 models that could affect freshwater habitats and species (Pearce et al., 2018).

Variable	2040	2090	2110
Mean air temperature	+ > 0.8°C	+ > 2.7°C	+ > 3.0°C
# of hot days (>25°C)	+15 to 20 days	+50 to 60 days	+ > 70 days
Change in # of dry days (< 1mm)	+3 to 9 days	+12 to 21 days	+18 to 21 days
Change in # of rain days (> 1mm)	-5 to -10 days	-10 to -20 days	-10 to -20 days
Change in # of heavy rain days (> 25mm)	0 to +5 days	0 to +5 days	0 to +5 days
Mean annual low flow	-40% to +20%	0 to -80%	N/A
Mean annual flood	-20% to +40%	0 to +80%	N/A
# of windy days (> 10m/s)	0 to -2	-2 to -4	-3 to -4

3.0 Risk assessment

Risk is defined by the IPCC as the likelihood of an event occurring combined with the impacts of the event (IPCC, 2014). From a climate change perspective, risk is the probability of being exposed to an altered climatic condition and the sensitivity of a species or habitat to those conditions (Figure 1). The vulnerability of a species or habitat to climate change – or the likelihood of negative effects – is a combination of risk, as well as the adaptive capacity of the species or habitat to changing conditions (Figure 2) (ACG, 2005, IPCC, 2014). For example, species that can migrate may have higher adaptive capacity to climate change than sessile species or ones that are reliant on specific habitat types and thus are less vulnerable to climate change. As well as geographical range shifts, research is also showing the potential for local physiological acclimatisation or genetic adaptation to changing conditions (Kelly and Hofmann 2013). However further New Zealand studies, both of species response and regional scale changes in environmental conditions, are required to be able to account for this adaptation in assessing risk for New Zealand species or the Auckland region.

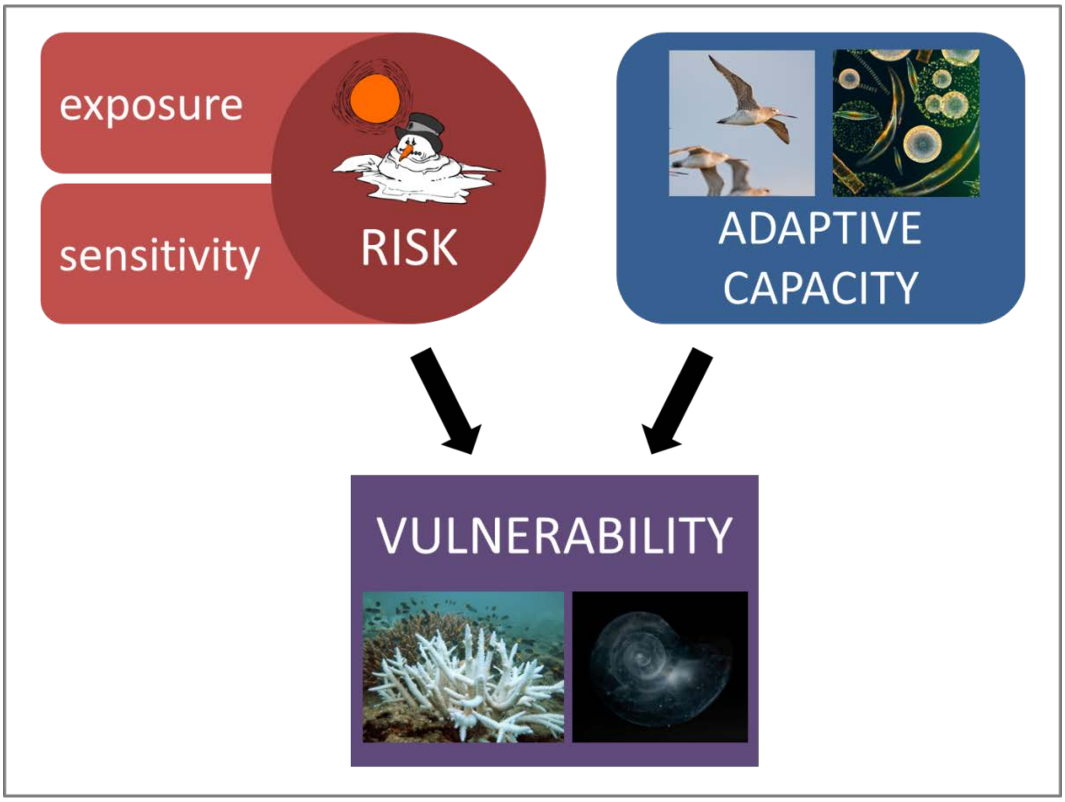

Figure 1. Relationship between risk (probability of exposure + sensitivity to conditions), adaptive capacity (e.g., ability to migrate or adapt to new conditions), and vulnerability (i.e., probability of negative effects).

To classify the sensitivity of aquatic species and habitats in the Auckland region to the potential climate change stressors outlined in Section 2, we used the above mentioned published expert opinion surveys, along with climate-specific studies for marine and freshwater species and habitats. We then compared these data to the projections generated using RCP 8.5 scenario. The "high," "medium," and "low" categories are consistent with the categories used by Teck et al., (2010) to assign level of sensitivity to climate change factors for different marine species and habitats. Table 3 presents the assessed sensitivity of seven marine and two freshwater habitats in the Auckland region as well as two ecologically, economically, and/or culturally important species groups each from marine (shellfish and fish) and freshwater ecosystems (fish and macroinvertebrates). While the NIWA projections provided a range of predicted change, we used the average projections for assigning sensitivity. This is a more conservative approach for assessing sensitivity than using the maximum potential change. We recognize this approach does not account for variability in future conditions but provides a robust estimate of expected change by averaging across multiple model outputs. In reality, conditions are likely to be highly variable and the frequency, magnitude, and duration of extreme events are likely to be more important than average conditions in determining the sensitivity of aquatic ecosystems to climate change (Katz and Brown, 1992, Miller et al., 2011). Variable conditions and extreme events, however, are much more difficult to model (Meehl et al., 2000).

Table 3. Sensitivity matrix for key aquatic habitats and species found in the Auckland region to the direct effects of climate change.

Habitat/species	Water temperature	Extreme rainfall	Nutrients	Ocean acidification	Sea level rise	Water circulation
Intertidal mud flats	High	High	Low	Moderate	High	Moderate
Intertidal rocky reef	High	High	Moderate	High	High	Moderate
Mangroves	Low	Low	Low	Low	High	Low
Kelp forests	High	Moderate	Moderate	Moderate	Moderate	High
Seagrass	Moderate	Moderate	Low	Low	Moderate	High
Subtidal rocky reef	High	Moderate	Moderate	High	Low	Moderate
Subtidal soft bottom	Moderate	High	Low	Low	Low	Low
Freshwater hard bottom	Low	High	Moderate			
Freshwater soft bottom	Low	High	Moderate			
Marine shellfish	Moderate	High	Low	High	Moderate	Low
Marine fish	Moderate	Low	Low	Moderate	Low	Low
Freshwater fish	High	Low	Low			
Freshwater invertebrates	Moderate	High	Low			

3.1 Increased water temperature

Sea surface temperatures around New Zealand are projected to increase by an average 2.5°C by 2090 under the RPC 8.5. Water temperature of the surface ocean has already increased by 0.2°C per decade since 1946 for the western Tasman Sea and 0.1°C per decade since 1953 at the Portobello Marine Lab near Dunedin (Shears and Bowen, 2017). There has been no significant warming trend in water temperature in north eastern New Zealand (measured at Leigh Marine Lab) since 1968, but water temperature was highly variable depending on the phase of longer-term oceanic cycles, particularly ENSO (Shears and Bowen, 2017). Extreme ocean warming events – or marine heatwaves (Hobday et al., 2016) – are becoming increasingly common (Oliver et al., 2018), including in the Tasman Sea where anomalous temperatures 1.5 to 3°C above average were recorded in 2015/2016 (Oliver et al., 2017) and in 2017/2018 (ABM and NIWA, 2018).

Increased water temperature affects organisms on multiple levels from behaviour to metabolism and survival. Organisms living close to their thermal tolerance will be disproportionately affected by increased temperatures (Somero, 2002). Intertidal mud flats and rocky reefs, along with kelp forest and subtidal rocky reefs are highly sensitive to increased water temperatures (Table 3). Many species in these habitats are already close to their thermal limit and are sensitive to temperature increases, including kelp species (Filbee-Dexter et al., 2016, Schiel et al., 2004) and cold water corals (Anderson et al., 2015). In some cases, increasing water temperatures can alter entire food webs by disrupting the balance between producers, primary consumers, and secondary consumers (Vergés et al., 2016). Increasing temperature will likely result in the immigration of sub-tropical marine species (Doney et al., 2012) and could result in increased zoonotic disease transmission and lowered immunity to infection (Harvell et al., 2002, Frost 2019, Law et al., 2018, Poulin and Mouritsen 2006).

Increased water temperature will likely drive marked change in freshwater habitats (Woodward et al., 2010). While the NIWA report does not provide projections for changes to stream temperatures, an increase in mean air temperature of 3.3°C by 2110 (under RCP 8.5) will result in increases to stream temperature, particularly in locations where there is little riparian vegetation to shade the stream. The relationship between air temperature increase and water temperature increase is not 1:1 or linear in all systems, For a majority of temperate streams evaluated by Morrill et al., (2005), water temperature increased 0.6 to 0.8°C for every 1°C increase in air temperature. For urban, shallow, unshaded, and turbid streams (such as those common in Auckland), increases in water temperature could keep pace with increases in air temperature (Mohseni and Stefan, 1999).

As in marine habitats, increased water temperature in freshwater habitats can affect species in a range of ways (Death et al., 2016). For aquatic plants, higher stream temperature could result in higher growth rates (Friberg et al., 2009), including excess or nuisance growth of some species. In contrast, large animal species high in the food web are likely to be disproportionately negatively affected by increased water temperature (Petchey et al., 1999). Macroinvertebrates are also sensitive to increased water temperatures (Maxted et al., 2005). Quinn et al., (1994) demonstrated that lethal temperatures for 12 NZ macroinvertebrate taxa ranged from 26-32°C. Olsen et al., (2012) developed thermal criteria based on the response of nine macroinvertebrates to increased temperature. Upland streams less than 20°C and lowland streams less than 25°C would be suitable for all species, including the most sensitive. Indirect effects of altered temperature on NZ macroinvertebrates are likely on juvenile stages, from changes in periphyton diet as biomass and/or algal composition shifts in line with changes to stream environment from climate change (e.g., Clapcott and Goodwin, 2014).

Whilst fish species are generally more motile than macroinvertebrates, a combination of habitat fragmentation and complex migratory life-cycles amongst native species are likely to present considerable barriers to avoidance of thermal extremes in streams (Zwick, 1992). In the Auckland region, the most sensitive fish species to warming are expected to be adult banded kokopu, koaro, and common smelt (Olsen et al., 2012). Lethal temperatures for these species were 28.5^{o}C, 27^{o}C, and 28.3^{o}C, respectively (Main, 1998, Richardson et al., 1994). However, prolonged exposure to warm water greatly reduced the thermal tolerability of these species (i.e., reduced resilience to brief or maximum temperature events). For example, the lethal temperature for common smelt during prolonged periods was 26^{o}C compared to 28^{o}C for short-term exposure (Richardson and West, 1998). Stream temperature data across the region suggests that some streams reach at least 22^{o}C during the summer (Buckthought and Neale, 2016). Whilst that suggests that some species would experience temperatures near their lethal limit by 2110, particularly during autumn when maximum temperatures are projected to increase by more than 4^{o}C in some areas, there are likely sublethal effects that will occur, including changes in behaviour, metabolism, and diet as stream temperatures increase.

Our collective understanding of the effects on lake ecosystems is less robust than for streams, but it is likely that lakes will experience altered thermal stratification due to increased mean air temperatures and changes in windiness (i.e., strength, duration and direction of wind). Changes in the depth and duration of thermal stratification are likely to alter the intensity of low oxygen conditions in benthic habitats (Hamilton et al., 2013). This could support greater periodic nutrient release during overturn events, which could shift primary producers from high-value macrophytes to free-floating algae or phytoplankton. Increased frequency of El Nino-Southern Oscillation (ENSO) events could also change lake mixing dynamics by increasing the mixed depths (through greater wave activity) of the lake, which could disrupt the stratification of the water column.

3.2 Increased extreme rainfall events and dry days

Extreme rainfall events are predicted to increase in the Auckland region under RCP 8.5. More frequent rapid, heavy rainfall events are likely to increase freshwater input to coastal waters, causing temporary reductions in water column salinity in localised areas. These extreme events are also likely to increase the frequency of landslides and streambank erosion, increasing the sediment delivery to estuaries and the open coast. Community composition in intertidal and subtidal habitats are likely to be significantly degraded by increased sediment delivery and sediment deposition (Airoldi, 2003, Death et al., 2016, Holland et al., 1987).

Extreme rainfall events have the potential to fundamentally change freshwater habitats by altering community composition through altered hydrological and chemical stress, and indirectly by reduced habitat availability and changes in the food web. The average number of heavy rain days is expected to increase by up to five days (from 7.5 days at the Auckland Airport) by 2040, and the frequency of consecutive heavy rain days (>40mm) is also predicted to increase in the Waitakere and Hunua Ranges (Pearce et al., 2018). Changes in the timing and intensity of rainfall will alter hydrodynamic processes, including stream flow, channel erosion, and runoff of sediment and nutrients (Poff, 2002, Ryberg et al., 2012). Mean annual flood discharge is predicted to increase across the whole region due to more frequent extreme rain events, increasing rates of bankside collapse as shear stress increases proportionate to peak discharge (Pearce et al., 2018). These flood discharges also alter flow dynamics that affect fish (Crow et al., 2013) and macroinvertebrates (Booker et al., 2015), as well as scour freshwater habitats, displacing primary producers and macroinvertebrates (Scrimgeour and Winterbourn, 1989), altering stream community dynamics (Power et al., 1996) and possibly ecosystem services. Extreme rainfall events are also likely to increase turbidity, which is detrimental to many native New Zealand freshwater fish species, particularly migratory behaviour and recruitment of juveniles into upstream habitat (Rowe et al., 2000).

On the other end of the spectrum, mean annual low flow is projected to decrease across the whole region as a result of fewer rain days and higher evapotranspiration (Table 2). In addition, the number of rainy days is projected to decrease from 30 to 20 days across the region, particularly in spring (Pearce et al., 2018). Lower flows could result in higher nutrient and pollutant concentrations, as well as higher water temperatures and fewer thermal refuges (e.g., river pools) for fish and macroinvertebrates (Whitehead et al., 2009). Low flows also reduce connectivity across the landscape including extent of wetlands (Crook et al., 2015) and the amount of suitable habitat for fish and macroinvertebrates (Mantua et al., 2010), particularly for fish that need access to the stream bank for spawning (i.e., īnanga whitebait) (Hickford and Schiel, 2011).

Lakes are also likely to experience greater sediment and nutrient loading from runoff during extreme events. Potential effects of increased inputs include greater loss of macrophytes in shallow lakes due to increased competition with phytoplankton (from increased nutrient availability) and reduced light availability (from increased sediment delivery and resuspension) (Hamilton et al., 2013). Fewer rain days and lower mean annual flows could result in many lakes experiencing greater variability in water level and complex changes to residence time, which affect nutrient cycling, productivity, habitat availability, and biodiversity.

3.3 Changing macronutrient conditions

Primary productivity in aquatic ecosystems is typically limited by concentrations of nitrate or phosphate (Elser et al., 2007, Harrison et al., 1990, Pennock and Sharp, 1994). While excess nutrients can result in algal blooms and oxygen depleted waters (Rabalais et al., 2010), limited nutrients can hinder primary production and fundamentally alter community composition and food webs within fresh and coastal waters (Hecky and Kilham, 1988, Hutchins and Bruland, 1998). Primary producers form the base of the aquatic food web and are critical to the stability and resilience of these ecosystems (Likens, 1975, Pauly and Christensen, 1995, Power, 1992).

The NIWA projections estimate that nitrate and phosphate concentrations in marine waters will decline by 9.2 and 7.8 per cent respectively, by the end of the century. These changes are likely due to a combination of increasing water temperatures and altered circulation patterns (Polovina et al., 2011). Projections in mean wind speed predicted for the Auckland region suggest that wind speed could decrease by three per cent by the end of the century, with a seven per cent decrease in summer and five per cent decrease in autumn. With fewer windy days to mix the upper layer of the ocean, the water column could become more stratified – especially in combination with warming ocean temperatures – which will likely result in fewer nutrients cycled into surface waters from deep water. Kelp forest and seagrass habitats are highly susceptible to these altered circulation patterns because they rely on nutrients being continually replenished in the surface ocean in order to grow (Dayton et al., 1999, Hillman et al., 1989).

Moderate impacts of reduced nutrients are expected in intertidal, subtidal, and kelp forest habitats due to changes in primary productivity, which could indirectly alter interaction and food webs in these communities (Menge et al., 1999). New Zealand fisheries depend on the high levels of primary productivity and may be negatively affected by a reduction in nutrient concentrations (Leathwick et al., 2006).

The NIWA projections are at a relatively course scale and it is possible that coastal embayments and estuaries in particular may see an increase in nutrients due to increased runoff from land. For example, the Firth of Thames is particularly sensitive to nutrient enrichment and sediment loading (Zeldis et al., 2015). Not only does this enrichment have potential to affect these coastal ecosystems, but increased freshwater/nutrient input and phytoplankton blooms also have a strong influence on changes in pH (Law et al., 2017, Frost 2019). This again emphasises the potential for local and biotic interactions to alter outcomes from large scale projections.

In freshwater habitats, nutrient concentrations are expected to increase due to changes in rain frequency and intensity (see section 3.2) (Bouraoui et al., 2002). With lower mean annual flows, nutrients entering streams will be less diluted, resulting in higher nutrient concentrations (Conlan et al., 2007) and subsequent increases in primary productivity and decreases in dissolved oxygen concentration (Woodward et al., 2010). More extreme rainfall events could result in increased loads of nutrients due to increased land runoff (Whitehead et al., 2009), as well as the potential for increased wastewater overflow events into streams and lakes.

3.4 Ocean acidification (decreased pH)

Ocean acidification (OA) is often referred to as “the other CO_2 problem” (Doney et al., 2009). As atmospheric carbon dioxide (CO_2) concentration has increased, the oceans have acted as a buffer by absorbing an increasing amount of CO_2. This has altered the carbonate chemistry in the ocean, resulting in an excess of hydrogen ions (H^+) which decrease the pH of the water column by increasing its acidity. Since the beginning of the industrial revolution (early 1800s), the pH of the world’s ocean has decreased by 0.1 pH units, a 30 per cent increase in hydrogen ions (Raven et al., 2005).

Organisms with hard shells – shellfish, crabs, and corals, for example – are the most sensitive to changes in pH. As the pH of seawater declines, it becomes more difficult for organisms to form shells or exoskeletons, particularly during the larval stage. Under extreme OA conditions, shells do not form properly, and growth rates, metabolism, and reproduction can also be negatively affected (Doney et al., 2009). Other studies have shown that ocean noise increases under OA (Hester et al., 2008). Many larval fish use sound cues to choose appropriate nursery habitats (Simpson et al., 2011) and additional noise could result in the loss of homing ability for some fish species (Bignami et al., 2013).

There are thousands of species of shelled organisms in New Zealand and Auckland that play an important role in maintaining ecosystem health and diversity. As a result, studies on the effects of climate change in the marine environment have focussed on OA. Species-specific research studies on New Zealand molluscs have found significant impacts of OA on larval formation, survival, and shell formation of green lipped mussels (kuku) and pāua (Cunningham et al., 2016). The intertidal horn snail (koeti), which is very common on sand and mud intertidal flats throughout estuaries and harbours of the Auckland region, has also shown increased mortality and decreased shell growth with decreased pH (MacLeod, 2015, MacLeod and Poulin, 2015a, 2015b MacLeod and Poulin, 2016a, 2016b). Frost (Frost, 2014) also found significant effects of reduced pH waters on the early life stages of two types of echinoderms, including kina. Frost (2019) found that kina (*Evechinus chloroticus*) were inherently sensitive to small changes in pH and that projected changes in pH could alter population dynamics and hence the subtidal ecosystem.

A recent review of the potential impact of changes in the carbonate system and OA on New Zealand species (Law et al., 2018) further documented the sensitivity of calcifying organisms, particularly early life-history stages, to low pH. This study assessed the sensitivity to OA as medium to high for echinoderms, medium for cold water corals, low to medium for macroalgae and phytoplankton, and low for bacteria. Sensitivity to OA is currently unknown for bryozoa, sponges (but see Bates and Bell, 2018), crustaceans, fish, and higher trophic levels (e.g., sea birds) in New Zealand, but international studies have documented the direct and indirect negative effects of OA on many of these species (Cattano et al., 2018, Lim and Harley, 2018, Marshall et al., 2017, Swezey et al., 2017a). Sensitivity to OA appears to increase with trophic level, possibly due to a loss of prey species affected by altered pH (Guinotte and Fabry, 2008). In addition, interactive effects between OA, warming, pollution, and other stressors may alter the effects of OA on marine ecosystems (Kroeker et al., 2013, Swezey et al., 2017b). Changes in pH can alter the transmission success of parasites and diseases (Harland et al., 2015). Increased parasite loadings may also alter the response to climate change stressors such as increased pH (Law et al., 2018, MacLeod and Poulin 2015a, 2015b, MacLeod and Poulin 2016a, 2016b) highlighting the complexity of biotic interactions influencing climate change impacts.

3.5 Rising sea level

Sea level rise (SLR) will have the greatest impact on coastal habitats that sit at the land-sea margin and on marine species that rely on exposure to air throughout the tidal cycle. Intertidal and mangrove habitats are particularly susceptible to SLR because many in the Auckland region have little room to migrate up the shore due to coastal development or steep coastlines (Swales et al., 2008; Lundquist et al., 2011), a condition often referred to as “coastal squeeze”. In addition, if SLR exceeds the rate of sediment deposition, suitable habitat may not be available even if the shoreline is undeveloped (Swales et al., 2008). Impacts of sea level rise on coastal ecosystems are assessed in more detail in Bishop and Landers (2019).

4.0 Conclusion

Aquatic ecosystems are highly susceptible to many of the predicted effects of climate change outlined in the NIWA report for the Auckland region (Pearce et al., 2018). Changes in air temperature, water temperature, storm intensity, nutrient availability, ocean acidification, ocean circulation, and sea level rise could affect habitats, key species and ecological processes in freshwater and marine ecosystems. Any effects of climate change are likely to be made more complex across the Auckland region through interactions with other human-induced stressors (i.e., multiple stressor effects).

Law et al., (2018) emphasise the need to consider regional variation in climate change response in management decisions. In order to help inform the development of a climate action plan for the Auckland region and future management decisions, future work should focus on assessing how multiple stressors are likely to interact in aquatic ecosystems. To accomplish this, there are four pieces of information that are essential: (1) the species and habitats that are present in the Auckland region; (2) their exposure to climatic stressors; (3) their sensitivity to individual stressors; and (4) their overall vulnerability. Currently assessment of regional effects is limited by the low spatial resolution of available models and evaluating the risk and vulnerability of species and habitats to climate change will be an iterative process as models improve and our scientific understanding increases. In addition to Auckland Council's long-term state of the environment monitoring data that is proving invaluable in understanding ecosystem response to changing climate conditions (Hewitt and Thrush, 2010), Auckland Council will be undertaking marine habitat surveys over the next 10 years to identify the location and distribution of important habitats and species. This survey work will increase our ability to detect climate-related changes in key habitats and protect rare, sensitive, and important habitats in Auckland's marine ecosystems. There are also a number of research projects in progress around the country that will help to fill these gaps in our understanding.

Understanding the risk of Auckland's environmental capital to the combination of climate change and human-use stressors is equally important to understanding the risks of climate change alone. The health of Auckland's aquatic ecosystems is fundamental to the wellbeing of Auckland communities. Intact aquatic ecosystems provide a range of ecosystem services that we rely on every day, including flood protection, oxygen production, climate regulation, and food and clean water provision (Dymond, 2013, Townsend et al., 2011). While Auckland may have limited options to prevent global climate changes, local actions, such as reducing anthropogenic (human-caused) stressors and disturbance can increase the health of ecosystems. Healthy ecosystems are likely to be more resilient and have higher adaptive capacity to climate change effects. In the absence of understanding how climate and human activities cumulatively affect ecosystem structure, functioning, and ecosystem service provisioning, it is critical that precautionary and adaptive management principles be used in decision-making at every level (Kriebel et al., 2001, Tompkins and Adger, 2004) and that opportunities to restore or enhance natural ecosystems are explored.

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