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Climate resilience assessment of Northland's freshwater ecosystems


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Climate resilience assessment of Northland's freshwater ecosystems

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Prepared for Northland Regional Council

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Executive summary

This report assesses how climate change is likely to affect Northland's freshwater ecosystems and values, and how those effects may interact with existing pressures such as land use, sedimentation and water abstraction. The assessment supports Northland Regional Council (NRC) in addressing priority actions in the Te Tai Tokerau Climate Adaptation Strategy; these include improving understanding of climate change impacts on biodiversity and ecosystem function, and developing monitoring and response programmes. The assessment also aids NRC in meeting its obligations under the National Policy Statement for Freshwater Management 2020 to account for the reasonably foreseeable impacts of climate change when setting objectives, limits and monitoring programmes.

Across all scenarios considered, Northland is projected to become warmer and drier overall, as well as more climatically variable, with:

- substantial increases in the frequency of hot days
- reduced annual rainfall but more intense rainfall events
- longer and more frequent droughts
- increased fire risk.

These changes are expected to intensify from mid-century to end of century, particularly under higher-emissions scenarios.

Climate change will increasingly influence freshwater outcomes across all ecosystem types, with risk generally increasing over time and with more extreme climate scenarios. Several freshwater values emerge as consistently vulnerable:

- aquatic life, particularly native fish and macroinvertebrates, due to warming, low flows and habitat degradation
- lake water quality, driven by stronger stratification, internal nutrient loading and increased cyanobacteria blooms
- wetland extent and condition, especially where wetlands depend on shallow groundwater or seasonal rainfall
- threatened and taonga species, which face compound risks from temperature, flow disruption and habitat loss, increasing the likelihood of local extinctions.

These risks reflect direct links between climate stressors and biodiversity outcomes. Warming reduces thermal habitat suitability, sediment degrades habitat structure and spawning conditions, and reduced flows limit habitat availability and connectivity. These pathways highlight the importance of managing freshwater systems in ways that explicitly support biodiversity alongside water quality and quantity outcomes.

Sediment emerges as a dominant climate-exacerbated pressure across all freshwater environments, with projected increases in sediment loads likely to amplify existing water-quality and habitat issues, particularly during extreme rainfall events. Management actions that reduce sediment inputs – such as erosion control, riparian planting and wetland buffering – offer clear co-benefits for freshwater ecosystem health and biodiversity.

Wetlands and dune lakes are identified as highly climate-sensitive systems due to their dependence on water levels and susceptibility to threshold responses such as drying or persistent stratification. These ecosystems also support distinctive and often threatened biodiversity.

Their protection and restoration provide important hydrological buffering functions and will be critical for maintaining ecosystem resilience under climate change. Similarly, rivers and streams are highly sensitive to sediment, temperature, depleted dissolved oxygen and drying.

A key limitation of the current assessment is the absence of hydrological projections, including changes in river flows, flood frequency and groundwater recharge. This constrains confidence in predicting the magnitude and timing of impacts on flow-dependent values and highlights the importance of improving hydrological understanding to support future decision-making.

Overall, climate change is likely to:

- reduce the resilience of many freshwater systems to existing pressures
- increase the risk of crossing ecological thresholds for all ecosystems, but especially in lakes and wetlands
- exacerbate stressors in rivers through increased sediment loads, elevated temperatures and more frequent low-flow conditions
- complicate limit-setting and trend interpretation where climate signals interact with land-use effects.

In the medium term, targeted management actions are likely to maintain many freshwater values; however, by end of century, climate pressures are expected to increasingly outweigh management gains in the absence of substantial adaptation. This reinforces the need for precautionary, adaptive and place-based management, rather than reliance on historical baselines alone.

Priority actions for NRC include:

1. Integrate climate considerations explicitly into natural resource management and spatial planning, focusing first on high-confidence, high-risk values.
2. Invest in hydrological and groundwater modelling as a foundation for climate-resilient freshwater management.
3. Advocating for completion of downscaled hydrological predictions for Northland, to align with existing air temperature and rainfall projections.
4. Ensuring a long-term commitment to high-frequency monitoring for detecting climate signals and supporting attribution of change, including wetlands, lakes and river reference sites.
5. Use expert panel and scenario-testing approaches to explore interactions between climate change, management actions and land-use pathways.
6. Partner with iwi and hapū to incorporate mātauranga Māori indicators of freshwater change, resilience and well-being.

1. Introduction

Climate change is already influencing the natural environment across Aotearoa New Zealand, including freshwater systems. Increasing temperatures and shifting rainfall patterns are altering freshwater availability, affecting aquatic ecosystems and increasing the frequency and duration of natural hazards. To conserve ecosystems and maintain ecosystem values under these changing conditions, there is a need to understand how ecosystems and species are likely to respond to climate change so that management actions can be targeted and limited resources prioritised effectively. Work to assess the climate change vulnerability and resilience of species and ecosystems in Aotearoa New Zealand is ongoing. Examples include climate change risk assessments for Auckland's freshwater and marine environments (Foley and Carbines 2019), species-level vulnerability assessments for selected taonga freshwater species (Egan et al. 2020) and terrestrial taxa (Brumby et al. 2025). Other regions have also used expert panel processes to guide how climate change is accounted for in regional plans (e.g. Bay of Plenty: Carter et al. 2023; Gisborne: Ausseil et al. 2025).

In Northland, recent studies show that climate-related attributes such as water temperature, river flow, flood magnitude and lake water level are significant drivers of freshwater ecosystem condition. For example, water temperature and river flow have been identified as important drivers of periphyton growth and macroinvertebrate community composition in Northland rivers (Graham and Greenwood 2023; Kilroy and Snelder 2024). Modelling by Neverman et al. (2023) indicates that, among all regions in Aotearoa New Zealand, Northland is projected to experience the largest increase in sediment loads delivered to coastal receiving environments (49–233%) under all climate scenarios based on the International Panel on Climate Change (IPCC) Fifth Assessment Report projections (IPCC 2014). Sediment has also been identified as a major driver of macroinvertebrate community patterns in the region (Graham and Greenwood 2023). For Northland's dune lakes, research has documented gradual change in lake ecosystem communities associated with declining water quality in catchments dominated by pasture and exotic forestry (e.g. Hughes 2016; Kelly et al. 2016; Champion 2021). In addition, lake levels have declined markedly during recent droughts, and many lakes now remain stratified for longer periods, resulting in prolonged anoxic condition at depth (S. Sanwar, NRC, pers. comm., 30 September 2025).

To support the implementation of the Te Tai Tokerau Climate Adaptation Strategy,[1] Northland Regional Council (NRC) is seeking to address the strategy's priority action #17 to improve their understanding of climate change impacts on biodiversity and ecosystem function, as well as develop monitoring and response programmes. Alongside this, regional councils are required to account for '*the reasonably foreseeable impacts of climate change*' while setting freshwater objectives and limits under the National Policy Statement for Freshwater Management 2020 (NPS-FM). Many of the decisions made by NRC will have implications that extend over multiple decades. To address knowledge gaps and inform future freshwater management decisions, NRC sought advice on:

- the vulnerability of freshwater ecosystems (including rivers, lakes and wetlands) and freshwater values (such as native fish, macroinvertebrates, critical spawning / breeding habitats for

[1] Available from: https://ttcan.nz/wp-content/uploads/2024/11/Te-Tai-Tokerau-Climate-Adaptation-Strategy-Final-Version-05-4-2022.pdf

threatened fauna, lakes submerged plant community, nuisance algae and macrophytes) to frequent extreme weather events.

- how adverse effects on water quality, ecosystem integrity and ecosystem extent may be exacerbated by climate change, both with and without mitigation efforts and policy interventions, by mid-century and end of century.

This advice will support NRC in accounting for climate change impacts when developing regulatory and non-regulatory policies. It will also help shape action plans to improve climate resilience of high-value freshwater ecosystems. Specifically, understanding the vulnerability of freshwater resources and values across multiple climate scenarios will focus management effort on the most at-risk ecosystems and locations.

Climate-driven stressors identified in this assessment – particularly warming, reduced water availability, increased sediment, lake stratification, wetland drying and invasive species – have direct implications for biodiversity outcomes within freshwater ecosystems. These stressors influence the condition, extent and connectivity of habitats that support native fish, macroinvertebrates and threatened species, and therefore sit within the core responsibilities of NRC for maintaining ecosystem health and indigenous biodiversity.

By explicitly linking climate stressors to ecological responses and management levers, this assessment supports NRC in prioritising interventions that deliver co-benefits for freshwater management and biodiversity protection, including actions that enhance habitat quality, maintain refugia and reduce cumulative stressors on vulnerable species and ecosystems.

The advice will also guide the development of long-term monitoring approaches that integrate climate variables with NRC's existing state of the environment (SOE) monitoring programme, helping to identify the contribution of climate change to freshwater ecosystem responses. This, in turn, will support the management of other pressures, such as land-use change, by improving the ability to distinguish climate change effects from other stressors and by informing the setting of pragmatic freshwater objectives and limits.

Accordingly, this report provides recommendations on:

- best-practice approaches for long-term monitoring of climate variables (e.g. air temperature, evapotranspiration, solar radiation) alongside existing continuous freshwater monitoring (e.g. water temperature, dissolved oxygen, turbidity) to identify the effects of extreme weather events
- tracking freshwater ecosystem responses to changing climate patterns to support modelling of future ecosystem states, including the relative contribution of climate change to observed responses, and the effectiveness and lag times of mitigation and restoration actions in developed catchments.

1.1 Approach

To assess how climate change may affect Northland's freshwater ecosystems and values, we reviewed existing information on climate predictions, Northland's freshwater ecosystems and the responses of freshwater ecosystem values to climate-related drivers. In addition to literature review, meetings were held with relevant NRC staff to better understand current information limitations and knowledge gaps, including areas where spatial information or ecosystem classifications were less accurate.

The information gathered was used to undertake a qualitative risk assessment to identify the vulnerability of freshwater values to climate change. The assessment involved identifying stressor–response relationships between freshwater values and projected environmental changes driven by climate change. We also investigated the likely sensitivity of values to climate change based on available Aotearoa New Zealand literature and identified any known tipping points. Both direct and indirect relationships (through physical and chemical processes) between climate change stressors and ecosystem values were considered.

Following the risk assessment, we developed recommendations on best-practice approaches for monitoring climate change effects on freshwater ecosystems. This included consideration of long-term monitoring of climate and freshwater variables through both discrete SOE monitoring and continuous high-frequency freshwater monitoring.

We also provide commentary and lessons learned from involvement in expert panel processes conducted by regional councils across Aotearoa New Zealand. We acknowledge that it is challenging to predict how climate change may exacerbate other environmental effects, and how the impact of mitigation efforts or policy initiatives may influence outcomes. Accordingly, this report provides brief commentary and outlines a potential expert panel approach for Northland, which could be used to test future climate and policy scenarios.

2. Climate change scenarios considered

Key messages

Mid- and end-of-century climate change predictions for Northland were obtained from downscaled climate change projections (5 km grid resolution) for temperature, rainfall and wind. This was supplemented through considering other reports describing and predicting changes in Northland's climate.

We considered three downscaled climate projections, or Shared Socio-economic Pathways (SSP) scenarios, from the IPCC Sixth Assessment Report:

- **SSP1-2.6** – assuming global development follows a more sustainable path where warming remains below 2 °C
- **SSP2-4.5** – reflecting continuation of current global trends with approximately 2.7 °C of warming by 2100
- **SSP3-7.0** – a higher-emissions scenario where increased regional rivalries lead to warming of approximately 3.6 °C by 2100.

Across all scenarios, the downscaled projections indicate that Northland is likely to become warmer, have more hot days above 25 °C, receive reduced annual rainfall and have fewer windy days. Changes in the number of very rainy days (> 25 mm daily rainfall) and dry days (< 1 mm daily rainfall) varied by district. Predictions for mid-century were relatively similar across the three climate scenarios, except for an approximately 60% greater increase in the number of hot days under SSP3-7.0 compared with SSP1-2.6. By end of century, projections for all climate indicators diverged more clearly between scenarios.

Where previously reported, model predictions based on the IPCC Fifth Assessment Report were considered. Representative Concentration Pathway (RCP) scenarios RCP 2.6, RCP 4.5 and RCP 8.5 corresponded to scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 (an extreme scenario of enhanced fossil fuel development not included in the downscaled climate change projections).

There are inherent complexities in combining climate change projections with ecological knowledge while ensuring a degree of uncertainty remains in the scenarios considered. The risk assessment presented in this report is qualitative, so no attempt has been made to quantify uncertainty beyond identifying areas where uncertainty is greatest.

Assessment of how climate change may affect Northland's freshwater ecosystems was based on climate change projections downscaled to a 5 km grid resolution by Earth Sciences New Zealand (Gibson et al. 2024a, 2024b)[2], alongside other reports describing Northland's climate. The downscaled projections include temperature, rainfall and wind, and are based on outputs from approximately 100 global climate models developed for the IPCC Sixth Assessment Report (IPCC 2023). Three Shared Socio-economic Pathway (SSP) and global emissions scenarios were considered: **SSP1-2.6** sees global development following a more sustainable path with warming remaining below 2 °C; **SSP2-4.5** reflects a continuation of current global trends with approximately 2.7 °C of warming by 2100; and **SSP3-7.0** has higher emissions where increased regional rivalries lead to warming of approximately 3.6 °C by 2100.

Across all scenarios, the downscaled projections indicate that Northland is likely to become warmer and drier by experiencing more hot days (days with air temperature > 25 °C), less total annual rainfall and fewer windy days. Projections for changes in the number of very rainy days (> 25 mm daily rainfall) and dry days (< 1 mm daily rainfall) varied by district (Table 1). Although drought occurrence was not explicitly modelled, projected increases in air temperature and decreases in rainfall are expected to increase drought frequency and severity, consistent with previous climate projections (Pearce et al. 2016).

Mean predictions for mid-century were relatively similar across the three climate scenarios, except for an approximately 60% greater increase in the number of hot days under SSP3-7.0 compared with SSP1-2.6. By end of century, projections for all climate indicators diverged more clearly between scenarios. Under SSP1-2.6, little additional climate change was projected beyond mid-century, whereas projections indicated continued change under SSP2-4.5 and substantially larger changes under SSP3-7.0. Confidence intervals overlapped for some indicators, indicating ongoing uncertainty in the magnitude and, in some cases, the direction of projected change. Specifically, the change in climate indicators did not necessarily increase with escalating global emissions scenarios and some indicators could either increase or decrease. This uncertainty was greatest for projections of very rainy days and dry days.

A key limitation of the available downscaled climate projections is the absence of information on changes in hydrology, particularly river flows and associated metrics such as flood frequency. There is also limited detail on changes in water availability, including groundwater recharge. From an ecological perspective, understanding how hydrology may change under climate change is essential for assessing key drivers such as the frequency and magnitude of flood disturbances, low-flow conditions, spawning cues for fish, and water availability for lakes and wetlands. Consequently, the lack of hydrological predictions limits the robustness of the freshwater risk assessment presented in this report. While rainfall projections are considered, the complexity of hydrological systems means that rainfall alone provides limited insight into changes in river flow and groundwater at a regional scale. Earth Sciences New Zealand is currently undertaking work to develop hydrological predictions, and once available, inclusion of this information is recommended for future assessments. In addition, we assumed that increases in air temperature would result in increases in water temperature, recognising that local

[2] Projections and further supporting information are publicly available from the Ministry for the Environment: https://environment.govt.nz/facts-and-science/climate change/climate change-projections/

factors such as stream shading or groundwater influence will create spatial variability in thermal responses.

Alongside the downscaled climate change projections based on data from the IPCC Sixth Assessment Report, projections for tropical cyclones and ex-cyclones (Gibson et al. 2025) were considered. We also examined earlier climate projections for Northland based on the IPCC Fifth Assessment Report presented in Pearce et al. (2016)[3]; this included Representative Concentration Pathway (RCP) scenarios RCP 2.6, RCP 4.5 and RCP 8.5. These correspond to scenarios SSP1-2.6 (a reduction in emissions), SSP2-4.5 (continuation of current global trends) and SSP5-8.5 (an extreme scenario of enhanced fossil fuel development not included in the downscaled climate change projections). Although the projections presented in Pearce et al. (2016) have been superseded, their interpretation provides useful context for understanding potential changes in extreme weather events, such as cyclones and intense rainfall. This is particularly relevant because downscaled climate projections describe average conditions, whereas extreme events are known to have disproportionate impacts on freshwater ecosystems (e.g. Allen et al. 2024). Substantial interannual variability in temperature and rainfall – including that driven by large-scale climate oscillations such as the El Niño–Southern Oscillation, the Interdecadal Pacific Oscillation and the Southern Annular Mode – may also obscure longer-term climate trends (Pearce et al. 2016).

Although extreme weather events remain challenging to model, updated projections indicate that changes in the frequency of tropical cyclones and ex-cyclones affecting Aotearoa New Zealand remain uncertain. However, extreme rainfall associated with ex-cyclones is projected to increase by approximately 30–35% under the SSP3-7.0 emissions scenario (Gibson et al. 2025). This suggests that peak rainfall intensities are likely to increase when ex-cyclones affect Northland; this is despite projected declines in total annual rainfall and changes in the number of very wet days varying between districts. On average, approximately one ex-cyclone comes within 550 km of Auckland during each tropical cyclone season (November–April) (Lorrey et al. 2014), and a similar frequency can be expected for Northland given its proximity. Ex-cyclones may also generate extreme wind events; however, projections remain uncertain regarding future changes in cyclone-related wind intensity, even under higher-emissions scenarios (Gibson et al. 2025).

[3] Projection scenarios based on the IPCC Sixth Assessment Report are denoted as Shared Socio-economic Pathways (SSP), while scenarios based on the IPCC Fifth Assessment Report are denoted as Representative Concentration Pathways (RCP).

Table 1. Mean projected changes for Shared Socio-economic Pathway scenarios SSP1-2.6, SSP2-4.5 and SSP3-7.0 for Northland districts. Sourced from Ministry for the Environment climate change projections dashboard (MfE 2024) based on downscaled climate change projections produced by Earth Sciences New Zealand (Gibson et al. 2024a, 2024b).

Indicator	Description	1995–2014 baseline	Mid-century (2040–2060)			End of century (2080–2099)			Spatial variation across the region
			SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP1-2.6	SSP2-4.5	SSP3-7.0	
Average daily air temperature	Average daily air temperature per year or season. Significant increases are expected in summer, especially by end of century		+0.8 °C	+1.1 °C	+1.3 °C	+0.8 °C	+1.9 °C	+2.9 °C	Same prediction for all districts
Hot days (> 25 °C)	Number of days per year or season with a maximum daily air temperature over 25 °C	Far North 23.7 days Kaipara 25.4 days Whangārei 24.5 days	+22.7 d +21.6 d +21.8 d	+29.5 d +26.9 d +28.2 d	+38.9 d +35.3 d +37.0 d	+21.6 d +19.7 d +21.7 d	+56.9 d +52.0 d +56.0 d	+87.2 d +80.7 d +85.7 d	Least increase in Kaipara
Frost days (< 0 °C)	Number of days per year with a minimum daily air temperature below 0 °C	Far North 0.1 days Kaipara 1.2 days Whangārei 0.6 days	-0.1 d -0.6 d -0.3 d	-0.1 d -0.7 d -0.3 d	-0.1 d -0.8 d -0.4 d	-0.1 d -0.6 d -0.3 d	-0.1 d -1.0 d -0.5 d	-0.1 d -1.1 d -0.5 d	Currently frostier in Kaipara, but same change to minimal frost in all districts
Total rainfall	Total amount of rainfall per year	Far North Kaipara Whangārei	-1.4% -1.6% -0.4%	-3.1% -2.4% -2.0%	-3.0% -2.9% -1.6%	-2.2% -1.8% -2.5%	-4.8% -3.3% -3.3%	-11.6% -10.8% -9.4%	
Very rainy days (> 25 mm)	Number of days with rainfall > 25 mm in a year	Far North 13.7 days Kaipara 9.3 days Whangārei 13.6 days	-0.1 d +0.3 d +0.2 d	-0.5 d +0.1 d -0.2 d	-0.2 d +0.4 d +0.1 d	-0.3 d +0.1 d -0.3 d	-0.8 d +0.2 d -0.6 d	-1.9 d -0.4 d -1.6 d	
Dry days (< 1 mm)	Number of days with rainfall < 1 mm in a year	Far North 228.9 days Kaipara 221.2 days Whangārei 230.3 days	-1.0 d -0.1 d -1.0 d	-1.4 d -1.9 d -0.7 d	-1.5 d -1.5 d +0.4 d	0.0 d -0.1 d +1.3 d	+1.5 d +1.7 d +2.2 d	+6.9 d +8.2 d +7.7 d	

Indicator	Description	1995–2014 baseline	Mid-century (2040–2060)			End of century (2080–2099)			Spatial variation across the region
			SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP1-2.6	SSP2-4.5	SSP3-7.0	
Windy days	Days with wind speed > 10 m/s	Far North 30.8 days Kaipara 60.1 days Whangārei 45.2 days	-0.1 to -8.9 d -0.9 to -9.7 d -1.7 to -9.5 d			-0.2 to -21.5 d -0.5 d to -23.1 d -1.0 to -22.3 d			
Fire risk	Dependent on temperature, precipitation, relative humidity and wind		40–50% increase in the number of days per year of Very High and Extreme Forest Fire Danger (Pearce et al. 2016). Higher temperatures and lower rainfall will increase fire risk, although windy days (an exacerbator of fire risk) are projected to decrease						
Cyclones	Tropical cyclones (or ex-cyclones) may bring heavy rain and strong winds to the region		No projection information available			30–35% increase in extreme rainfall under SSP3-7.0 (Gibson et al. 2025)			

Indirect effects

Beyond the direct effects of changes in climate, there are several indirect effects associated with climate change that can significantly affect freshwater ecosystems. These can arise from natural processes or from climate-driven changes in human activities. For example, increased air and water temperatures can make conditions more favourable for invasive species, which may in turn impact valued native species or alter environmental conditions. Human activities may also shift in response to climate change in ways that have flow-on effects for freshwater ecosystems; for example, planting of exotic plantation forest on previously unforested land for carbon sequestration has been shown to reduce stream flows (Hughes et al. 2020). Where plantation forestry is harvested and replanted, flows are likely to increase temporarily post-harvest but then reduce again as canopy closure is achieved. Increased demand for water abstraction is also expected as rainfall decreases, which will further increase anthropogenic pressure on waterways.

Such indirect effects are an additional consideration beyond the direct effects of climate change considered in this report. Where known, examples of likely indirect effects are incorporated into the risk assessment. However, considerable uncertainty remains around indirect effects associated with changes in human activities in response to climate change, including changes in land use and the effects of changes in government climate response policy.

Uncertainty

Future projections of climate always contain uncertainty, even as climate models continue to improve. In addition, large-scale climate oscillations such as El Niño–Southern Oscillation and the Southern Annular Mode can introduce significant natural variability, and the implications of changes in climate on such oscillations remain uncertain (Bodeker et al. 2022). There are also inherent complexities in combining climate change projections with ecological knowledge, both of which carry their own uncertainties. Even when the best available knowledge is used to consider future ecosystem responses under climate change, some uncertainty is unavoidable. As the risk assessment presented in this report is qualitative, no attempt has been made to quantify uncertainty beyond identifying areas where uncertainty is greatest.

3. Risk assessment

Key messages

This review first analysed other recent climate change vulnerability assessments conducted in Aotearoa New Zealand. We then assessed the vulnerability of individual freshwater values to climate change using a qualitative risk assessment that considered the exposure of individual values to changes in climate stressors and the sensitivity of values to these stressors. For each value, both exposure and sensitivity were qualitatively assessed as 'low', 'medium' or 'high'.

Due to the qualitative approach, the assessment focused on the SSP2-4.5 scenario as a midpoint, with supporting commentary outlining available evidence for how values respond to each climate stressor. Exposure to all stressors increased from mid-century to end of century, with exposure to changes in rainfall, temperature and fire risk all being assessed as moderate by mid-century and high by end of century. All but one value displayed high sensitivity to at least one climate stressor, with available evidence able to indicate how values are likely to change. The assessment also suggested key influences requiring consideration to best understand how values will be influenced by climate change stressors.

For some values, classification as having low sensitivity to a particular climate stressor reflected uncertainty or limited evidence to support how a value responds to climate change. These knowledge gaps included the response of ammonia and nitrate concentrations as well as ecosystem metabolism to both temperature and rainfall.

In a climate change context, risk is defined as a combination of the likelihood of exposure to altered climatic conditions and the sensitivity of an ecosystem, species or value to these changes (Foley and Carbines 2019). Following consideration of climate projections, key stressors were identified for each ecosystem type to determine how freshwater ecosystems are likely to be affected. The vulnerability of individual freshwater values to climate change was then assessed using a qualitative risk assessment based on methodologies used in Foley and Carbines (2019), Markovic et al. (2017) and species-level vulnerability assessments (Egan et al. 2020; Brumby et al. 2025), including:

1. Identifying the extent to which the stressors acting on each value will change by mid-century and end of century based on projected environmental changes caused by climate change (i.e. assessing the **exposure** of a value to climate change stressors).
2. Investigating the likely **sensitivity** of values to climate change based on available Aotearoa New Zealand literature, including known stressor–response relationships and any tipping points.

As an example, the risk of threatened species being affected by climate change is influenced by both climate-driven stressors, such as temperatures and rainfall change (the exposure), and the species characteristics that determine how they respond to these altered stressors, e.g. thermal tolerance, life-history traits (their sensitivity). As such, exposure is determined by how the climate changes, while the sensitivity of a value is determined by the characteristics of the value itself.

Each risk component was scored as 'low', 'moderate' or 'high' based on the classification in Table 2. Both direct and indirect relationships (through other physical and chemical processes) between climate change stressors and ecosystem values were considered. Unlike other assessments, we do not present an overall risk classification for each value. Initially, there were attempts to combine the exposure and sensitivity classifications for individual attributes into a single risk classification for each value following the approaches taken by Brumby et al. (2025) and Foden et al. (2013); however, this resulted in very similar risk classifications for all values and was therefore judged to be unhelpful. Rather than develop a separate approach for classifying overall risk, we present the two risk components to show how values may respond to key climate stressors.

The qualitative risk assessment framework also provides a basis for informing freshwater limit-setting and environmental flow decisions. By identifying where climate change is likely to shift baseline conditions or increase the risk of ecological thresholds being exceeded, the assessment supports incorporation of biodiversity considerations – such as habitat availability, refugia and species-specific tolerances – into future planning and management decisions.

Table 2. Criteria used to classify exposure and sensitivity for the qualitative risk assessment of Northland's freshwater values.

Risk component	Classification	Criteria
Exposure	Low	• Minimal detectable change in stressor due to climate change, or direction of change is uncertain.
	Moderate	• Moderate change in stressor due to climate change (see Table 3).
	High	• Large change in stressor due to climate change (see Table 3).
Sensitivity	Low	• Value has minimal response to stressor and / or the direction of response is unknown. • Available evidence supports minimal response or little evidence for value responding to stressor. • No evidence for tipping points.
	Moderate	• Value responds to stressor in a consistent direction. • Value response to stressor may not be universal but available evidence shows a consistent response pattern.
	High	• Clear universal response to stressor with a consistent direction. • Strong evidence to support the likely response of the value to the stressor. • Tipping points are likely to be present or response to stressor is disproportionate.

3.1 Key climate change stressors for freshwater ecosystems

As outlined in Section 2, changes in air temperature, rainfall and wind strength are projected for Northland. Key stressors for freshwater ecosystems associated with these changes are reduced water availability (flows and levels), increased water temperatures, increased extreme rainfall and elevated fire risk in wetlands. Alongside this, a reduction in wind-driven mixing in lakes and low summer flows in low-gradient rivers will likely lead to stratification and increased prevalence of anoxic conditions. Further impacts on freshwater ecosystems driven by climate change include significant increases in sediment run-off (due to increased extreme rainfall) and increased impacts from invasive species (due to improved habitat suitability).

While described and evaluated as individual stressors, interactions will occur between climate stressors as well as with other stressors such as land-use change, water demand and disease. Such interactions are challenging to assess because of the multiple forms that interactive effects can take (synergies, antagonisms and additive effects; Côté et al. 2016) and their associated uncertainty. A recent example of the impacts of interacting stressors in Northland has been demonstrated by fish die-offs, with large numbers of bullies dying in Lake Mōkeno and Lake Humuhumu (M. Chakraborty, NRC, pers. comm., 7 November 2025). Initial findings from the Ministry for Primary Industries suggests these die-offs were likely caused by high parasite loads, possibly associated with increased water temperature and factors impacting fish immunity including harmful algal blooms, pollutants, toxins, and physiological stressors.

Temperature

Increases in air temperature are expected to result in higher water temperatures, with river water temperature generally increasing 0.6 °C for every 1 °C increase in air temperature (Morrill et al. 2005), and shallow lakes increasing by approximately 0.8 °C for every 1 °C increase in air temperature (Meerhoff et al. 2012). Small streams, shallow lakes and wetlands are particularly vulnerable because their high surface-area-to-volume ratios increase sensitivity to changes in air temperature (Hussain 2023b).

Elevated water temperatures are likely to lead to a progressive, localised loss of sensitive macroinvertebrate and fish species as waterways warm, accompanied by contractions in species' ranges (Davies-Colley et al. 2013). Increased water temperatures are also expected to increase benthic periphyton cover and the frequency and magnitude of periphyton blooms for Northland rivers (Kilroy and Snelder 2024). In turn, increased periphyton cover can alter macroinvertebrate communities, favouring smaller taxa such as chironomid larvae and snails, potentially reducing food availability for fish (Braccia et al. 2014; Quinn and Hickey 1990).

High water temperature will also increase fish metabolic rates, leading to greater growth rates and food demands (Volkoff and Rønnestad 2020). In addition, elevated temperatures have been shown to reduce the swimming performance of some native fish species, which may exacerbate existing fish-passage barrier issues or create new barriers during low flows (Crawford et al. 2024).

Reduced rainfall

The effects of reduced rainfall are already evident from drought impacts observed across Northland, as the reduction in the quantity of water entering freshwater ecosystems from rain leads to reduced river flows and lower water levels in lakes and wetlands. In rivers, assessments of drought effects show that macroinvertebrate community indicators are negatively correlated with the New Zealand Drought Index (NZDI) at some (but not all) monitored sites. While indicators generally recover following drought, impacts have been greater in pastoral streams that are subject to other stressors (Death et al. 2020; Graham and Greenwood 2023). Mean annual 7-day low flow has been shown to be a strong predictor of benthic periphyton cover, and therefore reduced low flows are likely to increase periphyton cover (Kilroy and Snelder 2024). Low flows can also lead to reduced dissolved oxygen in lowland rivers, which can subsequently impact aquatic life when dissolved oxygen concentrations drop below species requirements (Davies-Colley et al. 2013; Pardo and Garcia 2016).

In lakes, reduced rainfall causes declines in water level (e.g. Lake Taharoa; Pham 2022). This can result in the temporary loss of littoral habitat, exposing vulnerable species such as dune lake galaxiids to increased predation by trout (F. Dovan, Department of Conservation [DOC], pers. comm., 17 September 2025). Long-term reductions in rainfall and associated declines in soil moisture also have the potential to alter wetland character, with reduced annual rainfall leading to peat growth cessation or retreat, decreased wetland extent and shifts in vegetation composition favouring invasive dryland plants (Keegan et al. 2022).

Because surface water quantities can be linked to groundwater, changes in river flows and lake levels will vary between catchments, depending on surface water–groundwater interactions. In some catchments (e.g. areas with basalt geology), aquifers may sustain surface flows during dry periods, provided sufficient recharge occurs at other times of the year. In contrast, surface waters in other catchments may be largely disconnected from groundwater and therefore more vulnerable to prolonged drying. Therefore, it is important to identify how changes in rainfall impacts groundwater recharge, groundwater level and subsequently groundwater-fed surface waterbodies to understand how different waterbodies will be affected by climate change. In coastal areas, this is further complicated by sea-level rise, as there is also high potential for groundwater levels to increase and the possibility of salinisation occurring due to high sea levels (Pearce et al. 2016).

Extreme rainfall

Alongside reduced annual rainfall, extreme rainfall intensity associated with cyclones is projected to increase by 30–35% under the SSP3-7.0 scenario (Gibson et al. 2025). This is expected to affect freshwater ecosystems through increased flood and debris flows, leading to greater erosion and increases in the magnitude of flood disturbances. Such disturbances are likely to alter habitat more severely than current flood regimes and may provide increased opportunities for fast-recolonising species to gain competitive advantages when ecological communities are ‘reset’ by floods (Chase 2003; Death 2008).

Predicted increases in sediment loads for Northland rivers are also expected to cause large changes in physical habitat, with increases exceeding other regions of Aotearoa New Zealand (Neverman et al. 2023). Significant effects of sediment and organic debris deposition associated with extreme weather events have already been observed in some lakes, such as the smothering of kākahi in Lake Rotokawau (Hussain 2023a). An increased frequency of extreme rainfall events may also facilitate flood-mediated dispersal of exotic species, while altered disturbance regimes may favour the establishment of invasive plants in ephemeral wetlands (Hamilton et al. 2013; Tanentzap et al. 2014).

Although projections are uncertain for other cyclone-related effects, strong wind events associated with cyclones have the potential to significantly disturb shallow lakes, including burying vegetation, altering nutrient resuspension and triggering shifts from clear-water, plant-dominated systems to turbid, algae-dominated states (Chao et al. 2017).

Fire

Wetlands are also expected to face increased fire risk due to higher air temperatures and generally drier conditions (Pearce et al. 2016). Increased fire frequency is likely to facilitate the invasion of exotic plants, which often re-establish more rapidly following fire and may create positive feedback loops where invading species are themselves highly flammable (Christensen et al. 2019).

Increases in the frequency and extent of fires in terrestrial environments are also likely to further localised decreases in soil moisture and create increased pressure for water abstraction from waterbodies to support firefighting efforts.

Wind

The combination of fewer windy days, higher temperatures and reduced flows is likely to increase the occurrence of stratification and anoxia in lakes and in low-gradient reaches of some lowland rivers (Martinsen et al. 2019). These conditions can alter internal nutrient cycling by prompting anoxia-driven phosphorus release from sediments and may lead to fish kills (Landman et al. 2005).

Grouping of climate stressors

For the purposes of the risk assessment, climate indicators were grouped into four stressor categories: temperature, precipitation, wind and fire risk (Table 3). The degree of projected change for each stressor at mid-century and end of century was classified as low, moderate or high based on the authors' expert judgement, which was informed by climate projections and the magnitude of change expected to produce ecological responses. Cyclone effects were included within the precipitation and wind stressors. Stressor classifications were based on the SSP2-4.5 climate scenario, representing the midpoint of scenarios considered, with SSP1-2.6 and SSP3-7.0 addressed in the supporting commentary. To ensure consistent evaluation across values, indirect stressors were not used to assign exposure classifications, but key indirect impacts are described in the accompanying commentary.

Indirect effects

In addition to direct effects, climate change may have significant indirect effects on Northland's freshwater ecosystems. These include increased human demand for water, which may contribute to saltwater intrusion in groundwater, as well as sea-level rise and altered estuarine dynamics affecting īnanga spawning habitat. Many Northland catchments are low gradient with considerable tidal influence, so the effects of sea-level rise may extend long distances inland, depending on the degree of movement in the saltwater wedge.

Another important indirect effect is the increased risk posed by invasive species, as projected climate changes are likely to make environmental conditions more favourable for some species. For example, rising soil temperatures are expected to enable red-eared slider turtles (ranked among the world's most invasive species by the IUCN; Lowe et al. 2000) to breed successfully in Northland (N. Fitzgibbon, NRC, pers. comm., 25 September 2025). Increased climate stress on native species will also make it easier for new invasive species already adapted to Northland's climate to establish, such as the gold clam (*Corbicula fluminea*; Somerville et al. 2025).

Implications for biodiversity management

Many of the identified climate stressors act through well-understood ecological pathways that directly affect biodiversity outcomes. For example, increased sediment loads degrade habitat quality for benthic organisms and fish spawning, elevated water temperatures reduce thermal habitat suitability and increase metabolic stress, and reduced flows limit habitat availability, connectivity and access to refugia.

Importantly, these pathways also point to management interventions with clear co-benefits for freshwater ecosystems and biodiversity. Actions such as erosion control, riparian planting to increase shade, wetland protection and restoration, and catchment-scale land management can reduce multiple stressors simultaneously. Prioritising these interventions in high-risk catchments provides an opportunity to enhance ecosystem resilience under climate change while supporting NRC's biodiversity objectives.

Table 3. Grouping and classification of climate stressors used in the risk assessment of freshwater values based on the SSP2-4.5 climate scenario. The relative degree of change across each climate stressor is expected to be similar for the SSP1-2.6 and SSP3-7.0 scenarios.

Stressor	Climate indicators	Degree of change	
		Mid-century	End of century
Rainfall	Total rainfall Very rainy days Dry days Cyclones	Moderate	High
Temperature	Average daily air temperature Hot days (> 25 °C) Frost days (< 0 °C)	Moderate	High
Wind	Windy days	Low	Moderate
Fire risk	Number of days with very high fire risk	Moderate	High

3.2 Risks to freshwater values

Following the approach described above (p. 10–11), risk assessments for freshwater values in rivers, lakes and wetlands are summarised in Table 4–7, with accompanying commentary for each value describing the evidence supporting the assessment and detailing any additional comments. Exposure (projected change in each climate stressor under SSP2-4.5) and sensitivity (evidence-based response of each value) were assessed for the indicators used to monitor each value, with the results summarised in Tables 4–7. Exposure was assessed for both mid-century and end-of-century scenarios, while the assessment of sensitivity was based on how values respond to stressors and is not expected to change over time. The trajectories of change for each value are predicted to be similar across the three climate scenarios. Any scenario-specific details are addressed within the commentary for each value.

Table 4. Summary of the risk assessment for freshwater values related to **streams and rivers** in the Northland Region. * indicates values that are components of the overall 'Ecosystem Health' value in the National Policy Statement for Freshwater Management 2020 (NPS-FM; MfE 2024). † indicates regional attributes not included in the NPS-FM. Cell colours indicate the classification of risk components as low (green), medium (orange) or high (red).

Value	Attributes	Stressor	Exposure		Sensitivity
			Mid-century	End of century	
Water quality*	Ammonia (toxicity)	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	Low
	Nitrate (toxicity)	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	Low
	Dissolved reactive phosphorus	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	Moderate
	Dissolved oxygen	Temperature	Moderate	High	Moderate
		Rainfall	Moderate	High	Moderate
	Suspended fine sediment	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	High
	Water temperature†	Temperature	Moderate	High	High
		Rainfall	Moderate	High	Low
Water quantity*	N/A	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	High
Habitat*	Deposited fine sediment	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	High
Aquatic life*	Fish	Temperature	Moderate	High	High
		Rainfall	Moderate	High	Moderate
	Macroinvertebrates	Temperature	Moderate	High	Moderate
		Rainfall	Moderate	High	High
	Periphyton (trophic state)	Temperature	Moderate	High	Moderate
		Rainfall	Moderate	High	Moderate
Ecological processes	Ecosystem metabolism	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	Low
Human contact	*E. coli*	Temperature	Moderate	High	Low
		Rainfall	Moderate	High	Moderate
	Cyanobacteria (planktonic)	Temperature	Moderate	High	Moderate
		Rainfall	Moderate	High	Moderate

Table 5. Summary of the risk assessment for freshwater values related to **lakes** in the Northland Region. * indicates values that are components of the overall 'Ecosystem Health' value in the National Policy Statement for Freshwater Management 2020 (MfE 2024). Cell colours indicate the classification of risk components as low (green), medium (orange) or high (red).

Value	Attributes	Stressor	Exposure		Sensitivity
			Mid-century	End of century	
Water quality*	Total nitrogen (trophic state)	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Moderate
	Total phosphorus (trophic state)	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Moderate
	Ammonia (toxicity)	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Low
	Dissolved oxygen	Temperature	Moderate	High	High
		Rainfall	Moderate	High	Moderate
		Wind	Low	Moderate	Moderate
Water quantity*	N/A	Temperature	Moderate	High	Moderate
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Low
Aquatic life*	Phytoplankton (trophic state)	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Moderate
	Submerged plants (natives)	Temperature	Moderate	High	Moderate
		Rainfall	Moderate	High	Moderate
		Wind	Low	Moderate	Low
	Submerged plants (invasive species)	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Low
Human contact	*E. coli*	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Low
	Cyanobacteria (planktonic)	Temperature	Moderate	High	High
		Rainfall	Moderate	High	High
		Wind	Low	Moderate	Moderate

Table 6. Summary of the risk assessment for freshwater values related to **wetlands** in the Northland Region. Cell colours indicate the classification of risk components as low (green), medium (orange) or high (red).

Value	Stressor	Exposure		Sensitivity
		Mid-century	End of century	
Wetland extent	Temperature	Moderate	High	Moderate
	Rainfall	Moderate	High	High
	Fire	Moderate	High	Low
Wetland state / quality	Temperature	Moderate	High	Moderate
	Rainfall	Moderate	High	Moderate
	Fire	Moderate	High	High

Table 7. Summary of the risk assessment for freshwater values related to **all freshwater ecosystem types** in the Northland Region. Cell colours indicate the classification of risk components as low (green), medium (orange) or high (red).

Value	Stressor	Exposure		Sensitivity
		Mid-century	End of century	
Threatened species	Temperature	Moderate	High	High
	Rainfall	Moderate	High	High
	Wind	Low	Moderate	Low
	Fire	Moderate	High	High
Natural form and character	Temperature	Moderate	High	Moderate
	Rainfall	Moderate	High	Moderate (rivers) / High (lakes)
	Wind	Low	Moderate	Low
	Fire	Moderate	High	Moderate

Rivers and streams

The values included in the risk assessment for streams and rivers were based on those in the NPS-FM (MfE 2024; see Table 4). As many values are influenced by flow characteristics, the lack of hydrological projections was a key gap for assessing risks to values in rivers and streams.

Water quality

The attributes used to assess water quality for rivers and streams in the NPS-FM include **ammonia toxicity, nitrate toxicity, dissolved reactive phosphorus, dissolved oxygen and suspended fine sediment**. Ammonia and nitrate were assessed as having a low sensitivity to changes in temperature and rainfall due to inconsistent evidence to determine the direction of response. Dissolved oxygen was assessed as having moderate sensitivity to both changes in temperature and rainfall, while suspended sediment was assessed as having low sensitivity to changes in temperature but high sensitivity to changes in rainfall. At a landscape scale, ammonia, nitrate, dissolved reactive phosphorus and suspended sediment are also influenced by the physiographical characteristics of catchments (Rissman and Pearson 2020). As the landscape physiographical characteristics will not alter with climate change, existing process-attribute gradients will remain and likely maintain current spatial variability.

It is unclear how ammonia, nitrate and dissolved reactive phosphorus concentrations will respond to climate change. Increases in temperature may increase nitrogen uptake on land through increasing terrestrial plant growth, as well as accelerate nitrification and denitrification (Fowler et al. 2015; Viancelli and Michelon 2024). The combination of increased uptake and reduced rainfall will likely reduce leaching into waterways and transport downstream (Oduor et al. 2023). However, decreased river flows will reduce the dilution of nutrient concentrations, and a rise in rainfall extremes will increase the export of nutrients during extreme weather events. Intense rainfall increasing the export of nutrients is particularly true for dissolved reactive phosphorus, as overland flow tends to transport more phosphorus (McDowell 2008).

Modelling has been conducted overseas using the Soil Water Assessment Tool model and climate projections from the IPCC Fifth Assessment Report to predict changes in annual nitrate loads for a catchment with a Mediterranean climate (Oduor et al. 2023). The modelling results suggested that loads would decrease by 17.7% by mid-century and 12.8% by end of century under an RCP4.5 climate scenario. However, for the same catchment, nitrate concentrations were predicted to increase by 34.8% (mid-century) and 45.1% (end of century) under the same scenario due to decreased river flow reducing dilution. While model outputs for a Mediterranean climate are not directly applicable to Northland, this shows that changes in nitrate depend on the interplay of multiple processes. As concentrations are the more relevant indicator for ecosystem health, hydrological projections are needed to better assess how ammonia, nitrate and dissolved reactive phosphorus concentrations will respond to climate change.

Increased temperatures and nutrient concentrations, along with reduced river flows due to lower annual rainfall will increase primary production, causing reductions in dissolved oxygen concentration and increased diel variation (Foley and Carbines 2019; Wilcock et al. 1998). Slower water velocities in low-gradient rivers as flow reduces will also reduce reaeration and mixing of waterways, resulting in some waterways acting more like wetlands than flowing rivers with areas of low dissolved oxygen concentrations (M. Chakraborty, NRC, pers. comm., 30 September 2025). Additionally, the operation of pumped flood protection schemes following heavy rainfall events can cause low dissolved oxygen events due to the discharge of deoxygenated flood water from swamps and surrounding lowland pasture with reducing geochemical conditions following flood events (M. Chakraborty, NRC, pers. comm., 23 March 2026). Such events may occur more often if flood frequencies increase or may compound the effects of reduced dissolved oxygen during low flows.

The NPS-FM attribute band criteria for dissolved oxygen assess 7-day mean minimum and 1-day minimum concentrations to protect ecosystems against short-duration events that exceed the mortality thresholds of sensitive species (Davies-Colley et al. 2013). The combination of reduced dissolved oxygen concentration and greater diel variation will mean that 7-day mean minimum and 1-day minimum concentrations will decrease, although the magnitude of reductions will be influenced by localised factors driving changes in primary production, such as shading.

For suspended sediment, modelling indicates that loads from Northland rivers may increase 86% by 2040 and 105% by 2090 under the RCP 4.5 scenario based on downscaled IPCC Fifth Assessment Report projections (Neverman et al. 2023). Although the magnitude of change varies across climate scenarios, all scenarios project substantial increases driven by greater erosion associated with changing rainfall patterns and increases in the amount of mass movement due to sediment being transported by overland flow due to increased rainfall intensity. Even under the lowest-change scenario, suspended sediment loads were projected to increase 49% by 2090 under the RCP 2.6 scenario, and 233% by 2090 under the most extreme RCP 8.5 scenario.

As suspended sediment loads increase, visual clarity (the NPS-FM attribute) is expected to decline. Event sampling data from the Hātea and Ōtaika catchments may help translate modelled changes in sediment load into likely changes in suspended sediment concentrations and clarity (Chakraborty 2021). However, there is uncertainty in how these increases will be distributed over time. Current predictions and monitoring data suggest that much of the sediment load may occur during storm events, meaning baseflow suspended sediment concentrations may change less than storm-event concentrations (Chakraborty 2021; Neverman et al. 2023). Because changes in suspended sediment are primarily driven by rainfall and flow, temperature is expected to have little direct effect on sediment.

While not included in the NPS-FM, water temperature is a regional water-quality attribute included in Northland’s regional plan. Water temperature is expected to be highly sensitive to increases in air temperature, as river water temperatures generally increases 0.6 °C for every 1 °C increase in air temperature (Morrill et al. 2005). Therefore, changes water temperatures will directly correspond to changes in air temperate, although local factors such as stream shading or groundwater influence will create spatial variability in thermal responses. It is unclear how rainfall will alter water temperature, as changes in rainfall are likely to both directly influence river flows and indirectly alter groundwater by influencing groundwater recharge.

Changes in water-quality attributes will vary across different climate scenarios. At mid-century, differences between the three scenarios are small. However, by end of century, projections diverge for temperature increase and annual rainfall decline, so expected changes in water quality also diverge. A further consideration is that the attribute bands for ammonia and nitrate are based on acute toxicity rather than ecological relevant concentrations, meaning ecological impacts may occur before state changes are detected.

Water quantity
While there are no specific attributes for water quantity defined in the NPS-FM, the general response of flows to climate change was assessed in terms of the **frequency and magnitude of high and low flows**. The flow response was found to have a high sensitivity to changes in rainfall and a low sensitivity to changes in temperature. Flow is both a freshwater value and a key driver of other freshwater values such as water quality and aquatic life. Potential tipping points include when water velocities in low-gradient reaches drop to a point where water stagnates and become anoxic, and when small streams dry, causing a temporary loss of habitat and leaving stagnant pools disconnected. In some cases, these thresholds may not represent permanent tipping points, as seasonal recovery can occur when flows increase in autumn and winter, although repeated or prolonged low-flow events could reduce resilience over time. While previous downscaled climate projections based on the IPCC Fifth Assessment Report have included river flow predictions, the most recent downscaled climate projections only include temperature and rainfall. This is a key gap for predicting climate change impacts on water quantity and other flow-dependant values.

Rainfall directly affects water quantity, as rainfall is the key supply of water for Northland’s freshwater ecosystems, while temperature has a small influence through evaporation. Decreases in annual rainfall will generally reduce flows. The largest projected decreases in rainfall are for spring (Gibson et al. 2024a, 2024b), meaning that flows are likely to reduce earlier in the summer and remain low for longer. Under the highest emissions SSP3-7.0 scenario, there is also a relatively large decline predicted for winter rainfall. Declines in winter rainfall are likely to affect basalt aquifers, as winter is a critical period for groundwater recharge (S. Osbaldiston, NRC, pers. comm., 12 January 2026).

By length, more than 80% of Northland’s rivers are made up of lower order streams that are either ephemeral or intermittently flowing streams; this means that there is a high risk of a large proportion of the stream network drying due to decreased rainfall. Changes in the distribution of rainfall will also alter the frequency and magnitude of high flows, and increases in the intensity of extreme rainfall events may increase peak flood flows (Gibson et al. 2025). Higher air and water temperatures will increase evaporation and transpiration, thus contributing to decreased flow. However, changes in evaporation from rivers are dependent on shading, while transpiration will be influenced by the vegetation present; therefore, water quantity is sensitive to changes in rainfall but less so to changes in temperature.

Previous climate models based in the IPCC Fifth Assessment Report have suggested that river flows are likely to decrease slightly, with the largest decreases in summer and slightly more floods over three times the median flow (Pearce et al. 2016).

Habitat
The sole attribute for habitat in streams and rivers is **deposited fine sediment**. While having low sensitivity to changes in temperature, deposited fine sediment is highly sensitive to changes in overland flow, sediment run-off, bank erosion and transport driven by changes in rainfall and flow. We expect deposited fine sediment to increase with changes in rainfall and associated changes in flow. This is

because recent modelling predicted that under climate change, the suspended sediment loads from Northland rivers are predicted to increase 86% by 2040 and 105% by 2090 under the RCP 4.5 scenario (based on downscaled IPCC Fifth Assessment Report projections; Neverman et al. 2023). While the relationship between suspended and deposited sediment is difficult to quantify due to the variability in sediment transport between individual rivers, it is assumed that percentage increases in deposited fine sediment broadly match changes in suspended sediment (Carter et al. 2023). Therefore, deposited fine sediment is expected to increase markedly.

While the magnitude of change in suspended sediment loads varies between climate scenarios, all scenarios represent a significant increase of at least one attribute band specified in the NPS-FM. Under the lowest-change scenario reported in Neverman et al. (2023), suspended sediment loads still increased 49% by 2090 under RCP 2.6, and 233% by 2090 under the most extreme RCP 8.5 scenario. Modelling suggests that there will be disproportionate increase in mass movement erosion from soft-rock hill country but surficial and stream bank erosion are also likely to be exacerbated with the increased magnitude of extreme rainfall events (Neverman et al. 2023).

Investigation of physiographic drivers of water quality in Northland has shown a strong correlation between local geological characteristics and elevated suspended sediment (Rissman and Pearson 2020). As geology will remain constant, areas that currently have high sediment run-off will likely continue the same pattern compared with other catchments, and therefore, existing spatial variability in deposited sediment is expected to be maintained.

Aquatic life

The attributes used to assess aquatic life for rivers and streams in the NPS-FM include **fish, macroinvertebrates and periphyton**. All three attributes are directly affected by climate change stressors and are indirectly affected through other freshwater values such as water quality, flow and habitat. Fish were assessed as having a high sensitivity to changes in temperature and a moderate sensitivity to changes in rainfall. Macroinvertebrates were assessed as having a high sensitivity to both changes in temperature and rainfall, while periphyton was assessed as having a moderate sensitivity to both changes in temperature and rainfall.

Increases in temperature and changes in rainfall are both expected to have negative effects on Northland’s freshwater fish communities. While the current drivers of the Fish Index of Biotic Integrity (the reporting metric for fish in the NPS-FM) in Northland are unknown (Sanwar 2024), understanding of fish ecology provides a broad indication of how fish communities are likely to respond to climate stressors. The combination of increased temperatures, lower summer flows and the complex migratory life cycles of native species means that it will be challenging for fish to avoid thermal extremes due to the loss of refugia such as deep pools; there is also the potential for fish-passage barriers to be more severe at low flows (Zwick 1992).

Species present in Northland that have been shown to be highly sensitive to warming include adult banded kōkopu, kōaro and common smelt (Olsen et al. 2012). Lethal temperatures for these species are 28.5 °C, 27 °C and 28.3 °C, respectively (Main 1988; Richardson et al. 1994). However, prolonged exposure to warm water greatly reduces the resilience of these species to temperature spikes. For example, the lethal temperature for common smelt during prolonged exposure was 26 °C, compared to 28 °C for short-term exposure (Richardson and West 1998).

Initial inspection of water temperature data from a small number of continuously monitored sites suggests that some sites have already reached or are approaching summer temperatures high enough to cause significant thermal stress for fish (Davies-Colley et al. 2013; Goodwin and Young 2022; NRC unpublished data). Based on climate projections for air temperature, water temperatures will increase by nearly 1 °C by mid-century under SSP3-7.0 and by end of century under SSP2-4.5. Given that fish are simultaneously subject to the impacts of changes in dissolved oxygen, increased periphyton growth and related shifts in food availability, it is likely that species will be excluded from some parts of the river network as water temperatures exceed species' tolerances. Additionally, increases in temperature may favour invasive species such as red-eared slider turtles, which can both predate on and compete with native fish species.

Change in flow will also affect fish through both altering habitat and affecting spawning. The increased duration and extent of drying in low-order streams that make up much of Northland's river network may result in localised reductions in abundance or species' ranges. Predicted increases in river sediment loads (Neverman et al. 2023) are likely to alter habitat through increased deposition in some areas, while higher peak flood flows may increase disturbance and scour in others. Rising suspended sediment concentrations could further affect fish dispersal and feeding, as banded kōkopu have been shown to avoid rivers with high concentrations of suspended sediment (Rowe et al. 2000). Alongside the effects on adult fish, changes in flow patterns may alter spawning cues for species such as shortjaw kōkopu (F. Donovan, DOC, pers. comm., 17 September 2025).

Analysis of macroinvertebrate data for Northland showed that multiple drivers influence macroinvertebrate communities, with top predictors differing between macroinvertebrate indices (Graham and Greenwood 2023). Relevant drivers linked to climate change included base flow index, dissolved inorganic nitrogen, dissolved oxygen, mean air temperature, NZDI, rain days > 10 mm and turbidity. NZDI was a key indicator of macroinvertebrate communities and is an aggregate index of drought indicators based on precipitation, soil moisture and temperature. Recent droughts showed declines in the Macroinvertebrate Community Index and Semi-quantitative Macroinvertebrate Community Index as NZDI increased, although both indices recovered following drought (Death et al. 2020).

Under climate change, increases in temperature and decreased rainfall during spring and summer are likely to affect macroinvertebrate communities in the same way as drought, with the magnitude of these effects increasing from mid-century to end of century. Elevated periphyton growth may also contribute to shifts in macroinvertebrate communities by altering food availability and changing diurnal dissolved oxygen patterns. As water temperatures increase, flow velocities decrease and dissolved oxygen declines, and sensitive taxa are likely to be lost from some areas as species tolerances are exceeded (Davies-Colley et al. 2013). Initial inspection of water temperature data from a small number of continuously monitored sites suggests that some sites are already reaching summer temperatures high enough to cause significant thermal stress (Davies-Colley et al. 2013; NRC unpublished data).

In addition to the effects of high temperatures and low flows, extreme rainfall events and associated increases in deposited sediment are expected to have a significant negative effect on macroinvertebrate communities. Greater peak flood flows will alter habitat more than current flood disturbances; this will provide increased opportunities for faster recolonising species to gain competitive advantages when ecological communities are 'reset' by floods (Chase 2003; Death 2008). Predicted increases in sediment loads for Northland rivers, and therefore deposited fine sediment, will also cause large changes in physical habitat (Neverman et al. 2023). Elsewhere in Aotearoa New Zealand, deposited fine sediment has been shown to have a strong non-linear effect on sensitive mayfly, stonefly and caddisfly taxa, including a tipping point at approximately 20% deposited fine sediment cover, beyond which losses increase rapidly (Burdon et al. 2013). As sediment loads increase over time and under more extreme climate scenarios, the effects of climate change on macroinvertebrate communities are expected to intensify.

Key drivers of benthic periphyton cover in Northland are mean annual 7-day low flow, monthly maximum water temperature and the proportion of coarse bed substrate. Catchment geology also influences the relationship between periphyton and environmental drivers through effects on nutrient concentrations and visual clarity (Kilroy and Snelder 2024). Therefore, increases in temperature will increase periphyton cover and biomass, with larger increases by end of century and under the SSP3-7.0 scenario. Similarly, decreases in river flows associated with projected rainfall changes will also promote periphyton growth.

However, increased temporal variability in periphyton cover and biomass may occur, as Pearce et al. (2016) suggest there may be a slight increase in the frequency of floods exceeding three times the median flow. Combined with increases in deposited fine sediment and the potential for higher peak flood flows, this may increase the frequency of flow events that remove periphyton (noting that actual periphyton removal flows likely vary across rivers; Kilroy and Snelder 2024). As nutrient responses to climate change remain uncertain, it is unclear how these changes will affect periphyton, although spatial variation in periphyton biomass and cover is likely to persist due to catchment geology remaining constant. Similar patterns are expected for nuisance macrophytes in small streams due to shared drivers promoting growth.

Ecological processes

Ecosystem metabolism is the attribute used to assess ecological processes in the NPS-FM, and it was assessed as having a low sensitivity to temperature and rainfall. This classification was due to a lack of evidence to determine how ecosystem metabolism will respond to climate change stressors, including the potential for the direction of the response to be inconsistent depending on how intermediary drivers (nutrient concentrations and suspended sediment / light availability) respond to climate change.

As an indicator of instream ecological processes, ecosystem metabolism incorporates both gross primary production and ecosystem respiration (Goodwin and Young 2022). It not only signals changes in microbial processing but can also indicate changes in invertebrates and fish communities / population demographics, as body size, temperature, nutrients and food supplies can all impact their respiration (Freshwater Science and Technical Advisory Group 2019). Gross primary production is driven by photosynthesis from aquatic plants and periphyton, with the rate of photosynthesis determined by aquatic plant biomass, light levels, nutrient concentrations, carbon dioxide availability and temperature. Ecosystem respiration is dependent on the active biomass of living organisms, nutrient concentrations, oxygen availability and temperature (Goodwin and Young 2022). Therefore, both gross primary production and ecosystem respiration will increase with rising temperatures, although it is uncertain how nutrient concentrations will change with temperature. As a result, it is also unclear how nutrient concentrations will influence both aspects of ecosystem metabolism.

Changes in river flow resulting from changes in rainfall will have diverging effects. Lower and more settled flows will allow a greater accumulation of aquatic plant and periphyton biomass (increasing gross primary production and ecosystem respiration) but also reduce reaeration (Kilroy and Snelder 2024). Higher peak flood flows will increase suspended sediment loads (Neverman et al. 2023). This will likely decrease light availability and, in turn, reduce photosynthesis, while also increasing the removal of periphyton. However, current predictions and monitoring data suggest that sediment loads may be concentrated during storm events, so light levels during base flows may remain relatively similar (Chakraborty 2021; Neverman et al. 2023).

Given that ecosystem metabolism is a balance of photosynthesis (increasing dissolved oxygen) and respiration (depleting it), it is unclear how the combined effects of climate change will alter metabolism. Changes in temperature will likely increase both aspects of metabolism (potentially resulting in limited net change), while changes in rainfall could have a positive or negative effect depending on how flow and suspended sediment regimes influence photosynthesis rates. To date, attribute bands have not been defined for ecosystem metabolism; therefore, assessing the magnitude of changes in ecosystem metabolism in response to changes in climate stressors requires further information.

Human contact

The attributes used to assess human contact for rivers and streams in the NPS-FM are ***E. coli* concentration and planktonic cyanobacteria biovolume** (for lake-fed rivers only). *E. coli* concentration was assessed as having a low sensitivity to temperature and a moderate sensitivity to rainfall, while planktonic cyanobacteria biovolume was assessed as having a moderate sensitivity to temperature and low sensitivity to rainfall.

Recent investigation of drivers of *E. coli* concentrations in Northland did not identify any consistent relationships with other water-quality parameters, rainfall, river flow or stream morphology (Muirhead et al. 2023). High concentrations of *E. coli* were associated with areas of erosion-prone land developed for agriculture and floodplains with poorly drained soil where pastures have been developed (Rissman and Pearson 2020). This suggests that correlations observed at a national scale between *E. coli* and rainfall, temperature and turbidity may not hold true in Northland (Davies-Colley et al. 2018). Rather, intensive land use is a key driver of high *E. coli* concentrations in Northland, so changes in land use (including those driven by climate change) are a likely pathway for changes in *E. coli* concentrations (Muirhead et al. 2023). It is likely that the predicted increases in erosion will mobilise greater quantities of *E. coli* from agricultural land, but the degree of increase will be mediated by how intensive land uses are managed (Neverman et al. 2023).

Only a small proportion of Northland's rivers are classed as lake-fed, so the planktonic cyanobacteria attribute is only applicable to a few rivers across the region. The biovolume of planktonic cyanobacteria in these rivers will be driven by in-lake biovolumes, which are influenced by temperature, nutrient concentrations and wind conditions (refer to lakes section below). Water storage dams or ponds are also a potential source of planktonic cyanobacteria. It is likely that more water storage will be developed in response to climate change, but the quality of outflows from water storage facilities should be addressed as part of their outflow management.

Lakes

Values included in the risk assessment for lakes were based on those in the NPS-FM: namely, water quality, water quantity, aquatic life and human contact (Table 5). Key tipping points for lakes were identified as thermal stratification thresholds, critical water-level reductions affecting littoral zones, and temperature-driven regime shifts between macrophyte-dominated clear-water states and algal-dominated turbid states. There are multiple recent examples of lake collapse in Northland following droughts and cyclones, which indicates that Northland lakes are highly vulnerable to climate stress. Examples of lake collapse include sediment smothering of submerged vegetation in Lake Taharoa following Cyclone Gabrielle, as well as hypoxia followed by large-scale algal blooms and acidification in Lake Waiparera (S. Sunwar, NRC, pers. comm., 2 April 2026).

Water quality

The attributes used to assess water quality for lakes include **total nitrogen, total phosphorus, ammonia toxicity and dissolved oxygen**. All attributes of water quality were assessed as being highly sensitive to changes in temperature and rainfall, and moderately sensitive to changes in wind. Total nitrogen, total phosphorus and dissolved oxygen are moderately sensitive to changes in wind, while ammonia toxicity has a low sensitivity to changes in wind. Total nitrogen and total phosphorus are used to determine lake trophic state by combining concentrations with chlorophyll-*a* and water clarity to calculate the Trophic Lake Index. There is a moderate risk of change by mid-century and a high risk of change by end of century, with the trophic state of many lakes likely to shift from mesotrophic to eutrophic bands, or from eutrophic to supertrophic bands.

Total nitrogen and phosphorus are expected to increase with elevated temperatures due to enhanced mineralisation rates, increased internal loading from anoxic sediments, and greater catchment nutrient mobilisation during intense rainfall events. Temperature increases of 2–3 °C could accelerate nutrient cycling by 20–30% (Liikanen et al. 2002), while reduced spring rainfall may concentrate nutrients during critical growth periods. Under SSP3-7.0 scenarios, supertrophic conditions may become common in currently eutrophic systems, while SSP1-2.6 may maintain manageable nutrient levels through reduced warming.

Ammonia toxicity risk increases substantially with temperature, as the toxic un-ionised fraction increases exponentially above 20 °C. Combined with pH increases from algal blooms (Hussain 2023b), ammonia could exceed toxicity thresholds more frequently by end of century, particularly under SSP3-7.0 warming scenarios.

Dissolved oxygen faces severe depletion risks, with stronger thermal stratification extending anoxic periods in deeper lakes. Shallow lakes, such as Lake Rototuna, may experience disrupted mixing above 25 °C summer water temperatures, leading to persistent bottom-water anoxia and nutrient release events.

Water quantity

While there are no specific attributes for water quantity defined in the NPS-FM, the response of **lake levels** to climate change was assessed and found to have a high sensitivity to changes in rainfall, a moderate sensitivity to changes in temperature and a low sensitivity to changes in wind. The current state of water quantity shows lakes maintaining relatively stable levels despite recent dry periods (Champion 2021). There is a moderate risk of change by mid-century and a high risk by end of century, with water levels likely declining 0.5–1.5 m in perched dune lakes (Pham 2022). It is possible that this will cause shallow lakes to dry or become wetlands.

Water quantity is expected to decrease with increased temperature due to enhanced rates of evaporation from lakes and evapotranspiration across catchments, with a 26% increase in evapotranspiration already observed between 1981 and 2022 (Pham 2022). Temperature effects intensify exponentially above 25 °C mean annual air temperatures as water loss via evaporation and evapotranspiration accelerates. Similarly, water quantity responds negatively to reduced rainfall, with spring precipitation projected to decline by up to 10% by mid-century and 20% by end of century in eastern Northland (Champion 2021). This combination will create compound stress, as reduced recharge coincides with peak evaporative demand. While wind patterns interact with temperature to determine evaporative losses from shallow lakes, the reduction in the frequency of windy days means that wind is unlikely to compound drying rates.

Critical tipping points occur when water levels drop below 1 m depth, as littoral habitat is eliminated and sediments are exposed to oxidation. The shallow Te Hiku lakes face potential complete drying under extreme drought scenarios, representing an irreversible state change (Champion 2021). Uncertainty remains regarding groundwater contributions and their response to both changes in rainfall and sea level rise-induced saline intrusion in coastal areas. Under SSP1-2.6, adaptive management may maintain functional lake levels through demand management, while SSP3-7.0 scenarios suggest 20–30% volume losses becoming permanent by end of century, with some systems transitioning to seasonal wetlands (inferred from temperature and rainfall projections; Delclaux et al. 2007).

An additional consideration is the uptake of water by exotic forestry, as it potentially doubles drawdown rates during harvest rotations (Rip et al. 2016). However, without future land-use scenarios, it is not possible to quantify the effects of forestry on water availability. Overall, we classify water quantity as having a moderate to high risk of change due to a shifting climate led by the combination of temperature-driven evapotranspiration increases, rainfall reduction and anthropogenic water demands, with exposure increasing from moderate (mid-century) to high (end of century).

Aquatic life

The attributes used to assess aquatic life for lakes in the NPS-FM include **phytoplankton (trophic state), as well as native and invasive species of submerged plants**. The current state of aquatic life shows 14 lakes in outstanding condition and eight in high condition, with over 50% of lakes maintaining excellent or high LakeSPI scores (Champion and Burton 2018; Champion 2021). There is a moderate risk of change by mid-century and a high risk by end of century.

Phytoplankton biomass was assessed as having high sensitivity to changes in temperature and rainfall, and moderate sensitivity to changes in wind. Biomass will increase with temperature through extended growing seasons and enhanced nutrient availability. Cyanobacteria dominance becomes likely above 25 °C (Chao et al. 2017), with toxic bloom frequency potentially doubling by end of century. Wind pattern changes may reduce mixing, promoting surface algae scums. Under SSP3 scenarios, year-round bloom conditions could develop in currently mesotrophic systems. Many lakes will likely shift from mesotrophic to eutrophic bands, or from eutrophic to supertrophic bands, with increased degradation from mid-century to end of century.

Native submerged plants are moderately sensitive to changes in temperature and rainfall and have low sensitivity to changes in wind. Plant species face declining habitat suitability as water levels drop and turbidity increases from increased sediment inputs. Native charophytes, currently dominant in approximately 85% of high-value lakes, may lose 30–50% of their coverage by 2090 as maximum colonisation depths decrease from 7–8 m to 4–5 m (Hussain 2023b; Clayton and Edwards 2006). *Nitella* beds are particularly vulnerable to stress from epiphyton growth, silt deposition and water-level fluctuations (Hussain 2023b), with losses of > 30% macrophyte coverage potentially triggering a regime shift to turbid states (Thiemer et al. 2021; Zhang et al. 2021). Under SSP1, management interventions may maintain coverage above critical thresholds, but SSP3 scenarios suggest widespread collapse of native macrophyte communities by end of century.

Invasive submerged plants have high sensitivity to changes in rainfall and temperature, but low sensitivity to changes in wind. Currently, Northland's lakes have relatively low levels of invasive species, with invasive impact indices below 25% in most lakes, although species like *Utricularia gibba* and *Potamogeton crispus* are present (Champion and Burton 2018). There is a moderate risk of increased invasion by mid-century and a high risk by end of century, with invasive impact indices potentially increasing from low (< 25%) to moderate (25–50%) or high (> 50%) bands. Invasive species risk increases dramatically with temperature, particularly for subtropical weeds (Champion 2021). Currently, controlled species like alligator weed may overwhelm biocontrol agents above 25 °C mean temperatures, as observed at Lake Parawanui (Champion and Burton 2018). New invasive macrophytes from Australia could establish by mid-century under SSP3-7.0, with propagule pressure increasing through extended growing seasons (Champion 2014). The extended growing season under all scenarios increases propagule pressure and establishment windows (Champion 2014).

Overall, the combination of changes in phytoplankton, native submerged plants and invasive species will interact and could cause cascading effects as changes in climate intensify: phytoplankton blooms reduce light for native macrophytes, macrophyte loss increases nutrient availability for phytoplankton and invasive species exploit gaps created by native species decline. Under SSP1-2.6, targeted management may maintain ecological integrity in priority lakes, but projected climate changes under the SSP3-7.0 scenario suggest fundamental restructuring of aquatic communities may occur, with dominance shifting from native macrophytes to phytoplankton and invasive species assemblages.

Human contact
Similar to rivers, the attributes used to assess human contact for rivers and streams in the NPS-FM are ***E. coli* concentration and planktonic cyanobacteria biovolume**. *E. coli* concentration was assessed as having a low sensitivity to temperature, wind and rainfall, while planktonic cyanobacteria biovolume was assessed as having a high sensitivity to temperature and rainfall, and low sensitivity to wind.

Generally, *E. coli* concentrations are expected to correlate with rainfall and temperature, However, work done in Northland rivers did not identify any consistent relationships, and it is unknown whether these findings translate to Northland's lakes (Muirhead et al. 2023). Therefore, it is unclear how *E. coli* concentrations in lakes will respond to climate change. Intensive land use was a key driver of high *E. coli* concentrations in rivers, so changes in land use (including those driven by climate change) are a likely pathway for changes in lake *E. coli* concentrations (Muirhead et al. 2023).

Planktonic cyanobacteria pose the greatest human health risk, with biovolume likely exceeding the 1.8 mm^3/L threshold in the NPS-FM more frequently. Temperature increases will drive increased cyanobacterial growth and favour toxic species, with microcystin production potentially increasing substantially under end-of-century warming (Wood et al. 2015, 2017). The combination of rainfall associated nitrate pulses with warm water temperatures can also trigger cyanobacteria blooms in shallow lakes, suggesting that large pulses from extreme rainfall events could trigger prolonged blooms, although this can vary based on lake characteristics and nutrient conditions (Wood et al. 2017). Calm anticyclonic conditions predicted for Northland will further promote surface accumulations and the persistence of cyanobacteria blooms.

Wetlands

Wetlands include a broad range of ecosystems from bogs to gumlands and swamp. When considering the impact of climate change on wetlands, it is necessary to distinguish between natural wetlands that have intrinsic ecological value and constructed wetlands that have been created to assist in mitigating specific environmental issues (even though they may also have associated ecological values). As this risk assessment considered the effect of climate change on ecological values, only natural wetlands were considered. An additional stressor to consider for wetlands is fire, as it can have significant direct effects on wetland vegetation. The values for wetlands included in this risk assessment are taken both from the NPS-FM and discussions with NRC staff (Table 6).

Wetland extent
Wetland extent was assessed as having a moderate sensitivity to changes in temperature, a high sensitivity to changes in rainfall and a low sensitivity to changes in fire.

The reduction in annual rainfall, changes in seasonal rainfall patterns and changes in rainfall intensity will affect wetlands by influencing wetland hydrology as well as altering the recharge of groundwater feeding into wetlands. Both direct changes in rainfall inputs and changes in groundwater will reduce water availability for wetlands, likely leading to shifts in wetland vegetation composition over time and reducing wetland extent, exacerbating the already high loss of Northland's original wetlands (Robertson et al. 2016; Rissman et al. 2019). This will be compounded by higher air temperatures increasing water losses as evaporation. The current understanding of groundwater recharge and the interactions between Northland wetlands and groundwater is limited; therefore, it is not possible to relate climate projections to the rate at which wetlands will change (K. Hansen and J. Griffin, NRC, pers. comms., 16 September 2025). However, connections with groundwater may influence how resilient wetlands are to seasonal changes in rainfall, with the complete drying of wetlands being a key tipping point. An additional complication for coastal wetlands is the effect of sea level rise on groundwater levels, as this will likely further influence changes in groundwater level.

As changes in air temperature and annual rainfall by mid-century are relatively similar for SSP2-4.5 and SSP3-7.0, these scenarios are likely to initially have a similar impact on wetland extent. By end of century, the three climate scenarios diverge, with SSP3-7.0 having a greater impact on wetland extent due to a greater magnitude of change. While increases in fire risk and the frequency of fire disturbances in wetlands will alter vegetation composition, there is no clear evidence to suggest that changes in fire regimes will alter wetland hydrology (McGlone 2009) and so wetland extent.

Wetland quality

The key indicator used to monitor wetland quality in Northland is the **Wetland Condition Index** (NRC 2023). The Wetland Condition Index is an aggregate index of wetland ecological integrity combining qualitative scores for wetland hydrology, soils / nutrients, ecosystem intactness, native animal dominance and native plant dominance. Wetland quality was assessed as having a moderate sensitivity to changes in temperature and rainfall, and a high sensitivity to changes in fire.

Increases in air temperature and the effective loss of frosty days will increase the length of the growing season, and combined with reduced annual rainfall, favour the invasion of wetlands by dryland plants (Robertson et al. 2016). Increases in extreme rainfall are expected to increase fine sediment inputs into wetlands due to increased sediment loads in wetland inflows (Neverman et al. 2023). Predictions for increases in sediment loads vary between mid-century and end of century and between climate change scenarios (see Section 3.2 – Rivers and streams – Habitat), but all scenarios represent a significant increase in sediment inputs. Under the lowest-change scenario reported in Neverman et al. (2023), sediment loads still increased 49% by 2090 under RCP 2.6, and 233% by 2090 under the most extreme RCP 8.5 scenario.

In turn, wetland quality will be affected through the input of nutrient-rich sediment from pastoral land altering physico-chemical parameters and having potential implications for plant composition and diversity (Burge et al. 2020). Monitoring in Auckland and Hawke's Bay following Cyclone Gabrielle has shown increased sedimentation in wetlands but no short-term decline in wetland quality, suggesting that the impacts of extreme weather may take time to become apparent through gradual shifts in wetland vegetation (Allen et al. 2024). An increased frequency of extreme rainfall events could also aid flood-mediated movement of exotic species (Hamilton et al. 2013).

More frequent fires are expected to significantly degrade wetland quality, as increased disturbance alters vegetation communities and facilitates increased dryland plant invasion; this is because exotic species are often quicker to re-establish post-fire (Christensen et al. 2019). Gumlands are a specific concern, as the frequency of fires is in this wetland type is expected to increase from once every 1,000 years to once every 20 years (K. Hansen, NRC, pers. comm., 16 September 2025). In turn, this may create a positive feedback loop if invading exotic species are more flammable, potentially further increasing the fire frequency.

Values spanning all freshwater ecosystem types

Two values (Threatened species and Natural form and character) span all freshwater ecosystem types. To reduce repetition, the risk assessment for these values has been combined across all ecosystem types (Table 7).

Threatened species
In general, threatened species are subject to the same overall pressures as the broader freshwater ecosystem. However, consideration also needs to be given to protecting the specific requirements for threatened species to complete all stages of their life cycle. Many of the threatened freshwater species (as listed by the New Zealand Threat Classification System) and other freshwater species of conservation interest present in Northland are identified in Ruehle (2023), including vascular plants, non-vascular plants, freshwater macroinvertebrates, fish, birds and amphibians. Additional species, such as those classified as 'at risk' or 'data deficient' are likely also of interest for regional biodiversity management.

Assessing the climate change vulnerability of individual threatened species was beyond the scope of this risk assessment, but some threatened species have already been assessed as part of work to assess the climate change vulnerability of selected taonga freshwater species (Egan et al. 2020) and terrestrial species (Brumby et al. 2025) based on species traits (Table 8). Table 8 is not an exhaustive list of the threatened species present in Northland; rather, it indicates the species that have been assessed as part of national-scale climate change vulnerability assessments. All assessed threatened species present in Northland display traits that make them highly vulnerable to climate change, but how species will respond to climate change stressors remains uncertain. A similar assessment of the climate change vulnerability of Aotearoa New Zealand's freshwater fish is currently underway by DOC.

Based on national assessments of threatened species found in Northland, the overall threatened species value was evaluated as being highly sensitive to changes in temperature, rainfall and fire regimes, and as having low sensitivity to changes in wind. This assessment reflects the potential for climate-related disturbances to extirpate local populations of threatened species.

Table 8. Threatened species identified as occurring in Northland by Ruehle (2023) and results of trait-based climate change vulnerability assessments (CCVA) completed for terrestrial (Brumby et al. 2025) and freshwater taonga species (Egan et al. 2023). N/A = not assessed. NZTCS = New Zealand Threat Classification System.

Species	Name (NZTCS)	Taxa type	Brumby et al. (2025) terrestrial species CCVA ranking	Egan et al. (2023) freshwater taonga species CCVA ranking
Anarhynchus frontalis	Wrybill (ngutu pare / ngutu parore)	Bird	Highly vulnerable, priority 1	N/A
Anas chlorotis	Brown teal (pāteke)	Bird	Highly vulnerable, priority 1	N/A
Anas superciliosa	Grey duck (pārera)	Bird	Highly vulnerable, priority 3	N/A
Botaurus poiciloptilus	Australasian bittern (matuku hūrepo)	Bird	Highly vulnerable, priority 2	N/A
Hydroprogne caspia	Caspian tern (taranui)	Bird	Highly vulnerable, priority 3	N/A
Poliocephalus rufopectus	New Zealand dabchick (weweia)	Bird	Highly vulnerable, priority 4	N/A
Galaxias postvectis	Shortjaw kōkopu (kōkopu)	Fish	N/A	Insufficient information
Geotria australis	Lamprey (piharau)	Fish	N/A	Very highly vulnerable (corresponds to the priority 1 ranking from Brumby et al. 2025)
Neochanna heleios	Northland mudfish	Fish	N/A	N/A
Echyridella aucklandica and Echyridella menziesii	Freshwater mussel (kākahi)	Macroinvertebrate	N/A	Insufficient information
Galaxias 'dune lakes'	Dune lake galaxiid	Fish	N/A	N/A
Edpercivalia dugdalei	Caddisfly	Macroinvertebrate	N/A	N/A
Helicopsyche torino	Caddisfly	Macroinvertebrate	N/A	N/A
Paxillostium nanum	Freshwater snail	Macroinvertebrate	N/A	N/A
***Zephlebia* aff. *pirongia* sp. 1**	Mayfly	Macroinvertebrate	N/A	N/A
Corybas carsei	Swamp helmet orchid	Vascular Plant	N/A	N/A
Hibiscus diversifolius* subsp. *diversifolius	–	Vascular Plant	N/A	N/A
Isolepis lenticularis	Aquatic sedge	Vascular Plant	N/A	N/A

Species	Name (NZTCS)	Taxa type	Brumby et al. (2025) terrestrial species CCVA ranking	Egan et al. (2023) freshwater taonga species CCVA ranking
Korthalsella salicornioides	Dwarf mistletoe	Vascular Plant	N/A	N/A
Kunzea robusta	Rawirinui (rawirinui)	Vascular Plant	N/A	N/A
Leptospermum scoparium* var. *incanum	Manuka	Vascular Plant	N/A	N/A
Machaerina complanata	–	Vascular Plant	N/A	N/A
Ophioglossum petiolatum	Stalked adder's tongue fern	Vascular Plant	N/A	N/A
Pterostylis micromega	Swamp greenhood	Vascular Plant	N/A	N/A
Pterostylis puberula	Dwarf greenhood	Vascular Plant	N/A	N/A
Schoenus carsei	–	Vascular Plant	N/A	N/A
Syzygium maire	Swamp maire (maire tawke)	Vascular Plant	N/A	N/A
***Thelymitra* 'Ahipara'**	Sun orchid	Vascular Plant	N/A	N/A
Todea barbara	Royal fern	Vascular Plant	N/A	N/A
Trithuria inconspicua	Hydatella	Vascular Plant	N/A	N/A
Utricularia australis	Yellow bladderwort	Vascular Plant	N/A	N/A

Areas in Northland with a high number of threatened species occurrences include the Poutō Peninsula, Waipoua Forest, Aupōuri Peninsula, Lake Ōmāpere, Puketi Forest, Bay of Islands, Pukenui Forest, Russell Forest and the east coast of the North Island in general. Most records occur on natural land-cover types and in outstanding or high-value lakes, which is likely a function of both habitat use and the spatial focus of sampling effort (Champion 2021; Ruehle 2023). Consideration of the effects of climate change on threatened species needs to account for individual species characteristics, such as reproductive habitat, dispersal corridors and mechanisms, as response to climate stressors will differ among species. It is likely that several species will face local extinctions, especially under SSP3-7.0 projections (Champion 2021). For example, shortjaw kōkopu populations in Northland face loss of habitat due to increased erosion, which alters habitat structure and increases sedimentation in key habitats (F. Donovan and C. Nicholson, DOC, pers. comm., 17 September 2025).

Reproduction is likely one of the first demographic parameters of threatened species to be impacted by climate change, as increased environmental stress can reduce breeding success, climate-driven changes disrupt behavioural cues, and changes in water flow, water level and sedimentation alter spawning and breeding habitats. A key mitigation measure is the protection of critical spawning and breeding habitats because the loss of these habitats represents a major tipping point for species persistence. However, understanding species requirements for spawning and breeding habitats remains a key knowledge gap for implementing effective protection actions for most species. In particular, for threatened fauna, there is a need to identify such habitats within current species distributions. Connectivity between adult habitat and spawning and breeding habitats is also a critical consideration, as loss of connectivity can prevent reproduction and contribute to local extinctions. For example, dune lake galaxiids[4] spawn in the vegetated littoral zone of Lakes Taharoa and Waikere. As low lake levels are expected more frequently, these species are likely to experience increased disconnection from their spawning habitats, with consequent disruption to reproduction (Dunn et al. 2025).

Natural form and character

While there are no specific attributes for natural form and character defined in the NPS-FM, the natural character of Northland's rivers has previously been assessed using indicators of river shape, flow regime, water quality, the presence of human modifications, native and exotic flora and fauna, and the character of the wider landscape (Booth et al. 2013). Most of these indicators correspond to attributes included in this risk assessment, including water quality, water quantity, habitat and aquatic life. Alongside these attributes, the prevalence of invasive species is a further indictor for which the effects of climate change can be anticipated. Higher temperatures will increase the impact of existing invasive species and enable the establishment of new invasive species as conditions become more suitable, including through increased growing season length and greater propagule pressure. Tipping points will exist where increases in temperature allow species to establish local breeding populations, such as red-eared slider turtles. An increased frequency of extreme rainfall events under climate change could also aid flood-mediated movement of exotic species (Hamilton et al. 2013).

The current state of natural form and character of lakes reflects the diverse lake types present in Northland, from oligotrophic dune lakes to eutrophic volcanic systems (Champion and de Winton 2012; Champion 2021). Lake morphology will shift through littoral zone exposure and sedimentation, and reduced water levels will eliminate shallow bays critical for wildlife (Champion 2021). Notably, catchment erosion from intense rainfall events may accelerate infilling rates by two- to threefold. The distinctive clear-water character of dune lakes faces fundamental alteration, with irreversible shifts to turbid states possible once macrophyte coverage drops below a 30% threshold (Hussain 2023a), consistent with European restoration guidelines (Hilt et al. 2006).

For wetlands, an increased frequency of fires will degrade natural character through increased disturbance, altering vegetation communities and facilitating increased dryland plant invasion post-fire. The long-term reduction in water availability also has the potential to alter wetland character, with reduced annual rainfall resulting in peat growth cessation or retreat, decreased wetland extent and change in vegetation composition favouring invasive dryland plants (Keegan et al. 2022).

However, changes in human modifications and the character of the wider landscape depend on land-use change in response to both climate change and associated regional and national policy settings. Therefore, not all indicators of natural form and character can be assessed without future land-use

[4] Listed in Ruehle (2023) as 'Taxonomically indistinct' and noted as overlooked in databases due to being genetically similar to dwarf īnanga. Now classified as 'Threatened – national endangered', which is the most recent conservation status of New Zealand freshwater fishes (Dunn et al. 2025).

scenarios. Based on the available attributes and indictors already assessed here, natural form and character is expected to be moderately sensitive to changes in fire, temperature and rainfall (high sensitivity for lakes) with low sensitivity to changes in wind. This reflects that natural form and character is a function of multiple attributes, and changes in a single attribute may be partially buffered by others.

In summary, wetlands and dune lakes emerge as particularly climate-sensitive ecosystems due to their dependence on water levels, groundwater interactions, and susceptibility to threshold responses such as regime shifts, drying or persistent stratification. These systems also support unique and often threatened biodiversity. Their protection and restoration provide important hydrological buffering functions, including flow attenuation, sediment retention and thermal regulation, while also enhancing habitat availability. Managing invasive species in these systems is likely to become increasingly important under warming conditions, as climate change may favour the establishment and spread of non-native species.

3.3 Limitations of risk assessment

While the risk assessment showed that many freshwater values are exposed and sensitive to climate change stressors, considering values at a regional scale is too coarse to identify clear management priorities at local or sites scales. In particular, the absence of downscaled hydrological and groundwater projections limits confidence in assessing flow-dependent stressors and groundwater-linked ecosystem responses.

The assessment also relies primarily on projected changes in mean climate conditions, whereas many ecological impacts are driven by extreme events, cumulative pressures, and interactions among climate stressors and other drivers such as land use, abstraction and invasive species. These interacting and potentially non-linear effects are not explicitly quantified.

Sensitivity classification should also be interpreted with caution. Values classified as having low sensitivity may reflect uncertainty or limited evidence rather than low risk (e.g. ecosystem metabolism), highlighting priorities for further research. Some ecological responses may also occur with time lags or before they are detectable using existing monitoring indicators.

4. Monitoring climate change effects on freshwater

Key messages

Monitoring how freshwater ecosystems respond to climate change involves both monitoring rapidly responding changes in climate and slower responding freshwater attributes. It is essential to develop an improved understanding of causal links and identify lag times between changes in climate stressors and ecological effects. A key element to achieve this is the collection of robust long-term datasets, especially in developed catchments where multiple pressures operate concurrently. Without robust long-term monitoring, it will be challenging to confidently distinguish the effects of climate change from other environmental pressures.

Freshwater monitoring should represent the varied freshwater ecosystems present across Northland and retain currently monitored attributes. Monitoring frequency should involve a combination of continuous monitoring to capture extremes and regular discrete monitoring to continue tracking freshwater attributes. It should also include less regular or more dispersed monitoring for slower responding attributes or patchily distributed threatened species.

Key gaps in existing monitoring that require attention include work to build a better understanding groundwater–surface water interactions and wetland hydrology. Targeted monitoring of metals and emerging contaminants guided by land-use information would aid in identifying new and potential sources of pollution. In addition, investing in data infrastructure would help retain invasive and threatened species observations that can inform how species distributions shift with climate change.

How best to partner with iwi and hapū to incorporate mātauranga Māori freshwater indicators should also be considered. This includes co-developing cultural monitoring frameworks that reflect local priorities, maintain Māori leadership and data sovereignty, and are explicitly used to inform freshwater planning decisions.

Tracking the response of freshwater ecosystems to climate change involves both monitoring changes in climate and the response of freshwater ecosystems. Climate variables such as air temperature, evapotranspiration and rainfall provide fast-responding indicators of climate and allow climate stressors to be quantified. In contrast, ecological responses in freshwater ecosystems reflect the cumulative effects of climate change on freshwater values and may take longer to be detectable. **Monitoring both climate variables and freshwater responses is therefore essential** for developing causal understanding, improving attribution and identifying lag times between changes in climate stressors and ecological effects – particularly in developed catchments where multiple pressures operate concurrently.

Long-term environmental datasets are essential for tracking climate change effects, linking climate drivers to freshwater responses and providing input data for modelling future ecosystem states. NRC already invests substantially in environmental monitoring, and existing data are directly relevant to climate change assessment. **Applying best-practice monitoring principles will maximise the usefulness of current datasets**. For many environmental variables, best practise is set out in the National Environmental Monitoring Standards (NEMS),[5] which provide nationally consistent guidance. Key principles across the NEMS include maintaining stationarity for monitoring locations and methods, explicitly accounting for uncertainty when changes are unavoidable, and using quality codes to ensure that lower-quality data are retained but interpreted appropriately. Where no NEMS guidance exists, monitoring should follow published protocols where possible. If monitoring methods change, overlapping data collection using both old and new methods should be undertaken for a sufficient time to assess potential step changes.

Maintaining long-term monitoring of adequate reference sites is particularly important for climate change assessment. Although reference sites will be affected by climate change, they provide essential context for distinguishing climate-driven change from other pressures, identifying the influence of large-scale climatic variability (e.g. El Niño–Southern Oscillation) and interpreting trends observed in more developed catchments.

A key challenge in linking climate change to ecological responses is ensuring sufficient statistical power to detect change while accounting for ongoing improvements in monitoring methods. The ability to detect statistically significant change varies among indicators, especially for discretely sampled variables. Monitoring programmes therefore need sampling frequencies appropriate to the timescales over which change is expected, with higher frequencies required for shorter assessment periods. Methodological improvements can also complicate trend assessment. For example, improvements in wetland mapping resolution allow smaller wetlands to be detected, which affects apparent changes in wetland extent over time (J. Griffin, NRC, pers. comm., 16 September 2025).

Monitoring designed to track climate change effects is distinct from monitoring intended to evaluate the effectiveness of mitigation or restoration actions. Climate-focused monitoring should prioritise representativeness across ecosystem types to support attribution and modelling of future states, whereas assessing mitigation effectiveness requires targeted monitoring designed for that purpose.

Recent external reviews indicate that **NRC's current surface water monitoring networks are broadly ecologically representative**. The river monitoring network provides balanced coverage across freshwater management units (Clapcott and Goodwin 2021), lake monitoring programmes are appropriate for tracking ecological condition and water quality (Champion 2021), and proposed wetland monitoring sites capture a representative range of wetland types (Clarkson and Price 2022). Existing monitoring locations are therefore suitable for tracking climate change effects and should be

[5] Available from: https://www.nems.org.nz/

maintained (Figure 1). Groundwater monitoring locations should also be retained to maintain the continuity of long-term data records.

Where mitigation or restoration efforts are implemented, additional targeted monitoring should be undertaken to assess their effectiveness and separate these effects from other environmental drivers. The same holds true for areas where there is investment in land development to ensure sufficient input data are available for modelling future ecosystem states or conducting expert panel processes (depending on the spatial scale of development).

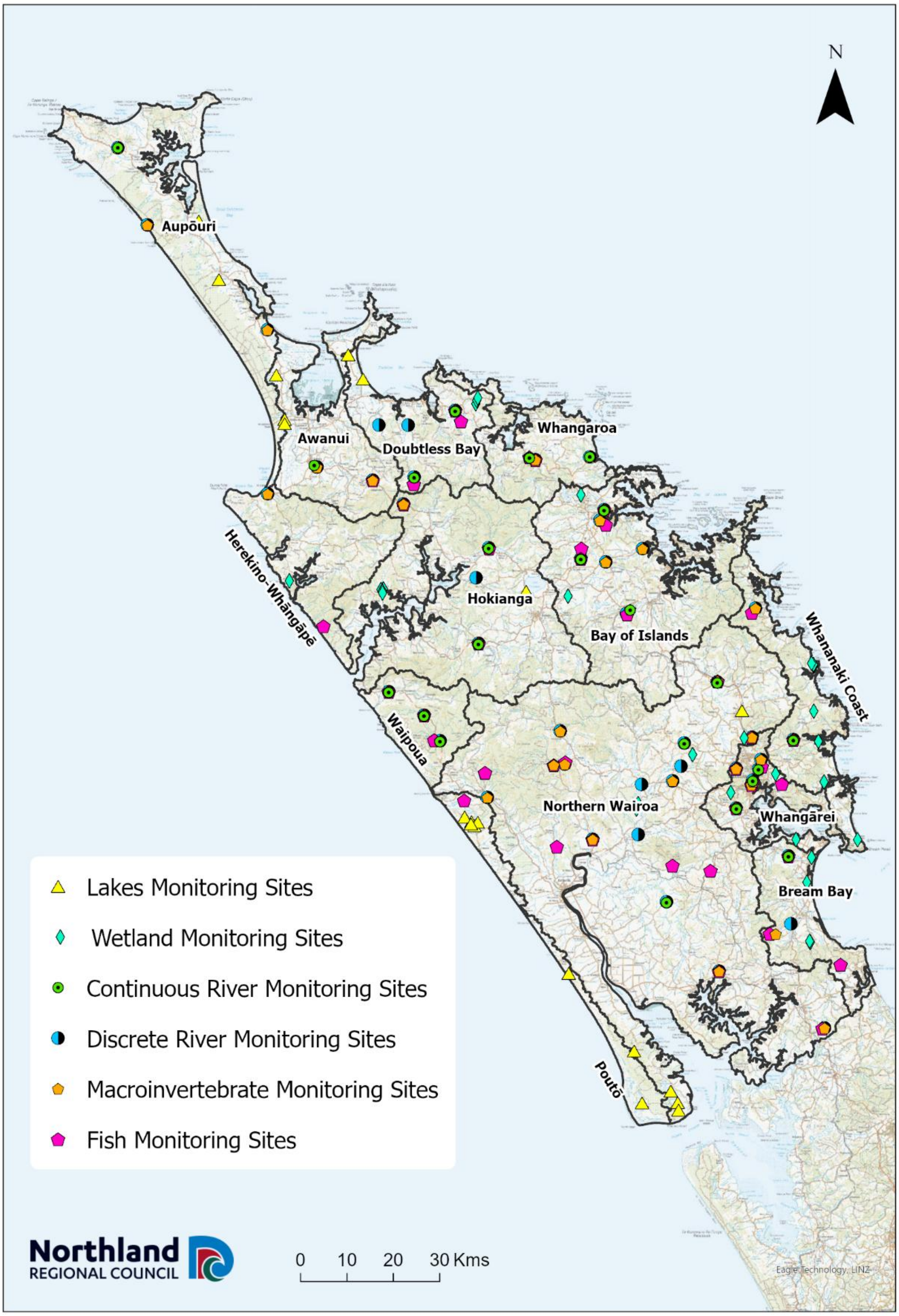

Figure 1. Map of Northland Regional Council's current river and lake monitoring network. Continuous river monitoring sites include discrete river monitoring. Discrete river monitoring includes sites monitoring, macroinvertebrates, periphyton and water quality. Groundwater monitoring sites are not shown.

4.1 Monitoring climate

Key climate variables for assessing impacts on freshwater ecosystems include air temperature, evapotranspiration, rainfall and wind. Both instantaneous weather conditions (e.g. peak temperatures, rainfall intensity) and long-term climate patterns are relevant. Extreme conditions are particularly important for understanding disturbance processes and thresholds, while long-term climate data inform modelling of freshwater responses, such as changes in water availability and flow regimes.

Best practice for monitoring rainfall is documented in the NEMS for rainfall recording (NEMSWG 2017), while NEMS for air temperature and wind are currently under development. Evapotranspiration and potential evapotranspiration time-series are available for all Aotearoa New Zealand climate stations and modelled datasets for approximately 5 km pixels within the Virtual Climate Station network (operated by Earth Sciences New Zealand and MetService; Tait et al. 2006), with methods aligned to World Meteorological Organization standards. Ongoing work to improve spatial representation of evapotranspiration, including the use of remote sensing approaches, will further support assessments of recharge and water availability (Mourot et al. 2019).

For climate monitoring to support freshwater management, is must be possible to relate climate data to freshwater monitoring records. Monitoring locations should collect representative data at the catchment or Freshwater Management Unit scale, but climate and freshwater monitoring sites do not need to be co-located. Maintaining long-term records is critical, so changes in monitoring locations should be minimised. Short- to medium-term instrument deployments or comparisons may be useful for investigating local climate–ecosystem relationships or improving spatial resolution for modelling inputs.

4.2 Monitoring freshwater

Monitoring freshwater ecosystems to track responses to climate change and extreme weather events involves a combination of continuous monitoring, routine discrete monitoring and less frequent or spatially dispersed surveys. Together, these approaches capture both fast-responding environmental conditions and slower ecological responses across a range of freshwater values. Recommendations for how to best track responses to climate change are summarised in Table 9.

Maintaining long-term reference sites is critical for separating climate change effects from other drivers and for assessing whether responses observed in Northland are consistent with national patterns. While the existing river monitoring network includes a small number of reference sites, lake and wetland monitoring networks prioritise high-value systems that are not true reference sites due to mixed land use within their catchments. Moreover, groundwater monitoring focuses on coastal aquifers and areas of high abstraction demand. Retaining existing reference sites is therefore important, and targeted supplementary monitoring may be required. For lakes and wetlands, data from the least-impacted sites could be combined with expert judgement to estimate reference conditions where true reference sites are unavailable.

To further separate climate change effects from other pressures, such as land-use change, it would be beneficial to incorporate information on those pressures into analyses of long-term monitoring datasets, or through targeted monitoring linked to consent conditions or collaboration with industry groups.

Table 9. Summary of monitoring recommendations for tracking responses to climate change across freshwater ecosystem types.

Ecosystem types	Monitoring recommendations
Across all ecosystem types	• Maintain long-term monitoring of reference sites and existing surface water monitoring networks. • Apply best-practice monitoring principles to maximise the usefulness of current datasets. • Investigate integrating existing data sources to centralise observations for both threatened and invasive species.
Rivers and streams	• Clarify sediment monitoring objectives to determine whether suspended sediment gauging or repeated sediment source fingerprinting would best meet information needs. • Consider targeted monitoring of small, low-order streams that are under-represented in current networks.
Lakes	• Expand water-level monitoring in high-value lakes. • Expand continuous dissolved oxygen monitoring to additional high-value lakes.
Wetlands	• Implement water-level monitoring in high-value wetlands. • Consider monitoring Australasian bittern (*Botaurus poiciloptilus*) as an indicator species to signal changes in wetland conditions.
Groundwater	• Develop the understanding of aquifers beyond coastal aquifers and areas of high abstraction demand, particularly where groundwater may sustain surface flows (e.g. basalt geology).

Continuous monitoring

The key advantage of continuous monitoring is that the high-frequency data enables environmental extremes to be captured. Hydrological monitoring of river flows and water levels is a key source of information for assessing water availability and disturbance regimes and supporting flow projections. While river hydrological monitoring aligns well with river ecology and water-quality networks, lake water-level monitoring is currently limited to 12 sites, and wetland water-level monitoring is minimal (Clapcott and Goodwin 2021; Chakraborty 2023; K. Hansen, NRC, pers. comm., 16 September 2025). Expanding water-level monitoring in high-value lakes and in wetlands is recommended.

Understanding groundwater–surface water interactions is also important for modelling climate-driven changes in water availability. Current groundwater monitoring focuses on coastal aquifers and areas of high abstraction demand, with continuous groundwater monitoring occurring at 12 sites (S. Osbaldiston, NRC, pers. comm., 23 October 2025). Further developing the understanding of other aquifers, particularly where groundwater may sustain surface flows (e.g. basalt geology), would improve assessment of climate change effects.

For rivers, continuous high-frequency monitoring currently includes dissolved oxygen and turbidity (as a proxy for suspended sediment) alongside river flow, water temperature, conductivity and pH. Dissolved oxygen is measured at seven telemetered and 15 non-telemetered sites, with data records available from at least 2019. Monitoring should be maintained at existing sites to preserve continuity. Event sampling has allowed turbidity data to be related to suspended sediment loads in two rivers, but this approach is resource intensive and difficult to scale up (Chakraborty 2021). Multiple monitoring approaches are recognised in the NEMS for suspended sediment (NEMSWG 2025), and recommendations from the recent review of Northland's sediment monitoring network (Anderson 2024) should be implemented where feasible. Decisions about monitoring approaches should be guided by management information needs, including whether the priority is tracking change in ecological state or informing mitigation actions. Investigations targeting changes in ecological state should be focused on reference sites, while investigation of mitigation actions should include control sites to separate climate signals from mitigation effects; for example, implementing a paired monitoring design involving reference and impact sites is preferable.

Monitoring resources are limited, and large increases in sediment load are predicted. Therefore, a key consideration is whether to monitor changes in suspended sediment through the proxy of turbidity or use suspended sediment gauging at multiple flows to relate turbidity data to suspended sediment loads. Suspended sediment gauging would allow ground-truthing of sediment predictions through generating site-specific regression relationships between turbidity and suspended sediment load without the cost of event sampling. Accurate ground-truthing of sediment predictions, including high-flow events, would require development of a sediment rating curve over a variety of flows (Hicks et al. 2019). As sediment loads are predicted to change over time, sediment gaugings would need to periodically be repeated to validate or update suspended sediment estimates generated from turbidity data.

There are few recent examples of suspended sediment gaugings, as reported suspended sediment studies employ automated event sampling (e.g. Hoyle et al. 2011). However, the calibration dataset for updating the national sediment load model for Aotearoa New Zealand compiled measured stream sediment loads from suspended sediment gauging, including six sites in Northland (Hicks et al. 2019). Alternatively, repeating sediment fingerprinting using stable isotopes would allow investigation of whether sediment sources are changing, or targeted monitoring of sediment management interventions could assess the efficacy of mitigation actions. Another low-cost option would be using grab samples to calibrate turbidity records to suspended sediment concentrations and infill gaps during high flows should over-ranging of turbidity sensors occur (see NEMSWG 2025 for guidance). Therefore, consideration needs to be given to whether information is needed to track changes in current state or guide the implementation of management actions.

For lakes, NRC's continuous monitoring of temperature and dissolved oxygen at 12 outstanding lakes provides long-term datasets for distinguishing climate signals from natural variability (Champion 2021;

Chakraborty 2023). Telemetered buoys at Lakes Taharoa and Ngatu provide high-resolution data for multiple parameters, assisting detection of climate-driven changes in stratification and nutrient cycling that would not be captured by monthly sampling (Chakraborty 2023). Dissolved oxygen is a key attribute for continuous monitoring because it is highly sensitivity to temperature changes (see Section 3.2), with projections showing that 2–3°C warming could accelerate nutrient cycling by 20–30% (Liikanen et al. 2002) and trigger persistent anoxia events that release legacy nutrients from sediments (Hussain 2023b). We recommend that NRC strengthen climate change assessment by extending continuous dissolved oxygen monitoring to additional high-value lakes prone to stratification. We also advise further implementation of monthly profiling during critical stratification periods, deploying hypolimnetic sensors as recommended by Elliott et al. (2020). If resources are constrained, expanding the spatial coverage of continuous lake monitoring could be done with short-term sensor deployments in additional lakes (provided current lake monitoring is maintained). Such additions would provide an indication of the stratification regimes and enable calculation of the hypolimnion oxygen depletion rates for more lakes. Connecting wind data with dissolved oxygen records may also improve understanding of changes in lake mixing.

Continuous nutrient monitoring is currently a lower priority, as existing evidence suggests nutrients are not the primary driver of river ecosystem health in Northland (Graham and Greenwood 2023; Kilroy and Snelder 2024), and nutrient concentrations are captured though routine discrete sample. Short-term deployments during extreme rainfall events may nevertheless provide useful information on nutrient pulses.

Routine discrete monitoring

Routine discrete monitoring, such as NRC's SOE programme, complements continuous monitoring by tracking the state and trends of a broad suite of freshwater attributes indicating water quality, ecosystem health and human contact in rivers and lakes. As these networks are broadly ecologically representative, they provide valuable information for calibrating models. Known biases should be addressed, particularly the under-representation of small, low-order streams. We support the recommendation of Clapcott and Goodwin (2021) to undertake targeted monitoring of these streams.

A further gap in current discrete monitoring is limited coverage of metals and emerging contaminants. Although these attributes are not included in this risk assessment, it is possible that climate-driven erosion or land-use change could introduce new sources of pollution. For example, high concentrations of total aluminium have been recorded in the Northern Wairoa catchment and associated with high suspended solids following rainfall events (Chakraborty 2025). It is expected that such peaks will increase as the intensity of rainfall events escalates and sediment loads increase under climate change. A targeted monitoring approach informed by land-use spatial data is likely to be sufficient to address this risk of emerging contaminants.

Less regular or more dispersed monitoring

Some attributes fall outside monthly SOE monitoring because their slow response warrants less frequent monitoring, or because their patchy spatial distributions mean existing monitoring networks do not adequately capture species patterns. For example, wetland monitoring or LakeSPI monitoring of lake macrophyte communities, undertaken every few years, can still capture temporal change over long periods and allow tracking of ecological components not represented by continuous or monthly discrete monitoring, such as wetland condition or species presence.

Tracking freshwater ecosystem responses to climate change could also include assessing or modelling shifts in species distributions, including threatened and invasive species. This first requires understanding current species distributions, as existing monitoring networks are not designed for this purpose. Ruehle (2023) demonstrated how existing databases can be used to compile existing records of threatened species from multiple sources. This approach could be extended by developing data infrastructure that brings together monitoring data and observations from multiple sources (e.g. NRC, DOC, Ministry for Primary Industries, and community monitoring and citizen scientists through platforms such as iNaturalist). While this would require an initial investment and coordination across organisations, it would likely require less long-term investment than establishing an additional monitoring programme. Currently, the distribution of invasive species in Northland is not well mapped, so integrating existing data sources for both threatened and invasive species could support assessment and modelling of distributional changes in response to climate change.

Potential value of indicator species

Certain species may be suitable indicator species of ecosystem responses to climate change, through changes in distribution, abundance or reproduction. Potential indicator species include those whose requirements encapsulate those of associated species, or species with well-defined ecological requirements (Carignan and Villard 2002). In wetlands, Australasian bittern (*Botaurus poiciloptilus*) could serve as landscape-scale indicators of suitable emergent vegetation and food availability and can be monitored using acoustic recorders (O'Donnell and Williams 2015). Implementing such an approach may require extending the critical bird habitat coastal layer in the Proposed Regional Plan to include key inland wetland landscapes, particularly if an observed-versus-expected approach is adopted.

In rivers, long-term records of macroinvertebrate communities at reference sites can indicate ecological shifts in response to long-term environmental changes; however, linking such signals to climate change would require sufficient environmental information to account for non-climate drivers. In a management context, developing indicator species may also offer co-benefits for other regional roles and responsibilities. In addition, they may promote advocacy and public engagement, as the public are likely to more actively support efforts with tangible outcomes for key species compared to less tangible environmental parameters.

In lakes, aquatic plants already serve as indicators through the LakeSPI native plant condition index, but changes in depth distributions could provide additional information on changes in water clarity and temperature. For example, native charophyte meadows have retreated to shallower waters as clarity declined in Lake Rotokawau (Champion and Burton 2018). Other species, such as the native bladderwort *Utricularia australis,* appear highly sensitive to water-quality changes, and replacement by *Utricularia gibba* under warmer, more nutrient-rich conditions may provide a further indictor of climate-driven change, albeit one constrained by current species distributions (Champion 2021). There may also be value in retaining monitoring resources to assess unexpected changes in freshwater ecosystems, particularly following climate extremes. Understanding causes of unexpected changes, such as lake collapses, could provide information on factors that influence the resilience of waterbodies to climate extremes, and so indicate the vulnerability of other waterbodies or offer evidence to guide mitigation efforts.

4.3 Cultural monitoring and mātauranga Māori indicators

Monitoring approaches that incorporate mātauranga Māori provide a critical complement to biophysical monitoring by capturing changes in freshwater systems that are not always detected through standard indicators. Mātauranga Māori is a distinct knowledge system grounded in relationships between people, place and the environment, and expressed through values such as whakapapa, mauri and kaitiakitanga (Clapcott et al. 2018). Cultural (or biocultural) monitoring integrates ecological observations with cultural values, practices and lived experience to assess freshwater condition and resilience in a more holistic and place-based way.

These approaches are particularly important for understanding climate change effects. Conventional monitoring frameworks are often constrained by fixed temporal scales and standardised indicators, whereas mātauranga Māori monitoring reflects event-based, seasonal and intergenerational understandings of change (Clapcott et al. 2025). This enables detection of environmental variability, extremes and thresholds that are central to climate-driven change. For example, cultural monitoring in the Te Wairoa catchment demonstrated that sedimentation impacts were clearly expressed through declines in mahinga kai availability, access and ecosystem condition, highlighting cumulative effects that may not be fully captured through standard water-quality metrics alone (Galvan et al. 2024).

Effective incorporation of mātauranga Māori in NRC's monitoring programmes requires co-development with iwi and hapū. Monitoring frameworks should be jointly designed, with indicators reflecting local priorities such as mahinga kai, taonga species and culturally significant sites. These may include species presence and condition, timing of seasonal events, accessibility of harvest and culturally grounded assessments of flow, habitat and water quality. Cultural flow preference studies demonstrate how flow regimes can be explicitly linked to cultural values, identifying thresholds below which cultural well-being and ecosystem function are compromised (Tipa and Nelson 2012).

Cultural monitoring is most effective when undertaken alongside biophysical monitoring, with each knowledge system informing interpretation. Evidence shows that bringing together knowledge holders – rather than simply integrating datasets – leads to more meaningful and actionable outcomes (Clapcott et al. 2018). Story-based approaches further support this by capturing intergenerational knowledge of environmental change, species behaviour and river condition, providing insight into long-term trends and variability (Stevens et al. 2026).

Importantly, care is required to avoid reducing mātauranga Māori to a set of indicators within existing institutional frameworks. There is increasing recognition that the institutionalisation of cultural monitoring can create risks, including loss of context, dilution of meaning and misalignment with iwi and hapū priorities if not led appropriately. Addressing this requires maintaining Māori leadership, ensuring monitoring frameworks remain grounded in tikanga and place, and supporting appropriate governance and data sovereignty arrangements (Tadaki et al. 2022).

For climate resilience, mātauranga Māori monitoring provides particular value by identifying early signals of change, detecting thresholds (e.g. loss of mahinga kai) and supporting the identification of refugia and resilient habitats. These approaches capture cumulative effects across interacting stressors such as sediment, temperature and flow, and directly link environmental condition to cultural well-being and biodiversity outcomes.

For Northland, there is a clear opportunity to partner with iwi and hapū to co-develop a cultural monitoring framework that complements existing SOE monitoring. This would strengthen understanding of climate impacts on taonga species and mahinga kai, support identification of biodiversity refugia and inform freshwater limit-setting, environmental flow decisions and restoration priorities. To be effective, this will require early and ongoing partnership, recognition of Māori data sovereignty and sustained resourcing to support iwi and hapū leadership in monitoring and interpretation.

5. Distinguishing climate change from other drivers – lessons from regional expert panel approaches

Key messages

Exploring the likely outcomes of different climate change scenarios is a challenge because separating the effects of climate change from other drivers requires a detailed understanding of stressors and ecological outcomes. Regional councils have increasingly used independent expert panels to integrate modelling, monitoring and expert judgement where data or model coverage are limited. A key strength is that these panels use consistent climate assumptions across management scenarios, allowing clear separation between 'climate-only' and 'land-use or policy' effects.

Findings from expert panel assessments in other regions suggest that small but detectable climate-driven degradations are likely without action by mid-century. These effects are dominated by increased thermal and sediment stress and reduced low-flow reliability. By end of century, climate pressures on flow, temperature and erosion will intensify. Without expanded catchment-scale interventions and adaptive policy, these will increasingly outweigh mitigation outcomes, leaving some attributes below national bottom lines – particularly in erodible and thermally exposed lowland reaches.

An expert panel approach would offer NRC a method to evaluate and compare different climate and management scenarios, especially for attributes with limited data coverage or where interactions between ecosystems instances are poorly understood.

Separating climate change from other drivers is challenging and requires a detailed understanding of stressors and ecological outcomes. Several regional councils across Aotearoa New Zealand have engaged in expert panel processes to explore the likely ecological outcomes under different stressor scenarios. This section details learnings from these processes, drawing examples from multiple regions.

5.1 Separating signals with an expert panel approach

Regional councils have increasingly used independent expert panels to integrate modelling, monitoring and expert judgement where data or model coverage are limited. A key strength is that these panels use consistent climate assumptions across management scenarios, allowing clear separation between 'climate-only' and 'land-use or policy' effects. Two common features make climate effects distinguishable from other stressors: (1) scenarios can hold climate signal constant across options so 'management vs climate' can be compared cleanly; and (2) semi-quantitative rubrics can record direction / magnitude of change, effects on other attributes and confidence by waterbody class.

In the Whaitua Te Whanganui-a-Tara assessment, climate change was assumed consistently across 'business-as-usual (BAU)', 'improved' and 'water-sensitive' (i.e. 'sensitive') scenarios to estimate the net effect of climate plus management relative to current conditions (Greer et al. 2020). In a related assessment, changes in low-flow regimes, flood frequency and hydrological variability under climate scenarios were quantified and linked to changes in habitat, temperature and ecological health metrics (Thompson et al. 2020). This allowed panels to attribute whether observed or predicted changes in aquatic life reflected hydrological alteration from climate or land-use abstraction, or both. Bay of Plenty's expert panel likewise combined a climate change scenario with a good management practice (GMP) scenario – alone and together – to isolate climate pressure from management gains across biophysical and land-cover classes (Zygadlo et al. 2023). Using an alternative approach, Tairāwhiti's panel used staged time horizons (2040, 2060, 2090) and a 'full afforestation' bookend to bound the potential effects of mitigation relative to the persistent influence of climate-exacerbated erosion and heat stress (Ausseil et al. 2025).

5.2 Panel findings on exacerbation under climate change

Without extra mitigation (i.e. under BAU or climate-only scenarios), detectable climate-driven deteriorations emerge by mid-century. This is especially apparent for flow regimes (lower minima, larger floods), suspended and deposited fine sediment, thermal stress and consequent ecological health – effects that are amplified in urbanising catchments.

In Te Whanganui-a-Tara, BAU showed no improvement for most attributes and one-band degradations for dissolved copper and zinc at several urban sites as impervious cover grew (Greer et al. 2020). The flow panel also found reductions in mean annual low flow of approximately 10–20 % in many eastern and northern catchments by mid-century, intensifying thermal stress and reducing dilution capacity. Such hydrological tightening amplifies contaminant concentrations and reduces habitat availability during critical periods (Thompson et al. 2020).

Further, climate change undermines progress where legacy stressors or specific geologies dominate. In Tairāwhiti, climate change will likely increase erosion, temperature stress and flood-related contaminant loads, eroding gains from land-based actions; some attributes remain below bottom lines even by 2090 (Ausseil et al. 2025). In the Bay of Plenty, climate-only scenarios produced small-to-moderate degradations in most indicators and up to two-band declines for suspended sediment and temperature in low-gradient volcanic catchments (Zygadlo et al. 2023).

With scaled mitigation and policy initiatives (e.g. GMP or water-sensitive urban development), the effects of climate change are still evident at mid-century timescales (about 2040–2060). In Whanganui-a-Tara, 'improved / sensitive' scenarios offset many climate pressures: metals and pathogens improve where there is widespread implantation of stormwater capture / treatment, roof-material changes, wastewater leak / overflow reduction, fencing and riparian planting. Recreation suitability jumps by one to two bands in many sub-catchments, and copper and zinc improve one to two bands at priority sites under the 'sensitive' scenario (Greer et al. 2020). These results demonstrate that mitigation can largely prevent climate-driven backsliding and, in some cases, deliver net improvements. In the Bay of Plenty, climate change + GMP holds or improves many attributes relative to current, while client change alone tends to degrade them – clearly separating the climate signal from management effect (Zygadlo et al. 2023).

By end of century (about 2090), some improvements may be observed as the result of broad-scale mitigations. In Tairāwhiti, even ambitious implementation shows incremental improvements, but sediment-dominated catchments with erodible terrain and thermal stress may not meet bottom lines in all locations; climate change continues to diminish benefits, especially via mass movement of sediment and heat stress (Ausseil et al. 2025). Te Whanganui-a-Tara flow panel modelling confirmed that such mitigations also moderate climate–flow impacts – for example, by restoring baseflow stability through wetland and riparian recharge, improving low-flow refugia and buffering temperature peaks where shading is extensive (Thompson et al. 2020).

The ecosystem integrity and extent of freshwater systems (rivers, lakes, wetlands, estuaries) are strongly influenced by climate change through multiple interacting stressors. Across the three regions, degraded ecological health typically reflects combined effects of fine sediment, high temperatures and low dissolved oxygen, altered flows and habitat, and – in specific lowland areas – eutrophication. Lagoonal and long-residence estuaries appear especially sensitive to climate-amplified sediment and nutrient pulses, implying that upstream sediment controls and riparian shade must scale with projected flood regimes.

5.3 Impacts of an expert panel approach on Northland's assessment

An expert panel approach provides a practical way for Northland to evaluate and compare how freshwater and biodiversity outcomes are likely to respond under different climate and management scenarios. This is particularly valuable where data are limited or where multiple stressors interact. Explicit scenario testing can support adaptive planning and future programme changes by enabling NRC to test how different interventions (e.g. erosion control, riparian shading, flow management, urban infrastructure upgrades) are likely to influence ecological outcomes, including for threatened species and sensitive habitats, under future climate conditions. By mid-century, small but detectable climate-driven degradations are likely without action, dominated by increased thermal and sediment stress and reduced low-flow reliability. With targeted erosion control, riparian shading and upgraded stormwater / wastewater systems, many attributes can be maintained or slightly improved despite climate change. By end of century, climate pressures on flow, temperature and erosion will intensify. Without expanded catchment-scale interventions and adaptive policy, these effects will increasingly outweigh mitigation outcomes, leaving some attributes below national bottom lines – particularly in erodible and thermally exposed lowland reaches.

Practical implications for Northland (a potential expert panel approach):

1. Use scenario testing to evaluate biodiversity outcomes under future climate and management pathways, including implications for threatened species, habitat availability and ecological thresholds. This can inform adaptive planning, limit-setting and future plan changes.
2. Determine current state for all attributes for all water management areas.
3. Apply an integrated panel rubric that scores *climate-only, management-only,* and *combined effects* by attribute and ecosystem type, with explicit confidence ratings and clear implications for biodiversity outcomes. Include a flow-condition tier (low-flow, flood-pulse, flow-variability metrics) to trace hydrological pathways to water-quality and ecological indicators.
4. Link causal assessments from flow and temperature drivers through to periphyton, macroinvertebrates and fish responses, avoiding double-counting overlapping stressors.
5. Use staged horizons (2040, 2060, 2090) to show how the relative influence of climate increases over time and how mitigation strength must scale accordingly.
6. Prioritise sediment, temperature and low-flow vulnerability classes with a focus on ecosystems and locations that support high biodiversity values or threatened species. Identify and protect potential climate refugia (e.g. shaded headwaters, groundwater-fed systems). For example, erodible terrain and low-gradient warm reaches require riparian shade, space planting and storm- and flood-sediment controls, while spring-fed or shaded headwaters may serve as refugia.
7. Explicitly outline urban contributions. Where urban growth is material, include stormwater capture / treatment, roof-material changes and wastewater fixes to elicit improvements in *E. coli* and metals.
8. Reflect uncertainty and confidence transparently, and use this to guide precautionary decision-making and prioritisation of monitoring and adaptive management actions.
9. Link freshwater and estuarine outcomes – for long-residence estuaries and dune lakes, integrate flow-retention and flushing capacity into scenario evaluation.

Overall, this approach will support more adaptive, evidence-informed planning, enabling NRC to move beyond static assessments and instead test how different management choices influence freshwater and biodiversity outcomes over time.

6. Recommendations

Northland's freshwater ecosystems face significant challenges because of climate change. Detectable climate-driven degradation of freshwater values is likely by mid-century, with pressures on flow, temperature and erosion intensifying by end of century. In the medium term, targeted management actions are likely to maintain many freshwater attributes; however, over longer time frames, climate pressures are expected to increasingly outweigh management actions.

To guide resource management decisions, the following recommendations focus on ensuring suitable information is available to track climate impacts, inform statutory and non-statutory planning processes, and support the evaluation of future management and climate scenarios. To ensure suitable information is available to track the response of freshwater ecosystems to climate change and inform planning processes, we recommend:

1. Advocating for completion of downscaled hydrological predictions for Northland to align with existing air temperature and rainfall projections. This is essential for understanding how water availability, low-flow reliability and flood disturbance are likely to shift with climate change.
2. Maintaining existing freshwater monitoring networks (both sites and attributes monitored) to track changes in attribute state across an ecologically representative network and to provide input data for modelling future states, with particular emphasis on long-running and reference sites to preserve continuity of long-term records.
3. Expanding water-level monitoring in high-value lakes and wetlands to provide information on changes in hydrology.
4. Clarifying sediment monitoring objectives to determine if suspended sediment gauging or repeated source fingerprinting would provide the most useful information, depending on whether the primary management need is to track state change, attribute sources or evaluate mitigation effectiveness.
5. Consider targeted monitoring of small, low-order streams that are under-represented in current networks to improve the accuracy of modelling future states and better reflect climate sensitivity in headwater environments.
6. Investigating the development of shared database infrastructure to centralise observations of threatened and invasive species, enabling more accurate assessments of current distributions and improving the ability to detect climate-driven range shifts over time. In turn, this could assist in linking monitoring results from freshwater attributes with biodiversity indicators and species traits.
7. Improving the clarity and consistency of reporting on current state for freshwater values to better identify degraded attributes and support transparent evaluation of potential outcomes under different climate change scenarios.
8. Investigating the effectiveness of mitigation and restoration actions, as well as the influence of specific land uses, to inform model parameterisation of future-state models. This may require targeted or short-term monitoring additional to long-term networks, potentially in collaboration with industry bodies or other partners.

Consideration should also be given to how best to partner with iwi and hapū to incorporate mātauranga Māori indicators of freshwater change, resilience and well-being. This includes co-developing cultural monitoring frameworks that reflect local priorities and maintain Māori leadership and data sovereignty. These frameworks can be explicitly used to inform freshwater planning decisions, including limit-setting, environmental flows, identification of biodiversity refugia and restoration priorities under climate change.

Examining future scenarios for freshwater values will require consideration of both the documented responses of freshwater attributes to climate change and the effects of management scenarios, including land-use change. While long-term monitoring data are essential for detecting change over time, it can be difficult to disentangle climate signals from other sources of variability using monitoring data alone. As a result, modelling approaches that draw on long-term datasets provide a means to predict future states under current trajectories. Expert panel approaches offer a complementary, flexible framework for testing multiple combined climate and management scenarios, explicitly incorporating uncertainty and expert judgement. Together, these approaches provide a robust basis for guiding freshwater management decisions under climate change, supporting both near-term adaptation and longer-term strategic planning.

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8. References

Allen W, McCarthy J, Jolly B, Planzer S, Sprague R, Richardson S, Baker C, Graham E, Mahlum S, Hickford M, et al. 2024. Ecological impacts of Cyclone Gabrielle. Wellington: Manaaki Whenua Landcare Research. Report: LC4549. Prepared for Ministry of Business, Innovation and Employment. https://www.landcareresearch.co.nz/assets/researchpubs/Cyclone_Gabrielle_Integrated_ecological_assessment_Full_report.pdf

Anderson E. 2024. Review of regional sediment monitoring network for Northland. PDP Report. Prepared for Northland Regional Council.

Ausseil O, Heath M, Clapcott J, Madarasz-Smith A, Muirhead R, Murphy P, Neverman A, Norton N. 2025. Tairāwhiti water quality and ecosystem health expert panel report. Report prepared for Gisborne District Council.

Bodeker G, Tait A, Morgenstern O, Noone D, Revell L, McDonald A, Cullen N, Renwick J, Katurji M. 2022. Aotearoa New Zealand climate change projections guidance: interpreting the latest IPCC WG1 report findings. Prepared for the Ministry for the Environment. Report number CR 501. https://environment.govt.nz/assets/publications/Climate-Change-Projections-Guidance-FINAL.pdf

Booth K, Ballinger J, Blunden G, Farrow M, Glover N, Gregson J, Jones D. 2013. Natural character in Northland: application of the River Values Assessment System (RiVAS). Lincoln: Lincoln University. LEaP Research Paper No. 23. https://www.nrc.govt.nz/media/3tuf3ewf/naturalcharacterinnorthlandrivasreport23.pdf

Braccia A, Eggert SL, King N. 2014. Macroinvertebrate colonization dynamics on artificial substrates along an algal resource gradient. Hydrobiologia. 727:1–18. https://doi.org/10.1007/s10750-013-1779-z

Brumby A, Marshall, Murray T, O'Donnell C, Richards R. 2025. Trait-based climate change vulnerability assessments of terrestrial taxa in Aotearoa New Zealand. Science for Conservation. 343.

Burdon FJ, McIntosh AR, Harding JS. 2013. Habitat loss drives threshold response of benthic invertebrate communities to deposited sediment in agricultural streams. Ecological Applications. 23(5):1036–1047. https://doi.org/10.1890/12-1190.1

Burge OR, Clarkson BR, Bodmin KA, Bartlam S, Robertson HA, Sukias JPS, Tanner CC. 2020. Plant responses to nutrient addition and predictive ability of vegetation N:P ratio in an austral fen. Freshwater Biology. 65(4):646–656. https://doi.org/10.1111/fwb.13452

Carignan V, Villard MA. 2002. Selecting indicator species to monitor ecological integrity: a review. Environmental monitoring and assessment. 78(1):45–61. https://doi.org/10.1023/A:1016136723584

Carter R, McBride C, Norton N, Clapcott J, Franklin P, Scholes P, Suren A, Donald R, Bermeo S. 2023. Expert panel estimates of water quality and ecological attributes under Current State, Natural Land Cover and a hypothetical future land cover scenario. Whakatāne: Bay of Plenty Regional Council. Environmental Publication 2023/05.

Chakraborty M. 2021. Evaluation of NRC event-triggered (stormflow) automated sediment monitoring. Northland Regional Council Memo, dated 15 October 2021.

Chakraborty M. 2023. Northland Regional Council Environmental Monitoring Plan – Lakes water quality monitoring network.

Chakraborty, M. 2025. Assessment of the risks of elevated aluminium in surface waters of the northern Wairoa Catchment. Whangārei: Northland Regional Council. https://www.nrc.govt.nz/media/02hb4idt/risks-of-elevated-aluminium-in-surface-waters-of-northern-wairoa-catchment-may-2025.pdf

Champion PD. 2014. Northland Lakes Strategy Part II: update and implementation strategy. Hamilton: National Institute of Water & Atmospheric Research. NIWA Client Report No: HAM2012-038. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/ne4pt3da/northlandlakesstrategypartiiupdateandimplementationstrategy.pdf

Champion P. 2021. Review of Northland Lakes Strategy 2020 and recommendations for the future. Hamilton: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2021106HN. Prepared for Northland Regional Council.

Champion P, Burton T. 2018. Northland lakes annual report: spring 2018. Hamilton: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2018317. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/z10jqahz/northland-lakes-ecological-status-2018-spring-niwa-for-nrc.pdf

Champion PD, de Winton MD. 2012. Northland Lake Strategy. Hamilton: National Institute of Water & Atmospheric Research. NIWA Client Report No: HAM2012-121. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/wvch2li2/northlandlakesstrategy.pdf

Chao JY, Zhang YM, Kong M, Zhuang W, Wang LM, Shao KQ, Gao G. 2017. Long-term moderate wind induced sediment resuspension meeting phosphorus demand of phytoplankton in the large shallow eutrophic Lake Taihu. PloS One. 12(3):e0173477. https://doi.org/10.1371/journal.pone.0173477

Chase JM. 2003. Community assembly: when should history matter? Oecologia. 136:489–498. https://doi.org/10.1007/s00442-003-1311-7

Christensen B, Cashmore P, Crump S, Hobbs J. 2019. Fire disturbance favours exotic species at Kaituna Wetland, Bay of Plenty. New Zealand Journal of Ecology. 43(2):1–7. https://www.jstor.org/stable/26626237

Clapcott J, Ataria J, Hepburn C, Hikuroa D, Jackson A, Williams E. 2018. Mātauranga Māori shaping marine and freshwater futures. New Zealand Journal of Marine and Freshwater Research. 52(4):457–466. https://doi.org/10.1080/00288330.2018.1539404

Clapcott J, Goodwin E. 2021. Ecosystem representativeness of Northland's river monitoring network: a review. Nelson: Cawthron Institute. Cawthron Report No. 3660. Prepared for Northland Regional Council.

Clapcott J, Hoani-Waaka A, Kitson J, Baker M, Eveleens RA, Tadaki M. 2025. Out of sync: transforming environmental monitoring through Indigenous perspectives of time. Earth Stewardship. 2(3):e70021. https://doi.org/10.1002/eas2.70021

Clayton J, Edwards T. 2006. LakeSPI – a method for monitoring ecological condition in New Zealand lakes. Hamilton: National Institute of Water & Atmospheric Research. Technical Report Version 2. https://niwa.co.nz/sites/default/files/import/attachments/lakespi_report.pdf

Côté IM, Darling ES, Brown CJ. 2016 Interactions among ecosystem stressors and their importance in conservation. Proceedings of the Royal Society B. 283(1824):20152592. http://dx.doi.org/10.1098/rspb.2015.2592

Crawford RM, Gee EM, Dupont DW, Hicks BJ, Franklin PA. 2024. High water temperature significantly influences swimming performance of New Zealand migratory species. Conservation Physiology. 12(1):coae047. https://doi.org/10.1093/conphys/coae047

Davies-Colley R, Franklin P, Wilcock B, Clearwater S, Hickey C. 2013. National Objectives Framework – temperature, dissolved oxygen & pH: proposed thresholds for discussion. Hamilton: National Institute of Water & Atmospheric Research. NIWA Client Report No: HAM2013-056. Prepared for Ministry for the Environment. https://environment.govt.nz/assets/publications/Files/national-objective-framework-temperature-dissolved-oxygen-ph-2013.pdf

Davies-Colley R, Valois A, Milne J. 2018. Faecal contamination and visual clarity in New Zealand rivers: correlation of key variables affecting swimming suitability. Journal of Water and Health. 16(3):329–339. https://doi.org/10.2166/wh.2018.214

Death RG. 2008. The effect of floods on aquatic invertebrate communities. In: Lancaster J, Briers RA, editor. Aquatic insects: challenges to populations.: proceedings of the Royal Entomological Society's 24th symposium. Wallingford: CABI. p. 103–121. https://doi.org/10.1079/9781845933968.0103

Death R, Nicholson C, Chakraborty M, Pohe S. 2020. Ecological health of stream invertebrate communities in Northland. Can state of the environment data identify drought impacts? Palmerston North: Massey University. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/wgkdryw0/ecological-health-of-stream-invertebrate-communities-in-northland.pdf

Delclaux F, Coudrain A, Condom T. 2007. Evaporation estimation on Lake Titicaca: a synthesis review and modelling. Hydrological Processes: An International Journal. 21(13):1664–1677. https://doi.org/10.1002/hyp.6360

Dunn NR, Closs GP, Crow SK, David BO, Goodman JM, Griffiths M, Hicks AS, Hickford MJH, Jack DC, Kitson JC, et al. 2025. Conservation status of New Zealand freshwater fishes, 2023. Wellington: Department of Conservation. New Zealand Threat Classification Series 46. https://www.doc.govt.nz/globalassets/documents/science-and-technical/nztcs46.pdf

Egan E, Woolley J-M, Williams E. 2020. Climate change vulnerability assessment of selected taonga freshwater species: technical report. Christchurch: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2020073CH. Prepared for Te Wai Māori Trust. https://waimaori.maori.nz/wp-content/uploads/2020/09/2020073CH_Report_FINAL_15April-Technical-Report.pdf

Elliott S, Verburg P, Champion P. 2020. Nutrient load limits to protect high-value Northland dune lakes: review of existing information. [Wellington]: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2020060HN. Prepared for Northland Regional Council.

Foden WB, Butchart SHM, Stuart SN, Vié J-C, Akçakaya HR, Angulo A, DeVantier LM, Gutsche A, Turak E, Cao L. 2013. Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. PLoS ONE. 8(6):e65427. https://doi.org/10.1371/journal.pone.0065427

Foley MM, Carbines M. 2019. Climate change risk assessment for Auckland's marine and freshwater ecosystems. Auckland: Auckland Council. Technical Report 2019/015.

Fowler D, Steadman CE, Stevenson D, Coyle M, Rees RM, Skiba UM, Sutton MA, Cape JN, Dore AJ, Vieno M, et al. 2015. Effects of global change during the 21st century on the nitrogen cycle. Atmospheric Chemistry and Physics. 15(24):13849–13893, https://doi.org/10.5194/acp-15-13849-2015

Freshwater Science and Technical Advisory Group. 2019. Report to the Minister for the Environment. Wellington: Science and Technical Advisory Group. https://environment.govt.nz/assets/Publications/Files/freshwater-science-and-technical-advisory-group-report.pdf

Galvan A, Kawana K, Harcourt N, Robson-Williams M. 2024. The health of cultural values and mahinga kai in the Te Wairoa-Hōpūpū-Hōnengenenge-Mātangirau, Wairoa river catchment and the impacts of sediment. Australasian Journal of Water Resources. 28(2):173–192. https://doi.org/10.1080/13241583.2024.2403814

Gibson PB, Campbell I, Lewis H, Rampal N, Fedaeff N, Woolley J-M. 2024b. User Guidance of CMIP6 Downscaled Data for Aotearoa New Zealand. Wellington: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2024187WN. Prepared for the Ministry for the Environment. https://climatedata.environment.govt.nz/files/CMIP6_guidance_doc_June2024.pdf

Gibson PB, Lewis H, Campbell I, Rampal N, Fauchereau N, Harrington LJ. 2025. Downscaled climate projections of tropical and ex-tropical cyclones over the southwest Pacific. Journal of Geophysical Research: Atmospheres. 130(14):e2025JD043833. https://doi.org/10.1029/2025JD043833

Gibson PB, Stuart S, Sood A, Stone D, Rampal N, Lewis H, Broadbent A, Thatcher M, Morgenstern O. 2024a. Dynamical downscaling CMIP6 models over New Zealand: added value of climatology and extremes. Climate Dynamics. 62:8255–8281. https://doi.org/10.1007/s00382-024-07337-5

Goodwin E, Young RG. 2022. Dissolved oxygen and ecosystem metabolism measurement in Northland rivers. Nelson: Cawthron Institute. Cawthron Report 3684A. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/jwaj2pv1/dissolved-oxygen-and-ecosystem-metabolism-measurement-for-northland-rivers-2022.pdf

Graham E, Greenwood M. 2023. Drivers of macroinvertebrate communities in Northland streams. Hamilton: National Institute of Water & Atmospheric Research. NIWA Client Report No: 202384HN. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/k5bcl5bb/drivers-of-macroinvertebrate-communities-in-northland-streams.pdf

Greer M, Ausseil O, Clapcott J, Farrant S, Heath M, Norton N. 2020. Whaitua te whanganui-a-tara water quality and ecology scenario assessment. Taupō: Aquanet Consulting Limited. Prepared for Greater Wellington Regional Council.

Hamilton DP, McBride CG, Özkundakci D, Schallenberg M, Verburg P, de Winton M, Kelly D, Hendy C, Ye W. 2013. Effects of climate change on New Zealand lakes. In: Goldman CR, Kumagai M, Robarts RD, editors. Climate change and inland waters. Chichester: John Wiley & Sons. p. 337–366. https://doi.org/10.1002/9781118470596.ch19

Hicks M, Semadeni-Davies A, Haddadchi A, Shankar U, Plew D. 2019. Updated sediment load estimator for New Zealand. Christchurch: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2018341CH. Prepared for Ministry for the Environment. https://environment.govt.nz/assets/Publications/Files/updated-sediment-load-estimator-for-nz.pdf

Hilt S, Gross EM, Hupfer M, Morscheid H, Mählmann J, Melzer A, Poltz J, Sandrock S, Scharf EM, Schneider S, van de Weyer K. 2006. Restoration of submerged vegetation in shallow eutrophic lakes–a guideline and state of the art in Germany. Limnologica. 36(3):155–171. https://doi.org/10.1016/j.limno.2006.06.001

Hoyle J, Hicks M, Roulston H. 2011. Sampled suspended sediment yields from the Waikato region. Hamilton: National Institute of Water and Atmospheric Research. NIWA Client Report No: CHC2011-135. Waikato Regional Council Technical Report 2012/01. Prepared for Environment Waikato. https://www.waikatoregion.govt.nz/assets/WRC/WRC-2019/TR201201.pdf

Hughes AO, Davies-Colley R, Bellingham M, van Assema G. 2020. The stream hydrology response of converting a headwater pasture catchment to *Pinus radiata* plantation. New Zealand Journal of Marine and Freshwater Research. 54(3):308–328. https://doi.org/10.1080/00288330.2020.1750434

Hughes B. 2016. Lake FMUs for Northland: recommendations for policy development. Lyttelton: Land Water People. Client Report Number: 2016-003. https://landwaterpeople.co.nz/wp-content/uploads/2018/02/Definition-of-Freshwater-Management-Units-Northland-lakes.pdf

Hussain E. 2023a. Rotokawau freshwater mussel relocation & habitat remediation. Auckland: Submerged Environmental. Prepared for the Department of Conservation.

Hussain E. 2023b. Rototuna freshwater mussel relocation & habitat remediation. Auckland: Submerged Environmental. Prepared for the Department of Conservation.

IPCC. 2014. Climate Change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC.

IPCC. 2023. Climate Change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva: IPCC.

Keegan LJ, White RSA, Macinnis-Ng C. 2022. Current knowledge and potential impacts of climate change on New Zealand's biological heritage. New Zealand Journal of Ecology. 46(1):1–24. https://www.jstor.org/stable/48652113

Kelly D, Peacock L, Jiang W. 2016. Nutrient Management for Northland Dune Lakes. Nelson: Cawthron Institute. Cawthron Report No 2796. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/3r3bvwrt/nutrientmanagementfornorthlandsdunelakes.pdf

Kilroy C, Snelder T. 2024. Periphyton in Northland rivers: testing national nutrient criteria, and an analysis of predictors of biomass and cover within the region. Christchurch: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2023259CH. Prepared for Northland Regional Council. https://www.envirolink.govt.nz/assets/Envirolink/2309-NLRC233-Periphyton-nutrient-criteria-and-drivers-for-Northland-rivers.pdf

Landman MJ, Van Den Heuvel MR, Ling N. 2005. Relative sensitivities of common freshwater fish and invertebrates to acute hypoxia. New Zealand Journal of Marine and Freshwater Research. 39(5):1061–1067. https://doi.org/10.1080/00288330.2005.9517375

Liikanen ANU, Murtoniemi T, Tanskanen H, Väisänen T, Martikainen PJ. 2002. Effects of temperature and oxygenavailability on greenhouse gas and nutrient dynamics in sediment of a eutrophic mid-boreal lake. Biogeochemistry. 59(3):269–286. https://doi.org/10.1023/A:1016015526712

Lorrey AM, Griffiths G, Fauchereau N, Diamond HJ, Chappell PR, Renwick J. 2014. An ex-tropical cyclone climatology for Auckland, New Zealand. International Journal of Climatology. 34(4):1157–1168. https://doi.org/10.1002/joc.3753

Lowe S, Browne M, Boudjelas S, De Poorter M. 2000. 100 of the world's worst invasive alien species: a selection from the Global Invasive Species Database. Auckland: Invasive Species Specialist Group. Updated and reprinted version: November 2004.

Main MR. 1988. Factors influencing the distribution of kokopu and koaro (Pisces: Galaxiidae) [MSc thesis]. Christchurch: University of Canterbury.

Markovic D, Carrizo SF, Kärcher O, Walz A, David JNW. 2017. Vulnerability of European freshwater catchments to climate change. Global Change Biology. 23(9):3567–3580. https://doi.org/10.1111/gcb.13657

Martinsen KT, Andersen MR, Sand-Jensen K. 2019. Water temperature dynamics and the prevalence of daytime stratification in small temperate shallow lakes. Hydrobiologia. 826:247–262. https://doi.org/10.1007/s10750-018-3737-2

McDowell RW. 2008. Factors influencing phosphorus loss from grazed pastures. In: McDowell RW, Houlbrooke DJ, Muirhead RW, Müller K, Shepherd M, Cuttle SP, editors. Grazed pastures and surface water quality. New York: Nova Science Publishers.

McGlone MS. 2009. Postglacial history of New Zealand wetlands and implications for their conservation. New Zealand Journal of Ecology. 33(1):1–23. http://www.jstor.org/stable/24060858

Meerhoff M, Teixeira-de Mello F, Kruk C, Alonso C, González-Bergonzoni I, Pacheco JP, Lacerot G, Arim M, Beklioğlu M, Brucet S, et al. 2012. Environmental warming in shallow lakes: a review of potential changes in community structure as evidenced from space-for-time substitution approaches. Advances in Ecological Research. 46:259–349. https://doi.org/10.1016/B978-0-12-396992-7.00004-6

Morrill JC, Bales RC, Conklin MH. 2005. Estimating stream temperature from air temperature: implications for future water quality. Journal of Environmental Engineering. 131(1):139–146. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:1(139)

Mourot F, Westerhoff R, Macdonald N, Cameron S. 2019. Better spatial characterisation of evapotranspiration and rainfall recharge estimates to groundwater using remote sensing multispectral techniques at lysimeter sites. Lower Hutt: GNS Science. GNS Science Report 2019/17.

Muirhead R, Hudson R, Cookson A. 2023. A review of river microbial water quality data in the Northland region. [Wellington]: AgResearch. Client Report Number: RE450/2023/029. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/svbp5rnk/a-review-of-river-microbial-water-quality-data-in-the-northland-region.pdf

[NEMSWG] National Environmental Monitoring Standards Working Group. 2017. National Environmental Monitoring Standards: rainfall recording. Measurements of rainfall data for hydrological purposes. Version 2.1. https://www.nems.org.nz/documents/rainfall-recording

[NEMSWG] National Environmental Monitoring Standards Working Group. 2025. National Environmental Monitoring Standards: suspended sediment. Measurement of fluvial suspended sediment load and its composition. Version 2.0.0. https://www.nems.org.nz/documents/suspended-sediment

Neverman AJ, Donovan M, Smith HG, Ausseil A-G, Zammit C. 2023. Climate change impacts on erosion and suspended sediment loads in New Zealand. Geomorphology. 427:108607. https://doi.org/10.1016/j.geomorph.2023.108607

[NRC] Northland Regional Council. 2023. Biodiversity Team | Te Tira Rerenga Rauropi: annual report 2022–2023. Whangārei: Northland Regional Council. https://www.nrc.govt.nz/media/ltxfdclz/annual-biodiversity-report-2023-final.pdf

O'Donnell CFJ, Williams EM. 2015. Protocols for the inventory and monitoring of populations of the endangered Australasian bittern (*Botaurus poiciloptilus*) in New Zealand. Wellington: Department of Conservation. DOC Technical Series 38.

Oduor BO, Campo-Bescós MÁ, Lana-Renault N, Casalí J. 2023. Effects of climate change on streamflow and nitrate pollution in an agricultural Mediterranean watershed in Northern Spain. Agricultural Water Management. 285:108378. https://doi.org/10.1016/j.agwat.2023.108378

Olsen D, Tremblay L, Clapcott J, Holmes R. 2012. Water temperature criteria for native aquatic biota. Auckland: Auckland Council. Technical Report 2012/036. https://knowledgeauckland.org.nz/media/1718/tr2012-036-water-temperature-criteria.pdf

Pardo I, García L. 2016. Water abstraction in small lowland streams: unforeseen hypoxia and anoxia effects. Science of The Total Environment. 568:226–235. https://doi.org/10.1016/j.scitotenv.2016.05.218

Pearce P, Paul V, Mullan B, Zammit C, Sood A, Collins D, Bell R, Law C. 2016. Climate change projections and implications for Northland. Auckland: National Institute of Water & Atmospheric Research. NIWA Client Report No: 2016072AK. Prepared for Northland Regional Council. https://niwa.co.nz/sites/default/files/Northland%20Region%20climate%20change%20projections%20and%20implications%20ELF16102%20FINAL%20v2.pdf

Pham H. 2022. Assessment of Lake Taharoa water level. Whangārei: Northland Regional Council. Report No: TR2022/SWQty/02. https://www.nrc.govt.nz/media/puqjyves/assessment-of-lake-taharoa-water-level.pdf

Quinn JM, Hickey CW. 1990. Characterisation and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. New Zealand Journal of Marine and Freshwater Research. 24:387–409. https://doi.org/10.1080/00288330.1990.9516432

Richardson J, Boubée JA, West DW. 1994. Thermal tolerance and preference of some native New Zealand freshwater fish. New Zealand Journal of Marine and Freshwater Research. 28(4):399–407. https://doi.org/10.1080/00288330.1994.9516630

Richardson J, West DW. 1998. Thermal tolerance of common smelt: implications for Huntly Power Station. [New Zealand]: National Institute of Water & Atmospheric Research. NIWA Client Report No: ELE90235. Prepared for Electricity Corporation of New Zealand.

Rip B, Stephens T, Augustinus P. 2016. Historic changes to water quality indicators in Poutō dune lakes. Auckland: University of Auckland, Dairy NZ Ltd. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/we2fywrc/rippetal2016historicchangestowaterqualityindicatorsinpoutodunelakes.pdf

Rissman C, Lindsay J, Couldrey M, Pearson L. 2019. Mapping of Northland's hydric soils, wetlands, and water bodies. Invercargill: Land and Water Science. Land and Water Science Report 2019/28. Prepared for Northland Regional Council. https://www.envirolink.govt.nz/assets/Envirolink/Reports/1955-NLRC214-Mapping-of-Northlands-hydric-soils-wetlands-and-water-bodies.pdf

Rissman C, Pearson L. 2020. Physiographic controls over water quality state for the Northland Region. Invercargill: Land and Water Science. Land and Water Science Report 2020/05. Prepared for Northland Regional Council. https://www.nrc.govt.nz/media/zrnpfc4p/physiographic-controls-over-water-quality-state-for-the-northland-region.pdf

Robertson H, Bowie S, Death R, Collin D, editors. 2016. Freshwater conservation under a changing climate: proceedings of a workshop hosted by the Department of Conservation, 10–11 December 2013, Wellington. Christchurch: Department of Conservation. https://www.doc.govt.nz/Documents/conservation/climate-change-proceedings.pdf

Rowe D, Hicks M, Richardson J. 2000. Reduced abundance of banded kokopu (*Galaxias fasciatus*) and other native fish in turbid rivers of the North Island of New Zealand. New Zealand Journal of Marine and Freshwater Research. 34(3):547–558. https://doi.org/10.1080/00288330.2000.9516956

Ruehle B. 2023. Database and eDNA records for freshwater species of conservation interest. Whangārei : Northland Regional Council. Report No: TR2023/ FEW/01. https://www.nrc.govt.nz/media/1wmap5m0/database-and-edna-records-for-freshwater-species-of-conservation-interest_july-2023.pdf

Sanwar S. 2024. State of the environment. Northland freshwater fish monitoring 2023/24: technical report. Report No. TR2024/FWQlty/01. Whangārei: Northland Regional Council. https://www.nrc.govt.nz/media/uqufhupk/northland-soe-freshwater-fish-monitoring-technical-report-2023-2024.pdf

Somerville R, MacNeil C, Lee F. 2025. Habitat suitability of Aotearoa New Zealand for the recently invaded gold clam (*Corbicula fluminea*). New Zealand Journal of Marine and Freshwater Research. 59:4:762–779. https://doi.org/10.1080/00288330.2024.2368856

Stevens E, Brierley G, Hikuroa D. 2026. Stories and storytelling processes to support river knowledge and practice. Environment and Planning F. https://doi.org/10.1177/26349825261423644

Tadaki M, Astwood J-R, Ataria J, Black M, Clapcott J, Harmsworth G, Kitson J. 2022. Decolonising cultural environmental monitoring in Aotearoa New Zealand: emerging risks with institutionalisation and how to navigate them. New Zealand Geographer. 78(1):37–50. https://doi.org/10.1111/nzg.12325

Tait A, Henderson R, Turner R, Zheng X. 2006. Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. International Journal of Climatology. 26:2097–2115. https://doi.org/10.1002/JOC.1350

Tanentzap AJ, Lee William G, Monks A, Ladley K, Johnson PN, Rogers GM, Comrie J, Clarke D, Hayman E. 2014. Identifying pathways for managing multiple disturbances to limit plant invasions. Journal of Applied Ecology. 51(4):1015–1023. https://doi.org/10.1111/1365-2664.12271

Thiemer K, Schneider SC, Demars BO. 2021. Mechanical removal of macrophytes in freshwater ecosystems: Implications for ecosystem structure and function. Science of The Total Environment. 782:146671. https://doi.org/10.1016/j.scitotenv.2021.146671

Thompson M, Clapcott J, Holmes R, Franklin P, Heath M. 2020. Flow and allocation expert panel report: ecological health impacts of different river water abstraction regime scenarios for the Te Awa Kairangi, Wainuiomata and Orongorongo. Prepared for Whaitua Te Whanganui-a-Tara | Greater Wellington Regional Council. https://www.gw.govt.nz/assets/Documents/2022/05/Flow-Expert-Panel-Report-FINAL-August-2020.pdf

Tipa G, Nelson K. 2012. Identifying cultural flow preferences: Kakaunui River case study. Journal of Water Resources Planning & Management. 138(6):660–670. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000211

Viancelli A, Michelon W. 2024. Climate change and nitrogen dynamics: challenges and strategies for a sustainable future. Nitrogen. 5(3):688–701. https://doi.org/10.3390/nitrogen5030045

Volkoff H, Rønnestad I. 2020. Effects of temperature on feeding and digestive processes in fish. Temperature. 7(4):307–320. https://doi.org/10.1080/23328940.2020.1765950

Wilcock RJ, Nagels JW, McBride GB, Collier KJ, Wilson BT, Huser BA. 1998. Characterisation of lowland streams using a single-station diurnal curve analysis model with continuous monitoring data for dissolved oxygen and temperature. New Zealand Journal of Marine and Freshwater Research. 32:67–79. https://doi.org/10.1080/00288330.1998.9516806

Wood SA, Borges H, Puddick J, Biessy L, Atalah J, Hawes I, Dietrich D, Hamilton DP. 2017. Contrasting cyanobacterial communities and microcystin concentrations in summers with extreme weather events: insights into potential effects of climate change. Hydrobiologia. 785(1):71–89. https://doi.org/10.1007/s10750-016-2904-6

Wood SA, Puddick J, Borges H, Dietrich DR, Hamilton DP. 2015. Potential effects of climate change on cyanobacterial toxin production. In: Botana LM, Vilariño N, editors. Climate change and marine and freshwater toxins. Berlin: De Gruyter. p. 155–180.

Zhang X, Zhang J, Li Z, Wang G, Liu Y, Wang H, Xie J. 2021. Optimal submerged macrophyte coverage for improving water quality in a temperate lake in China. Ecological Engineering. 162:106177. https://doi.org/10.1016/j.ecoleng.2021.106177

Zwick P. 1992. Stream habitat fragmentation – a threat to biodiversity. Biodiversity & Conservation. 1:80–97. https://doi.org/10.1007/BF00731036

Zygadlo M, Norton N, Clapcott J, Franklin P, Scholes P, Suren A, McBride C, Carter R, Bermeo S, Donald R. 2023. Expert panel estimates of change to river water quality and ecological attributes under scenarios of climate change and land management. Whakatāne: Bay of Plenty Regional Council. Environmental Publication 2023/08. https://atlas.boprc.govt.nz/api/v1/edms/document/A4582252/content

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