Climate Change Vulnerability Assessment of Freshwater Ecosystems and Values of the Taiari River Catchment and Management Options

Prepared by

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Contents

Figures

Tables

1. Executive Summary

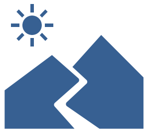
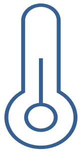
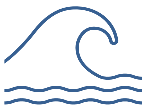
The Taiari River is the second-largest river in Otago and flows from the sub-alpine uplands in the Māniatoto for more than 280 km to Taiari Mouth. The river catchment contains several key freshwater values and unique ecosystems. In this report, the Taiari is split into four subcatchments, each with their own unique freshwater values and climate change risks. The four subcatchments are the lower Taiari basin, the Mid Taiari, the Māniatoto and the Taiari/Waipōuri uplands. The Taiari scroll plain in the Māniatoto basin is one of the only inland scroll plains in New Zealand, Sutton Salt Lake in the Mid Taiari is the only inland saline lake wetland system in New Zealand, and the Waipōuri-Waihora wetland complex represents a significant wetland system in the lower Taiari basin. There is also a second upland environment above the Waipōuri-Waihora wetland complex which contains Lake Mahinerangi and several alpine wetlands. The Taiari River is one of 14 rivers in DOC's Ngā Awa River Restoration Programme.

Using the best available data and expert knowledge this report summarises the key freshwater ecosystem and species values within the catchment, describes how climate change could impact these values, and outlines the future management and research options to mitigate the effects of climate change on the catchment.

The first part of this report examines the historical context of the Taiari catchment and implications for the future and outlines the climate-change scenarios and projections for the Taiari. The report then deals separately with the four main subcatchments. For each subcatchment, the key freshwater values are outlined, placed in the context of their sensitivity to climate change, then how predicted climate change exposure may affect these values is discussed. Finally, we propose an initial selection of management options that could be employed to protect these key freshwater values.

Climate change impacts

The local climate change projections for the catchment are described by, and sourced from, Goldsmith (2023). The historic rainfall and temperature records, and future climate and hydrological projections were produced by the National Institute of Water and Atmospheric Research (NIWA) and Filmer and Fitzharris (2002). These projections are outlined below.

	Lower Taiari Basin	Mid Taiari	Māniatoto	Taiari/Waipōuri Uplands
	Increases in projected mean annual flows, and flood flows. No change in annual low flows except for Silver Stream which increases.	No change in projected mean annual flows in the north, but increases downstream. Increases in flood flows. Decrease in annual low flows.	No change in projected mean annual flow initially, changing to a slight increase. Decrease in annual low flows. Increases in projected annual flood flows.	Increases in projected mean annual flows, and flood flows. Decrease in annual low flows.
	Increases in historical and projected annual temperature, projected extreme hot (+30˚C) days. Decrease in annual frost days.	Increases in projected annual temperature, projected extreme hot (+30˚C) days. Decrease in annual frost days.	Increases in historical and projected annual temperature, historical maximum and projected minimum air temp, projected hot (+30˚C) days. Decrease in annual frost days.	Increases in projected annual temperature, projected extreme hot (+30˚C) days. Decrease in annual frost days.
	Increases in projected annual rainfall, historical annual max 1-day rainfall, annual projected heavy rain days. Decrease in annual dry days.	Increases in projected annual rainfall, and annual projected heavy rain days. Increase in annual dry days in the north and decrease downstream.	No change in historical rainfall but an increase in projected annual rainfall. Increase in annual heavy rain days and annual dry days.	Increases in projected annual rainfall, annual projected heavy rain days, and annual dry days.
	Historical decreases in annual wind speed. Decreases in projected extreme wind.	Historical decreases in annual wind speed. Decreases in projected extreme wind initially, changing to an increase in the north and west.	Historical decreases in annual wind speed. Increase in projected extreme daily wind speeds.	Increases in projected extreme daily wind speeds.
	Sea level rise, 13.5cm from the last century. 13-30cm projected to 2040, and 40 to 100cm to 2090.			

Climate change sensitivity and exposure

The four main subcatchments each face different challenges based on the variation in ecosystems, habitat, and species they contain. The key risks each subcatchment faces are:

Lower Taiari basin

- The Waipōuri/Waihora lake-wetland complex represents a significant habitat for fish, invertebrates, and birds. Rising sea level, and extreme weather events, could cause the loss of aquatic plants in the lakes causing a permanent shift to a turbid, eutrophic system.
- In the surrounding hill streams, increased rain events leading to elevated flow may allow for trout incursions into areas where only native fish are present.

Mid Taiari

- Several species of threatened native fish inhabit the Mid Taiari. If minimum flow and water quality is maintained in the mainstem, fish communities should be minimally impacted, but for smaller streams projected extreme flood and drought events could have a greater impact.
- Sutton Salt Lake is the only inland, saline lake in New Zealand. Due to the delicate water balance of the system, it is considered a high-risk environment.

Māniatoto

- The scroll plains are an internationally significant wetland complex hosting significant native biodiversity.
- Several native and introduced fish species live within the Māniatoto area. These fish communities will be exposed to the impacts of climate change given that the area is relatively arid and has high water demand for usage in agriculture.
- Increasingly dry and hot summers will reduce the water level in the main stem and tributaries to those that stress or kill fish. Extreme flood events can be followed by low oxygen/blackwater events which can cause mass fish and/or bird die offs.

Taiari/Waipōuri Uplands

- Many inland and alpine wetlands exist within the uplands of the catchment and are already at moderate to high risk from climate change.
- The effects on these wetlands may be partly determined by water draw-down rates and irrigation water storage in the surrounding area and in part by changes to more woody vegetation in response to increased temperatures and altered fire management.

- 'Nationally Endangered' Eldon's and dusky galaxias have fragmented distributions across the uplands which are most of the last remaining habitat for the species.
- Changes to vegetation could alter the hydrology of the upland catchment and increase the risk of wildfire which could impact Eldon's and dusky galaxias habitat.
- Maintaining barriers for trout migration and other pest species is critical for ensuring protection of the non-migratory galaxiids in the area.

Climate change management

Several management options are discussed for each subcatchment and a table outlining all management options has been produced. Many options are unique to the subcatchment but some are relevant for all subcatchments. Some of these catchment-wide management options include:

- Wetland protection and restoration of riparian habitats to ensure more stable in-stream habitat conditions. Wetlands mitigate the impacts of both drought and floods as well as supporting highly diverse aquatic flora and fauna (including fish and birds).
- Management of invasive species to maintain predator exclusion and to manage the increased risk of fire from wilding invasive plants such as pines.
- Development of a regional non-migratory galaxiid conservation plan to protect these unique species, several of which are found nowhere else on Earth outside Otago.
- Land-use diversification to reduce reliance on irrigation and decrease debt-servicing thus increasing resilience to climate change on multiple fronts.

The management options listed here and throughout the report are presented to stimulate discussion about how the community may proactively address the challenges that may arise from climate change within the Taiari catchment.

Previous work

Orchard (2022 & 2023) held strategy workshops with mana whenua, community members, regional council, and DOC to discuss Te Mana o Taiari Matatū ki te Taiao, a climate resilience strategy for the natural environment of the Taiari catchment. This focused on identifying the important values within the catchment, developing potential adaptation pathways for climate change, and shorter-term objectives. The ecological, socio-economic, and cultural values and solutions of the community were explored. This report complements those workshops by providing an assessment of the impact's climate change could have on the freshwater ecosystems and species of the Taiari catchment. Many of the freshwater features discussed in this report overlap with those identified by the community and mana whenua.

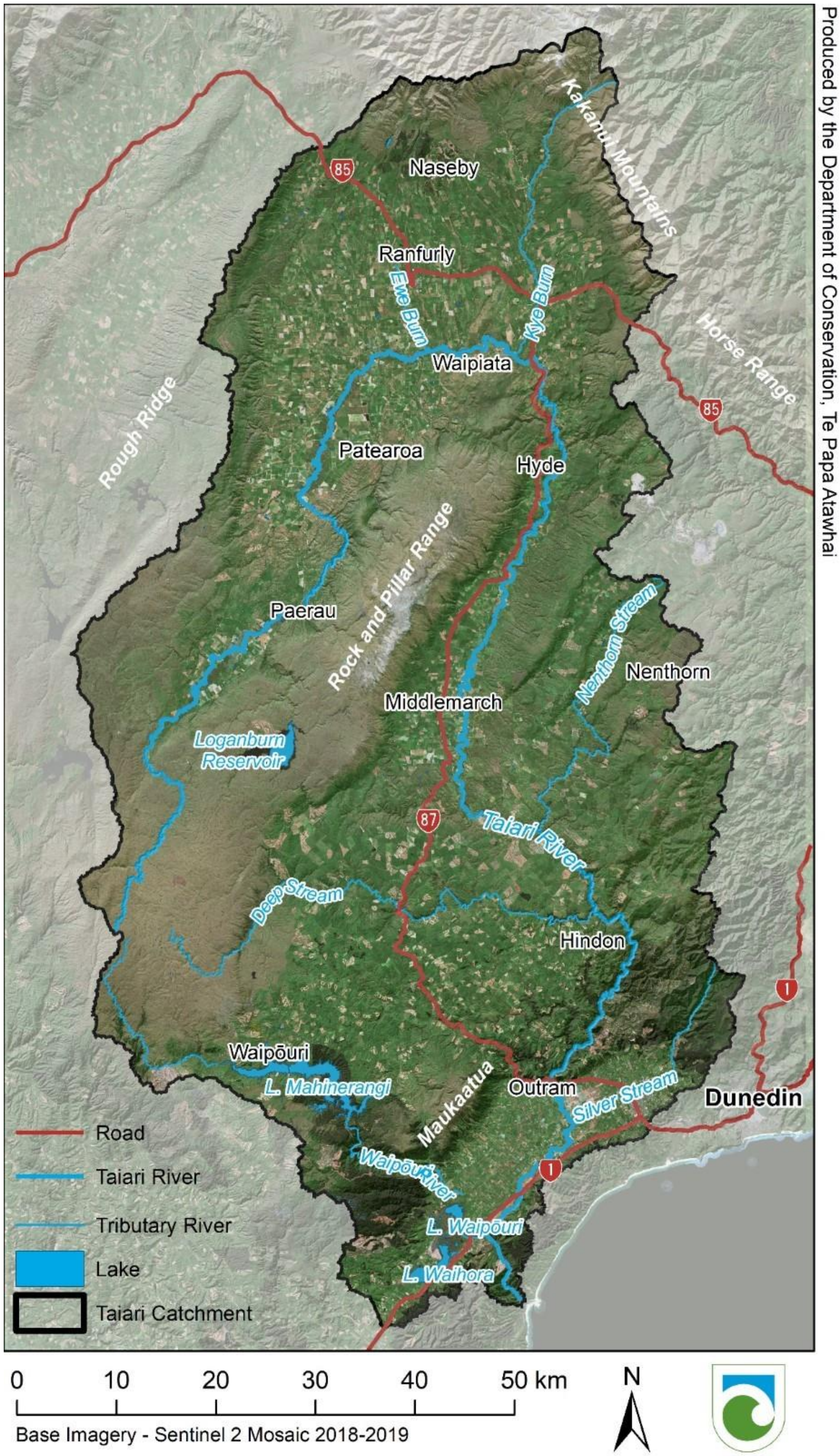


Figure 1. The Taiari catchment, showing the course of the Taiari River and its main tributaries

2. Purpose of this Report

The Taiari River catchment extends approximately 150 km inland, to the north and west of Dunedin. It comprises approximately 5,700 km^2, rising to an altitude of 1,643 m a.s.l. and contains many diverse landscapes and water bodies (Fig. 1).

The aims of this report are to:

(i) assess climate change vulnerability of the aquatic biota and habitats of the Taiari River catchment, and;

(ii) to explore catchment management opportunities to protect biota and habitats in the face of a changing climate.

We assess the likely future trajectory of the climate and sea level based on both statistically downscaled global climate model scenarios (Goldsmith 2023) and on our analysis of relevant, empirical, historical climate, weather, and sea-level trends. We assess the existing published literature on the biota and habitats present within the catchment to determine their vulnerability to the impacts of climate change based on our assessment of the likely climate change scenarios for the Taiari catchment. We identify potentially vulnerable aquatic biota and habitats and make some preliminary recommendations about key management options that could improve aquatic ecology resilience to the direct and indirect effects of climate change. Some of the opinions and recommendations expressed are relatively speculative, being based on extensive but incomplete knowledge and experience of what is a large, complex ecosystem – appropriate critical thinking and caution should be exercised in accepting any recommendations.

^Taiari scroll plain, Māniatoto

In this document

We divided the Taiari catchment into four distinct regions:

The Lower **Taiari** Plain and estuary

The middle gorge from Outram Glen and upstream into the dry and rocky Mid Taiari area

The Māniatoto Plain

The high country, which includes the Lammermoor and Rock and Pillar Ranges, and the uplands above Waipōuri.

These landscape regions span a range of climatic conditions, geomorphologies, and vegetation types.

The Taiari catchment has three distinct climatic zones (Filmer & Fitzharris 2002): a sub-humid upper catchment with higher rainfall (including the Lammermoor and Rock and Pillar ranges), a central semi-arid region with hot summers, cold winters and rainfall between 300 and 500 mm/year, and the lower Taiari Plain, which has milder temperatures and a relatively moderate rainfall of 500 to 900 mm/year.

3. Historical context – implications for near-future impacts on the Taiari

Information on inferred and measured historical climate in the Taiari catchment indicates the natural range of climate variation that occurred over different time scales: (1) over the past few thousand years (inferred from palaeoecological proxies) and (2) over the past century and decades (measured at weather stations in the catchment). Together, these sources indicate the historical climate and climate variability that have influenced the current species and habitat distributions in the catchment during the latter half of the Holocene. Such information is helpful in assessing the risk of future climate change to these species and habitat distributions. For example, if past climate variations had been small compared to the forecast climate change, then the risk of future climate change to the species and habitats is likely to be higher than if these species and habitats had endured a larger or comparable range of climate variations in the past.

3.1. Holocene climate

Palaeo-ecological reconstructions suggest that, as the glaciers of the late Pleistocene retreated and sea level rose during the early Holocene (c. 10,000 to 7,000 years ago), the climate in Otago was warm and dry, and scrub and grasslands dominated the vegetation in the interior, while tall conifer forests were common in the coastal environment (McGlone and Wilmshurst 1999). Towards the mid-Holocene (from 7,000 to 5,000 years BP[1]), pollen records from Otago show progressive afforestation by conifers while conifer/broadleaf forests expanded in coastal areas (Prebble and Shulmeister 2002). The global climate during this period is referred to as the Holocene Global Thermal Maximum (also known as the Holocene Climatic Optimum), when global mean air temperature exceeded the late 19th century global mean air temperature by around 0.7°C (95% CI = 0.3 to 1.8°C) (Kauffman et al. 2020). From around 5,000 years BP, a cooling phase occurred, culminating in the Little Ice Age roughly between 1400 and 1800 AD. Pollen records from Otago indicate that during this period there was progressive incursion of southern beech (*Nothofagus menziesii*) forest

[1] BP (before present) years is a timescale used to specify when past events occurred using 1950 as the date considered present.

(from 4,000 to 2,000 years BP) along with an increase in rimu (*Dacryidium cupressinum*), indicating that the winters became increasingly cooler and wetter on the coast (McGlone & Wilmshurst 1999a). Inland Otago pollen records from this period suggest a drying climate (McGlone & Moar 1998), and charcoal remains indicate that much of the lowland forest in inland Otago was destroyed by naturally occurring, lightning-induced fires at the time (McGlone 1988).

Widespread charcoal remains in Otago dating from c. 700 years BP show that forests were burnt again after Polynesian arrival in the region. Subsequently, distinguishing the signatures of climate change vs. anthropogenic impacts on the landscape becomes difficult.

Analysis of sediment archives from Waihora (Lake Waihola; Fig. 2) show that after Europeans settled the area, podocarp forests were progressively displaced by grasslands in the Lower Taiari Plain and the prevalence of exotic pine trees and pine forests increased (https://lakes380.com/lakes/lake-waihola/). Furthermore, the abundance of kahikatea (*Dacrydium dacrydiodes*) declined markedly shortly after Europeans began settling the Lower Taiari Plain (Schallenberg et al. 2012). These changes were due to land-use change, not climate change.

Climate reconstructions from plant phytolith data from a core collected near the junction of the Taiari and Waipōuri Rivers (Fig. 2) suggest that annual average precipitation at the site peaked at approx. 850 mm between c. 8,000 and 6,000 years BP, after which precipitation gradually declined to the current annual mean of 750 mm (Prebble & Shulmeister 2002). The same study inferred that average autumn temperatures between c. 8,000 and 6,000 years BP were slightly cooler than the current average autumn temperature in the lower Taiari; however, the authors admitted that their ability to resolve small changes in temperature from the data was limited (Prebble & Shulmeister 2002). In contrast, most published mid-Holocene temperature reconstructions indicate that the mid-Holocene was warmer than the present (e.g., Kauffman et al. 2020; Fig. 3).

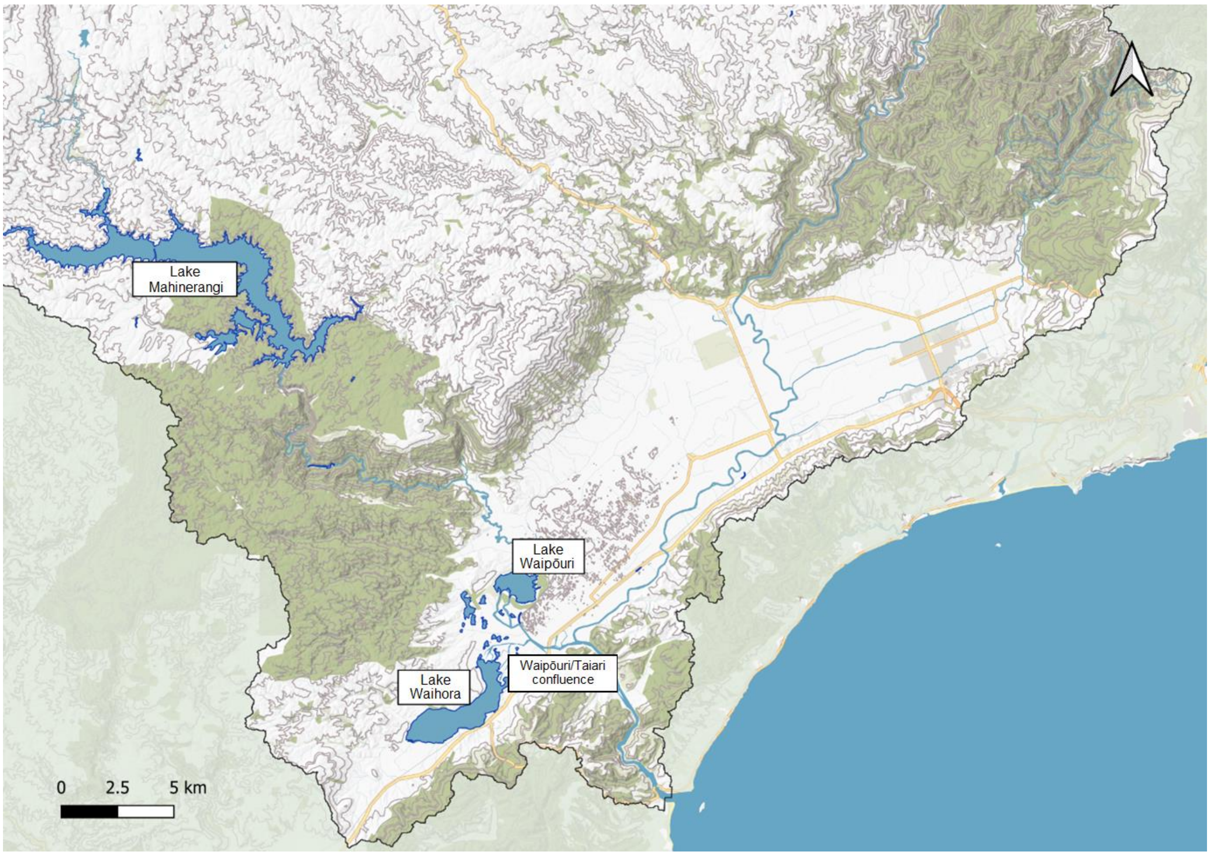


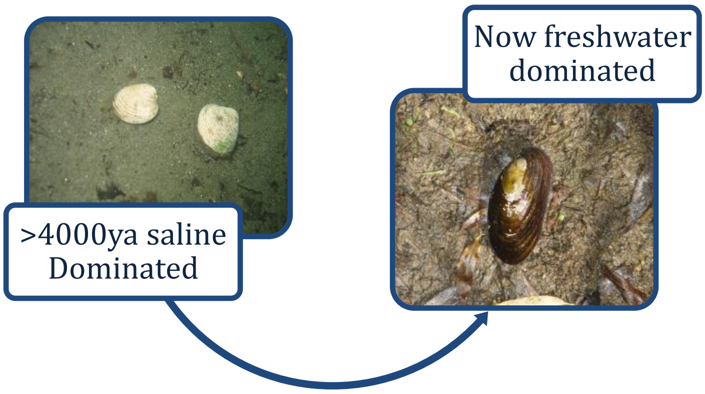
Figure 2. Lower Taiari catchment indicating lakes Waipōuri and Waihora which make up a larger lake/wetland complex, the confluence between the Waipōuri and Taiari rivers, and the general topography of the lower catchment. The light green shading shows current areas of bush and forest.

3.2. Holocene sea level

Inferences about palaeo-sea level variation in waters around New Zealand are confounded by New Zealand being a relatively tectonically active country. Consequently, to infer historical sea levels on the Otago coast, one must first account for potential vertical land movements due to seismic events and fault ruptures. The Akatore and Titri faults run parallel to the coast along the seaward side of the Lower Taiari Plain (Litchfield & Norris 2000; Litchfield 2001). Evidence suggests that the Titri fault did not rupture during the Holocene (Litchfield 2001). On the other hand, evidence suggests two major ruptures of the Akatore fault have occurred in the past 3,800 years. However, as this fault runs off the coast near Taieri Mouth, fault movements would not have directly altered the configuration of the Taiari estuary or the mixing of marine and freshwater in the Taiari River (except for the short-term impacts of a potential tsunami event). Therefore, we can interpret palaeo-evidence of water level and salinity changes in the lower Taiari estuary, lakes and wetlands as resulting from variations in sea level, freshwater inputs from the catchment and natural sediment infilling, rather than from vertical land movements.

Gibb's (1986) late-Holocene sea-level curve for New Zealand indicates that, post-ice age, rapidly rising sea levels reached a relatively stable plateau (very near the current sea level) around 7,000 years ago. However, his analysis also showed that sea level slightly over-shot the current level by 0.6 to 0.9 m between 3,000 and 4,000 years ago. This period of higher sea levels is known as the mid-Holocene sea level high stand.

Sediment cores collected from Lake Waihora (Schallenberg et al. 2012), the Waipōuri/Waihora Lake Wetland Complex (Cadmus 2004), and the lower Taiari Plain (Prebble & Shulmeister 2002) provide insights into sea-level variations in the Lower Taiari Plain during the Holocene (Figs 2 and 3). These studies found that increases in salinity occurred during the mid-Holocene in the Lower Taiari Plain, as evidenced by 4,000-year old estuarine cockle beds (*Austrovenus stutchburyi*) that covered the bottoms of Lakes Waihora (Schallenberg et al. 2012) and Waipōuri (Cadmus 2004). To support cockles, mean salinity would have been around 15 ppt at the time compared to today which is typically less than 2 ppt. Diatom analyses from the Lake Waihora core by Margaret Harper (Victoria University Wellington) indicate that starting around 4,000 years ago, salinity in Lake Waihora declined to its current state, which is characterised by infrequent, minor, and transient saline intrusions (Schallenberg & Burns 2003). Thus, today, the lakes have kākahi/freshwater mussel (*Echyridella menziesii*) beds instead of estuarine cockles (M. Schallenberg pers. obs.). All of this evidence indicates that, over the past 4,000 years, the Lower Taiari lakes and associated wetlands transitioned from estuarine conditions to mainly freshwater conditions (Fig. 3).



3.3. Historical weather station records and climate projections

The recording of measurements of Otago's climate and sea levels began after European settlement of the region. Goldsmith (2023) analysed temporal trends in historical air temperature, wind speed and rainfall records from some Otago weather stations (Table 1). Care must be taken in interpreting these historical data because some time series are composites from different instruments and different sites (Goldsmith 2023). In addition, air temperature records can be affected by urbanisation and other local factors which may affect local near-ground temperatures. The data generally suggest that temperatures have increased, that wind speeds have decreased, and that there has been little change in rainfall at the sites presented in the Goldsmith (2023) report. It is not clear to what extent the recorded trends from a few weather stations can be generalised across the Taiari catchment, but these records allow comparisons of trends shown in historical, measured records with future trends projected for the catchment from the downscaled global circulation models. As the global climate models are strongly forced by atmospheric CO_2 concentrations, and because anthropogenic CO_2 concentrations began to rise with the spread of the industrial revolution in the 1800s, it is expected that modelled future climate and sea-level trends will reflect to some degree the climate and sea-level trends observed over the past century or so.

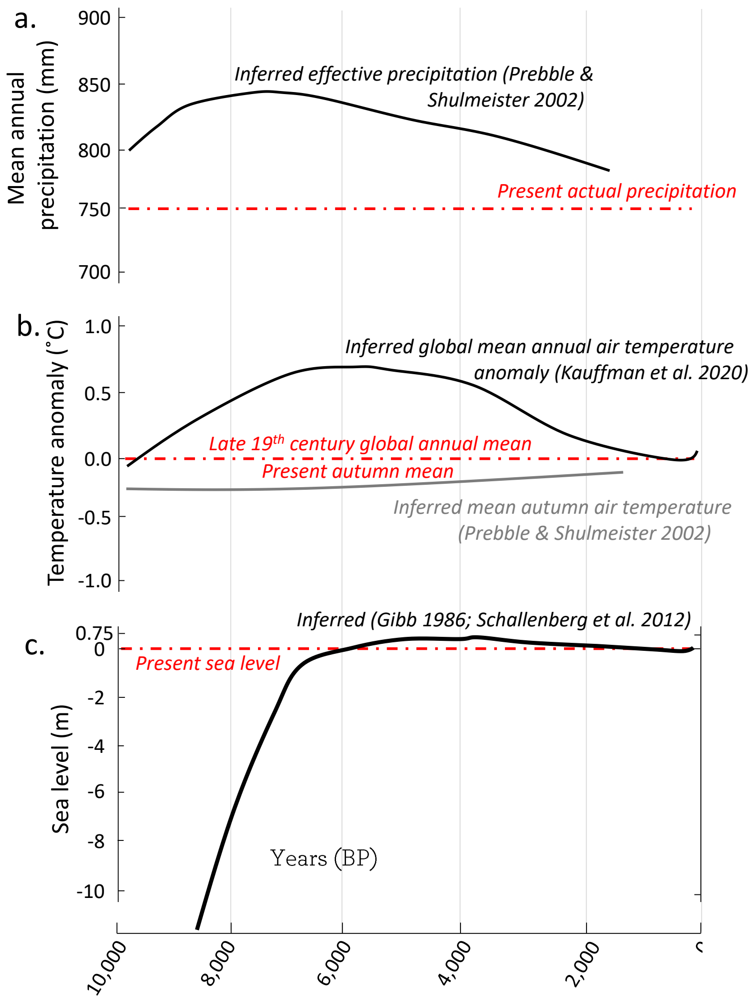


Figure 3. Approximate Holocene climate and sea-level variations relevant to the Lower Taiari Plain. a. Inferred effective precipitation (precipitation – evaporation) based on phytolith assemblages for the Lower Taiari Plain and from present actual precipitation at Momona airport (Prebble & Shulmeister 2002). **b.** Temperature anomaly compared to the late 19th century mean global air temperature (Kauffman et al. 2020) and to the the Lower Taiari Plain mean autumn air temperature (Prebble & Shulmeister 2002). **c.** mean sea level jointly inferred for New Zealand (Gibb 1986) and for Lake Waihora (Schallenberg et al. 2012).

The weather station data extracted by Goldsmith (2023) indicate that air temperatures have been rising at between 0.15°C to 2.4°C per decade at the four sites in the Taiari catchment (Table 1). This range encompasses the approximately 0.5°C per decade rise in mean annual temperature for the Taiari catchment projected in earlier analyses, as summarised in Goldsmith (2023). Thus, the historical air temperature trends are broadly consistent with the projections in Goldsmith (2023), which project increasing trends for all greenhouse gas emission scenarios to 2090.

Wind-speed records from weather stations in the catchment show historically decreasing mean annual wind speeds from -0.16 to -0.25 m s^{-1} per decade (Table 1). This trend is at odds with the predicted wind-speed trends, which indicate little change in wind speeds to the year 2090 at Ranfurly, Middlemarch and Dunedin Airport under both the RCP 4.5 and RCP 8.5 scenarios (Goldsmith 2023).

Table 1. Approximate historical climate trends from sites in the Taiari Catchment, estimated from graphs presented in Goldsmith (2023).

Site(s)	Record length	Approximate trends
Mean annual air temperature		
Naseby	1923 to 2016	+0.15 °C per decade
Ranfurly at Eweburn	1897 to 1922	+2.4 °C per decade
Ranfurly EWS	2002 to 2021	+1.0 °C per decade
Dunedin airport	1963 to 2021	+0.17 °C per decade
Extreme maximum air temperature		
Naseby	1923 to 2016	+0.3 °C per decade
Extreme minimum air temperature		
Naseby	1923 to 2016	+0.4 °C per decade
Mean annual wind speed		
Ranfurly	2001 to 2021	-0.25 m s^{-1} per decade
Middlemarch	2001 to 2021	-0.2 m s^{-1} per decade
Dunedin airport	1992 to 2021	-0.16 m s^{-1} per decade
Highest daily wind run		
Ranfurly	2003 to 2019	-125 km per decade
Middlemarch	2003 to 2018	0
Dunedin airport	2005 to 2021	0
Mean annual rainfall		
Ranfurly	1897 to 2021	0
Middlemarch	1909 to 2021	0
Annual maximum 1-day rainfall		
Mosgiel	1952 to 2021	+2.9 mm per decade
Outram	1948 to 2019	+3.1 mm per decade

No apparent trend in historical mean annual rainfall was observed in the weather station data from Ranfurly and Middlemarch; however, increases in annual maximum 1-day rainfall of 2.9 to 3.1 mm per decade were observed at Mosgiel and Outram (Table 1). The climate models predict that mean annual rainfall will increase towards the coast by up to 15% for the RCP 8.5 scenario by 2090, with little increase further inland (e.g., in the Māniatoto). Rainfall seasonality is predicted to increase (i.e., drier in summer, wetter in winter), especially inland, and frequency of heavy rain days is predicted to increase slightly, by 1 to 2 days per year by 2090 (Goldsmith 2023). Thus, the historical trends for mean annual rainfall (no trends) are at odds with the projections (increasing trend), but historical trends for maximum 1-day rainfall events show an increase over time, which is consistent with a slight increase in the frequency of heavy rain days predicted by the climate model.

3.4. Historical Sea level records and projections

Denys et al (2020) analysed century-long sea-level trends from tide gauge data at five New Zealand ports. The data were corrected for vertical land movement. The records showed linear increases in sea level of 1.35 mm yr^{-1} for Dunedin (Fig. 4). These linear rates contrast with the accelerating projected rate of sea level rise predicted in the Otago Climate Change Risk Assessment, under which sea level is expected to rise 0.9 m to 1.2 m by 2090 under RCP 8.5 (Tonkin & Taylor 2021). To achieve these projected rates of sea level rise, the average future rate would be around 10 times the average historical rate observed at Dunedin over the past century (1.35 mm yr^{-1}; Denys et al. 2020).

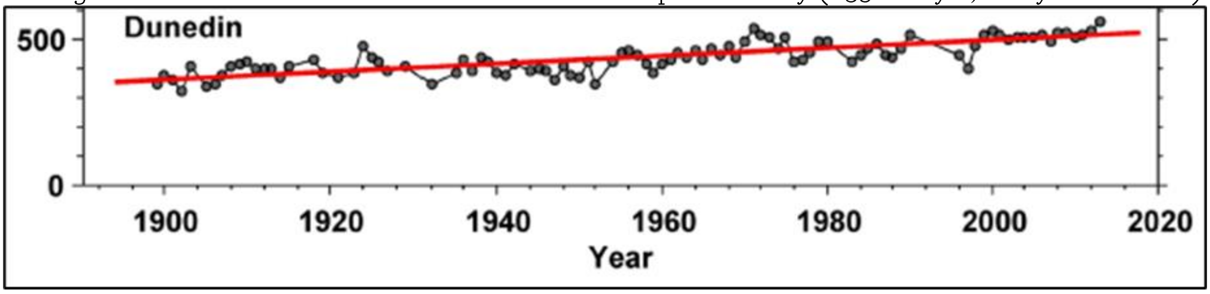


Figure 4. Sea level measured from tide gauges at Dunedin, adjusted for vertical land movement. Vertical axis scale is in mm, but the vertical axis values are arbitrary. Slope of the red line is 1.35 mm year-1. Adapted from Denys et al. (2020).

The most recent MfE guidance (Ministry for the Environment, 2024) notes firstly that sea level rise lags behind other climate impacts (i.e., like heatwaves) that respond to emissions. Secondly, while reaching the higher emissions scenarios currently being modelled (i.e., SSP5-8.5) has become less likely, nonetheless 'high emissions cannot be ruled out for many reasons' such as 'higher than anticipated population and economic growth'. SSP5-8.5 projections can also result from strong feedback from climate change, meaning high-end projected climate impacts might also materialise while following a lower emission path'[2].

[2] See Box 3, page 41, MfE 2024 for further context. SSP5-8.5 is one of the emissions scenarios modelled in the IPCC6th Assessment Report from Working Group III after the Otago Climate Change Risk Assessment was published in 2021. SSP = Shared Socioeconomic Pathway.

4. Climate-Change Scenarios

4.1 Summary of Climate and Sea-Level Projections in Goldsmith (2023)

The following text is largely derived from NIWA (2018), as described in Goldsmith (2023).

4.1.1 Climate models and the temporal and spatial resolution

Six global climate models (GCMs) using data from the IPCC Fifth Assessment with a resolution of 27 km have been chosen for dynamical downscaling to simulate future climate change within New Zealand by NIWA (BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISSE2-R, HadGEM2-ES and NorESM1-M; IPCC 2013, Ministry for the Environment 2018). These downscaled climate change projection models are at a 5 km x 5 km resolution over New Zealand and are presented over a 20-year average temporal scale across two time frames, 2031-2050 (termed '2040') and 2081-2100 (termed '2090'). The General Climate Model outputs have also been downscaled to produce future climate projections for the Otago Region based on two representative concentration pathways (RCPs) discussed below.

Model assumptions

The GCMs rely on several underlying assumptions, with the main one being the different greenhouse gas emission scenarios, known as RCPs. There are four main RCPs used for the NZ predictions based on potential future emissions. RCP2.6 is the best-case scenario requiring a significant reduction of greenhouse gas emissions, RCP4.5 and 6.0 are mid-range scenarios requiring stabilization of emissions based on intergovernmental agreements (e.g. Paris Climate Change Agreement), and RCP8.5 is the 'business as usual' case with greenhouse gas emissions continuing at the current rate. Predictions for each milestone year (2040 and 2090) are based on the modelled average from the decade before and after as this will likely be an accurate representation of climatic events in this time period (IPCC 2013, Ministry for the Environment 2018). For the Taiari catchment, GCMs using RCP 4.5 and RCP 8.5 were computed.

Key climate parameters and their predicted change over time

From these models, several key climate parameters within the Taiari catchment have been predicted to change over time. These parameters are temperature (average, extreme hot days, and frost days), precipitation (annual rainfall, extreme rainfall events, and annual dry days), hydrological flow, and wind speed. Average temperature increases with time and emission scenario to 0.5-1.5°C by 2040, and 0.5-3.5°C by 2090. The number of extreme hot days (days >30°C) is also expected to increase while the number of frost days (days <0°C), which have already been falling, will continue to decrease. These predictions are more drastic under RCP8.5. Annual rainfall is also expected to increase particularly during winter seasons with extreme rainfall events becoming more severe. The number of annual dry days varies on a regional scale with a decrease projected for coastal areas and an increase inland (i.e., more dry days in the Māniatoto). Mean annual flows and flood events are also expected to increase within the Taiari catchment. Across the four distinct geographical regions of the Taiari catchment these changes vary, as detailed below.

Geographical variation in predicted change across the Taiari catchment

More extreme hot days are predicted (an increase of 0 to 4 by 2040 and 8 to 20 by 2090 depending on the scenario) with larger increases likely to occur in the upper catchment.

Rainfall is generally predicted to become heavier catchment-wide, with an increase in mean annual rainfall likely. Changes may be relatively small by 2040 (between -5% and +5%), but larger increases are predicted by 2090, particularly in the lower catchment downstream of the Taiari Gorge, which could expect a 15% increase in rainfall. Heavy rain days are also likely to increase across the

(Below) Taiari Scroll plain after snowfall which could become less frequent under the climate model predictions.

catchment (by between zero and six days), with the highest increase in heavy rain days occurring in the upper Silver Stream catchment, north of the Taiari plain, and the lowest increase occurring in Mid Taiari and Māniatoto. Some parts of the catchment may also see the number of dry days increasing. The Māniatoto, which is already very dry, could have an increase in the number of annual dry days (between four and six additional days) and some areas like Pātearoa, may receive up to ten additional dry days. This increase will also likely be larger in the upper catchment (between six and ten days) under the high range scenario by 2090 (RCP 8.5). The Mid Taiari is not likely to see a marked increase in the number of dry days. The lower Taiari plain, which receives the fewest number of dry days, may see between four and six fewer dry days a year by 2090.

The number of snow days is predicted to decrease across the catchment with the largest reduction occurring in the coldest, mountainous areas of the upland catchment. The duration of snow cover is also likely to decrease, especially at lower elevations. This decrease will likely cause changes to the annual cycle of river flow, as areas that currently receive snow will experience increasing rainfall as snowlines rise in altitude (Ministry for the Environment 2018). Therefore, tributaries of the Taiari River which are influenced by snow and snowmelt will have a higher likelihood of large winter floods occurring.

Current wind patterns across the catchment vary considerably and this is reflected in future climate predictions. Currently higher and more exposed areas tend to experience windier conditions with higher wind gusts. Most of the catchment should experience little change in extreme winds under the lower emissions scenario (RCP4.5), but some areas such as Ranfurly and Naseby may experience a significant increase in extreme daily wind-speed under the higher emissions scenario (RCP8.5). There is currently a downwards trend in extreme daily wind-speed in the Lower Taiari Plain observed at the Dunedin Aero Site over the past 30 years, and NIWA modelling suggests this trend will continue with a decrease by 1 to 2% by 2090.

The average discharge of the Taiari River catchment as a whole, will remain largely unchanged in future predictions; however, the upper and lower flow limits are predicted to become more pronounced with lower water levels due to extended dry periods being more severe in the mid and upper catchment. Some localized changes in mean flows may also occur. Under RCP4.5 the Silver Stream catchment, which flows into the Lower Taiari Plain, may show an increase in mean annual flow between 5 and 20%, while under RCP8.5 this flow may increase by as much as 50% by 2090. High-flow and flood events are also predicted to become more extreme across

most of the catchment, more so under the higher emissions scenario (RCP8.5), with the largest increases predicted for the tributaries which flow into the Māniatoto.

Uncertainty

For the models discussed, there are two main areas of uncertainty. Firstly, future greenhouse gas emission scenarios are difficult to predict and therefore the actual outcome may be lower or higher than what is predicted. Secondly, several large-scale climate oscillations (e.g., El Niño/ La Niña, Interdecadal Pacific Oscillation, etc.) can occur which can introduce significant natural variability to climate trends that GCMs cannot always account for.

4.2 Climate change and hydrology of the Taiari Catchment (Filmer & Fitzharris 2002)

In 2002, a University of Otago climatologist and his student produced a report called 'Impacts of climate change on the hydrology of the Taiari and Waipori River Systems' for Marc Schallenberg (Filmer & Fitzharris 2002). This report was commissioned to help understand how future climate change could impact the water balance of the Lower Taiari Plain, and in particular, the Waipōuri/Waihora Lake-Wetland Complex. The report used a water-balance approach (based on catchment precipitation, runoff, evaporation, and storage), which was calibrated to data from numerous weather stations and hydrological sites in the Taiari catchment. The model had a monthly temporal resolution and was, therefore, able to resolve changes in seasonal water balance parameters. Two NIWA/IPCC carbon-emission scenarios were used to drive the model: Scenario 1 assumed rapid economic growth, no curtailment of CO_2 emissions and an increase of atmospheric CO_2

concentrations to 700 ppm by the year 2100, whereas under Scenario 2, CO_2 emissions would be limited to 550 ppm. Under Scenario 1, the global mean temperature rise was assumed to be approximately 3.0°C (over the 1990 level) and global sea level was assumed to rise by between 13 and 70 cm by the year 2100. Under Scenario 2, the global mean temperature rise was assumed to be approximately 2.0°C and global sea level was assumed to rise by between 9 and 53 cm by the year 2100.

The analysis of recent weather station data showed pronounced seasonality in runoff in the catchment. While both rainfall and evaporation were highest in summer, runoff in summer was lower than that in winter because of evaporation, evapotranspiration and irrigation takes. Both climate change scenarios projected reduced snow storage, increased precipitation, and substantially increased evaporation, leading to lower river flows in summer and higher river flows in autumn and winter, relative to current flows. Any increases in irrigation would further exacerbate future lower summer water flows into the Waipōuri/Waihora Lake-Wetland complex. Increased intensity of winter runoff and reduced summer flows would cause greater extremes of water flows in summer and winter, probably increasing the impacts of low flows and floods on aquatic ecosystems.

Pātearoa township bridge being cleared of debris after flooding in the Māniatoto in January 2021 (Source: Central Otago District Council/Fulton Hogan/Otago Daily Times)

4.3 Summary of historical trends and projections

Table 2. Historical climate and sea level trends, and future forecasts relevant to the Taiari catchment. Projections from Goldsmith (2023) apply to both RCP 4.5 and RCP 8.5 projected out to 2090. Projections from Filmer & Fitzharris (2002) apply to both scenarios (atmospheric CO_2 reaches 700 ppm by 2100; CO_2 is limited to 550 ppm by 2100 and other greenhouse gases are limited to 1990 levels). [1]The exception is that flows from the Silver Stream are projected to increase; also across most of the Taiari catchment annual flows will increase by the end of the century under the high emissions scenario; [2] https://niwa.co.nz/natural-hazards/hazards/sea-levels-and-sea-level-rise

	Trends				
	Lower Taiari	Mid Taiari	Māniatoto	Uplands	Reference
Temperature					
Mean annual air temperature (historical)	↑		↑		Goldsmith (2023)
Mean annual air temperature (projection)	↑	↑	↑	↑	Goldsmith (2023)
Extreme maximum air temperature (historical)			↑		Goldsmith (2023)
Days > 30˚C (projection)	↑	↑	↑	↑	Goldsmith (2023)
Extreme minimum air temperature (historical)			↑		Goldsmith (2023)
Annual frost days (projected)	↓	↓	↓	↓	Goldsmith (2023)
Precipitation					
Mean annual precipitation (historical)		o	o		Goldsmith (2023)
Mean annual rainfall (projection)	↑	↑	↑	↑	Goldsmith (2023)
Annual maximum 1-day rainfall (historical)	↑				Goldsmith (2023)
Annual heavy rain days (projection)	↑	↑	↑	↑	Goldsmith (2023)
Annual dry days (projection)	↓	↑ & ↓	↑	↑	Goldsmith (2023)
Hydrology					
Mean annual runoff (projection)	↑	0			Filmer & Fitzharris (2002)
Mean annual river flow (projection)	↑	o & ↑	o &↑	↑	Goldsmith (2023)
Mean annual (Q95) low flows (projection)	o & ↑	↓	↓	↓	Goldsmith (2023)
Mean annual flood flows (projection)	↑	↑	↑	↑	Goldsmith (2023)
Wind					
Mean annual wind speed (historical)	↓	↓	↓		Goldsmith (2023)
Highest daily wind run (historical)			↓		Goldsmith (2023)
Extreme wind (projection)	↓	↓&↑	↑	↑	Goldsmith (2023)
Sea level					
Sea level rise (rate from past century)	13.5 cm	n/a	n/a	n/a	Denys et al. (2020)
Seal level (increase from 2000 projected to 2040)	13 to 30 cm	n/a	n/a	n/a	NIWA[2]
Sea level (increase from 2000 projected to 2090)	40 to 100 cm	n/a	n/a	n/a	NIWA[2]

5. The Sensitivity-Exposure model

The conceptual model (derived from Dawson et al. (2011) and Robertson et al. (2016)) depicts the relationship between a species or ecosystem and its vulnerability and exposure to negative impacts from climate change (Fig. 5). The x axis (exposure to climate) is determined by a species' habitat location and range, future climate predictions for that habitat, and overall characteristics of that habitat. The y axis is determined by a species relative sensitivity or adaptability to changes within that habitat, which are largely driven by biological factors (physiological constraints, phenotypic plasticity etc.). When placing species along these axes, the overall vulnerability of a species to change can be determined, showing which species and habitats are most at risk when assessing climate predictions. This can in turn inform and prioritise management recommendations, strategies, and funding at both a species and habitat level. Employing this model, along with the most accurate climate predictions, establishes relationships between the degree of change and magnitude of impacts on values which can help inform the identification of climate impacts in future (Orchard 2022). This could improve the success of future management strategies for vulnerable species and habitat. Where possible, we place the information on valued species and habitats in this report within the context of this sensitivity-exposure model to help prioritise potential investment in mitigating future climate change impacts.

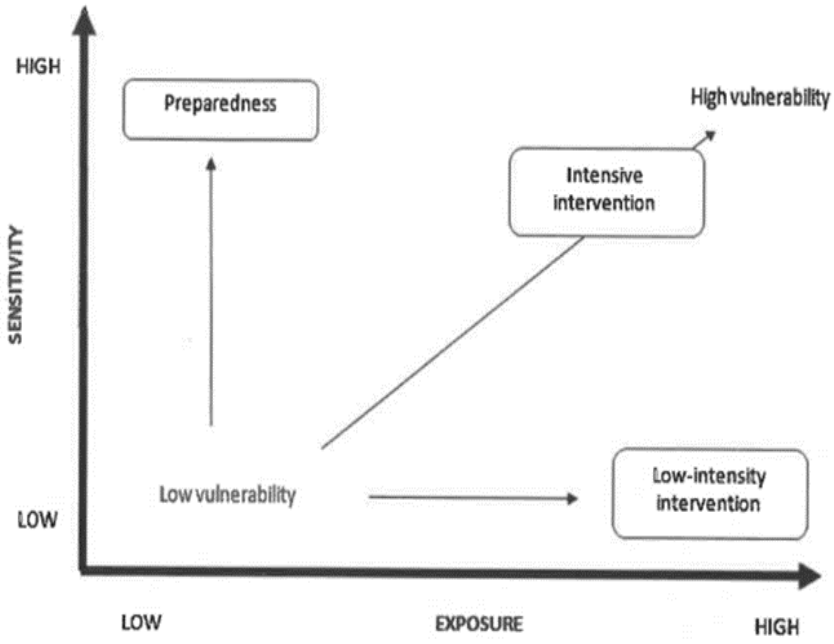


Figure 5. Vulnerability of freshwater ecosystems to impacts from climate change is defined by the relationship between exposure and sensitivity, based on Dawson et al. (2011). Intensive intervention is required to avoid impacts where the species or ecosystem is highly sensitive and is subject to high exposure due to its geographical location. Extracted from Robertson et al (2016): Freshwater conservation under a changing climate; DOC report, 93 p.

6. The Lower Taiari

The Lower Taiari catchment includes the river downstream from Outram, including all tributaries below an altitude of approximately 200 metres (excluding the upper Waipōuri River). The area is the surface of a tectonic basin impounded by the Chain Hills block on its seaward side through which the lower Taiari River cuts and discharges to the sea at Taiari Mouth. Approximately 10 km inland from Taiari Mouth, situated on the Lower Taiari Plain, are Lakes Waihora and Waipōuri which are part of the Waipōuri/Waihora Lake-Wetland Complex (Figs. 6 and 7). This is a small remnant of what was once a much larger coastal lake-wetland area that existed prior to hydrological modification during post-European settlement (Shaw & Farrant 1949, Wanhalla 2015). The lakes are situated at sea level and are connected to the sea via a c. 10-km-long reach of the Taiari and Waipōuri Rivers. The maximum depth of Lake Waihora generally ranges from c. 1.7 to 2.2 m, and that of Lake Waipōuri from c. 0.8 to 1.2 m, while the normal tidal range for Lake Waihora is c. 20–50 cm and that for Lake Waipōuri is c. 40 to 55 cm (Schallenberg et al. 2003b).

Where the Taiari River connects to the Waipōuri/Waihora Lake-Wetland Complex, the river is tidal and so its influence on the lakes and wetlands varies with the various tidal cycles and with freshwater flows in the Taiari and Waipōuri Rivers. The Waipōuri River, which enters the Lake-Wetland Complex at the north end of Lake Waipōuri,

Waipōuri/Waihora Lake-Wetland Complex

Figure 6. The lower Taiari catchment featuring the river mouth, Lake Waihora, Lake Waipōuri, Waipōuri river inflow, Silver Stream inflow, and the Taiari River inflow (Supplied by Whirika).

is regulated by a series of upstream hydro-electric dams, the largest of which impounds Lake Mahinerangi, an artificial reservoir. Water collected from agricultural land on the Taiari Plain is pumped into Lake Waipōuri at the Taiari Main Drain, which is operated to minimise flooding of the drained farmland in Lower Taiari Plain. The lakes and wetlands are connected by a network of channels that flow through the remaining wetland area. Lake Waihora has a mean non-tidal water residence time of 153 days compared with 1.9 days for Lake Waipōuri (Schallenberg et al. 2003b). Changes to the wider catchment vegetation and the drainage of most of the original surrounding wetlands have markedly affected the hydrology and increased the sedimentation rate of the lakes (Cadmus 2004; Schallenberg et al. 2012).

6.1 Sensitivity

An important aquatic ecological gradient in the Lower Taiari is the marine vs. freshwater water gradient, which creates a tidal, brackish zone (Prebble et al. 2002; Schallenberg et al. 2003a; Schallenberg et al. 2012). Therefore, both sea level and freshwater inflows determine the position of the brackish zone, highlighting the sensitivity of this system to both of these drivers. The relatively small sea-level high stand that occurred during the mid-Holocene (estimated to be approximately 0.75 m above current sea level) resulted in much of the Lower Taiari Plain transforming into a temporary lagoonal estuary, dominated by cockles/tuaki (Schallenberg et al. 2012).

Wetlands of the lower Taiari

6.1.1 Lake/wetland ecosystem, invertebrates and macrophytes- sensitivity

Drought conditions can result in increased salinity in the lower catchment

By comparing a drought year with a wetter year, Schallenberg & Burns (2003) showed that saline intrusions into Lakes Waihora and Waipōuri were strongly influenced by the freshwater inflows to the system. A drought year resulted in a significant summer/autumn saline intrusion, whereas no saline intrusion was observed in a non-drought year. The salinity variations in the two years resulted in markedly different zooplankton communities and abundances in the lakes (Schallenberg et al. 2003a). The saline intrusion in the drought year resulted in fewer species, a lower zooplankton abundance, and the dominance by an estuarine copepod, which contrasted to the year without a saline intrusion. Experiments showed that keystone species, such as the important grazer *Daphnia thomsoni (previously known as D. carinata)*, were excluded from the lake during the brackish-water phase and largely replaced by the estuarine copepod *Gladioferens pectinatus* (Hall & Burns 2002a; Schallenberg et al. 2003a). Experiments examining both temperature and salinity effects on the reproduction and survival of these two species showed important interactions between the effects of these two environmental drivers on zooplankton species (Hall & Burns 2002b; 2002c). Observed variations in salinity in the lakes are also likely to affect the phytoplankton community (e.g., Flöder et al. 2010), as well as other organisms, including invertebrates, aquatic plants and fish (see below).

A survey of the submerged aquatic plant community of Lake Waihora by Schallenberg & Waite (2004) reported the presence of eleven species, with only one invasive species, *Elodea canadensis*, present in low abundance. Submerged plant cover was quite extensive across the lakebed. The distribution of the plants suggested that the occasional salinity gradient in the lake may have influenced the distribution of plant species along the main axis of the lake.

^ *Elodea canadensis*

The submerged plants of Lake Waihora were again surveyed in June 2023 (de Winton et al. 2023), as part of a LakeSPI (lake submerged plant index) survey. A similar community, species richness, distribution, and coverage of macrophytes was reported as that observed 19 years earlier (Schallenberg & Waite 2004). The lake was assessed to have a high LakeSPI score (i.e. a good condition). *Elodea canadensis* persisted in 2023 but was still not highly invasive in this lake. De Winton et al. (2023) also discussed the structuring effect of transient salinity intrusions to the lake on the macrophytes as well as the benefit of low levels of salinity in limiting the ability of invasive macrophytes to gain a competitive advantage in many brackish lakes. This re-survey of the macrophytes of Lake Waihora indicates that the aquatic plant community of lake has been resistant and resilient to stressors and that an undesirable regime shift to a more turbid, algal-dominated state has not occurred (Schallenberg & Sorrell 2009).

Kākahi (*Echyridella menziesii*) are known to inhabit the south-western, less brackish, part of Lake Waihora (Schallenberg & Waite 2004), suggesting that occasional saline intrusions from the north-east end of the lake may constrain the distribution of *E. menziesii*. In addition, kōura (freshwater crayfish) inhabit the Waipōuri/Waihora wetlands (Ryder & Tocher 2020), and this valued species may be vulnerable to salinity. Thus, there is some suggestion that salinity is already structuring the species distributions in Lake Waihora and, with salinity effects likely to intensify as a consequence of sea level rise, changes to the distributions of valued species such as aquatic macrophytes, freshwater mussels and freshwater crayfish are likely to occur. Several fish species also are known to occur within the wetland complex. For more information on this please refer to section 6.1.4.

Key species within the lake-wetland complex

Kākahi
(freshwater mussel)

Mātātā
(fernbird)

Kōura
(freshwater crayfish)

Kotoreke
(marsh crake)

Matuku-hūrepo
(Australasian Bittern)

Some species may be displaced if sea level rise influences salinity in the wetlands

Species with low salinity tolerance are likely to be progressively replaced by estuarine species. Systems such as Waituna Lagoon (Southland), Wainono Lagoon (Canterbury), and Wairewa/Lake Forsyth (Canterbury) provide some indication of the types of communities and ecosystems that the Lower Taiari system could transition toward. These systems have submerged plant communities comprised of seagrasses (e.g., *Ruppia* sp.), charophytes (e.g., *Lamprothamnium macropogon*, *Myriophyllum* sp., and *Stuckenia pectinatus*), and seem to be resistant to colonisation by invasive macrophytes, but lack kākahi and kōura (M. Schallenberg, pers. obs).

The lakes and the associated wetlands also provide habitat for over 50 diverse species of birds (Ryder & Tocher 2020), including populations of regionally significant species, e.g. mātātā (fernbird), kotoreke (marsh crake) and the matuku-hūrepo (Australasian bittern) (https://www.tenohoaka.org.nz/the-wetlands). Up to 80 species of birds have been recorded in the area according to a DOC report that notes the international and cultural significance of the wetlands (DOC 1996).

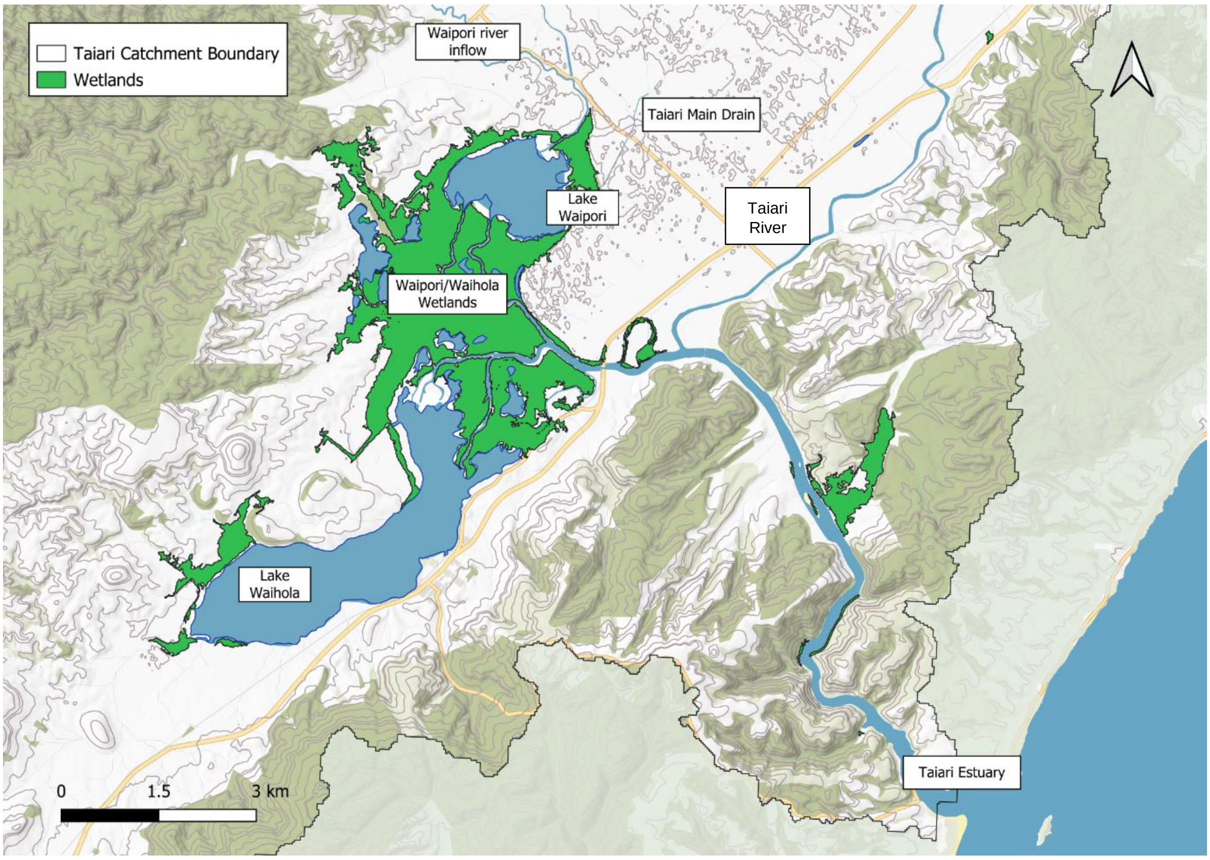


Figure 7. Topographic map showing the Waipōuri/Waihora lake/wetland complex and the Taiari Estuary. The thin black line is the Taiari catchment boundary. The dull green shading indicates forest and white indicates exotic grasslands.

6.1.2 Sensitivity of invertebrate communities in the stony-bottomed tributaries of the lower Taiari

Macroinvertebrate biodiversity and community composition in the stony-bottomed tributaries of the lower and middle Taiari River are driven by agricultural land-use intensity (Dolédec et al. 2006, Matthaei et al. 2006, Niyogi et al. 2007) and physical disturbance regimes (Townsend et al. 1997a,b, Matthaei & Townsend 2000).

In a survey of 54 stream sites across the lower and middle Taiari, macroinvertebrate taxon richness was shown to be highest in tributaries with intermediate physical disturbance regimes (intensity of flood-related episodes of bed movement; Townsend et al. 1997a,b). Insect larvae belonging to the pollution-sensitive orders mayflies, stoneflies and caddisflies (Ephemeroptera, Plecoptera and Trichoptera, EPT) and mostly widespread species dominate in non-polluted streams, as has been shown in several surveys of lower and middle Taiari streams spanning gradients of agricultural catchment land-use intensity (Dolédec et al. 2006, Matthaei et al. 2006, Niyogi et al. 2007). Because EPT taxa are often also sensitive to high water temperature, the invertebrate communities in these non-polluted streams can be expected to be quite sensitive to climate warming (as discussed further under 'Exposure').

Several rare and threatened freshwater invertebrate species with restricted ranges occur in streams draining into the lower and middle Taiari, for example the nationally critical stonefly *Teraperla johnsi* occurs on Maukaatua (Ryder & Tocher 2020). Little is known of the ecology or biology of these threatened species (Ryder & Tocher 2020).

Sensitive EPT invertebrate taxa may be displaced by a warming climate.
As land-use intensity increases (e.g. in streams draining dairy farms or deer farms), pollution sensitive EPT taxa become rarer, whereas pollution-tolerant taxa such as chironomid midges, mud snails (*Potamopyrgus antipodarum*), Oligochaete and Nematode worms become more prevalent and can dominate the communities. Because these taxa can also generally tolerate warm water temperatures, the invertebrate communities in these polluted streams are likely to be much less sensitive to climate warming than their non-polluted counterparts (see 'Exposure').

6.1.3 Estuarine mysids of the lower Taiari – sensitivity

The mysid communities of the lower Taiari dominate the crustacean biomass in the lower reaches of the river and estuary and comprise four main species, *Tenagomysis chiltoni, T. novae-zealandiae, T. macropsis* and *Gastrosaccus australis* (Bierschenk 2014). All four species occur widely in streams along the Otago coastline, with *T. chiltoni* and *T. novae-zealandiae* occurring in most systems, whereas *T. macropsis* and *G. australis* only occur in open estuarine systems with regular tidal exchange (Lill et al. 2011)[3]. Relatively little is known of the ecological role of mysids in the lower Taiari (Willhelm et al. 2002). However, given their omnivorous diet and substantial biomass, they almost certainly represent a key node in the system's food webs, both as predators and prey (Willhelm et al. 2002; Lill et l. 2011; Bierschenk 2014).

Research across multiple Otago estuaries indicates that complex interactions between habitat, tides, salinity and temperature determine the distribution of the mysid fauna (Lill et al. 2011;

[3] For further detail see Appendix 1.1. 'Sensitivity of Estuarine Mysids'.

Biershenk 2014). What is remarkable is their ability to maintain a relatively stable distribution across multiple tidal cycles (Bierschenk 2014). How they do this in an estuarine system that is highly dynamic with respect to every key physical and chemical variable is unknown.

6.1.4 Fish - sensitivity

The lower Taiari supports a regionally significant and diverse fish fauna, comprising native and introduced species, with multiple studies having been completed over the past 25 years across the area. However, most of the fish community research has focussed on the area upstream of Henley rather than the lower estuarine reaches which represent a more challenging environment in which to conduct fisheries research. Larval drift studies conducted in 1999 along the lower reaches down to Taieri Mouth recorded seven larval and juvenile fish species, with common bully (*Gobiomorpus cotidianus*), īnaka (*Galaxias maculatus*) and triplefin (*Forsterygion nigripenne*) being abundant, and lower numbers of pātiki (black flounder; *Rhombosolea retiarii*), clingfish (*Dellichthys morelandi*), smooth leatherjacket (*Meuschenia scaber)* and European perch (*Perca fluviatilis*) (Sutherland et al. 2001). Smelt (*Retropinna retropinna*) and yelloweye mullet (*Aldrichetta forsteri*) *are* also abundant (G. Closs pers. obs.). Recent surveys using eDNA suggests the overall composition of the fish assemblage has not changed markedly over the past 20+ years (https://www.wilderlab.co.nz/explore).


Common Bully


Īnaka


Smelt

Further upstream, the lakes and wetlands support large populations of native longfin tuna (*Anguilla dieffenbachii*), shortfin tuna (*A. australis*), common bully, common smelt, īnaka and giant kōkopu (*G. argenteus*), as well as non-native brown trout (*Salmo trutta*) and European perch (*Perca fluviatilis*). Extensive studies by Kattel (2007), Ludgate & Closs (2003) and Goldsmith (2004) in the late 1990s and early 2000s found lake and wetland communities were dominated by īnaka, common bully and perch. More recent sampling suggests this pattern of abundance broadly continues (https://www.wilderlab.co.nz/explore). Both shortfin and longfin tuna are also abundant, although greater abundance of tuna in more isolated, harder to access ponds suggested some level of fishing (poaching) pressure has occurred in more accessible areas


Shortfin tuna


Giant kōkopu


Brown trout

in the past (Clucas 2004). Whether this is still the case is unknown as there have been no recent comparable surveys to assess abundance. Fish community diversity and size composition is related to pond size, with species richness declining with pond size (David 2001; Ludgate & Closs 2003). The smallest ponds generally contain low numbers of common bully, large perch and tuna (David 2001; Ludgate & Closs 2003). Removal of large adult perch can result in significant increases in the abundance of either perch or common bully (Ludgate & Closs 2003). Smelt and īnaka are seasonally abundant in the lakes, particularly over summer (Kattel 2007). Īnaka migrate downstream to spawn along the Waipōuri River in autumn (G. Closs Pers. Obs.). Spawning sites of smelt are unknown - most likely they are located along the sand banks of the channels draining Lake Waihora.

Stream fish communities in the area vary greatly depending on stream size, altitude, distance from lower Taiari basin and habitat (David et al. 2002; Kristensen & Closs 2008). Larger streams throughout the area are dominated by brown trout – Silver Stream supports a particularly significant brown trout spawning run and plays a key role in supporting the brown trout fishery across the area (Kristensen & Closs 2008; Jones et al. 2019). Brown trout populations are migratory in the lower reaches, but transition to resident fish communities with increasing altitude, stream gradient and upstream of barriers to migration (Kristensen and Closs 2008; Jones et al 2019). Significant populations of giant kōkopu also occur in streams across the lower Taiari basin, particularly where suitable habitat exists (extensive riparian cover and/or woody debris[4]; David et al 2002). More intensive searches of the area would undoubtedly reveal more populations. Streams flowing into Lake Waihora support the largest populations with a broad size range of fish indicating strong annual recruitment (David et al. 2002). Well-organised, stable dominance hierarchies of giant kōkopu in these streams suggest these populations are habitat/energy limited, rather than recruitment limited (Hansen & Closs 2009). Otolith analysis of giant kōkopu and the capture of galaxiid whitebait in Lake Waihora in winter confirm these populations are largely land-locked and are recruiting most likely from within Lake Waihora (David et al. 2004), as are common bully (Closs et al 2003). Elsewhere, populations of giant kōkopu in lowland lower Taiari streams (Boundary, Ōwhiro, Mill) tend to be dominated by larger fish, suggesting a degree of recruitment limitation (David et al. 2002). Where giant kōkopu are abundant, trout are generally absent, suggesting aggressive and intact populations of giant kōkopu can resist trout in smaller streams

[4] Note: Development of guidance on 'In-stream habitat restoration using woody debris' is underway, (Ebi Hussain (Auckland Council) via the councils Fish SIG, also see 'Habitat requirements of native freshwater fish in Aotearoa New Zealand' (Petrove, N., McEwan, A., Paltridge A. *in press*, Department of Conservation).

(David et al. 2002). Redfin bullies are also present in many of the smaller streams draining into Lake Waihora and elsewhere where riffle habitat is present.

Smaller streams that enter the estuarine Taiari mainstem downstream of the wetlands support communities of banded kōkopu and kōaro e.g., Picnic Gully (Kater 2004). Banded kōkopu dominate downstream reaches, with the proportion of kōaro increasing with distance upstream (Kater 2004). These streams are prone to drying during prolonged dry periods, and fish abundance may be significantly reduced following these events, although recolonisation by whitebait is relatively rapid (Kater 2004). Panoko (Torrentfish *Cheimarrichthys fosteri*) can occasionally be caught in the Waipōuri River upstream of Lake Waipōuri (G. Closs pers obs). Ammoecoetes of kanakana can also be occasionally caught in most of these small streams indicating adults are spawning upstream (G. Closs pers. obs). A collaborative survey led by DOC in 2023 was positive for kanakana eDNA and pheromones upstream of both Lake Waipōuri and Lake Waihola, within Silver Stream (Kavazos and Richarson 2023) and Meggat Burn (Richarson & Kavazos unpublished).

There are still significant knowledge gaps with respect to the fish communities of the lower Taiari catchment. On account of its depth and size, the lower Taiari River has received limited sampling. Similarly, due to challenging access, few of the streams entering the estuarine lower Taiari have been sampled extensively – populations of banded and giant kōkopu likely occur in some of these unsurveyed streams. Smelt, black flounder and yellow-eye mullet can be abundant in the lower reaches of the river, but the ecology of these three species has received minimal study, either in the Taiari or elsewhere. The spawning sites of smelt are currently unknown. Similarly, the life cycle of black flounder is poorly known. The widespread occurrence of kanakana ammocoetes indicates kanakana spawning is occurring in the local catchment, but they are generally considered sparse rather than common. The kanakana pheromone concentrations detected in 2023 suggest abundances could be high in Silver Stream, and upstream of Lakes Waipōuri and Waihora (Kavazos and Richarson 2023). Many of the smaller streams around the lower Taiari basin have not been surveyed, particularly in the upper reaches, and indeed some of the larger streams are also poorly known due to difficult access. Many smaller streams flowing down the flanks of Maukaatua


Banded kōkopu


kōaro


Panoko


Kanakana

enter the Taiari Flood Protection Scheme, and hence fish communities are likely impacted by the barriers to migration that this system may create (e.g., flood gates, weirs, pump stations). The impact of this flood protection system on fish communities is unknown. The patterns described above are broadly consistent with patterns seen during the 2023 eDNA and pheromone surveys suggesting fish communities have not markedly changed over the past ~20 years or so (Kavazos & Richarson 2023; Wilderlab 2023 - https://www.wilderlab.co.nz/explore).

6.2 Exposure

6.2.1 Lake/wetland ecosystem, invertebrates and macrophytes

The key climate-change-related risk factors in the Lower Taiari Lakes are sea-level rise and changes to freshwater inflows. Historical sea-level records and future projections indicate that sea level will continue to rise, at least in the near future. Historical weather station data in the catchment do not show clear trends in mean annual rainfall (i.e., no substantial change over the past century). Projections based on climate-change scenarios suggest a small increase in mean annual rainfall may occur, but there is more confidence in projections of increased seasonality of runoff with decreased runoff in summer and increased runoff in winter, with related impacts on river flows. A slight increase in extreme flood events is projected, particularly in winter. Lower summer flows also indicate that saline intrusions in summer/autumn will increase in intensity as a result of climate change. This will exacerbate the salinizing influence of rising sea levels in terms of summer/autumn saline intrusions.

Consequently, from the perspective of both ecological sensitivity and confidence in climate and sea level perturbations, the Lower Taiari lakes and wetlands appear to be highly exposed to the disrupting effects of climate change and sea level rise, as expressed by increasing overall saline influence and more seasonal variability in salinity and water levels. The Lower Taiari lakes and wetlands are already prone to the effects of flooding and saline intrusions. Thus, the future predicted changes will result in the greater salinity variations and slightly more flooding than are currently typical for this system.

Small organisms and aquatic plants may be at risk under the future climate scenarios

Small organisms such as phytoplankton and zooplankton are highly vulnerable to salinity stress due to their limited abilities to osmoregulate. Submerged aquatic plants and benthic invertebrates have limited ability to take advantage of freshwater refugia. Therefore, they are quite exposed to the disrupting effects of projected salinity increases.

Both temperature and salinity affect shallow lake functioning via well-studied mechanisms. For example, increasing temperature increases nutrient cycling in lakes, whereas increasing salinity interferes with phosphorus binding in lake sediments (thereby increasing phosphorus availability) and causes changes in community structure, altering food webs and energy flow. Predicting the combined outcome of warming and salinity increases in lakes is a complex problem (Scheffer et al. 2001; Jeppesen et al. 2003; Brucet et al. 2012); therefore, predicting the net outcome of future sea level rise and warming on the lakes of the lower Taiari Plain is not straightforward. However, we recognise the benefits to water quality and ecological values of healthy macrophyte communities in the lakes (Schallenberg & Sorrell 2009). The certain rise in salinity and water levels, combined with the likely warming of the two lakes, suggests a future risk to the ecological integrity of the lakes that could manifest as a rapid regime shift in response to macrophyte collapse (Fig. 8).

Submerged aquatic plants are critical to water quality and lake health.

The biggest threat to the health of shallow lakes is the loss of the submerged aquatic plant community – and a shift to a more generally turbid or murky condition (Fig. 8). Plants provide habitat, compete with algae for nitrogen and phosphorus, produce chemicals that suppress algal growth and stabilise the lakebed reducing how much sediment the wind can stir up. Aquatic plants are mainly threatened by turbidity or murkiness of the water, which is caused by suspended sediment and high phytoplankton biomass and reduces light penetration into the water column (Scheffer 2004). In New Zealand, the loss of aquatic plants from shallow lakes has been associated with a high percentage of pasture in the catchment, with the presence of the invasive submerged plant *Egeria densa,* and with the presence of certain bottom-feeding and herbivorous invasive fish species (including goldfish, koi carp, catfish, rudd and tench; Schallenberg & Sorrell 2009).

Two surveys of the aquatic plants of Lake Waihora have been undertaken (Schallenberg & Waite 2004; de Winton et al. 2023). Both surveys found that most of the lakebed was inhabited by aquatic plants. The assessment of the health of the aquatic plant community indicated a "high" overall condition, with good native plant diversity and only one invasive species present (*Elodea canadensis*; de Winton et al. 2023). Overall, the aquatic plant community and coverage of the lakebed appeared to have changed little in the 20 years between surveys. Nonetheless at present, these lakes are considered impacted, and potentially on the brink of progressing to a more turbid state. Ongoing management to reduce sediment and nutrient inputs is recommended.

Threats to the aquatic plant community in Lake Waihora include:

1. Excessive nitrogen and phosphorus loads to the lake (fuels phytoplankton and macroalgae blooms);
2. Excessive sediment loads to the lake (increases turbidity/murkiness, reduces light penetration into the lake);

3. Excessive phytoplankton biomass (increases murkiness, reduces light penetration into the lake);
4. Reduction in the biomass of important grazers of phytoplankton (e.g., *Daphnia*, kākahi);
5. Invasion by *Egeria densa* and/or bottom feeding or herbivorous fish;
6. High swan densities (which graze down plants and defecate nutrients into the lake).

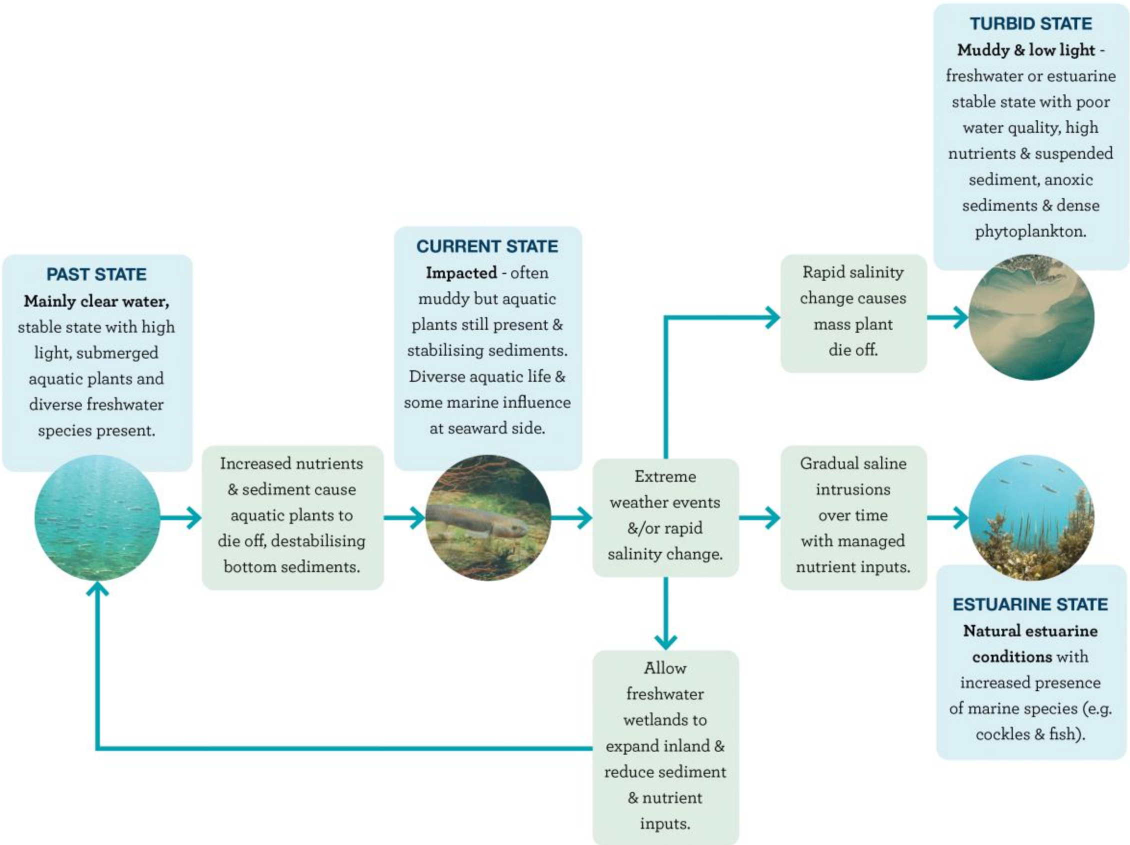


Figure 8. Alternative stable state shifts that could happen in the Waipōuri/Waihora Lake-Wetland Complex

Overall, the lake-wetland complex is somewhat exposed to predicted impacts of climate change, mainly as a result of sea-level rise, projected reductions in summer/autumn freshwater inflows and warming water temperatures. At the time of first European settlement in the Taiari Plain, the wetlands were much more expansive than they are now with active drainage continuing today to prevent inundation of productive land. Therefore, if the wetland complex were allowed to expand beyond the constraints of the stop-banks in a strategic and controlled manner, then freshwater habitats would shift towards higher areas of the basin, allowing freshwater species to adapt to rising sea levels. However, if flood protection schemes are bolstered against rising water levels, this could limit/delay marine intrusions but eventually the highly productive and diverse freshwater and brackish lakes and wetlands of the Lower Taiari plain will disappear, to be replaced by an estuarine environment. It is therefore key to ensure there is good wetland and freshwater habitat upstream of the current wetland system. The management of this system is crucial to safeguard many of the values identified by the community and mana whenua (Orchard 2022).

6.2.2 Freshwater invertebrates - Exposure

Large knowledge gaps exist on Taiari specific invertebrate communities, but inference can be made from the wider literature.

To our knowledge, no climate-change related research on benthic macroinvertebrate communities has been conducted in the Taiari River or in its tributaries.

Kākahi (freshwater mussels) are present in the Waipōuri and Taiari rivers but have not been comprehensively surveyed since an early study in Lake Waihora that identified mussels more than 50 years old (Grimmond 1968) – among the oldest formally aged in New Zealand thus far. Kākahi are dependent on a range of fish species (including common bully) to complete their life cycle although no studies of fish-kākahi relationships have been completed locally (see Melchior et al. 2023).

ExStream experiments indicates elevated temperatures will exacerbate negative impacts of sediment, nutrient and/or pesticides.

ExStream System experimental system

Several manipulative experiments have investigated effects of different climate-change factors on lotic macroinvertebrates in southern New Zealand. Two of these have been conducted in the *ExStream System*, an outdoor setup comprising 128 circular flow-through stream 'mimics' (or mesocosms) fed by the Kauru River in North Otago. The *ExStream System* is a tightly controlled, statistically powerful, and highly field-realistic setup located in a catchment immediately north of the mid Taiari – thus the findings of the *ExStream* studies are highly relevant to the Taiari catchment.

In the first of the two ExStream climate-change related experiments, Piggott et al. (2015) investigated how deposited fine sediment and elevated nutrient concentrations interact to affect stream macroinvertebrate community dynamics along a water temperature gradient ranging from 0 to 6°C above ambient (eight levels)[5]. As a stressor main effect, raised temperature strongly changed the composition of the benthic invertebrate community. In general, the more pollution sensitive taxa decreased in abundance while pollution tolerant species either increased in abundance or were unaffected.

[5] See Appendix A1.2. 'Lower Taiari Stream invertebrates - Exposure' for further detail.

In the second experiment, Macaulay et al. (2021a) investigated the individual and combined effects of raised water temperature (ambient, 3°C above) and pulsed exposure to imidacloprid (the world's most commonly used insecticide at four environmentally relevant levels between 0 and 4.6 µg/L) on invertebrate communities representative of fast- and slow-flowing microhabitats.

The combined effects of the stressor manipulations and a 10-day natural heatwave (during which the Kauru River watering the channels reached 29.8°C) drastically reduced relative abundances of EPT and insects overall and caused a shift to oligochaete-, crustacean- and gastropod-dominated communities.

Complementary laboratory research on 2 species of native mayflies (Macauley et al. 2020) indicated that elevated temperatures synergistically increased the toxicity of imidacloprid[6]. A longer-term experiment (Macauley et al. 2021b) examined interactions between heatwaves, starvation and long-term exposure to low concentrations of imidacloprid. The simulated heatwaves alone caused such drastic negative effects on *Deleatidium* survival and mobility that mainly antagonistic interactions were observed with the other stressors.

A 2018 heatwave demonstrated that the ExStream temperature elevations are relevant now and likely to be exceeded with climate change.

Due to the natural heatwave overlaying the experimental heating, the water temperatures in that experiment reached very high maximum values, yet they remain environmentally realistic. An 18-day heatwave in January 2018, about 1 month after the experiment, resulted in even hotter temperatures in the Kauru River, with river water temperatures 0.5 km upstream of the mesocosm site reaching >31°C (Otago Regional Council, unpublished data). Thus, the daily temperature maxima during the heatwave (28.0–32.9°C in heated and 25.0–29.8°C in non-heated mesocosms) were already almost entirely realistic under current climate conditions, and even the peak temperatures in heated channels could easily be exceeded during the coming decades of continuing climate warming.

[6] For further detail see Appendix 1.3 'Complementary laboratory research – invertebrate communities….'.

The pollution-tolerant native New Zealand mud snail is invasive overseas – and responded positively to heating.

The only taxon in the mesocosm benthos that responded positively to the heating in Macaulay et al. (2021a) was *Potamopyrgus antipodarum* (New Zealand mud snail). These snails are known to be pollutant-tolerant (Stark & Maxted, 2007) and often thrive in streams affected by agricultural stressors such as nutrients and sediment (Matthaei et al. 2010; Wagenhoff et al. 2011). In Macaulay et al. (2021a), this species was also unaffected by imidacloprid (whereas the mayfly *Deleatidium* spp. was strongly reduced by imidacloprid) and responded positively to slow flow velocity (another stressor related to water abstraction for agriculture).

Sensitive invertebrate species are likely at risk

When combined with the findings of the two mesocosm studies above, this experimental multiple-stressor research strongly suggests that increased water temperatures (both chronic increases and heatwaves of increasing severity) are likely to critically affect sensitive freshwater organisms such as mayflies and stoneflies, and that the impacts of widespread pesticide use on freshwater ecosystems under global climate change cannot be ignored. These findings are likely to apply to the stony-bottomed tributaries of the Taiari river catchment and to stony-bottomed streams in other regions of New Zealand, and also in other parts of the world. The latter is because EPT insect taxa are well-known to be sensitive to a wide range of pollutants, which is a key reason why they are used in the biomonitoring of lentic ecosystems.

In keeping with these findings from stream mesocosms, *P. antipodarum* was also the most tolerant freshwater invertebrate taxon to high water temperatures in several 96-h laboratory tests, with median lethal temperatures of 32.4°C (Quinn et al. 1994) and 33.6°C (Cox & Rutherford, 2000). The tolerance of *P. antipodarum* to so many stressors may explain why it has become a successful worldwide invader of lotic and lentic habitats (Alonso & Castro-Díez, 2012). **This unusual tolerance also suggests the invasiveness of this snail may increase even further under future global climate change scenarios (Daufresne et al. 2004; Huang et al. 2011).**

Impacts on stream invertebrates of increased habitat disturbance – as expected with climate change – may be less important than other pressures.

Climate change may also influence diversity and composition of the macroinvertebrate communities in the stony-bottomed tributaries of the Taiari catchment via changes to the physical disturbance regime of these streams (e.g., during extreme rain events or floods). In a survey of 54 stream sites across the lower

Stonefly nymph (Angus McIntosh University of Canterbury) and middle Taiari, macroinvertebrate taxon richness was shown to be highest in tributaries with intermediate physical disturbance regimes (Townsend et al. 1997a,b)[7].

In 1993/1994, most of the 54 stream sites surveyed in Townsend et al. (1997a,b) had moderate disturbance regimes (between 25-75% disturbance intensity), and invertebrate taxon richness at these sites ranged from around 20 to more than 30 taxa per site. Given the climate projections for the Taiari, this distribution could shift towards the highly disturbed end of the disturbance intensity scale, and mean taxon richness in these streams could decline accordingly. However, this disturbance-driven decline in invertebrate taxon richness is unlikely to be large. This is because the predicted increases in rainfall, heavy-rain days and flood frequency and magnitude are not drastic and the entire Taiari catchment lies in a region of low to moderate annual rainfall (by New Zealand standards).

Moreover, and importantly, these flood-disturbance driven patterns are overlaid by the water-temperature and land-use-intensity driven effects discussed above. In our view, the impact of climate-induced changes to the flood disturbance regime on the benthic invertebrate communities in the Taiari catchment will most likely be less influential than these other drivers (i.e., temperature, sediment and nutrients).

6.2.3 Mysids - Exposure

The four species of mysid present in the Taiari River are widely distributed in estuaries along the Otago coastline, suggesting that these communities are relatively resilient with respect to varying environmental conditions (Lill et al. 2011). *Tenagomysis novae-zealandiae* and *T. chiltoni* are present in most estuaries, with their longitudinal distribution along each system determined by salinity and temperature (Lill et al. 2011). *Tenagomysis macropsis* and *G. australis* are only present in open systems but are abundant in every estuary where there is regular tidal exchange (Lill et al. 2011). Within each estuary their distribution is highly dynamic, with longitudinal position determined by interactions between freshwater inflows, estuary morphology, season, life history stage, etc. (Lill et al. 2011; Bierschenk 2014).

The mysid communities in estuaries along the coast exhibit a clear and consistent longitudinal structure. Thus, *T. chiltoni* is always dominant upstream of all other species and is the only species that can persist in freshwater (Lill et al. 2011). Of the two pelagic species, *G. australis* is generally more abundant upstream of *T. macropsis* irrespective of season, river discharge or tidal state (Bierschenk 2014). Clearly, given the consistent longitudinal structuring of mysid communities,

[7] For further detail see Appendix 1.4. 'Impacts of increased habitat disturbance on stream invertebrates".

changes to sea level, freshwater inflow, temperature and so on, changes to the distribution of the mysids along the estuary will occur. However, the Taiari estuary is currently a very dynamic system, with considerable daily, seasonal and annual variation in the patterns of tidal exchange. ***Shifting patterns of distribution in response to past flood and drought events occur and indicate a highly resilient assemblage that is well adapted to variable sea levels and persisting in these extremely dynamic systems (Lill et al. 2011).***

6.2.4 Fish - exposure

The risk of direct local climate change impacts to stream fish communities across the lower Taiari catchment appears to be relatively low. The communities are dominated by relatively widespread migratory species that have the capacity to readily recolonise streams following local disturbance, such as floods or droughts. However, freshwater species need 'room' to migrate inland as the Waipouri/Waihora complex increases in salinity, otherwise significant population decreases may occur in response to loss of highly productive lake and wetland habitat. For example, the important whitebait species īnaka and kōkopu may be impacted, with flow on effects on tuna.

Picnic Gully stream at Taiari Mouth periodically ceases to flow, resulting in the loss of fish when dry (Kater 2004). When flow resumes, the stream is quickly recolonised by banded kōkopu and kōaro. Clearly, this recolonisation process is dependent on the availability of whitebait and other juvenile fish to recruit into the system. However, all of the common migratory species in the region are locally abundant and present in streams along the Otago coastline, suggesting a large and relatively resilient pool of recruits should be available to recolonise habitat subject to local disturbance. The impact of larger-scale events, such as a regionally significant and catastrophic flood or drought events, are more difficult to predict. Recolonisation of individual streams would depend on the regional extent of the disturbance and the poorly understood patterns of dispersal and migration of fish larvae/whitebait in the near-coastal marine habitats. Recent studies of kōaro, bluegill bully and torrentfish suggest larval dispersal from river mouths can be restricted, with many fish returning to their natal streams to live (Warburton 2015; Warburton et al. 2018; Augspurger et al. 2023). If so, recolonisation following regionally significant events may be slow.

Species with early life history stages that occur in the parts of the system subject to tidal influence are likely to be most exposed to the impacts of sea level rise – this includes īnaka, common smelt, giant kōkopu, kōaro, common bully, redfin bully, black flounder, triplefin, and introduced perch. Spawning of īnaka mainly occurs upstream of the confluence of the Taiari and Waipōuri Rivers, coinciding with the limits to the upstream penetration of high-salinity water. Smelt likely spawn along the river channel, depositing their eggs on the sandy substrate that comprise much of the bed of the lower Taiari River. Higher sea levels and increased tidal influx would presumably drive spawning of these two species further upstream. Whether successful spawning continued would very much depend on the availability of suitable habitat, which would be management dependent (i.e. status of flood banks). If there is little suitable habitat above the current lake-wetland system, there could be significant detrimental impacts on whitebait species, and the species that depend on them (e.g., tuna). Perch are unable to tolerate significantly increased salinity, hence their downstream distribution would likely be restricted to some extent. Larvae and juveniles of the other species rear in various other parts of the lower Taiari floodplain and estuarine system – given these species are all amphidromous or have marine larvae, their life histories are unlikely to be severely impacted by increased tidal flux, although distribution within the system may change. ***The adults of these species are all relatively tolerant or primarily occur in tributary streams, hence are unlikely to be significantly impacted by initial rises in sea level. Again, some minor shifts in distribution may occur around the saline/freshwater interface.***

6.3 Management Options

6.3.1 Lake/wetland ecosystem, macrophytes, wetland vegetation, invertebrates, and birds.

The sensitivity and exposure of the biota of Lakes Waihora and Waipōuri warrant careful consideration of potential management actions to minimise or slow down effects of climate change. The key driver of change will likely be increasing marine influence, due to a combination of increasing sea level and projected reductions in summer and autumn runoff and freshwater flows into the Lower Taiari Plain. This perturbation may be seasonal, depending on how much winter runoff increases. Management options for wetlands across the lower Taiari also need to recognise that increasing salinity will impact on the ability of different plants to grow in downstream areas – for example, extensive dieback of willows has occurred in the Henley area during previous extended incursions of seawater (G. Closs pers.obs.).

The bolstering of flood protection works and increasing the pumping of water out of drains could limit marine intrusions into the Lower Taiari Plain, but this would prevent new wetland habitats from forming as water levels rise in the future. To slow the effects of saline intrusions into the lake-wetland complex, freshwater inputs to the lake-wetland complex could potentially be managed, but providing more freshwater flows in summer may be difficult due to projected increasing summer droughts, which will put pressure on the Taiari River as a source of irrigation water. The Waipōuri River has a flow regime that is managed for hydro-electric generation, which could potentially provide an opportunity to retain water in Lake Mahinerangi in winter so as to release it to the lake-wetland complex during summer/autumn, when Taiari River flows are likely to decline, and saline intrusions are likely to occur with greater frequency and magnitude.

In the absence of substantial intervention, the lake-wetland system is likely to revert back to an estuarine, lagoon ecosystem, somewhat similar to its state during the mid-Holocene (see Section 3.2). At the current rate of sea level rise, this is likely to take a few centuries to revert to a true estuarine system, with estuarine biota. If modelled projections of much higher rates of sea level rise turn out to be accurate, then the transition will happen by the end of this century. In the drought year of 1999, the salinity of Lake Waihora reached approximately 20% of seawater (Schallenberg et al. 2003; Schallenberg & Burns 2003). Saline intrusions of this magnitude are likely to become more frequent and intensify as the sea level rises. It will likely be as a result of such transient, extreme salinity events that the largest changes in species community composition in the lake-wetland complex will occur. The significant investment of mana whenua in Te Nohoaka o Tukiauau/Sinclair wetland restoration may need to consider this in long-term planning - for example, the downstream areas of the wetlands may become inhospitable to salt-intolerant species such as kahikatea within the life span of such long-lived plants.

Due to its tidal nature and its vulnerability to saline intrusions, the aquatic ecosystems of the Waipōuri/Waihora lake-wetland complex system are sensitive to sea-level rise. The system would be highly exposed if flood protection were to be bolstered and rising water levels were to be constrained to the current footprint of the lake-wetland complex. However, if water levels were allowed to rise in a controlled and strategic manner then freshwater wetlands could migrate upstream along the Taiari Plain into higher areas of the basin, resulting in only a moderate level of exposure to climate-change impacts.

Climate change also means that the wetland habitat utilized by 50-80 species of birds is at increased risk of compromise by extreme events (e.g., drought, fire and severe floods) – exacerbating pressures such as mammalian predation and human-related mortality (Ryder & Tocher 2020). There is a lack of recent bird distribution, abundance and habitat use data which is particularly important for threatened or uncommon native bird species (e.g., Australasian bittern; Ryder & Tocher 2020). Even with a gradual transition to a saline system freshwater mussels (kākahi) would only persist in upstream tributaries to the lakes if there is suitable habitat and host fish species present. Recent research (Fenwick et al. 2020) indicates significant genetic variation between subpopulations of this species that could be managed/protected by translocation to artificial lakes where there are no resident shellfish.

A gradual transition to an estuarine wetland/lagoon complex is desirable to ensure the aquatic plant community can adapt, avoiding a sudden die-off of saline-intolerant macrophytes (rooted aquatic plants). A sudden freshwater macrophyte die-off would greatly increase the risk of the system 'flipping' to an undesirable 'turbid stable state' (Fig. 8). Most people find a 'clear stable state' to be more aesthetically pleasing and inviting for recreation. Native biodiversity values are also higher in clear water systems where feeding efficiency is higher. This scenario would support maintenance of many values identified by mana whenua and the community (e.g., wetland health and mahika kai) in Orchard (2022). But, this is provided freshwater wetland habitat is available and accessible so species can migrate upstream of the current lake-wetland system. For more detailed information on fish species, see section 6.3.4.

It is important to note that currently the Waipōuri/Waihora lake-wetland complex is a protected area. At present, many of the important ecological values in the area exist largely within the boundaries of these protected areas. However, predicted climate change impacts mean these values could shift outside the reserve (e.g., upstream/inland). This may lead to discussions about the need to shift the boundaries of the current reserve or create new protected areas in the future (Orchard 2022). These discussions should involve a wide range of stakeholders including mana whenua and the broader community; similar issues are likely to apply to other areas of the Taiari catchment. It is important to work towards a balance between resilience of the built environment and human infrastructure needs and resilience of the natural environment (Orchard 2022).

Lake/Wetland Management Options Summarized

- Ensure freshwater flows into the wetland/lake complex are prioritised during summer drought to assist a gradual transition to estuarine.
- Promote wetland restoration (i.e., maintain/improve hydrology, reduce nutrient & sediment inputs) to enhance resilience of the system to perturbation.
- Community-wide engagement about ongoing investment in flood and drainage infrastructure, and options for managed retreat.
- Consider managed retreat combined with wetland restoration and fish barrier removal (e.g., Lee Stream).
- Construct wetlands upstream of Waipōuri /Waihola to intercept nutrients, sediments etc, buffer flows and improve water quality in the lakes [adapted from Ryder & Tocher Table 18 p. 71].
- Characterise the distribution and abundance of kākahi and whether it would persist in lowland tributaries (i.e., is suitable habitat available?). Consider whether translocation inland (e.g. to artificial reservoirs) would be appropriate.
- Update rare bird species abundance and distribution surveys, link to habitat protection and restoration needs. Species like Australasian bittern or South Island fernbirds may engage/inspire different (human) communities to those interested in rare fish (for example).
- Consider the expansion of current protected areas or the creation of new reserves to protect species and ecosystems that may shift as a result of climate change.

6.3.2 Stony stream invertebrates – Management options.

The detrimental effects of climate change driven increased mean water temperatures, and higher temperature peaks during heatwaves, on the macroinvertebrate community in the Taiari tributaries are likely to be serious enough on their own as global warming continues. Further, harsher physical disturbance regimes (increased flood frequency/intensity) could put further strain on flood-sensitive invertebrate taxa. **Therefore, to protect temperature- and pollution-sensitive EPT taxa (the larvae of mayflies, stoneflies and caddisflies), other human-induced stressors/pollutants such as pesticides, excess nutrients or fine sediment need to be minimised or at least kept at moderate levels.**

On the other hand, already polluted tributaries, where EPTs have already been lost and/or pollution levels are hard to reduce are perhaps a lower priority for management/mitigation/restoration measures. This is because global warming combined with the abovementioned agricultural stressors will make it very hard for EPTs to re-establish themselves. Moreover, the current, "degraded" pollution-tolerant fauna is likely to be resilient to further climate warming. **Consequently, it may make more sense to focus management/mitigation efforts on the tributaries that are currently still clean or just mildly polluted (so that EPTs can still thrive in them) - and to do our best to keep them this way.**

There are several reasons why we should care about EPT insect larvae, including but not limited to the following three. First, EPTs are key indicators of ecological stream health used worldwide and in New Zealand, therefore losing them would equal poor ecological health of the Taiari River's tributaries not only in our own country, but also in the eyes of the world. Second, EPT insect larvae are a preferred food source for both native fish and brown trout, thus healthy EPT populations are important for sustaining native fish biodiversity as well as healthy trout populations for recreational and guided fishing. Third, emerged adult EPT insects (e.g. during a mayfly hatch) are a significant food source for riparian spiders, birds and other animals, therefore EPT taxa are also an important part of the terrestrial food web.

Stony Stream Invertebrate - Management Options Summarized

- Stream restoration by fencing and riparian plantings, particularly in the headwaters and smaller tributaries where shading will reduce water temperatures and will also reduce sediment and nutrient inputs.
- Include wetland restoration wherever possible, even if small. Wetlands buffer water flows, improve water quality, increase biodiversity, and store carbon.
- Reduce pesticide use as negative impacts are aggravated by increased water temperatures.
- Prepare for extreme weather events, particularly high flows, by installing multiple small flow buffering devices in steep catchments (e.g., small detention bunds, leaky barriers).

6.3.3 Estuarine mysids – Management not needed

There appears to be both limited scope, or need to directly manage mysid communities with respect to the impacts of climate change. All four species are widely distributed along the Otago coastline, and indeed around New Zealand (Lill et al. 2010). Give the wide range of estuarine systems occupied, and the dynamic nature of many estuarine systems including the Taiari (Lill et al. 2011; Bierschenk 2014), we fully expect all four species to continue to remain abundant.

6.3.4 Fish – Management Options


Banded kōkopu (DOC)

The impact of extreme disturbance associated with flood, drought or fire appear to present the greatest climate-change risk for stream fish communities. For amphidromous fish species, recolonisation from the sea is likely, although this will depend on the extent of losses from other populations from the region. Currently, the banded kōkopu population is decimated every few years by drought in some of the smaller lower Taiari streams (e.g. Picnic Gully), but they are rapidly recolonised when flow resumes (G. Closs Pers. Obs). Clearly, the source of recruits into this system is highly dependent on the regional population of banded kōkopu. These fish are common in streams to the north and south of Taiari Mouth, so currently the regional pool is likely large (New Zealand Freshwater Fish Database). Generally, a programme of inter-annual monitoring of fish communities in streams needs to be developed to track changes in fish communities, particularly in smaller streams which are the most vulnerable to the impacts of floods and droughts.

Fish species with life-history stages in the tidal reaches of the Taiari/Waipōuri are likely to be those most directly exposed to climate change impacts, particularly rising sea levels and altered tidal exchange. As with mysids, most of these fish species are widespread and relatively abundant in these already dynamic systems, suggesting a high degree of resilience with respect to environmental variation. The spawning habitats of īnaka and smelt are strongly influenced by tidal exchange and would likely shift upstream to some degree in response to a rising sea level provided there is suitable habitat available. For both species, maintaining riparian habitat in a relatively undisturbed condition will be essential. Management of the lower Taiari flood protection scheme has implications for fish communities across the area. Extension of the scheme in response to rising sea levels will obviously result in some habitat loss and extend currently existing barriers to migration to some streams for migratory species. Conversely, managed retreat from some areas where continued flood protection is no longer economically viable has the potential to restore wetland habitat and provides opportunities to improve access to streams where fish barriers currently exist, e.g. Lee Stream.

Fish - Management Options Summarized

- Assess the wider regional pool of fish populations and determine whether focal locations (e.g., in the Taiari and elsewhere on the coast) could be protected to add resilience. Consider that under some circumstances, populations in the Taiari may supplement those in other locations along the coast.
- Develop guidance to tailor stream restoration to native galaxias by increasing instream cover (e.g., actively installing large woody debris[1], riparian plantings that provide overhanging vegetation, root mats, and undercuts).
- Ensure/restore fish passage upstream so that inland migration with freshwater/saline limit can occur.
- Identify key ‘source’ locations for landlocked populations (e.g., Alex Stream for giant kōkopu) and consider whether they need protection from climate change impacts.
- Identify important spawning sites for each species and tailor protection and restoration to address climate change trends (e.g., drought, changing distribution of pest plants like reed sweet grass *Glyceria maxima*).
- Characterisation of isolated native fish populations in small headwater streams (e.g., of the Waipōuri River).
- Development of strategies to protect and restore (e.g., via pre-emptive/post-event translocation) unique fish populations.
- Restore the upstream limits of estuarine spawning areas (e.g., for īnaka and smelt) to follow inland migration of this habitat with coastal salinisation.
- Develop a better understanding of smelt spawning locations.

7. Mid Taiari

For the purposes of this report, we are considering the Mid Taiari to include the Taiari and tributaries from Outram Glen upstream to Tiroiti just downstream of the confluence with the Kye Burn (Fig. 9). Many of the watercourses in this region are contained within steep gorges, although close to Middlemarch the Taiari flows through a more open valley. Significant tributaries include Lee Stream, Big Stream, Three O'Clock Stream, Deep Stream, Sutton Stream and Nenthorn Stream. Numerous smaller streams drain from the eastern slopes of the Rock and Pillar Range and western slopes of Taiari Ridge into the Taiari River. Of particular significance is Sutton Salt Lake, a shallow, inland, saline lake and possibly the only lake of this type in New Zealand. The lake is situated at an elevation of 250 m a.s.l, near Middlemarch, in an enclosed, rocky 8-ha drainage basin (Craw & Beckett 2004). The lake has no surface outflow and loses no water to groundwater. Sutton Salt Lake (Fig. 10) is fed by rainwater, and because annual evaporation greatly exceeds annual rainfall, the shallow lake completely evaporates during the dry summer months, when the salinity may approach approximately half that of sea water (Craw & Beckett 2004). When rainfall exceeds evaporation in winter, the lake fills to a maximum surface area of approximately 2 ha and a maximum depth of 40 to 50 cm. Analysis of water chemistry indicates that the salts in the lake derive from rainwater which has undergone c. 20,000 cycles of evaporation to dryness and refilling to achieve the lake's current salinity.

Taiari river near Hindon in the mid Taiari

Figure 9. The Mid Taiari catchment from north of the Taiari gorge to just south of the Kye Burn confluence. (Supplied by Whirika)

7.1 Sensitivity

7.1.1 Sutton Salt Lake Wetlands Area

Sutton Salt Lake is part of the Sutton Salt Lake Wetland Management Area, identified as a Schedule 9 regionally significant wetland in the Otago Regional Council's Regional Plan: Water (ORC 2022), and also as a moderately important site for the conservation of plants and invertebrates by the Department of Conservation (Allen & McIntosh 1997). This lake-wetland area is home to several nationally threatened species and communities, including plants and invertebrates, including the enigmatic tadpole shrimp (*Lepidurus apis veridis*) (Threatened, Nationally Endangered) and the critically endangered clam shrimp (*Eulimnadia marplesi*) (Threatened, Nationally Critical) (Grainger et al. 2018).

The uniqueness of the environment, the biotic communities, and the habitats of Sutton Salt Lake Wetlands Area, highlights the high ecological values present, which are primarily the result of interactions between the local water balance (e.g., precipitation vs. evaporation), the geomorphology of the area, and the high summer temperatures that occur there. The biotic communities of this area are likely to be sensitive to a changing climate, especially those affecting the annual water balance.

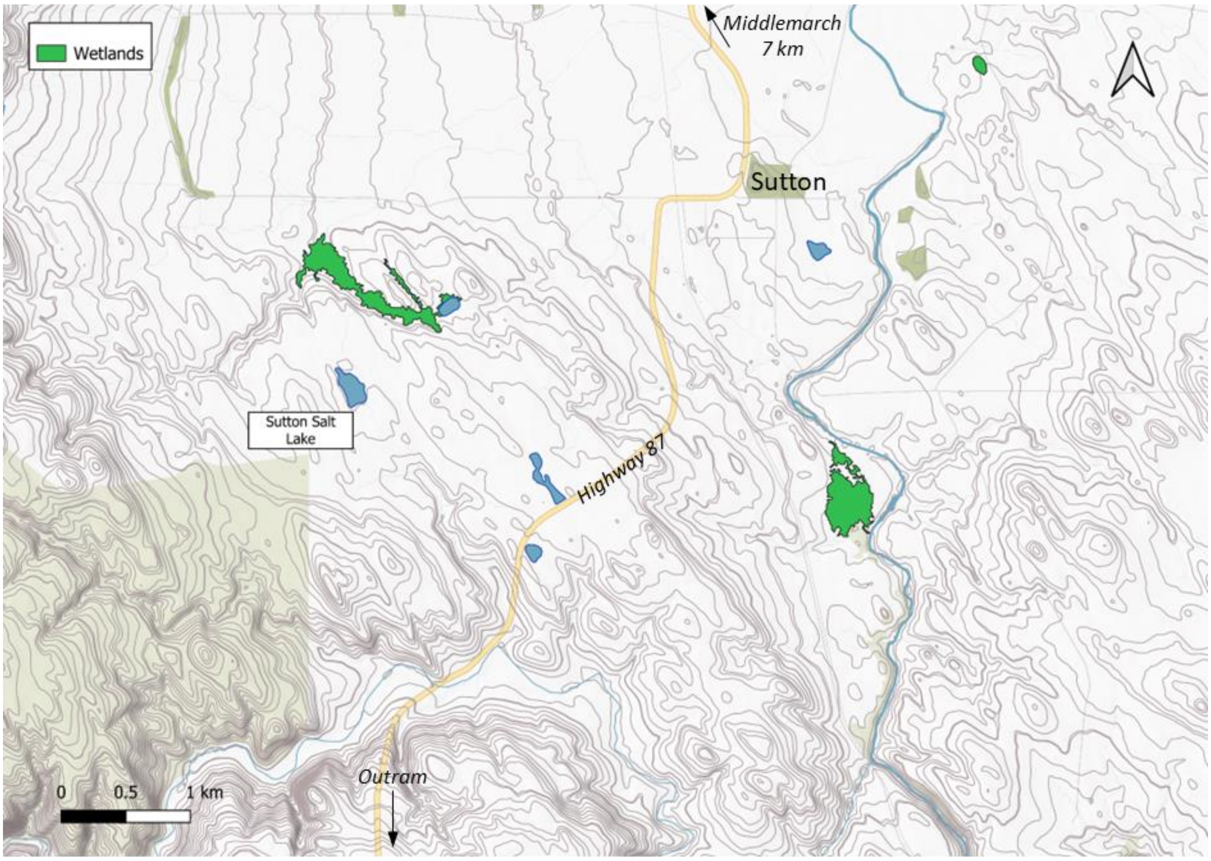


Figure 10. Topographic map showing the location of Sutton Salt Lake, between Outram and Middlemarch.

7.1.2. Invertebrates - Sensitivity

See discussion in section 6.2.2. that includes the stony-bottomed tributaries of the middle (and lower) Taiari.

7.1.3 Fish - Sensitivity

The New Zealand Freshwater Fish Database has surprisingly few records from streams across the Mid Taiari, to some degree reflecting the difficulty of accessing much of the river/stream network through this area (see Ryder & Tocher 2020 for summary maps). Brown trout and longfin tuna are the dominant fish species across the Mid Taiari, most often found in the larger rivers and streams. Brown trout are migratory within the system, moving between spawning streams and the mainstem of the Taiari. There is no evidence of significant spawning of 'sea-run' fish upstream of the Christmas Creek (59 km upstream) although only 15 km from the coast as the crow flies (Kristensen et al. 2011). Steep gradients and numerous smaller waterfalls between Lee Stream (41 km upstream) and Sutton Stream (88 km upstream) presumably act as a barrier to upstream migration of most trout from the lower Taiari area – the occasional fish may migrate through the middle gorge, but not in sufficient numbers to influence population dynamics (Kristensen et al. 2011). Juvenile trout do migrate downstream through the middle gorge from the upper Taiari catchments, supplementing populations of trout in the lower reaches of the Taiari (Mikheev et al. 2021). The upstream migration of longfin tuna does not appear to be impeded by the middle Taiari gorge as longfin tuna are common throughout the area, with records well upstream. European perch are also most likely present in the deeper pools of the Taiari River given their presence further upstream. There are sporadic records of kanakana and upland bully in the upper Taiari. A recent survey detected both eDNA and kanakana pheromones in Three O'Clock Stream and Christmas Creek at concentrations that suggest they are relatively abundant (Kavazos and Richarson 2023). On the other hand, the survey indicates Three O'Clock Stream may be the upper limit of the species in the Taiari. The low abundance of kanakana elsewhere reflects the wider decline in abundance of the species, the causes of which are uncertain. However, the reason for the low abundance of upland bully is unclear, given they are often abundant in river catchments to the north and south of the Taiari catchment, and suitable habitat appears to be present.

Multiple non-migratory galaxias species inhabit the mid Taiari (Fig. 11). There are large Taiari/Taieri flathead galaxias *Galaxias depressiceps* (Threatened, Nationally Vulnerable; Dunn et al. 2017) populations in Nenthorn, Sheepwash, Ross and Three O'Clock Streams and in Christmas Creek, all of which are genetically distinct from each other (Waters et al. 2023). Eldon's galaxias *G. eldoni* (Threatened, Nationally Endangered; Dunn et al. 2017) are present in the Traquair Burn catchment and the Three O'Clock, Sutton, Deep and Lee Stream headwaters. Central

Otago roundhead galaxias *G. anomalus* (Threatened, Nationally Endangered; Dunn et al. 2017) are less common in the Mid Taiari, but do inhabit the Sutton Lakes area, Scrub Burn and Prices Creek. Many of the smaller streams in this area, particularly those draining off the Rock and Pillar Range, have received limited sampling being hard to access and mostly on private property. It is likely that further populations of galaxiids will be detected in some of the streams in this area with further sampling.

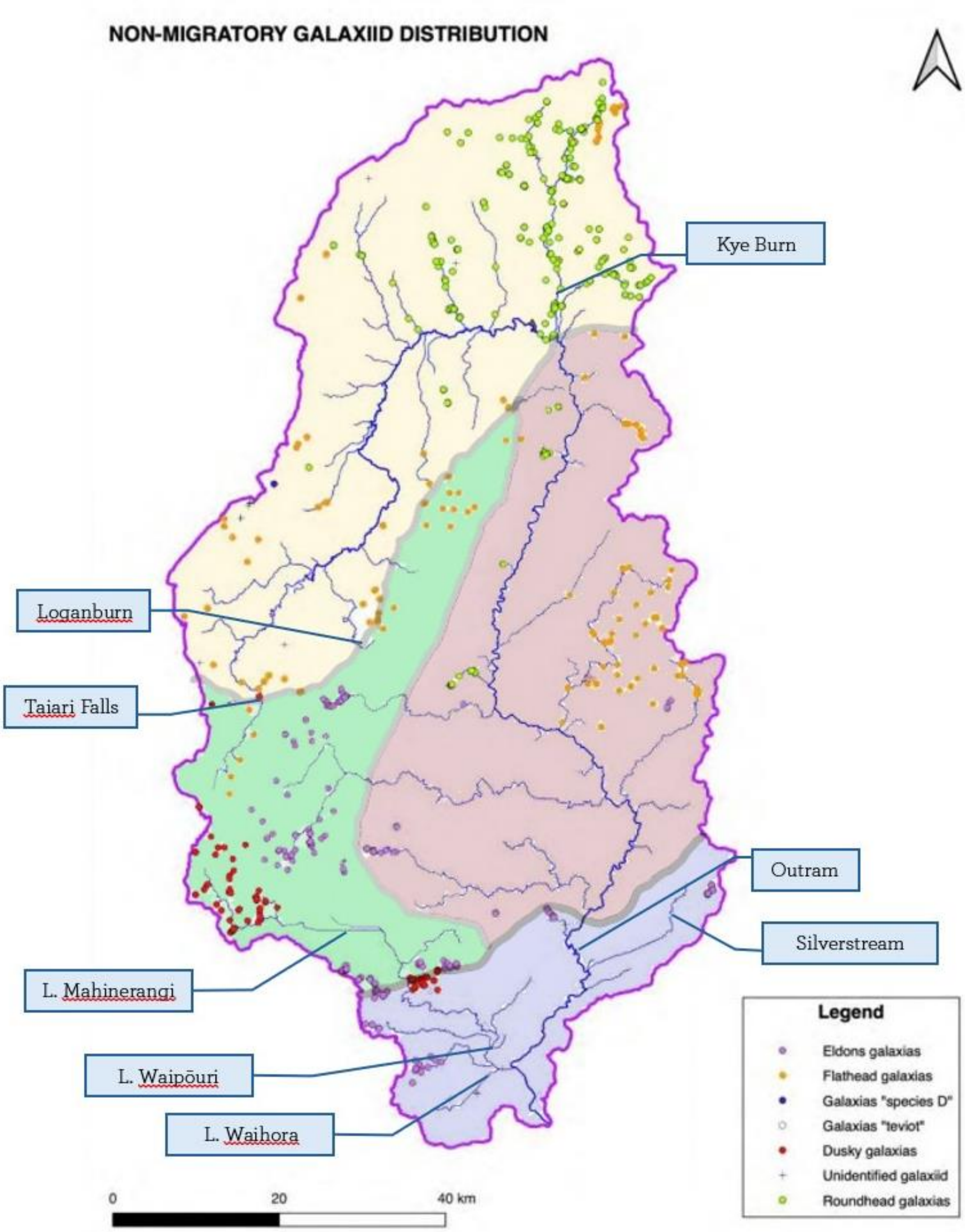
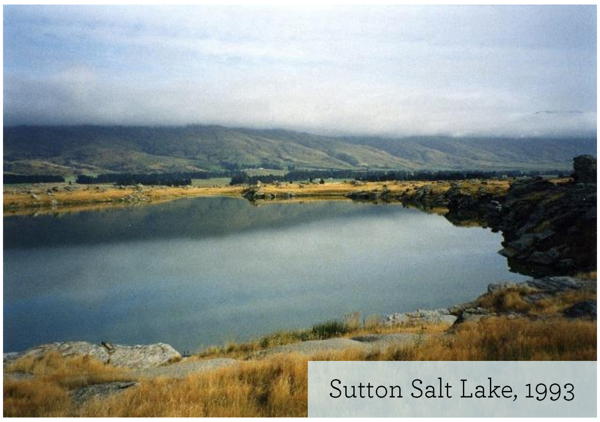


Figure 11. New Zealand Freshwater Fish Database records for non-migratory galaxias species distribution in the Taiari catchment split by approximate subcatchment (blue – lower Taiari, red – mid Taiari, yellow – Māniatoto, green – Taiari/Waipōuri). These records include all observations through time (since the NZFFD started), so the species may no longer be present in some locations. Adapted and used with permission from Ryder & Tocher (2020).

7.2 Exposure

7.2.1 Sutton Salt Lake Wetland Area

Due to its dependence on a unique water balance, the Sutton Salt Lake Wetland Area is probably the ecosystem in the Mid Taiari most sensitive to climate factors. The saline characteristics are dependent on the annual evaporation rate exceeding the annual precipitation rate and any change to the ratio between evaporation and precipitation will affect the hydrology and salinity of the system significantly. For example, if the balance shifts towards greater precipitation, the soils, wetlands and lake will hold more water for longer periods of time. Large increases in the ratio of seasonal precipitation to evaporation could result in greater hydrological connectivity with the landscape and eventual flushing of salt out of the system. In contrast, a shift towards less precipitation and/or greater evaporation could result in even dryer conditions, whereby the lake and wetland would remain dryer for longer periods of time and the lake water might not be replenished during winter. Projected warming temperatures would increase evaporation, whereas reductions in wind speeds (like those observed in the weather station data) would reduce evaporation. It is not clear what the net effect of these changes will be on the lake; however, the current conditions and current biotic communities of the Sutton Salt Lake Wetland Area are almost certain to alter with a changing climate.


Sutton Salt Lake, 1993

7.2.2 Invertebrates – Exposure

See section 6.2.2 that concludes invertebrates in tributaries of the mid (and lower) Taiari will be exposed to climate change pressures including increased disturbance and elevated temperatures. Of these elevated temperatures are more likely to exacerbate negative impacts of pre-existing pressures such as sediment, nutrients and/or pesticides.

7.2.3 Fish - Exposure

Fish communities in the mainstem of the Taiari are likely to be fairly resilient to the impacts of climate change, being dominated by brown trout and longfin eel. Changes to the frequency and intensity of floods and droughts are likely to be the main impacts of climate change. Previous floods and droughts have not had obvious impacts on fish communities, although impacts have not been assessed quantitatively. Prior to the operation of a minimum flow regime on the Taiari, sustained periods of very low flow were experienced on the Taiari, yet fish communities persisted.

Many pools in the Taiari mainstem are relatively deep and topographically sheltered, so likely provide a degree of refuge from the worst impacts of floods and droughts.

Smaller streams throughout the catchment are more vulnerable to the impact of an altered climatic regime, particularly with respect to drought. Smaller streams are generally more vulnerable to drying, wildfire and the impacts of stock watering, particularly during prolonged periods of hot dry weather. Whilst drought has been observed to reduce and restrict trout abundance and distribution, thus potentially benefiting galaxiids, low discharge also has negative impacts on galaxiid abundance. Low discharge may also limit galaxiid downstream and upstream movements, thus disrupting metapopulation processes[8] that provide a degree of resilience to disturbance in some galaxiid species, particularly *Galaxias anomalus* (Jones & Closs 2016).

7.3 Management Options

7.3.1 Sutton Salt Lake Wetland Area

The uniqueness and values of this area are dependent on the water balance (precipitation vs evaporation). It is likely that a changing climate will alter the water balance of the area, but it is not trivial to predict how this will play out. Filmer & Fitzharris (2004) predicted that winters would be wetter and summers would be dryer, but this system depends on the fine balance between precipitation and evaporation at the site, which is not possible to predict with accuracy. It seems that little could be done to mitigate any climate-driven changes to the water balance of this system. A precautionary feasibility study could be undertaken to assess the potential to translocate tadpole shrimp, clam shrimp, and threatened plant species associated with Sutton Salt Lake elsewhere. While it is likely that Sutton Salt Lake is the only inland saline lake in New Zealand, these species may be able to survive in other similar habitats, such as in salt pan sites in the Māniatoto, the Manuherekia River Valley, and the Clutha River valley (Rogers et al. 2000). However, these salt pans may also be negatively affected by future climate changes. Due to the high sensitivity and exposure of these species (and their habitat at Sutton Salt Lake), deeper investigations as to the ranges and habitat requirements of these species should be undertaken.

Given the high sensitivity of the Sutton Salt Lake Wetland Area to the local climate and geomorphology and the paucity of management interventions that could mitigate negative effects of climate change on the unique habitats and species found there, we assess this system to be highly vulnerable to the effects of climate change.

[8] 'Non-migratory' galaxiids don't migrate to and from the ocean (like īnaka) but it is still essential for them to move between different habitats (e.g., headwaters and downstream) at different life stages and different seasons. For example, juvenile fish may feed or shelter at different locations to adults, and adults will require specific spawning habitat and feed on larger invertebrates found in larger streams.

Management Options Summarized

- Examine the hydrology of the lake and explore options for maintaining saline water chemistry.
- Examine the habitat requirements and range of rare species at Sutton Salt Lake.
- Search for populations of the rare species outside the lake complex and develop/trial translocation to increase resilience of the species to localised impacts.

7.3.2 Invertebrates – Management Options

See discussion in Section 6.3.2 noting that management and restoration efforts would best be focussed on less impacted waterways where sensitive macroinvertebrate communities are still relatively intact. Restoration should focus on mitigating human induced stressors, such as sediment, nutrients and pesticides to increase the resilience of these systems to climate change (i.e., elevated temperatures and increased flood intensity). Small headwater streams offer opportunities to increase shading by riparian plantings, thus lowering water temperatures. The efficacy of landscape-scale small interventions in steep headwaters to slow flood flows and their impacts could be explored. Examples are sediment traps and leaky barriers.

7.3.2 Fish – Management Options

Assuming current minimum flow and water quality is maintained on the mainstem, the fish community structure seems unlikely to change markedly under current climate change scenarios. However, this depends on maintaining the deep, sheltered pools on the mainstem that offer refuge in extreme drought. The risk of climate-change impacts appears greater for smaller streams, where the impacts of floods or prolonged droughts are often more severe. During periods of extended drought, pressure to take water from these systems will increase, which could negatively impact fish communities. Management in these streams will largely require a focus on rare non-migratory galaxias species, although some streams in this area support significant trout spawning in the lower reaches (e.g., the Cap Burn; Kristensen et al. 2011). These spawning locations contribute to the Taiari River brown trout fishery, but also have the potential to negatively impact non-migratory galaxiid populations in the area (Jones & Closs 2016; Mikheev et al. 2021).

Irrespective of species, knowledge of the distribution and composition of fish communities in this area is limited. Surveys (e.g., using eDNA, spotlighting and electrofishing) of permanent streams in the area would greatly improve management of potentially threatened fish species, enabling targeted management of key stream habitat. As with streams around the Waipōuri River, many permanent streams in this area originate in tussock-covered headwaters, which could be vulnerable to changes in vegetation structure and wildfire during dry periods. Monitoring to firstly determine the extent of fish populations in the area, and then to establish management priorities, would be a useful first step. Proactively trialling some management interventions (e.g., headwater protection, fire risk reduction) could follow. Ongoing regular monitoring of fish populations is essential to assess management efficacy and/or persistence after severe events (and possible trout incursions). New techniques such as eDNA sampling make monitoring more cost-effective. Strategies to protect and restore populations following disturbance need to be developed, i.e. fish rescue and holding after disturbance, methods for reintroduction and translocation, etc. Expertise is developing in Australia around rare native galaxiid relocations to reduce the impact of wildfires and other extreme events (Lintermans 2013; Todd and Lintermans 2015). A key recommendation is that well-planned, proactive action to establish rare species in alternate locations is far likely to be successful than emergency responses (which tend to be poorly planned and underfunded).

Management Options Summarized

- Monitor fish communities (particularly rare non-migratory galaxias and kanakana), to assess their current state and trends, and to engage landowners. Evaluate habitat to establish management priorities.
- Monitor to detect and manage trout incursions to rare non-migratory galaxias habitat (e.g., Sheepwash Creek, Nenthorn Stream).
- Proactively develop translocation protocols and plans for rare galaxias species.
- Where increased drought is expected, maintain/increase minimum/environmental flows allocated to small streams where there are consented water takes – with the goal of maintaining instream habitat even as climate change progresses.
- Manage the minimum flow regime on the Taiari to preserve refuge habitats for fish (i.e., deep, sheltered pools) during extreme drought.
- Encourage and undertake small-scale interventions landscape-wide, especially in steep headwaters to slow flood flows e.g., sediment traps, leaky barriers.
- Consider changing land use to reduce/remove irrigation needs.
- Riparian margin restoration to increase shade, flow mitigation and to intercept sediments – prioritising less impacted streams where diverse invertebrate fauna are still present.
- Restore small wetlands (flow mitigation in both flood and drought).
- Assess and mitigate fish passage barriers – balancing galaxiid and trout management.
- Plant with wildfire resistance in mind (consider landscape-scale planning for this).

8. Māniatoto

For this report we have defined the Māniatoto as the area from the headwaters of the Taiari starting at Taiari Falls (west of Loganburn) downstream to Tiroiti (downstream of the confluence with the Kye Burn)(Fig.12). The Taiari River in the Māniatoto basin is a relatively slow-flowing stream with a low gradient that winds its way across the plain. The wider Māniatoto area includes some of the driest parts of the Taiari catchment (and New Zealand) with high levels of water demand for agriculture. The Māniatoto is also home to the extensive Taiari scroll plain, one of the only inland scroll plains in New Zealand and by far the largest of its kind in the country. The scroll plain is recognised as an internationally, nationally, and regionally significant wetland. It is made up of many wetland, ponds, and oxbow lakes which provide habitat for rare and endangered plans, fish, birds and insects. Wetlands mitigate climate change by storing carbon, while also increasing resilience to flood and drought along with many other ecosystem services such as increasing aquatic biodiversity. The scroll plains also offer potential for world class eco-tourism opportunities.

Taiari scroll plain (GHC)

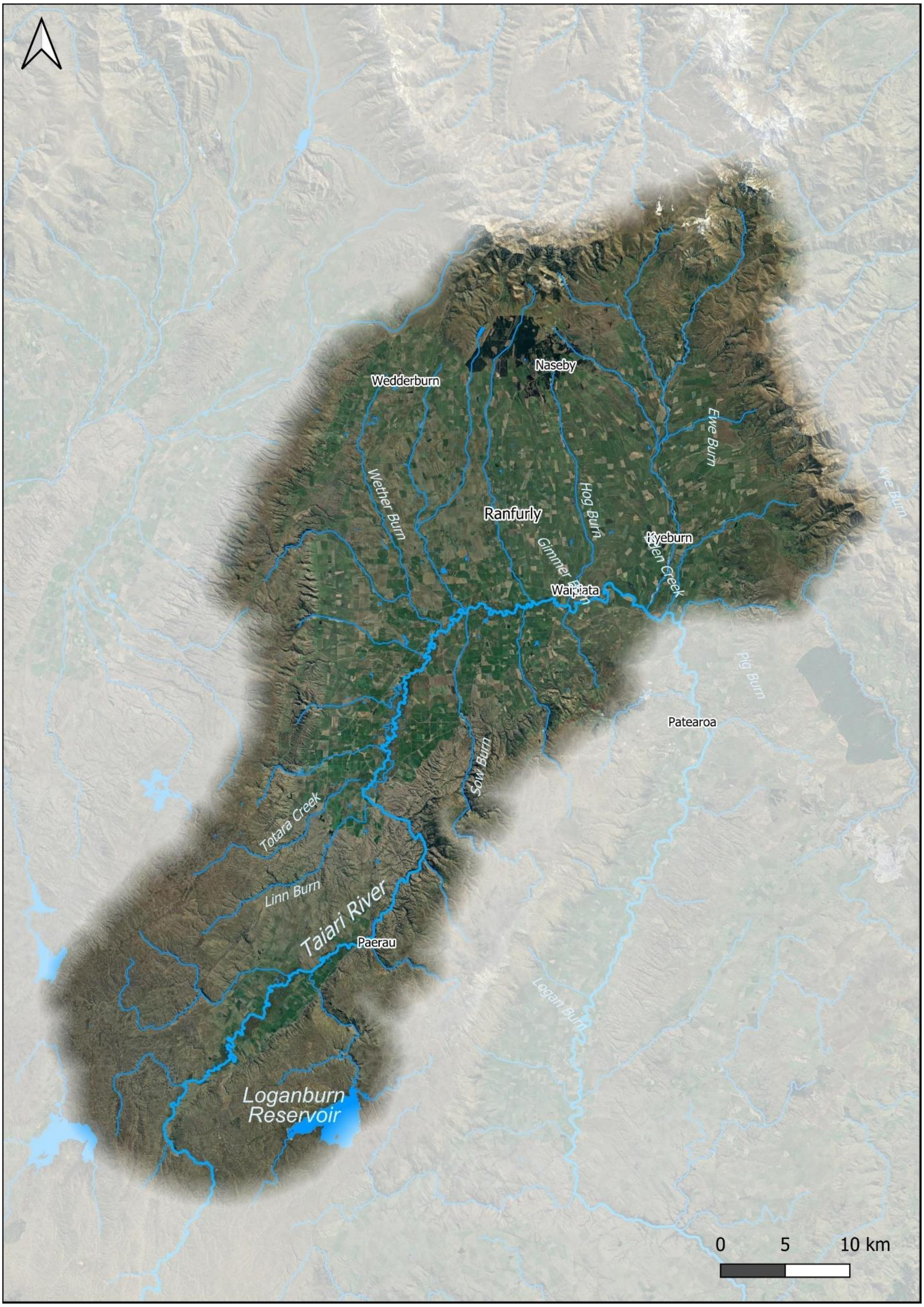


Figure 12. The Māniatoto subcatchment from the Kye Burn confluence, upstream across the scroll plain to the headwaters. (Supplied by Whirika).

8.1 Sensitivity

8.1.1 Scroll plains

The Taiari River in the Māniatoto basin is a relatively slow-flowing river with a low gradient that winds its way across the plain. The wider Māniatoto area includes some of the driest parts of the Taiari catchment with high levels of water demand for agriculture. The extensive Taiari scroll plain is one of the only inland scroll plains in New Zealand and is by far the largest of its kind in the country. The scroll plain is recognised as an internationally, nationally and regionally significant wetland. It is made up of many wetlands, ponds, and oxbow lakes which provide habitat for rare and endangered plants, fish, birds and insects, dependent on the dynamic nature of the meandering river (Ryder & Tocher 2020). Multiple threatened plant species are found there and up to 52 bird species use the wider wetland including the 'Threatened, Nationally Critical'[9] matuku-hūrepo or Australasian bittern *Botaurus poiciloptilus* and the 'At Risk, Declining' koitareke or marsh crake *Porzana pusilla affinis* (Grove 1994, Robertson et al. 2017).

The extensive Scroll Plains of the Māniatoto represent a significant wetland area that has nonetheless received limited study. Clearly, the wetland values are highly sensitive to the water balance across the floodplain (Goldsmith 2023). The land surrounding the wetlands supports areas of dryland and intensive irrigated grazing, with potential to impact both the wetlands and river. Invasive willows are a significant risk to the riparian communities across the floodplain, and domestic geese numbers are significant and appear to be increasing.

8.1.2 Invertebrates - Sensitivity

Although distance from Dunedin has limited the amount of research conducted by University of Otago researchers across the Māniatoto, several significant studies have been conducted, particularly in the upland stream habitats of the Kye Burn on both fish and invertebrates (e.g. Olsen et al 2001; Matthaei et al. 2000; Jones & Closs 2016). Invertebrate communities in the streams of the area are typical of upland southern New Zealand streams and are dominated by a suite of mostly widespread and common species (Olsen et al 2001; Matthaei et al. 2000). Limited research has been conducted in other habitats across the region, particularly in the lower gradient floodplain habitats. The only aquatic community study we are aware of is McMurtrie (1998) on invertebrate communities of ponds on the Upper Serpentine Flats, upstream of the Māniatoto, with communities largely dominated by common taxa. To date, there have been no detailed studies of the ponds and wetlands across the Taiari Māniatoto Scroll Plain ponds. Invertebrate communities

[9] Bittern meet this formal criteria with less than 250-1000 individuals and a predicted decline of 50-70%, also impacted by recruitment failure (i.e., low numbers of juveniles entering the adult population 'such that a catastrophic decline is likely in the future') being sparsely distributed and threatened overseas (see Robertson et al. 2017 for further detail).

in the various tributary streams across the area are presumably similar to those found in the Kye Burn or in adjacent catchments such as the Manuherekia (see Lange et al. 2014). McMurtrie (1998) also completed a single study of the composition of invertebrate communities in the Serpentine Flats area, just upstream of the Māniatoto. Communities in these ponds were dominated by a suite of widespread macroinvertebrates and zooplankton typical of pond communities elsewhere across the region (McMurtrie 1998).

8.1.3 Fish - Sensitivity

Fish communities are of significance given the presence of the non-migratory galaxias species *G. anomalus* (Central Otago Roundheads) and *G. depressiceps* Taiari flatheads) (e.g. Jones & Closs 2016) (Fig. 11).


Taiari scroll plain.

The 'Nationally Endangered' Central Otago Roundhead galaxias is present in many of the smaller gravel or cobble streams towards the downstream end of the Māniatoto, often in significant numbers. As its name suggests this species is found only in Central Otago, mainly in the headwaters of the Taiari (350-800m above sea level), with strongholds in the Ewe Burn and the Kye Burn. They are also found in the Manuherekia, a tributary that joins the Mata-Au/Clutha River at Alexandra. Galaxiids may also be present in the larger tributaries, in some cases all the way downstream to the confluence with the Taiari River, e.g. in the Kye Burn.

The 'Nationally Vulnerable'[10] Taiari Flathead has been found mainly in tributaries of the Māniatoto and also Nenthorn Stream in the lower Mid Taiari. There are some records in the tributaries of the Taiari Uplands. The Taiari Flathead is thought to only occupy 21 ha of habitat scattered across a range of locations. Their preferred habitat is small headwater streams, within grass and tussocks. Both the Central Otago Roundhead and the Taiari Flathead are particularly vulnerable to sedimentation (e.g., caused by stock access, forestry, landuse changes), changes to flow regimes (e.g., via abstraction or drought), and predation by trout and perch. The distribution of the galaxiids across the Māniatoto is determined by a complex interaction between multiple factors, including

[10] Same conservation threat status as our great spotted kiwi (https://www.doc.govt.nz/; accessed May 2024)

presence of barriers to trout, galaxiid life history (fecundity and propensity to disperse), habitat complexity, habitat quality (e.g., availability of instream cover), and flow regimes. Connectivity amongst galaxiid populations is unclear – larvae drift long distances downstream, but patterns of distribution suggest that some upstream post-larval migration may also occur (Jones and Closs 2016).

There is considerable scope to develop a galaxiid conservation plan across the region. Such a plan would aim to restore and protect core galaxiid populations (both *G. anomalus* and *G. depressiceps*) and build resilience in the face of on-going pressure from trout and increasing pressure from land-use intensification and water abstraction.

Brown trout and longfin tuna dominate the fish community, but European perch are also present in the river and associated ox-bow ponds. There is also a significant body of impounded water upstream of the Paerau Power Station, which currently represents the upstream limit for European perch but provides ideal habitat for their spread. The increasing number of irrigation storage ponds being developed across the area are also ideal habitat for perch, and potentially other non-native fish species present in New Zealand, such as rudd, tench and gambusia. Increasing the nutrient status of these standing water bodies significantly increases the risk that introduced species will establish and spread in these systems should they be released (see Bylak et al 2023).

Data from Tiaki Maniototo (Hogan 2024), suggests the Paerau Weir is acting as a barrier to the upstream migration of tuna. If the weir is preventing the upstream migration of tuna, approximately 500 km2 of catchment (assuming the Taiari Falls will also act as a barrier to tuna migration) has been unavailable to new recruits. Similarly, large tuna currently above the weir will need to negotiate the weir structure when migrating downstream. Maximising the extent of habitat available for native species will be critical in ensuring their resilience in a changing climate. The weir may also be a barrier to other migratory species, such as kanakana and kōaro.

Stream fish communities across the Māniatoto are similar to those of the Mid Taiari in many ways – a variety of small- to medium-sized streams with steep, often tussocked, headwater reaches which then run across the plains to the river. Many of these streams have been surveyed at various times over the past 30 years. Brown trout are often present in the reaches of streams flowing across the Māniatoto plain. Several streams, such as Logan Burn, Styx Creek and Kye Burn, are significant spawning streams, supporting the brown trout fishery across the Māniatoto and down into the Mid Taiari (Kristensen et al. 2011). Brook char are also present in the headwaters of several Māniatoto streams, particularly in streams draining from the Hawkdun Range and the Mt Ida Range (Dorsey 2020).

8.2 Exposure

8.2.1. Scroll plains

The increases in heavy rain days and number of dry days means that the scroll plains will be subject to more extremes of rainfall (i.e., both flood and drought). A similar pattern is seen in flow projections with increases in annual flood flows -and- annual low flows. Finally, air temperatures are expected to increase with more extreme hot days (defined as higher than 30°C). Given the arid nature of the subcatchment, and the high levels of water demand from agriculture, predicted increases in drought duration will exacerbate these pressures. More extreme floods following drought can increase erosion (and thus sediment inputs) and cause sudden inputs of organic matter (i.e., dead/dying vegetation) into waterways – leading to blackwater events when the vegetation decomposes.

8.2.2 Invertebrates - Exposure

The invertebrate community of the Māniatoto, while being fairly understudied, is exposed to climate change due to risks of higher temperatures, lower flows, and greater flood disturbances. It is difficult to determine the impact on exact species within the subcatchment but research outside of the Māniatoto has shown increased water temperatures and lower flows lead to a decrease in abundance of sensitive EPT taxa (Piggott et al. 2015, Macaulay et al. 2021a). This can lead to significant changes to the invertebrate community diversity as discussed in 6.2.2 and can have wider ramifications on the aquatic food web as many of these invertebrate species fill important trophic roles in aquatic ecosystems. Leading on from this, when many of these invertebrates metamorphose into their adult terrestrial life history stage, they provide an important food source for other terrestrial species like birds, reptiles, and larger invertebrates which could further impact the wider ecosystem.

8.2.3. Fish – Exposure

The fish community of the Māniatoto is also exposed to the impacts of climate change due to being a relatively arid area with high levels of water demand for agriculture. During dry summers, the mainstem of the Taiari river can remain at low levels for extended periods, and combined with the high daytime temperatures, reaches temperatures that can stress fish, particularly brown trout. Monitoring by Tiaki Maniototo following the 2022 flood also suggests a blackwater de-oxygenation event may have occurred in the river as floodwaters loaded with organic material drained off the floodplain and caused very low oxygen levels. This suggests fish kills are an ongoing possibility in warmer weather.

Small streams across the floodplain are also subject to water abstraction and loss of water through evaporation and groundwater loss, threatening fish communities in these streams. Whilst brown trout will be impacted by low water levels before galaxiids are severely impacted, loss of water represents a major threat to galaxiids as well (Shelley 2012) – particularly the species inhabiting small headwater streams. Increasing temperatures will also likely further restrict the distribution of brook char in the catchment, moving the interface between brook charr and brown trout upstream in streams where brook charr are present (Dorsey 2020). Climate projections for the Māniatoto indicate that tributaries in the northern Taiari, including the Ewe Burn and Kye Burn, are at particularly high risk for periods of low flow.

8.3 Management Options

8.3.1 Scroll plains

Continued protection and restoration of the scroll plains will increase their resilience to climate change which in turn will mitigate impacts on water quality and quantity downstream. Managing grazing pressure, exotic weed species (e.g., willows) and pest animals (e.g., feral geese, mustelids) would address several key pressures.

Ongoing review and adjustment to flow regimes will help to manage for multiple values in the catchment i.e., agriculture, rare native fish species, sport fisheries, mahika kai (e.g., tuna, kanakana), prevent deoxygenation events and increase resilience to climate change by reducing flow extremes. Local landowners could consider diversifying and changing to land uses with lower water/irrigation requirements and lower debt servicing to increase landowner resilience to climate change.

8.3.2 Invertebrates – Management Options

Management options for invertebrates in the Māniatoto are similar to those described in 6.3.1 and 6.3.2. The management options focus largely on mitigating sediment deposition, nutrient runoff, maintaining temperatures, protecting habitat, and establishing riparian habitat. The main tools for achieving this include:

- Stream restoration by fencing and riparian plantings, particularly in the headwaters and smaller tributaries where shading will reduce water temperatures and will also reduce sediment and nutrient inputs.
- Include wetland restoration wherever possible, even if small. Wetlands buffer water flows, improve water quality, increase biodiversity, and store carbon.
- Reduce pesticide use as negative impacts are aggravated by increased water temperatures.

8.3.3. Fish - Management Options

Monitoring of fish communities will be essential for determining the responses of Māniatoto fish communities to climate change and associated stressors, and for guiding management. The increasing number of irrigation dams represent potential habitat for invasive non-native fish, particularly perch, rudd and tench. Increasing intensification of land-use and associated inputs of nutrients to standing water bodies throughout this area will increase the likelihood of establishment of these invasive species should they be introduced. The low dissolved oxygen event following the 2022 summer flood also raises alarm bells, suggesting the potential for major fish kills, affecting longfin tuna and trout. The risk of blackwater events following floods requires careful monitoring and could potentially be mitigated by the maintenance of higher discharge levels through the Paerau Weir and/or Loganburn Reservoir. The effectiveness of the Paerau Weir at allowing passage of native freshwater species upstream and downstream should also be further assessed.

Recent surveys of streams draining the southern end of the Māniatoto by Tiaki Maniototo have greatly improved knowledge of fish communities in that area. Generally, greater amounts of water in river and stream channels year-round will improve ecosystem resilience. That said, increased discharge in smaller streams can also increase connectivity of fish populations and thus the spread of salmonids into galaxiid habitat. Hence, the improved understanding of trout and galaxiid distributions across the Māniatoto should be used to develop an integrated galaxiid-trout management plan for the area, including strategic removal of salmonids and construction of barriers to create galaxiid reserves that will increase the resilience of galaxiid populations throughout the area (see Jones & Closs 2016). Other management options are fencing off galaxiid spawning areas in spring, and protecting breeding grounds by riparian restoration in both streams and wetlands. Increasing shade in small streams helps to lower water temperatures and plantings can be tailored to intercept both sediment and nutrients.

Over the long term, eradication of brook char is worth considering given that they likely exclude native galaxias species from multiple stream reaches (Dorsey 2020). Currently all brook charr populations in the area are restricted to small streams and their populations appear to be slowly declining (Dorsey 2020). Given that brook charr range is likely to continue to decline and that recolonisation of streams where brook charr are eradicated or lost is unlikely (Dorsey 2020), then targeted eradication is viable. Further, most populations are in small streams, hence poisoning of brook charr by rotenone might be possible, followed by reintroduction of non-migratory galaxiid species where appropriate.

Management Options Summarized

- Continue the protection and restoration of the scroll plain and associated wetlands by managing grazing pressure, exotic weed species (e.g., willows), and pest animals (e.g., feral geese, mustelids).
- Consider diversifying and changing to land uses with lower water/irrigation requirements and lower debt servicing.
- Continue monitoring fish communities to inform management.
- Protect key non-migratory galaxiid habitat (e.g. by fencing off spawning areas in spring, riparian restoration of wetlands and streams (including small headwater streams) to protect breeding grounds and habitat.
- Develop a regional galaxiid conservation plan, to restore and protect core non-migratory galaxiid populations, to raise the profile of these unique taonga, and increase engagement from landowners and irrigators. The Spec Creek galaxiid sanctuary is great example of this being done by the local community and private landowners.
- Monitor/suppress/locally eradicate perch in the Paerau Power Station impoundment upstream of the weir (should it occur) to reduce risk of transfer.
- Provide irrigation pond owners information about pest fish species issues especially with respect to rare native fish species and management options. Encourage management of perch throughout the network of storage ponds in the catchment to reduce risk to rare native fish.
- Consider strategic eradication of brook char (that are already declining) to protect native galaxiids.
- Ongoing review and adjustment to flow regimes to manage for multiple values in the catchment (i.e., agriculture, rare native fish species, sport fisheries, mahika kai (e.g., tuna, kanakana), preventing deoxygenation events and increasing resilience to climate change.
- Assess the effectiveness of Paerau Weir at allowing passage of native freshwater species upstream and downstream.

9. The Taiari/ Waipōuri Uplands

The Taiari / Waipōuri uplands comprise the extensive area representing the headwaters of the Taiari and Waipōuri Rivers, much of it over 1,000 metres above sea level and tussock-covered (Fig. 13). Te Papanui Conservation Area encompasses a significant amount of this area, most of which is difficult to access. There are extensive wetland and bog systems throughout the uplands, although there is limited information on any of them. Similarly, there are many small streams throughout the area, but due to the challenges of access, few have been sampled.

Two significant lentic water bodies are located in the Taiari uplands. The Loganburn Reservoir (upper Taiari – Fig. 14) and Lake Mahinerangi (upper Waipōuri – Fig. 15) are both artificial reservoirs. The Loganburn Reservoir is located on the Rock and Pillar Range at c. 850 m a.s.l. This irrigation dam is approximately 4 km^2 in surface area and produces some electricity when water is released for irrigation by the Maniototo Irrigation Company. It occupies a basin that was known as the Te Paruparu-a-Te_Kaunia (Great Moss Swamp). Some of the original swamp is still in existence on the margins of the reservoir and is recognised as a regionally significant wetland with plant and lizard values. The reservoir is stocked with brown trout and also contains freshwater crayfish. *The non-migratory Taiari flathead, dusky and Eldons galaxias (i.e., G. depressiceps, G. pullus and G. eldoni* respectively) are present in the headwaters of the small streams across the area (Fig. 11). Lake Mahinerangi is located in the upper Waipōuri River catchment at 610 m a.s.l. The hydroelectric reservoir is approximately 10 km^2 in surface area with a maximum depth of 30 m and is stocked with brown trout and perch and supports a landlocked population of kōaro. It has an operating range of approximately 12 m.

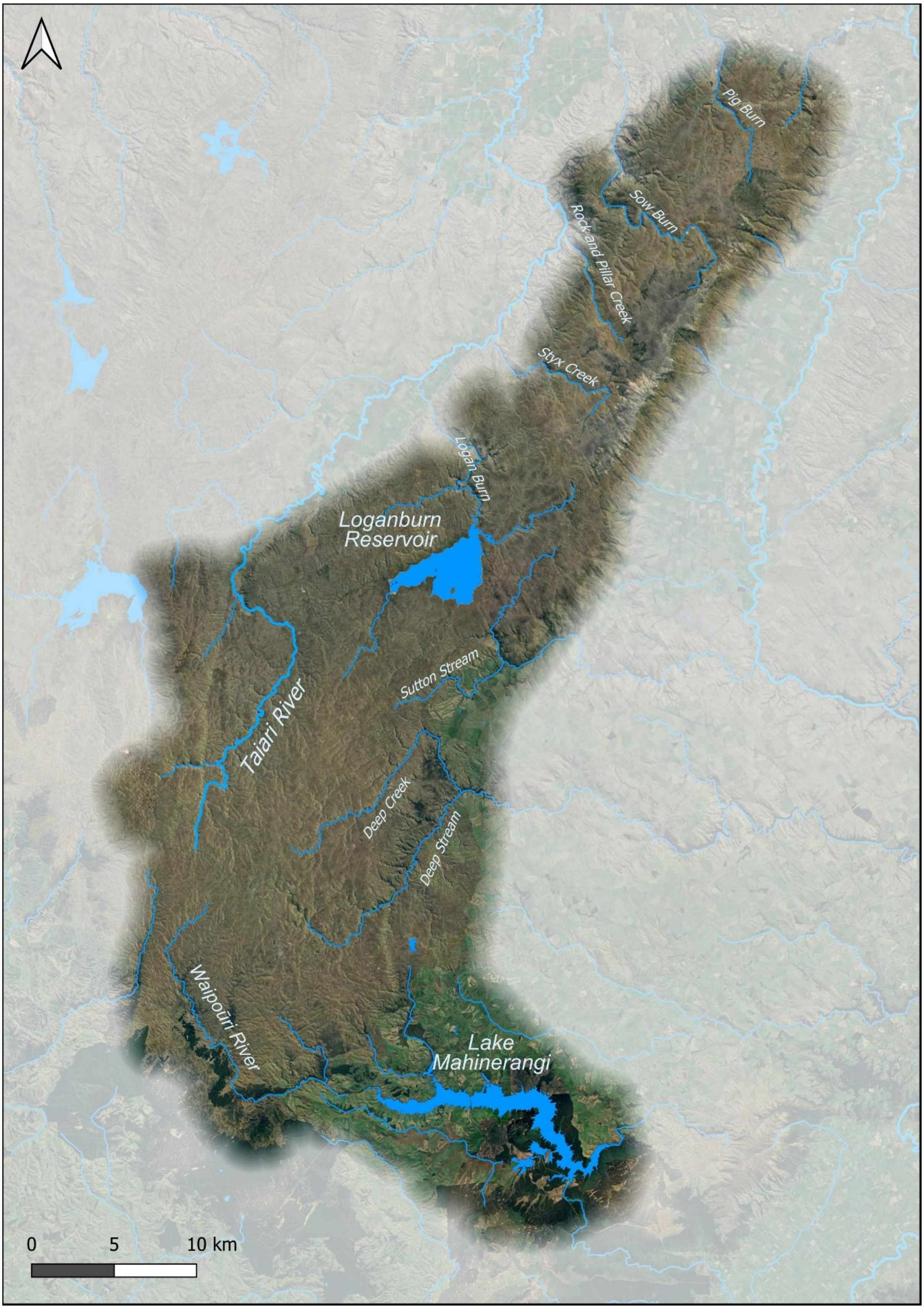


Figure 13. The Upper Taiari/Waipōuri subcatchment showing the alpine areas of the catchment and lentic bodies Lake Mahinerangi and Loganburn Reservoir. (Supplied by Whirika).

Goldsmith (2023) did not present any historical weather data from upland sites. Therefore, no information is available in this report on historical trends in climate variables in these high-altitude areas of the Taiari catchment. However, the climate models in Goldsmith (2023) projected a little warming by 2040 and more substantial warming by 2090 for these regions. In particular, a substantial reduction in the number of frost nights was predicted, while only relatively small changes in rainfall were projected for these regions. The number of dry days was projected to increase substantially, and wind speeds were projected to increase slightly.

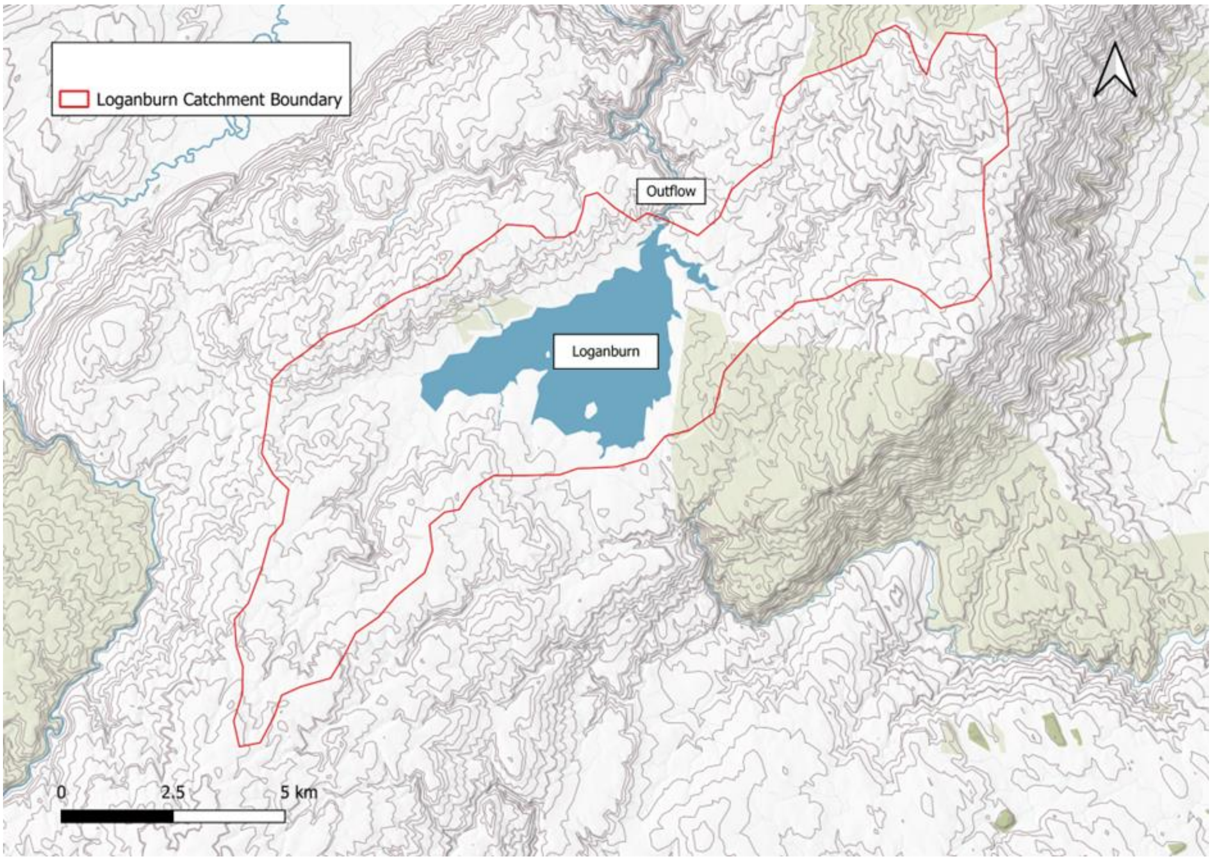


Figure 14. Topographic map of the Loganburn Reservoir in the Rock and Pillar Range, showing its approximate topographic catchment

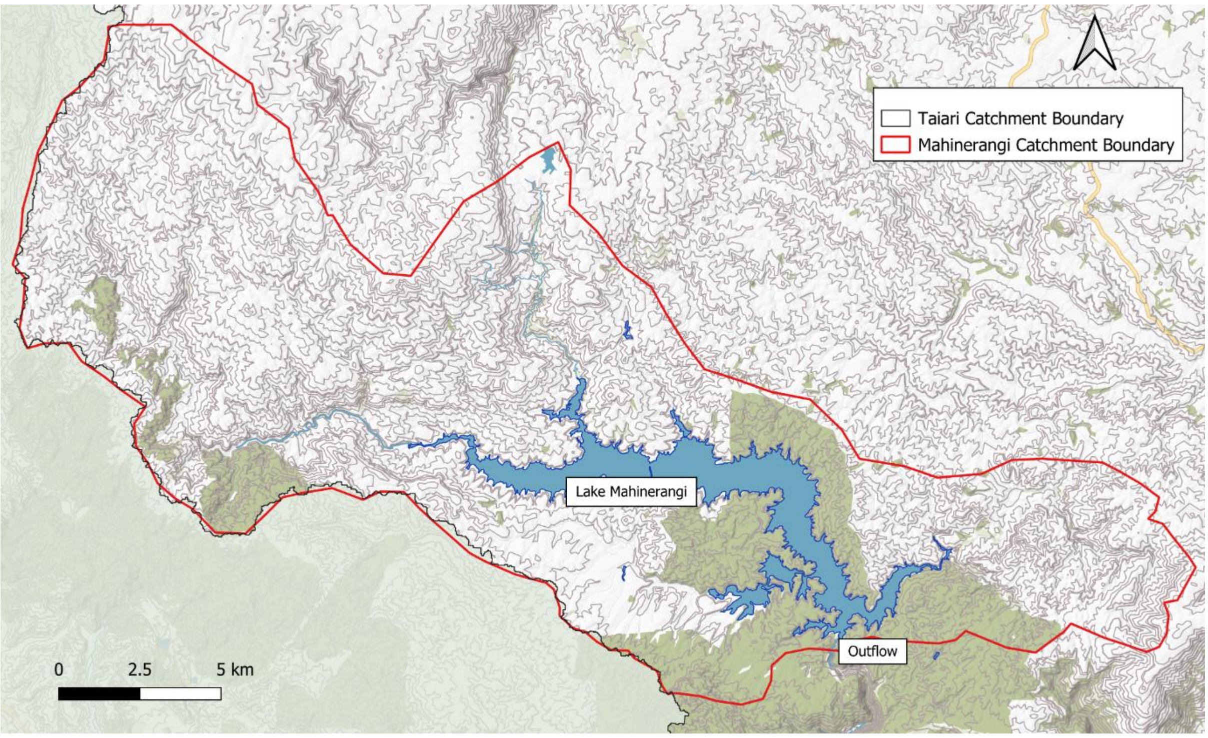


Figure 15. Topographic map of Lake Mahinerangi in the Upper Waipōuri River catchment, showing its approximate topographic catchment boundary. The dark green shading indicates forest. White indicates grasslands.

9.1 Sensitivity

9.1.1 Alpine wetlands and upland lakes

The alpine wetlands of the Taiari are described in the OCCRA 2021 report 'as those at >800 m altitude' with 'unique alpine bog plants, herbs and shrubs, diverse and unique invertebrates, non-migratory galaxias and alpine birds'.

The extensive bogs and wetlands of the Taiari and Waipōuri uplands are clearly sensitive to changes in climate in many inter-related ways. Changes to the vegetation of the area through woody vegetation succession and altered grazing and fire regimes have the potential to significantly alter the hydrology of the area (Mark and Dickinson 2008). The tall tussock vegetation that currently covers much of the area plays a key role in capturing and storing water across the area, and degradation of that ecosystem will likely have negative impacts on water yield from the upland areas (Mark and Dickinson 2008).

9.1.2 Upland lakes - Sensitivity

Lake Mahinerangi and the Loganburn Reservoir are artificial reservoirs with managed hydrology. Little is known about the ecological values associated within the reservoirs, although they are important recreational sports fisheries. Studies undertaken on Lake Mahinerangi in the 1960s (Mitchell 1975) and again in the 1990s (Burns & Schallenberg 1996) reported that the lake was mesotrophic. As the hydrology of these reservoirs is managed for irrigation and power generation, the effects of climate change on them will depend on how the management of the reservoirs is altered in response to a changing climate. This will be determined not only by the water balance, but also by the electricity market, regulations, and any consent conditions. The Loganburn Reservoir flooded the Great Moss Swamp, with only remnants of the swamp remaining around the riparian margins of the present reservoir. There is continuing pressure to raise the level of the Loganburn Dam to provide increased storage of irrigation water which would drown the last remnants of the Great Moss Swamp including rare native lizards in associated riparian habitat; it could also divert water from nearby waterways (Hitchmough et al. 2021, Ryder & Tocher 2020).

9.1.3 Fish - Sensitivity

The Taiari flathead galaxias (*G. depressiceps*) is widespread across the upper Taiari catchment (Fig. 11). Significantly, the Upper Taiari above Canadian Flats is reputedly trout-free (as suggested by limited surveying over the past 20 years) and is possibly the largest trout-free catchment containing non-migratory galaxiids in New Zealand. This Taiari flathead population is genetically distinct from other populations in the Taiari catchment indicating isolation for a long period of time (Waters 2023). There has been reasonably extensive sampling in recent years across the area in the upper Waipōuri. Eldon's and dusky galaxiids have a fragmented headwater distribution in streams across the area (Jones & Closs 2016; Waters 2023). Eldon's galaxias are found in the alpine headwaters of Deep Stream and Sutton Stream which flow down to the Mid Taiari upstream of Outram. Streams draining into Lake Mahinerangi support dusky galaxias as well as kōaro populations – the kōaro larvae presumably rear in the impounded waters of the Waipōuri Power Scheme threatening populations of non-migratory galaxiids (*G. pullis* and *G. eldoni*) directly upstream in the headwaters of the area (McDowall & Allibone 1994). A single population of introduced brook char also occurs in what was formerly Munro's Dam, a small fire dam upstream of Lake Mahinerangi, and occupies habitat that was presumably once occupied by dusky galaxiids (Dorsey 2020). This population could be the target of eradication given that once eradicated, there is no prospect of recolonisation by brook charr and their removal would allow for the reintroduction of the dusky galaxias.

9.1.4 Invertebrate communities in the stony-bottomed tributaries of the Taiari uplands - Sensitivity

A review by Jenkins et al. (2011) summarised the limited available literature on potential climate-warming effects on cold-adapted macroinvertebrate species (certain mayfly and stonefly species) in glacial and alpine river systems in New Zealand. While no studies from the Taiari catchment were included in this review, we will discuss this topic under 'Exposure' in this section because some of the findings from other NZ mountain ranges could also be relevant for the alpine regions of the Taiari catchment.

9.2 Exposure

9.2.1 Alpine wetlands

The risk tables in the 2023 Goldsmith report indicate montane and alpine wetlands in Otago are already at either moderate to high risk of impacts from higher temperature, drought, changes in rainfall, and reduced snow and ice. The risk ratings increase to 'high to extreme' by 2040, and to 'extreme' by 2090. Higher temperatures are likely to support the establishment of invasive species (e.g., wilding pine, hawkweed).

9.2.2 Upland lakes – Exposure

The artificial nature of Lake Mahinerangi and the Loganburn Reservoir and the ability to manage their hydrology, means that these water bodies may be less directly affected by a changing climate than other local systems. However, the managed discharges from these reservoirs are critical to the downstream Taiari and Waipōuri Rivers. Potential changes to the management of the reservoirs in relation to a changing climate and demands for electricity and irrigation could expose downstream aquatic ecosystems to risks associated with altered magnitudes and temporal patterns of water discharge and increasing saline intrusions.

9.2.3 Fish - Exposure

The Nationally Endangered Eldon's and dusky galaxiids have a fragmented headwater distribution in streams across the area. There two species cannot coexist with trout so most populations in the area are located upstream of barriers to trout migration (Jones and Closs 2016). To some degree, limited access protects these two species from further human-assisted trout introductions, and extensive impacts due to intensification of land use are unlikely due to the relatively high altitude. Where intensification does occur, as has happened at relatively high altitude elsewhere in New Zealand (e.g., Upper Rangitata and the headwaters of the Ashburton River (i.e., Ashburton lakes/Ōtūwharekai), noticeable impacts on water quality and aquatic biota are likely. However, changes in vegetation through long-term succession of woody vegetation (native and introduced) (e.g. the spread of wilding pines), has the potential to alter the hydrology of these small upland catchments (Mark & Dickinson 2008). Large flood events can provide opportunities for trout incursions upstream of barriers, thus monitoring and maintenance of these structures will be critical to the survival of upstream non-migratory fish populations. Increasing woody vegetation also changes fire risk - wildfire can have severe impacts on the ecology of small upland streams (Ensbey et al. 2023) that are Eldon's and dusky habitat. The trout-free status of the Taiari River upstream of Canadian Flats is obviously a point of risk for the important population of Taiari flathead galaxias in the Taiari catchment (Jones & Closs 2016).

9.2.4 Invertebrate communities of the Taiari uplands - Exposure

There is limited information that specifically relates to the impacts of water temperature on the freshwater invertebrate fauna of the Taiari uplands. Huryn (1996) found that the growth of *Deleatidium* sp. (mayflies) on the Rock and Pillar Range was temperature-dependent, with a fast-growing summer cohort, and a slower-growing winter cohort. Whilst there are probably two generations of *Deleatidium* sp. per year, the presence of overlapping cohorts results in an extended emergence period and complex size structure (Huryn 1996). More recent work by McCulloch et al. (2021) suggests that wingless morphs of the stonefly *Zealandoperla fenestra* on the Rock and Pillar Range have evolved relatively recently in response to the loss of tree cover.

More widely, Jenkins et al. (2011) reviewed the few available studies that allow projections regarding the potential effects of climate change on alpine stream communities in New Zealand. Four species of the mayfly genus *Deleatidium* are confined to the upper limits of lotic freshwaters in the altitudinal zone from the tree line to the permanent snow line in the Southern Alps and their neighbouring ranges (Hitchings 2009). All four are adapted to cold, fast-flowing streams and the frequently severe conditions imposed by an unstable terrain and high winds. A fifth cold-water specialist *Deleatidium* species is found at five stream sites in Mt Aspiring National Park (Winterbourn et al. 2008). A rise in water temperatures associated with global warming would likely result in a southward retreat of these alpine specialists (Winterbourn et al. 2008; Hitchings 2009). Moreover, a projected 3°C warming would displace the regression of annual degree days on a latitude southward by 670 km and result in extinction of these five alpine mayfly species (Winterbourn et al. 2008; Hitchings 2009). A similar concern is held for certain cold-water specialist stoneflies. Their larval stages inhabit high-altitude streams where there is a high degree of endemism. For example, in the Fiordland region of the Southern Alps there are 11 endemic stonefly species, with four of these occurring predominantly above the tree line (Peat & Patrick 1996). Though no studies on exclusively alpine mayflies or stoneflies have been conducted in the Taiari catchment, it is conceivable that one or more of cold-adapted *Deleatidium* or stonefly species also inhabit the alpine areas of the Taiari uplands (which reach an altitude of 1,643 m a.s.l., with the alpine zone beginning at about 1,200 m a.s.l.).

Because of the generally high degree of endemism in New Zealand, further aquatic invertebrate groups common in subalpine and alpine streams such as Trichoptera (caddisflies)(Peat & Patrick 1996) and net-winged midges (Blephariceridae) probably also contain several more endemic species adapted to cold water temperatures. Net-winged midges are well-known for their preference of cold, fast-flowing streams (Frutiger 2002; Frutiger & Buergisser 2002), and their larvae can be highly abundant in alpine streams, for example in Arthur's Pass National Park (C.D.

Matthaei, pers. Obs.). Such endemism in the Southern Alps and their neighbouring ranges may have resulted from repeated periods of glacial advance and retreats (Hitchings 2009), a process which has similarly produced high endemism rates in the cold-adapted aquatic fauna of Western Europe (Ward 1994). Most of these endemic aquatic species are vulnerable to extinction due to climate-change induced loss of extreme cold-water habitats (Winterbourn et al. 2008; Hitchings 2009), even though it is likely that many of these specialist species are yet to be formally identified by science.

9.3 Management Options

Much of the higher altitude areas of the Taiari uplands are protected within the Te Papanui Conservation Area, hence major changes to land-use are unlikely. That said, long term changes to vegetation structure are possible as a result of climate change, historically altered fire regimes, reduced grazing and wilding pines. Any of these has the potential to further alter fire risk with implications for local hydrology and ecosystem stability (Mark & Dickinson 2008; Ensbey et al. 2023). The current risk of climate change impacts on inland and alpine wetlands is considered moderate to high and is predicted to increase to extreme (Goldsmith 2023). Ongoing monitoring of vegetation structure, extent of wetlands/bogs, wilding pine invasions and patterns of fire are essential to understand and manage these risks to these upland ecosystems. The protection and restoration of the alpine wetlands should be prioritised (e.g., through landscape-scale management of hydrology, grazing and planting plans). Consider proactive translocations of rare plant and animal species, particularly from alpine wetlands where the altitude of climate zones is increasing, and the species has a limited known distribution.

Lake Mahinerangi and the Loganburn Reservoir are substantial, hydrologically-managed headwater reservoirs. Presumably, their management for hydroelectric generation and irrigation will be adapted as climate change impacts the water resources available to them. Climate and vegetation change could potentially impact the profitability of these reservoir enterprises. Temperatures, precipitation, and wind speeds are all predicted to increase somewhat in these catchments. The interactions between climate change and profitability of the enterprises could lead to changes in the discharge dynamics of these headwater reservoirs and this could have implications for downstream water bodies, as they will also be impacted by climate change.

The changes to power generation, irrigation and flow regimes could either exacerbate or help mitigate downstream climate change impacts. Schallenberg et al. (2003) identified the dynamics of discharge of the Mahinerangi Dam as a driver of saline intrusions in the Waihora/Waipōuri Lake-Wetland Complex. The Waipōuri River is a significant freshwater input to the lake-wetland complex and a regime of filling the reservoir in summer and discharging in winter could exacerbate summer/autumn saline intrusions to the lake-wetland complex. In contrast, releasing water in summer/autumn could reduce the extent of saline intrusions to the complex. At this stage, less is known about how the discharge dynamics of the Loganburn Reservoir affects the catchment downstream. A proactive response to climate change is recommended, such as the stakeholders proceeding through a facilitated multicriteria decision making process that takes into account a complex set of values such as infrastructure investment (including raising the level of the reservoir), minimum environmental flows, conservation opportunities/needs/risks and climate change.

Increased inputs of nutrients to the lakes (e.g., from intensification of agriculture) has the potential to increase the recruitment of kōaro and perch from both Mahinerangi and Loganburn Reservoirs, posing risks to non-migratory galaxiid species in upstream tributaries. Although not studied directly, lake productivity is bound to enhance survival of the pelagic larvae of these species. Similarly, increasing the nutrient status of these lakes will also increase the risk of other non-native species (e.g., rudd, tench) establishing should they be released into the lakes, with the likelihood that they would then spread downstream into lowland habitats. Indeed, this latter point can be applied to any of the irrigation storage ponds that are either already exist or are planned across the upper Taiari. As proposed for the Māniatoto, development of a regional non-migratory galaxiid conservation plan would support strategic investment in protection of the core habitat of these taonga species (e.g., Spec Creek galaxiid sanctuary).

Management Options Summarized

- Prioritise protection and restoration of these unique alpine wetlands through holistic measures (e.g., landscape-scale management of hydrology, grazing and planting plans) and management of rare species that may include translocations (e.g., from alpine wetlands to sites at higher altitude and further inland).
- Stakeholders and regulatory agencies work through a facilitated multicriteria decision-making process to explore the challenges and opportunities of climate change and how/if reservoir management could help mitigate some aspects of climate change (e.g., water levels downstream at the Waipōuri/Waihora lake wetland complex, native galaxiid management especially for drought and fire, sport and pest fish species).
- Develop a regional galaxiid conservation plan (as proposed in the Māniatoto) to: restore and protect core non-migratory galaxiid habitat; to raise the profile of these unique taonga; and increase engagement from and options for landowners and irrigators.
- Support research to understand the ecology of rare non-migratory fish species, and to support conservation management.
- Wilding pine control and landscape scale planting plan to encourage planting of fire-resistant species and fire breaks, as well as species that support desirable hydrology of small streams.
- Prioritise protection and restoration of small wetlands and headwater areas to help manage hydrology and buffer flows.

10. Knowledge gaps

Discussion of knowledge gaps focusses on points where management is possible. As with any extensive area, substantial knowledge gaps remain regarding the structure and function of Taiari ecosystems. Indeed, most species remain largely unstudied with minimal knowledge of any aspect of their biology. Increasing knowledge of the biology of most species is worthwhile and will lead to a greater understanding and appreciation of the Taiari biota but may not lead to direct management responses.

10.1 Poorly Known Ecosystems: Taiari River mainstem and Taiari uplands.

As with most larger rivers, minimal sampling or study of the Taiari River mainstem has been completed. Such systems are challenging to work in due to water depth and current. There is limited knowledge of what lives in the river, and minimal understanding as to how the river might respond to any specific environmental change. Such a statement could be extended to most larger rivers in New Zealand.

Similarly, the Taiari uplands have received minimal study, at least partly due to the lack of easy access to much of the area. Mark & Dickinson (2008) have demonstrated the role of tussocks in contributing to water capture and catchment hydrology. However, whilst the upland area is largely protected from direct development in the Te Papanui Conservation Area, altered fire and grazing regimes as a result of this protection will result in vegetation change, but there is little understanding as to how the vegetation will respond in the longer term. When combined with climate change, it is hard to predict how the vegetation may respond over the next 10-100 years. Changes in the vegetation will impact the streams and extensive wetlands of this area in complex ways (i.e. from reduced to increased water yield depending on the age and composition of the vegetational community).

Water abstraction and storage remains a major feature of the dryland agricultural systems of the area, with considerable potential to impact and degrade aquatic systems. By and large all aquatic systems will benefit from higher rather than lower flows over summer, and arguably, any abstraction that reduces river discharge below the 7-day Mean Annual Low Flow (7-day MALF) for extended periods is diminishing the integrity and size of the natural system. Significantly, many of the streams of the Māniatoto and Mid Taiari already are significantly below their natural 7-day MALF for extended periods over summer due to water abstraction for agriculture. Whilst reducing abstraction will likely improve overall stream health, better understanding of the ecology and distribution of non-migratory galaxiids is needed to mitigate against the potential negative impacts of increased trout populations. Crucially, better understanding is needed of population connectivity and distribution in both Taiari flathead and Central Otago roundhead galaxiids (Jones & Closs 2016). Based on this knowledge, robust and effective galaxiid-trout management plans could be developed that would ensure widespread and healthy galaxiid populations, along with a sustainable trout fishery. Connectivity is not such an issue with respect to dusky and Eldon's galaxiids – they do not disperse downstream, and they cannot coexist with trout (Jones & Closs 2016). The only realistic conservation strategy is protecting current populations from trout invasion, and restoring populations to streams from which they have been excluded by trout or brook charr. Methods and strategies to effectively remove trout from streams, including the use of rotenone (Pham et al. 2013, 2018), need to be investigated and developed.

Fish communities in the lower Taiari are an interesting mix of abundant native and introduced species. Perhaps contrary to popular expectations, both giant and banded kōkopu are abundant where there is suitable habitat, and this is despite the absence of any obvious barriers to trout movements. This raises the possibility that these aggressive and highly territorial galaxiid species can exclude trout provided they have suitable habitat, namely plenty of cover. This suggests that restoration of suitable habitat to smaller streams across the lower Taiari would lead to increases in the distribution and abundance of these two species. Restoration of giant and banded kōkopu to the smaller streams across the area probably would not come at the expense of the local trout fishery. Such streams provide little if any angling opportunity, and the improved whitebait abundance may well benefit the trout fishery (more large trout in the mainstem of the river) as well. While potential impacts of trout on native fish must be taken into account, the local trout fishery remains popular and is an important recreational resource. The potential to both enhance populations of the migratory galaxiids whilst still sustaining significant trout fisheries offers opportunities to engage a wide range of stakeholders, including Fish and Game. Knowledge of the movements and connectivity of the diadromous fish species in the catchment remains poorly understood, including the extent of lake rearing in giant kōkopu, kōaro and common and redfin bully (Hicks et al. 2017; Wansbrough et al. 2023).

This report has not focused on climate change impacts on aquifers in the Taiari catchment, mainly because little is known about the biota of the aquifers. There is some knowledge of the hyporheic (sub-surface) fauna of the Kye Burn (e.g. Olsen & Townsend 2003), but nothing of the fauna in deeper aquifers. The aquifers of the Lower Taiari Plain are important water sources for farming activities and the Lower Taiari-East Aquifer, which is principally fed by Silver Stream, is tapped by the Dunedin City Council for the municipal water supply. As such, some studies have been carried out on water quality of the Lower Taiari aquifers (e.g., Litchfield et al. 2002; Kensington et al. 2004). We have not assessed the effects of climate change on the water quality of these aquifers, although increasing salinisation of unconstrained aquifers of the Lower Taiari Plain will occur as sea levels rise. We therefore highlight that the effects of climate change on aquifer water chemistry and biota is a current knowledge gap.

Although we mention wetlands and discuss submerged aquatic plants in this report, we have not specifically assessed the effects of climate change on terrestrial wetlands and associated emergent plant species. These systems will exert major influences on the hydrology and physico-chemistry of the Taiari catchment hydro-system and they contain rare and threatened plant species, which we have not highlighted here. Therefore, we recommend that an assessment of climate change impacts on terrestrial wetlands of the Taiari catchment be undertaken by suitable botanists. The effects of land-cover change on water yield could also be discussed in such a report. Fire management also requires further extensive investigation, both in terms of a tool for managing vegetation, but also as a threat to existing vegetation, aquatic systems (particularly small streams) and property. Increased planting of exotic pine forest for carbon sequestration creates an obvious but surprisingly little discussed risk for increased the spread and impact of wildfire.

10.2 Lotic macroinvertebrates

To our knowledge there are no climate-change related studies on benthic macroinvertebrate communities in stony-bottomed streams that are specific to the Taiari River catchment, as discussed earlier. However, such studies may not be essential, given that several controlled manipulative experiments were conducted in the *ExStream System* mesocosms in North Otago, and the results from these experiments should be fairly "generic", as we explain above.

Moreover, there are no studies on cold-water specialist, exclusively alpine species from EPT taxa (mayflies, stoneflies or caddisflies) or net-winged midges, even though the existence of such species in the alpine areas of the Taiari uplands is likely and these species are highly vulnerable to climate warming, as discussed above.

11. Summary and conclusions

The Taiari River catchment encompasses a broad range of species and aquatic habitats which are likely to be affected by climate change and sea level rise in a wide variety of ways. To facilitate our assessment of the likely effects of climate change on the species and aquatic habitats, we divided the catchment into four climatic regions, which we assessed separately: (1) the lower Taiari Plain and surrounding hills, (2) Mid Taiari and (3) the Māniatoto, and (4) the Taiari uplands. A summary of our assessments is presented in Table 3.

Sea level rise is the key factor affecting aquatic habitats and structuring biotic communities of the lower Taiari Plain. This will push salt water further up into the Plain, increasing tidal mixing and salinity of the estuary and lake-wetland complex. Freshwater inflows from the Waipōuri and Taiari Rivers influence the inland progression of saline waters and, therefore, the freshwater flows that will be available in these rivers will potentially mitigate or exacerbate saline intrusions. If flood defences are bolstered, then the mainly freshwater lake-wetland complex will become estuarine and there will be a net loss of these highly biodiverse, productive freshwater habitats. On the other hand, if there is a strategic retreat from the lower part of the Taiari Plain allowing the wetland complex to expand beyond the stop-banks in a controlled manner, then new freshwater habitats will become available and exposure to the threat of sea level rise and climate change will be lessened. The availability of such habitat will largely determine the resilience of populations of migratory fish, birds and other flora and fauna dependent on the diversity and extent of these lowland freshwater habitats.

In the dry Mid Taiari area, the key factor affecting aquatic habitats will be the water balance that results from changes to temperature, precipitation, evaporation, and vegetation. The Sutton Salt Lake and associated wetland area is a unique aquatic habitat that is both highly sensitive and highly exposed to climate forcing. Therefore, this unique habitat and some of its rare species are under threat and there are few options for mitigation available. Species translocation may be the only reasonable way to adapt to climate change impacts on this system.

The vegetation of the dry inland and upland Taiari environments is changing in response to altered fire regimes (historical Māori and pastoral burning, and now extensive fire suppression), intensification of land use, extensive forestry, changes to grazing regimes and climate change. Understanding how these changes to the vegetation will impact water quality and quantity is poorly understood, and there is little to no consideration as to how this might impact streamflow into the future. Further, the increasing amount of woody vegetation across the landscape will alter fire risk, which will also interact with a changing climate. Predictions of a greater frequency of extreme events, particularly drought, suggest fire risk should be a key element of landscape management and planning.

The non-migratory *Galaxias* species of the Taiari are the fish species most at risk in the area, yet also present realistic and sustainable opportunities for protection and restoration. The knowledge of current and former populations of dusky and Eldon's galaxiids is good, and strategies for their protection and restoration could be readily developed, particularly with respect to the removal of trout and the creation of barriers to protect populations. There remain some knowledge gaps with respect to the distribution of Taiari flathead and Central Otago roundhead galaxias, but targeted sampling of streams could quickly resolve these knowledge gaps. Once that information is complete, a sustainable conservation strategy that directs how their life history and biology can be managed across a landscape inhabited by trout could be developed. Such a strategy needs to pragmatically recognise where trout and brook char can and cannot be eradicated. Further, knowledge and understanding of the circumstances (particularly habitats) where these galaxiids can coexist with trout and the role of upstream migration of galaxiids that may connect populations is urgently needed.

Knowledge gaps regarding New Zealand freshwater invertebrates are extensive - we know relatively little about the biology of most species. The ExStream research certainly highlights the sensitivity of many common macroinvertebrate species to a wide variety of stressors –highlighting the risks of obvious stressors such as excessive nutrients, fine sediments, pesticides, etc. However, little is known of the more range-restricted higher altitude species that occur on the Rock and Pillar and Hawkdun Ranges. Intuitively, it seems likely that these species would be sensitive to stressors such as increasing temperatures, altered vegetation and intensification of land use. Given their occurrence in small, higher altitude streams, they have limited options to expand their range upstream to escape these stressors. Our understanding of the distribution of many of these species, and the options for protecting them in face of changing climate and land use represent a significant knowledge gap.

This list of recommendations is not intended to be either extensive or exhaustive, but simply reflect some of the more obvious and potentially achievable projects based on our review of the area, our knowledge, and biases. For a more exhaustive list of potential projects, readers should also consult Ryder& Tocher (2020) and Orchard (2022 & 2023). Mātauranga and other holistic worldviews may be useful when considering these actions because they enable a broader suite of values to be assessed for decision-making (e.g., ecosystem services, different ways of valuing nature). Applying these knowledge frameworks could help identify actions to lessen the potential impacts of climate change while also providing positive outcomes for the stakeholders involved (Orchard 2022 & 2023).

Table 3. Summary of high priority threatened species and habitats, specific climate-related threats, sensitivity, exposure, and potential mitigations regarding the predicted effects of climate change on aquatic systems in the Taiari catchment. For additional / complementary recommendations, refer to Ryder & Tocher (2020).

Lower Taiari

Spp/Habitat	Issue	Mitigating factors	Management options
Coastal wetland/lake complex	Sea level rise and salinisation	System could shift to a native estuarine-lagoon community with equivalent values.	• Ensure freshwater flows into the wetland/lake complex are prioritised during summer drought to assist a gradual transition to estuarine. • Promote wetland restoration (i.e., maintain/improve hydrology, reduce nutrient & sediment inputs) to enhance resilience of the system to perturbation. • Community-wide engagement about ongoing investment in flood and drainage infrastructure, and options for managed retreat. • Consider managed retreat combined with wetland restoration and fish barrier removal (e.g., Lee Stream). • Construct wetlands upstream of Waipōuri/Waihora to intercept nutrients, sediments, buffer flows and improve water quality in the lakes [adapted from Ryder & Tocher 2020 Table 18 p. 71] • Consider the expansion of current protected areas or the creation of new reserves to protect species and ecosystems that may shift as a result of climate change.

Coastal galaxiids (e.g., banded kōkopu)	Local loss of populations due to extreme events (i.e., floods, fire).	Recruitment from wider regional pool along the coast.	• Assess the wider regional pool of fish populations and determine whether focal locations (e.g., in the Taiari and elsewhere on the coast) could be protected to add resilience. Consider that under some circumstances, populations in the Taiari may supplement those in other locations. • Develop guidance to tailor stream restoration to native galaxias by increasing instream cover (e.g., actively installing large woody debris[11], riparian plantings that provide overhanging vegetation, root mats, and undercuts). • Ensure/restore fish passage upstream so that inland migration with freshwater/saline limit can occur. • Identify key 'source' locations for landlocked populations (e.g., Alex Stream for giant kōkopu) and consider whether they need protection from climate change impacts. • Identify important spawning sites for each species and tailor protection and restoration to address climate change trends (e.g., drought, changing distribution of pest plants like reed sweet grass *Glyceria maxima*).
Non-migratory galaxiids and other fish species	Drought and fire, and/or trout incursions		• Characterisation of isolated native fish populations in small headwater streams (e.g., of the Waipōuri River).

[11] Note: Development of guidance on 'In-stream habitat restoration using woody debris' is underway, (Ebi Hussain (Auckland Council) via the councils Fish SIG, also see 'Habitat requirements of native freshwater fish in Aotearoa New Zealand' (Petrove, N., McEwan, A., Paltridge A. *in press*, Department of Conservation).

	eliminating isolated headwater populations (e.g., Upper Waipōuri) with unique species/subspecies.	• Development of strategies to protect and restore (e.g., via pre-emptive/post-event translocation) unique fish populations. • Restore the upstream limits of estuarine spawning areas (e.g., for īnaka and smelt) to follow inland migration of this habitat with coastal salinisation. • Develop a better understanding of smelt spawning locations.
Stony-bottomed stream invertebrate communities	Increasing water temperatures, increasing disturbance from extreme weather events.	• Stream restoration by fencing and riparian plantings, particularly in the headwaters and smaller tributaries where shading will reduce water temperatures and will also reduce sediment and nutrient inputs. • Include wetland restoration wherever possible, even if small. Wetlands buffer water flows, improve water quality, increase biodiversity, and store carbon. • Reduce pesticide use as negative impacts are aggravated by increased water temperatures. • Prepare for extreme weather events, particularly high flows, by installing multiple small flow-buffering devices in steep catchments (e.g., small detention bunds, leaky barriers[12]).
Freshwater mussel/kākahi	Lake Waihora/Waipōuri populations may eventually be	• Characterise the distribution and abundance of this long-lived species (including genetic information) and whether it would persist in lowland tributaries (i.e., are suitable fish hosts and habitat available?). Consider

[12] Sometimes referred to as 'nature based solutions'.

	eliminated by salinisation from sea level rise.		whether translocation inland (e.g. to artificial reservoirs) would be appropriate.
Birds	Riparian and wetland habitat compromised by extreme events (e.g., drought, fire, severe floods).		• [see Ryder & Tocher 2020 p. 75] Update rare species abundance and distribution surveys, link to habitat protection and restoration needs. Species like Australasian bittern or South Island fernbird may engage/inspire different (human) communities to those interested in rare fish (for example).

Mid Taiari

Spp/Habitat	Issue	Mitigating factors	Management options
Sutton Salt Lake	Increased air temperatures and hot days, lengthening the drying cycle of the lake. Alternatively increased extreme rainfall may extend 'aquatic' phases of		• Examine the hydrology of the lake and explore options for maintaining saline water chemistry. • Examine the habitat requirements and range of rare species at Sutton Salt Lake (e.g., tadpole shrimp and clam shrimp). • Search for populations of the rare species outside the lake complex and develop/trial translocation to increase resilience of the species to localised impacts.

	the system and decrease salinity.	
Mid Taiari mainstem	Changes to frequency and intensity of floods and droughts, altering water levels in the mainstem.	• Survey fish communities to understand current state and issues. • Maintain/increase the minimum flow regime on the Taiari to preserve refuge habitats for fish (i.e., deep, sheltered pools) during extreme drought. • Encourage small-scale interventions landscape-wide, especially in steep headwaters to slow flood flows (e.g., sediment traps, leaky barriers).
Rare non-migratory galaxias species including the Taiari flathead, Central Otago roundheads, dusky and Eldon's galaxias.	Reduced flows in small tributaries.	• Monitor fish communities, particularly the rare non-migratory galaxias to assess their current state and trends, and to engage landowners. Evaluate habitat (including at a sub-catchment scale) to establish management priorities. • Monitor to detect and manage trout incursions to rare non-migratory galaxias habitat (e.g., Nenthorn and Sheepwash Stream). • Proactively develop translocation protocols and plans for rare galaxias species (see M. Lintermans' research, U. Canberra). • Maintain/increase minimum environmental flows allocated to small streams. • Consider changing land use to reduce/remove irrigation needs. • Headwater and riparian margin restoration to increase shading, flow mitigation, and to intercept sediments. • Restore small wetlands (flow mitigation in both flood and drought).

			• Assess and mitigate fish passage barriers – balancing galaxiid and trout management (i.e., restricting trout access). • Plant with wildfire resistance in mind (consider landscape-scale planning for this).

Māniatoto

Spp/Habitat	Issue	Mitigating factors	Management options
Non-migratory galaxiids	Rare native species, experiencing multiple pressures that will be exacerbated by climate change.		• Continue monitoring fish communities to inform management. • Protect key non-migratory galaxiid habitat (e.g., by fencing off spawning areas in spring, riparian restoration of wetlands and streams (including small headwater streams) to protect breeding grounds and habitat. • Develop a regional galaxiid conservation plan, to restore and protect core non-migratory galaxiid populations (e.g., the Spec Creek galaxiid sanctuary), to raise the profile of these unique taonga, and increase engagement from landowners and irrigators. • Consider strategic eradication of brook char (that are already declining) to protect native galaxiids.
Pest and migratory species	Perch population upstream of	Paerau weir	• Monitor/suppress/locally eradicate perch in the Paerau Power Station impoundment (should it occur) to reduce risk of transfer.

	Paerau Power Station	• Provide irrigation pond owners information about pest fish species issues especially with respect to rare native fish species and management options. Encourage management of perch throughout the network of storage ponds in the catchment to reduce risk to rare native fish. • Assess the effectiveness of Paerau Weir at allowing passage of native freshwater species upstream and downstream.
Flow regime management	Increased probability of drought, floods and associated blackwater events.	• Ongoing review and adjustment to flow regimes to manage for multiple values in the catchment (i.e., agriculture, rare native fish species, sport fisheries, mahika kai (e.g., tuna, kanakana)), preventing deoxygenation events and increasing resilience to climate change.
Scroll plain and wetland restoration	Increased probability of extreme drought and floods.	• Continue the protection and restoration of the scroll plain and associated wetlands by managing grazing pressure while managing exotic weed species (e.g., willows) and pest animals (e.g., feral geese, mustelids). Wetlands mitigate climate change by storing carbon while also increasing resilience to flood and drought along with many other ecosystem services such as increasing aquatic biodiversity. The scroll plains also offer potential for world class eco-tourism opportunities. • Consider diversifying and changing to land uses with lower water/irrigation requirements and lower debt servicing.

Taiari/Waipōuri Uplands

Spp/Habitat	Issue	Mitigating factors	Management options
Upland and alpine bogs and wetlands	Increased drought and extreme weather events are likely to damage these unique ecosystems.		• Prioritise protection and restoration of these wetlands through holistic measures (e.g., landscape-scale management of hydrology, grazing, fire and planting plans).
Artificial reservoirs (i.e., Lake Mahinerangi, Loganburn Reservoir)			• Stakeholders and regulatory agencies work through a facilitated multicriteria decision-making process to explore the challenges and opportunities of climate change and how/if reservoir management could help mitigate some aspects of climate change (e.g., water levels downstream at the Waipōuri/Waihora lake wetland complex, native galaxiid management especially for drought and fire, sport and pest fish species).
Non-migratory galaxiids	Rare native species, experiencing multiple pressures that will be exacerbated by climate change.		• Develop a regional galaxiid conservation plan (as proposed in the Māniatoto) to: restore and protect core non-migratory galaxiid habitat (e.g., Spec Creek galaxiid sanctuary); to raise the profile of these unique taonga; and increase engagement from, and options for landowners and irrigators.

	Extreme weather events may cause incursion of trout to areas that are currently a native species refuge.	• Support research to understand the ecology of rare non-migratory fish species, and to support conservation management.
Wilding pines	Increasing fire risk and changes to hydrology.	• Wilding pine control and landscape scale planting plan to encourage planting of fire-resistant species and fire breaks, as well as species that support desirable hydrology of small streams. • Prioritise protection and restoration of small wetlands and headwater areas to help manage hydrology and buffer flows.
Unique aquatic invertebrate fauna of the Upper Taiari	Increased air and water temperatures, increased drought, causing extinction of cold-adapted species.	• Support characterisation of the fauna of the Upper Taiari and consider translocation options for rare species (e.g., from alpine sites to locations at higher altitude and further inland).

12. References

Allen RB, McIntosh PD (1997) Guidelines for conservation of salt pans in Central Otago. Science for Conservation 19. Department of Conservation. Wellington. 45 pp.

Alonso Á, Castro-Díez P (2012) The exotic aquatic mud snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca): State of the art of a worldwide invasion. Aquatic Sciences 74: 375-383.

Augspurger JM, Jarvis MG, Wallis GP, King TM, Ingram T, Hicks AS, Closs GP (2023) Landscape biogeography and population structuring of a facultatively amphidromous galaxiid fish, *Galaxias brevipinnis*. Cybium 47: 417-430.

Bierschenk BM (2014) Life history and distribution of mysid species in a large open estuary. PhD thesis, University of Otago, Dunedin.

Bierschenk BM, Burns CW, Schallenberg M, Closs GP (2021) Life histories of two hyperbenthic mysids (Mysidacea: Mysidae) in an open estuary. New Zealand Journal of Marine and Freshwater Research 55: 466-485.

Brucet S, Boix D, Nathansen LW, Quintana XD, Jansen E, Balayla D, Meerhof M, Jeppesen E (2012) Effects of temperature, salinity and fish in structuring the macroinvertebrate community in shallow lakes: Implications for effects of climate change. Plos One 7: e30877.

Burns CW, Schallenberg M (1996) Relative impacts of copepods, cladocerans and nutrients on the microbial foodweb of a mesotrophic lake. Journal of Plankton Research 18: 683-714.

Bylak A, Kukuła K, Easton R., Reid M, Closs GP (2023) Reservoirs facilitate colonization of river catchments by a native invasive fish through provision of pelagic larval rearing habitat. Biological Invasions 25: 1541-1559.

Cadmus RW (2004) What is, what was, and what will be: Environmental history as a basis for sustainable wetland restoration. MSc thesis, University of Otago, Dunedin.

Closs GP, Smith M, Barry B, Markwitz A (2003) Non-diadromous recruitment in coastal populations of common bully (*Gobiomorphus cotidianus*). New Zealand Journal of Marine and Freshwater Research 37: 301-313.

Clucas R (2004) Ka¯ putake oraka tuna hei mahika kai = Population parameters for longfinned (*Anguilla dieffenbacchii*) and shortfinned (*Anguilla australis*) eels at Sinclair Wetlands. MSc Thesis, University of Otago, Dunedin.

Connell JH (1978) Diversity in tropical rain forests and coral reefs. Science 199: 1302-1310.

Cox TJ, Rutherford JC (2000) Thermal tolerances of two stream invertebrates exposed to diurnally varying temperature. New Zealand Journal of Marine and Freshwater Research 34: 203-208.

Craw D, Beckett S (2004) Water and sediment chemistry of Sutton Salt Lake, east Otago, New Zealand. New Zealand Journal of Marine and Freshwater Research 38: 315-328.

Daufresne M, Roger MC, Capra H, Lamouroux N (2004) Long- term changes within the invertebrate and fish communities of the Upper Rhone River: Effects of climatic factors. Global Change Biology 10: 124-140.

David BO (2001) Ecology of the giant kōkopu. PhD thesis, University of Otago, Dunedin.

David BO, Closs GP, Arbuckle CJ (2002) Distribution of fish in tributaries of the lower Taiari/Waipori rivers, South Island, New Zealand. New Zealand Journal of Marine and Freshwater Research 36: 797-808.

David B, Chadderton L, Closs G, Barry B, Markwitz A (2004) Evidence of flexible recruitment strategies in coastal populations of giant kōkopu (*Galaxias argenteus*). DOC Science Internal Series 160: 1-23.

Dawson TP, Jackson ST, House JI, Prentice IC, Mace GM (2011) Beyond Predictions: Biodiversity Conservation in a Changing Climate. Science 332: 53-58.

Denys PH, Beavan RJ, Hannah J, Pearson CF, Palmer N, Denham M, Hreinsdottir S (2020) Sea level rise in New Zealand: The effect of vertical land motion on century-long tide gauge records in a tectonically active region. Journal of Geophysical Research: Solid Earth 125:e2019JB018055.

de Winton M, David S, Taumoepeau A (2023) LakeSPI survey for three lowland Otago lakes. NIWA Report prepared for the Otago Regional Council. Otago Regional Council, Dunedin. 34 pp.

DOC (1996) Lakes Waipori and Waihola wetland – management statement. Department of Conservation Te Papa Atawhai, Miscellaneous Report Series No. 29.

Dolédec S, Phillips N, Scarsbrook M, Riley RH, Townsend CR (2006) Comparison of structural and functional approaches to determining landuse effects on grassland stream invertebrate communities. Journal of the North American Benthological Society 25: 44-60.

Dorsey LW (2020) Some aspect of the ecology of non-native Brook Charr (*Salvelinus fontinalis*) in the headwater streams of Otago, New Zealand. PhD thesis, University of Otago, Dunedin.

Dunn NR, Allibone RM, Closs GP, Crow SK, David BO, Goodman JM, Griffiths M, Jack DC, Ling N, Waters JM, Rolfe JR (2017) Conservation Status of New Zealand Freshwater Fishes, 2017. Department of Conservation, Wellington. New Zealand.

Ensbey M, Legge S, Jolly CJ, Garnett ST, Gallagher RV, Lintermans M, Nimmo DG, Rumpff L, Scheele BC, Whiterod NS, Woinarski JCZ, Ahyong ST, Blackmore CJ, Bower DS, Burbidge AH, Burns PA, Butler G, Catullo R, Chapple DG, Dickman CR, Zukowski S (2023) Animal population decline and recovery after severe fire: Relating ecological and life history traits with expert estimates of population impacts from the Australian 2019-20 megafires. Biological Conservation 283: 110021.

Fenwick M, Hofstra D, Richie PA, Lee C, Longmore J, Hopkins A, Clearwater SJ (2020) How connected are Waikato River freshwater mussel populations? A preliminary result. Poster presentation to "Weathering the Storm", the NZHS, NZ Rivers Group, NZ Freshwater Sciences Society Joint Conference, Invercargill/Waihopi 1-4 December, 2020.

Filmer V, Fitzharris B (2002) Impacts of climate change on the hydrology of the Taiari and Waipori River systems. Department of Geology, University of Otago report prepared for Marc Schallenberg, Department of Zoology, University of Otago. 22pp.

Flöder S, Jaschinski S, Wells G, Burns CW (2010) Dominance and compensatory growth in phytoplankton communities under salinity stress. Journal of Experimental Marine Biology and Ecology 395: 223-231.

Frutiger A (2002) The function of the suckers of larval net- winged midges (Diptera: Blephariceridae). Freshwater Biology 47: 293-302.

Frutiger A, Buergisser GM (2002) Life history variability of a grazing stream insect (*Liponeura cinerascens minor*; Diptera: Blephariceridae). Freshwater Biology 47: 1618-1632.

Gibb JG (1986) A New Zealand regional Holocene eustatic sea level curve and its application to determination of vertical tectonic movements. A contribution to IGCP - Project 200. Royal Society of New Zealand Bulletin 24: 377-396.

Goldsmith M (2023) Climate change impacts and risks for the Taiari River catchment – a compilation of current research to support local decision-making. GHC Consulting Report 2023/01.

Goldsmith RJ (2004) Impacts of European perch *Perca fluviatilis* on native common bully *Gobiomorphus cotidianus*. PhD thesis, University of Otago, Dunedin.

Grainger N, Harding J, Drinan T, Collier K, Smith B, Death R, Makan T, Rolfe J (2018) Conservation status of New Zealand freshwater invertebrates, 2018. New Zealand Threat Classification Series, Department of Conservation. 29 pp.

Grimmond NM (1968) Observations on growth and age of *Hydridella menziesi* Gray (Mollusca: Bivalvia) in a freshwater tidal lake. MSc Thesis, University of Otago, Dunedin. 104 pp.

Grove P (1994) Maniototo Ecological District: Survey report for the Protected Natural Areas Programme. New Zealand Protected Natural Areas Programme Series No. 22. Department of Conservation, Wellington. 150 pp.

Hall CJ, Burns CW (2002a) Environmental gradients and zooplankton distribution in a shallow, tidal lake. Archiv fur Hydrobiologie 154: 485-497.

Hall CJ, Burns CW (2002b) Mortality and growth responses of *Daphnia carinata* to increases in temperature and salinity. Freshwater Biology 47: 451-458.

Hall CJ, Burns CW (2002c) Effects of temperature and salinity on the survival and egg production of *Gladioferens pectinatus* Brady (Copepoda: Calanoids). Estuarine, Coastal and Shelf Science 55: 557-564.

Hansen EA, Closs GP (2009) Long-term growth and movement in relation to food supply and social status in a stream fish. Behavioral Ecology 20: 616-623.

Hicks AS, Jarvis MG, David BO, Waters J, Norman MD, Closs GP (2017) Lake and species specific patterns of non-diadromous recruitment in amphidromous fish: the importance of local recruitment and habitat requirements. Marine and Freshwater Research 68: 2315-2323.

Hitchings TR (2009) Leptophlebiidae (Ephemeroptera) of the alpine region of the Southern Alps. Aquatic Insects 3: 595-601.

Hitchmough RA, Barr B, Knox C, Lettink M, Monks JM, Patterson GB, Reardon JT, van Winkel D, Rolfe J, Michel P (2021). Conservation status of New Zealand reptiles, 2021. New Zealand Threat Classification Series No. 35, Department of Conservation, Wellington. 15p.

Huang D, Haack RA, Zhang R (2011) Does global warming in- crease establishment rates of invasive alien species? A centurial time series analysis. PLoS ONE, 6, e24733.

Huryn AD (1996) Temperature-dependent growth and life cycle of *Deleatidium* (Ephemeroptera: Leptophlebiidae) in two high-country streams in New Zealand. Freshwater Biology 36: 351-361.

Intergovernmental Panel on Climate Change (IPCC) (2013) *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, TF, Qin, D, Plattner, GK, Tignor, M, Allen, SK, Boschung, J, … Midgley, PM (Eds), Cambridge and New York: Cambridge University Press.

IPCC (2007) Regional climate projections. *In:* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL), pp. 848–940. Cambridge University Press, Cambridge, UK & New York, NY, USA.

Jenkins KM, Kingsford RT, Closs GP, Wolfenden BJ, Matthaei CD, Hay SE (2011) Climate change and freshwater ecosystems in Oceania: an assessment of vulnerability and adaptation opportunities. Pacific Conservation Biology 17: 201-219.

Jeppesen E, Sondergaard M, Jensen JP (2003) Climate warming and regime shifts in lake food webs - some comments. Limnology and Oceanography 48: 1346-1349.

Jones DA, Akbaripasand A, Nakagawa S, Closs GP (2019) Landscape features determine brown trout population structure and recruitment dynamics. Ecology of Freshwater Fish 28: 554-562.

Jones PE, Closs GP (2016) Interspecific differences in larval production and dispersal in non-migratory galaxiids: Implication for metapopulation structure. Marine and Freshwater Research 67: 1479-1492.

Kattel GR, Closs GP (2007) Spatial and temporal variation in the fish community of a South Island, New Zealand coastal lake. New Zealand Journal of Marine and Freshwater Research 41: 1-11.

Kater CG (2004) Spatial and temporal variation in the abundance and habitat use of banded kōkopu *Galaxias fasciatus* in small coastal Otago streams. MSc thesis, University of Otago, Dunedin.

Kauffman D, McKay N, Routson C, Erb M, Daetwyler C, Sommer PS, Heir O, Davis B (2020) Holocene global mean surface temperature, a multi-method reconstruction approach. Scientific Data 7: 201.

Kavazos C, Richarson M (2023) Kanakana in the Taiari catchment. DOC Report. DOC – 7368815.

Kensington CG, Richards K, Murray DL, Peake BL (2004) Distribution of nitrogen species in groundwater of the Taiari Plain aquifer, New Zealand. Journal of Hydrology (NZ) 43:39-57.

Kristensen EA, Closs GP (2008) Environmental variability and population dynamics of brown trout (*Salmo trutta*) in an upstream and downstream reach of a small New Zealand river. New Zealand Journal of Marine and Freshwater Research 42: 57-71.

Kristensen EA, Closs GP, Olley R, Kim J, Reid M, Stirling C (2011) Determining the spatial distribution of spawning by anadromous and resident brown trout Salmo trutta L. using strontium content of eggs collected from redds. Ecology of Freshwater Fish 20: 377-383.

Lange K, Townsend CR, Matthaei CD (2014) Can biological traits of stream invertebrates help disentangle the effects of multiple stressors in an agricultural catchment? Freshwater Biology 59: 2431-2446.

Lill AWT. Closs GP, Schallenberg M (2011) Late summer hyperbenthic estuarine communities: comparing permanently open and intermittently closed systems along the Otago coastline. New Zealand Journal of Marine and Freshwater Research 45: 73-83.

Lill AWT, Lal A, Closs GP (2010) Life history and reproduction of two abundant mysids (Mysidacea: Mysidae) in an intermittently open New Zealand estuary. Marine and Freshwater Research 61: 633-641.

Lintermans M (2013) The rise and fall of a translocated population of the endangered Macquarie perch *Macquaria australasica* in southeastern Australia. Marine and Freshwater Research 64: 838-850

Litchfield NJ (2001) The Titri Fault system: Quaternary-active faults near the leading edge of the Otago reverse fault province. New Zealand Journal of Geology and Geophysics 44: 517-534.

Litchfield NJ, Norris RJ (2000) Holocene motion on the Akatore Fault, south Otago coast, New Zealand. New Zealand Journal of Geology and Geophysics 43: 405-418.

Litchfield N, Craw D, Koons PO, Edge B, Parraudin E, Peake B (2002) Geology and geochemistry of groundwater within the Taiari Basin, east Otago, New Zealand. New Zealand Journal of Geology and Geophysics 45: 481-497.

Ludgate BG, Closs G (2003) Responses of fish communities to sustained removals of perch (*Perca fluviatilis*). Reissued with corrections. Science for Conservation 210 (Reissue). Wellington, N.Z: Dept. of Conservation.

Macaulay SJ, Buchwalter DB, Matthaei CD (2020) Water temperature interacts with the insecticide imidacloprid to alter acute lethal and sublethal toxicity to mayfly larvae. New Zealand Journal of Marine and Freshwater Research 54: 115-130.

Macaulay SJ, Hageman KJ, Piggott JJ, Juvigny-Khenafou NPD, Matthaei CD (2021a) Warming and imidacloprid pulses determine macroinvertebrate community dynamics in experimental streams. Global Change Biology 27: 5469-5490.

Macaulay SJ, Hageman KJ, Piggott JJ, Matthaei CD (2021b) Time-cumulative effects of neonicotinoid exposure, heatwaves and food limitation on stream mayfly nymphs: A multiple-stressor experiment. Science of The Total Environment 754: 141941.

Mark AF, Dickinson KJM (2008) Maximising water yield with indigenous non-forest vegetation: a New Zealand perspective. Frontiers in Ecology and the Environment 6: 25-34.

McCulloch GA, Guhlin J, Dutoit L, Harrop TWR, Dearden PK, Waters JM (2021) Genomic signatures of parallel alpine adaptation in recently evolved flightless insects. Molecular Ecology 30: 6677-6686.

McDowall RM, Allibone RM (1994) Possible competitive-exclusion of common river galaxias (*Galaxias vulgaris*) by (*G. brevipinnis*) following impoundment of the Waipori River, Otago, New Zealand. Journal of the Royal Society of New Zealand 24: 161-168.

McGlone MS (1988) History of the New Zealand vegetation. *In*: Huntley B and Webb T III (*eds*), Vegetation History. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 557-599.

McGlone MS, Moar NT (1998) Dryland Holocene vegetation history, Central Otago and the Mackenzie Basin, South Island, New Zealand. New Zealand Journal of Botany 36: 91-111.

McGlone MS, Wilmshurst JM (1999) A Holocene record of climate, vegetation change and peat bog development, east Otago, South Island, New Zealand. Journal of Quaternary Science 14: 239-254.

McMurtrie P (1998) Horizontal variation in the composition of invertebrate communities in ox-bow lakes on the upper Serpentine Flats (Taieri River floodplain, Otago, New Zealand. BSc (Hons) thesis. Department of Zoology, University of Otago, Dunedin.

Matthaei CD, Townsend CR (2000) Long-term effects of local disturbance history on mobile stream invertebrates. Oecologia 125: 119-126.

Matthaei CD, Weller F, Kelly DW, Townsend CR (2006) Impacts of fine sediment addition to tussock, pasture, dairy and deer farming streams in New Zealand. Freshwater Biology 51: 2154-2172.

Matthaei CD, Piggott JJ, Townsend CR (2010) Multiple stressors in agricultural streams: interactions among sediment addition, nutrient enrichment and water abstraction. Journal of Applied Ecology 47: 639-649.

Melchior M, Squires NJ, Clearwater SJ, Collier K (2023) Discovery of a host fish species for the threatened New Zealand freshwater mussel *Echyridella aucklandica* (Bivalvia: Unionida: Hyriidae). New Zealand Journal of Marine and Freshwater Research 57: 152-159.

Mikheev PB, Jarvis MG, Matthaei CD, Ingram T, Reid MR, Nikiforov AI, Chemienko IS, Closs GP (2021) Straying of brown trout in the catchment of a large New Zealand river evaluated by otolith microchemistry. Ecology of Freshwater Fish 30: 422-443.

Ministry for the Environment (2018) *Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment, 2nd Edition.* Report prepared by National Institute of Water and Atmospheric Research Ltd (NIWA) for the Ministry for the Environment, Wellington.

Ministry for the Environment (2008) Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. Ministry for the Environment, Wellington.

Ministry for the Environment (2024) Coastal hazards and climate change guidance. Ministry for the Environment, Wellington.

Mitchell SF (1975) Some effects of agricultural development and fluctuation in water level on the phytoplankton productivity and zooplankton of a New Zealand Reservoir. Freshwater Biology 5: 547-562.

National Institute of Water and Atmospheric Research Ltd (NIWA) (2018) *Hydrological projections for New Zealand rivers under climate change*. Report prepared for the Ministry for the Environment by Collins D, Montgomery K & Zammit C. NIWA, Christchurch.

Niyogi DK, Koren M, Arbuckle CJ, Townsend CR (2007) Stream communities along a catchment land-use gradient: subsidy-stress responses to pastoral development. Environmental Management 39: 213-225.

Olsen DA, Townsend CR, Matthaei CD (2001) Influence of reach geomorphology on hyporheic communities in a gravel-bed stream. New Zealand Journal of Marine and Freshwater Research 35(1): 181-190.

Olsen DA, Townsend CR (2003) Hyporheic community composition in a gravel-bed stream: Influence of vertical hydrological exchange, sediment structure and physicochemistry. Freshwater Biology 48: 1363-1378.

Orchard S (2022) Te Mana o Taiari - Matatū ki te Taiao Hui Rautaki. Report prepared by Waterlink Ltd for the Department of Conservation. Department of Conservation, Dunedin.

Orchard S (2023) Te Mana o Taiari : Kā Tohu te Taiao. Climate change indicators for the Taiari catchment. Workshop report prepared by Waterlink Ltd for the Department of Conservation. Department of Conservation, Dunedin.

Otago Regional Council (2022) Otago Regional Plan: Water - updated 2022. Schedule 9. Otago Regional Council, Dunedin. https://www.orc.govt.nz/plans-policies-reports/regional-plans-and-policies/water.

Paul S, Krkosek M, Probert PK, Closs GP (2013) Osmoregulation and survival of two mysid species of Tenagomysis in southern estuaries of New Zealand. Marine and Freshwater Research 64: 340-347.

Paul S, May DM, Lee M, Closs GP (2016) Body and brood sizes of *Tenagomysis* spp. (Crustacea: Mysida) in southern estuaries in New Zealand. New Zealand Journal of Marine and Freshwater Reseearch 50: 433-443.

Peat N, Patrick B (1996) Wild Fiordland: discovering the natural history of a World Heritage Area. University of Otago Press, Dunedin.

Piggott JJ, Townsend CR, Matthaei CD (2015) Climate warming and agricultural stressors interact to determine stream macroinvertebrate community dynamics. Global Change Biology 21: 1887-1906.

Pham L, Jarvis MG, West D, Closs GP (2018) Rotenone has a short-term effect on New Zealand stream macroinvertebrate communities. New Zealand Journal of Marine and Freshwater Research 52: 42-54.

Pham L, West D, Closs GP (2013) Reintroduction of a native galaxiid (Galaxias fasciatus) following piscicide treatment in two streams: response and recovery of the fish population. Ecology of Freshwater Fish 22:361-373.

Prebble M, Schallenberg M, Carter J, Shulmeister J (2002) An analysis of phytolith assemblages for the quantitative reconstruction of late Quaternary environments of the Lower Taiari Plain, Otago, South Island, New Zealand I. Modern assemblages and transfer function. Journal of Palaeolimnology 27: 393-413.

Prebble M, Shulmeister J (2002) An analysis of phytolith assemblages for the quantitative reconstruction of late Quaternary environments of the Lower Taiari Plain, Otago, South Island, New Zealand II. Palaeoenvironmental reconstruction. Journal of Paleolimnology 27: 415-427.

Quinn JM, Steele GL, Hickey CW, Vickers ML (1994) Upper thermal tolerances of twelve New Zealand stream invertebrate species. New Zealand Journal of Marine and Freshwater Research, 28, 391-397.

Robertson HA, Baird K, Dowding JE, Elliott GP, Hitchmough RA, Miskelly CM, McArthur N, O'Donnell CFJ, Sagar PM, Scofield RP, Taylor GA (2017) Conservation status of New Zealand birds, 2016. New Zealand Threat Classification Series No. 19, Department of Conservation. Wellington. 23 pp.

Robertson H, Bowie S, Death R, Collins D (Eds) (2016) Freshwater conservation under a changing climate. Proceedings of a workshop hosted by the Department of Conservation, 10-11 December 2013, Wellington. Department of Conservation, Christchurch, 87 pp.

Rogers G, Hewitt A, Wilson JB (2000) Ecosystem-based conservation strategy for Central Otago saline patches. Science for Conservation 166. Department of Conservation, Wellington 38 pp.

Ryder G, Tocher M (2020) Review of Values, Freshwater Restoration Programmes and Research Needs Within the Taiari Catchment. Report prepared by Ryder Consulting for the Department of Conservation. Department of Conservation, Dunedin. 144 pp.

Schallenberg M, Goff J, Harper MA (2012) Gradual, catastrophic and human induced environmental changes from a coastal lake, southern New Zealand. Sedimentary Geology 273-274: 48-57.

Schallenberg M, Burns CW (2003) A temperate, tidal lake-wetland complex 2: Water quality and implications for zooplankton community structure. New Zealand Journal of Marine and Freshwater Research 37: 429-447.

Schallenberg M, Hall CJ, Burns CW (2003a) Consequences of climate-induced salinity increases on zooplankton abundance and diversity in coastal lakes. Marine Ecology Progress Series 251: 181-189.

Schallenberg M, Burns CW, Peake BM (2003b) A temperate, tidal lake-wetland complex 1: Water balance and ecological implications. New Zealand Journal of Marine and Freshwater Research 37: 415-428.

Schallenberg M, Sorrell B (2009) Regime shifts between clear and turbid water in New Zealand lakes: environmental correlates and implications for management and restoration. New Zealand Journal of Marine and Freshwater Research 43: 701-712.

Schallenberg M, Waite E (2004) *Survey of aquatic macrophytes in Lake Waihola - summer 2002-2003*. Report prepared for the Otago Regional Council. 18 p. (Zoology Dept. Limnology Report No. 9).

Scheffer M, Straile D, Van Nes E, Hosper H (2001) Climate warming causes regime shifts in lake food webs. Limnology and Oceanography 46:1780-1783.

Shaw MS, Farrant ED (1949) The Taiari Plain: tales of years that are gone. Christchurch, New Zealand, Caxton Press.

Shelley J (2012) Is there enough water for people and nature? Impacts of flow reduction on fish and aquatic invertebrates in small streams. MSc thesis, University of Otago, Dunedin.

Stark JD (1993) Performance of the macroinvertebrate community index: effects of sampling method, sample replication, water depth, current velocity, and substratum on index values. New Zealand Journal of Marine and Freshwater Research 27: 463-478.

Stark JD, Maxted JR (2007) *A user guide for the Macroinvertebrate Community Index*. Cawthron Institute. Peer-reviewed report for the NZ Ministry for the Environment.

Sutherland DL, Closs GP (2001) Spatial and temporal variation in the abundance and composition of ichthyoplankton in a large South Island, New Zealand river estuary. New Zealand Journal of Marine and Freshwater Research 35: 1061-1069.

Todd C, Lintermans M (2015) Who do you mover? A stochastic population model to guide translocation strategies for an endangered freshwater fish in south-eastern Australia. Ecological Modelling 311; 63-72

Tonkin J, Taylor H (2021) Otago Climate Change Risk Assessment. Main report. Prepared for Otago Regional Council, March 2021.

Townsend CR, Dolédec S, Scarsbrook MR (1997a) Species traits in relation to temporal and spatial heterogeneity in streams: a test of habitat templet theory. Freshwater Biology 37: 367-387.

Townsend CR, Scarsbrook MR, Dolédec S (1997b) The intermediate disturbance hypothesis, refugia, and biodiversity in streams. Limnology and Oceanography 42: 938-949.

Wansbrough J, Lokman PM, Closs GP (2023) Local variation in the timing of reproduction and recruitment in a widely distributed diadromous fish. New Zealand Journal of Marine and Freshwater Research DOI:10.1080/00288330.2023.2212912

Wagenhoff A, Townsend CR, Phillips N, Matthaei CD (2011) Subsidy-stress and multiple-stressor effects along gradients of deposited fine sediment and dissolved nutrients in a regional set of streams and rivers. Freshwater Biology 56: 1916-1936.

Wanhalla, A (2015) Living on the rivers' edge at the Taieri native reserve. In: Indigenous Communities and Settler Colonialism (Eds. Z. Laidlaw, A. Lester). Published by Cambridge Imperial and Post-Colonial Studies Series. Palgrave Macmillan, London. Pp 138-157.

Warburton ML (2015) Migratory movement of torrentfish (*Cheimarrichthys fosteri,* Haast 1874). PhD thesis, University of Otago, Dunedin.

Warburton ML, Jarvis MG, Closs GP (2018) Otolith microchemistry indicates regional philopatry in the larval phase of an amphidromous fish (*Gobiomorphus hubbsi*). New Zealand Journal of Marine and Freshwater Research 52: 398-408.

Ward JV (1994) Ecology of alpine streams. Freshwater Biology 32: 277–294.

Waters JM, King TM, Craw D (2023) Gorges partition diversity within New Zealand flathead *Galaxias* populations. Journal of Fish Biology doi: 10.1111/jfb.15635

Wilderlabs (2023) https://www.wilderlab.co.nz/explore

Willhelm F.M., Hamann J, Burns CW (2002) Mysid predation on amphipods and Daphnia in a shallow coastal lake: prey selection and effects of macrophytes. Canadian Journal of Fisheries and Aquatic Sciences 59: 1901-1907.

Winterbourn MJ, Cadbury S, Ilg C, Milner AM (2008) Mayfly production in a New Zealand glacial stream and the potential effect of climate change. Hydrobiologia 603: 211–219.

Appendix 1: Sensitivity of Mysids and Invertebrate Exposure in the lower Taiari basin

A1.1 Sensitivity of Estuarine mysids

The mysid communities of the lower Taiari dominate the crustacean biomass in the lower reaches of the river and estuary and comprise four main species, *Tenagomysis chiltoni, T. novae-zealandiae, T. macropsis* and *Gastrosaccus australis* (Bierschenk 2014). All four species occur widely in streams along the Otago coastline, with *T. chiltoni* and *T. novae-zealandiae* occurring in most systems, whereas *T. macropsis* and *G. australis* only occur in open estuarine systems with regular tidal exchange (Lill et al. 2011). *Tenagomysis chiltoni* and *T. novae-zeelandiae* are primarily epibenthic, with *T. chiltoni* dominating the river reaches upstream of Henley and into Lake Waihora, and *T. novae-zealandiae* dominating downstream from Henley to Taiari Mouth (Lill et al. 2011; Bierschenk 2014). *Tenagomysis macropsis* and *G. australis* are more pelagic and are found in greatest abundance in the open water of the river channel between Henley and Taiari Mouth (Bierschenk 2014). Relatively little is known of the ecological role of mysids in the lower Taiari (Willhelm et al. 2002). However, given their omnivorous diet and substantial biomass, they almost certainly represent a key node in the system's food webs, both as predators and prey (Willhelm et al. 2002; Lill et l. 2011; Bierschenk 2014).

Research across multiple Otago estuaries indicates that complex interactions between habitat, tides, salinity and temperature determine the distribution of the mysid fauna (Lill et al. 2011; Biershenk 2014). *Tenagomysis chiltoni* is an upper estuarine to freshwater species, being able to osmoregulate in freshwater at low temperatures (Bierschenk 2014, Paul et al. 2013). However, with a longer life cycle, it seems to be outcompeted by the more frequently reproducing *T. novae-zealandiae* in the lower estuarine reaches of rivers (Lill et al. 2010; Paul et al. 2016). However, *T. novae-zealandiae* is unable to effectively osmoregulate in freshwater at low temperatures, and hence their abundance declines over winter, particularly further upstream (Lill et al. 2010; Paul et al. 2013; Bierschenk et al. 2021). The presence of both *T. macrosis* and *G. australis* is restricted to rivers with regular tidal exchange, as in both species swimming activity is stimulated by water turbulence (Lill et al. 2011; Bierschenk 2014). In still water, they tend to become inactive (Bierrschenk 2014). The distribution of both species in the Taiari is quite dynamic. *Tenagomysis macropsis* tend to occur in greatest abundance downstream of *G. australis*, with the peak abundance of each species varying according to life history stage, river discharge and season (Bierschenk 2014). What is remarkable is their ability to maintain a relatively stable distribution across multiple tidal cycles (Bierschenk 2014). How they do this in an estuarine system that is highly dynamic with respect to every key physical and chemical variable is unknown.

A1.2 Lower Taiari Stream invertebrates - Exposure

In the first of the two climate-change related experiments, Piggott et al. (2015) investigated how deposited fine sediment and elevated nutrient concentrations interact to affect stream macroinvertebrate community dynamics along a water temperature gradient ranging from 0 to 6°C above ambient (eight levels). This gradient simulated the entire range of anthropogenic climate warming forecast for New Zealand at the time, of up to 5.1°C by 2090 (IPCC, 2007; Ministry for the Environment, 2008). As a stressor main effect, raised temperature strongly changed the composition of the benthic invertebrate community. Eight of the 13 abundant taxa (including 4 of the 5 EPT taxa, the most common of these being larvae of the mayfly *Deleatidium* spp.) declined in absolute abundance, whereas only two taxa (Copepoda and Nematoda) increased. Three taxa were unaffected by warming: the mud snail *Potamopyrgus antipodarum*, Ostracoda, and the cased caddis *Oxyethira* spp. (which is known to be atypically pollution-tolerant for an EPT taxon, as reflected in its low Macroinvertebrate Community Index score, see Stark & Maxted, 2007).

The two mesocosm experiments also allowed investigation of multiple-stressor effects of raised water temperature and other stressors. In Piggott et al. (2015), the negative effects of added fine sediment on the stream invertebrate communities were often stronger at raised temperatures, suggesting that streams already impacted by high sediment loads may be further degraded under a warming climate. However, the degree to which this will occur may also depend on in-stream nutrient conditions.

In Macaulay et al. (2021a), the very high yet realistic water temperatures reached in the experiment meant the negative effects of imidacloprid were clearest at ambient temperatures and fast flow (where pollution-sensitive EPT taxa were most common). These findings demonstrated the potential combined impacts of imidacloprid contamination and heatwaves on freshwater invertebrate communities under future climate scenarios and highlighted the need for more countries (including New Zealand) to take regulatory action to control neonicotinoid use.

A1.3 Complementary laboratory research - invertebrate communities in the stony-bottomed tributaries of the lower Taiari

Lab experiments also demonstrate higher temperatures increase the toxicity of imidacloprid to 2 native mayfly species

In recent years, the climate-change-focused *ExStream* mesocosm experiments described above have been complemented by several laboratory experiments, which mainly focused on population-level effects of climate-change-related and other stressors on nymphs of the pollution-sensitive mayfly *Deleatidium* spp. This mayfly is endemic to New Zealand, common, widespread, sensitive to organic contaminants and regularly used as a bioindicator of stream health (Stark 1993, Stark & Maxted 2007). In the first such experiment, Macaulay et al. (2020) investigated the individual and interactive effects of raised water temperature and imidacloprid on *Deleatidium* spp. and *Coloburiscus humeralis,* another common NZ mayfly. Mortality and immobility of both mayfly taxa increased synergistically with exposure to imidacloprid at higher temperatures, implying temperature-enhanced toxicity of imidacloprid.

A subsequent 6-week laboratory experiment with *Deleatidium* spp. nymphs (Macaulay et al. 2021b) investigated the potential for direct and delayed interactive effects of simulated heatwaves and starvation with chronic exposure to a field-realistic concentration of imidacloprid (0.4 µg/L). This experiment included two 6-day heatwaves, one during a starvation period prior to imidacloprid addition, and one during the first 6 days of imidacloprid exposure. The simulated heatwaves alone caused such drastic negative effects on *Deleatidium* survival and mobility that mainly antagonistic interactions were observed with the other stressors, though delayed synergisms between imidacloprid and the second heatwave also affected mayfly mobility. Toxicity of imidacloprid increased with time, with imidacloprid first affecting mayfly mobility after 12 days but eventually causing the strongest effects of all manipulated stressors. However, lethal effects of imidacloprid could only be detected in the absence of heatwaves and starvation, possibly as a result of selection for stronger individuals due to prior exposure to these stressors.

A1.4 Impacts of increased habitat disturbance on stream invertebrates

Climate change may also influence diversity and composition of the macroinvertebrate communities in the stony-bottomed tributaries of the Taiari catchment via changes to the physical disturbance regime of these streams. In a survey of 54 stream sites across the lower and middle Taiari, macroinvertebrate taxon richness was shown to be highest in tributaries with intermediate physical disturbance regimes (Townsend et al. 1997a,b). In these studies, the bed disturbance regime during floods at each site was quantified using painted tracer particles which were checked and replaced as needed five times during 1993/1994, with 'disturbance intensity' representing the average % of tracer particles that moved between consecutive sampling dates. Mean invertebrate taxon richness per stream site peaked at more than 25 taxa at intermediately disturbed sites (disturbance intensity around 50%), whereas both highly stable sites (disturbance intensity around 10%) and highly unstable sites (disturbance intensity around 90%) only contained 12-13 taxa each. According to the Intermediate Disturbance Hypothesis (Connell 1978), highly stable sites should contain mainly strong competitors and efficient predators, whereas highly unstable sites should contain mainly highly resilient or resistant taxa that excel at surviving bed-moving floods.

In the climate projections for the Taiari catchment (Goldsmith 2023, see also Section 4.1), rainfall is generally predicted to become heavier catchment-wide, and an increase in mean annual rainfall is likely (up to 15% downstream of the Taiari Gorge, with a smaller increase further upstream). Heavy rain days are also expected to increase across the catchment (by between zero and six days), with the highest increase predicted for the upper Silver Stream catchment north of the Taiari plain and the smallest increase in the drier Mid Taiari and Māniatoto. Consequently, flood events are also predicted to become somewhat larger and more frequent across most of the catchment, especially under the higher emissions scenario (RCP8.5), with the largest increases predicted for the tributaries which flow into the Māniatoto.