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Impacts and implications of climate change on Waituna Lagoon, Southland

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Cover: Waituna Lagoon. *Photo: Mary Beech*.

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Impacts and implications of climate change on Waituna Lagoon, Southland

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Abstract

Waituna Lagoon, near Invercargill, South Island, New Zealand, is a land-locked freshwater lagoon. It supports a variety of threatened species and is part of the ecologically significant Awarua Wetland Ramsar site. Periodically, the gravel lagoon barrier is manually opened to facilitate drainage of surrounding farmland and flushing of nutrient-rich water, turning the lagoon into an estuarine state until the barrier naturally closes. This report provides an assessment of potential climate change-related impacts on the lagoon, based on existing information. Projected increases in rainfall, freshwater inflows, flood events and inundation of surrounding land over the next several decades are likely to contribute to lower lagoon-bed light levels and higher levels of nutrients and sediment entering the lagoon. Such changes may increase algae growth and inhibit the growth of *Ruppia* spp., desirable native aquatic grasses. Nutrient and sediment inputs are known drivers of lagoon regime shifts (from a desirable macrophyte (freshwater plants)-dominated state to an undesirable algal-dominated state) and are closely linked to declines in water quality. If freshwater inflows increase as predicted, the lagoon will either need to be opened more frequently or the threshold for opening will need to be raised. This raises issues about land use around the lagoon and the long-term sustainability of the current manual opening regime. With ongoing sea level rise, the boundary of the lagoon is likely to shift landward and the intertidal zone is likely to shrink, which may affect wading birds that forage in the intertidal zone. Due to the complexity of the lagoon system, uncertainties about the trajectories of change in climate and sea level and the responses of the lagoon ecosystem, further research and ongoing monitoring is recommended as well as an adaptative management approach. This could include a variety of strategies for managing the lagoon and its biodiversity under both increasing freshwater inflow and saltwater inundation conditions.

Keywords: Waituna Lagoon, climate change, ecological implications, water level management

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1. Introduction

1.1 Purpose of this report

This report provides an assessment of potential climate change-related impacts on Waituna Lagoon, Southland, based on existing information. Projected changes in rainfall, air temperature, sea level and freshwater inflows to the end of this century are used to assess potential changes to the lagoon water temperature, water level, lagoon-bed light level and lagoon spatial extent. The ecological and management implications of these projected changes are considered and future research questions are identified and prioritised.

The information arising from this assessment is being provided to Waituna Lagoon stakeholders (Whakamana te Waituna, Living Water, and Arawai Kākāriki) to be used to evaluate the long-term viability of catchment management strategies. The report also provides a case study for rapid desktop assessments of potential climate change impacts on other coastal hydrosystems in New Zealand.

1.2 Climate change impacts on coastal hydrosystems

Coastal hydrosystems (including lagoons, estuaries and wetlands) are particularly susceptible to the impacts of climate change as they will be affected by changes to freshwater inflows, air temperature, rainfall, wind patterns as well as sea level rises (Lundquist et al. 2011; Rodriguez et al. 2017). The response of hydrosystems to these changes will be highly dependent upon the nature of the systems, the local topography and hydrological regimes and the potential for adaptive management interventions.

Recent work in New Zealand has focused on the classification of coastal hydrosystems (Hume et al. 2016) and the identification of climate change-related research gaps and needs in the coastal environment (Kettles & Bell 2016). A principal identified need is for a stocktake of New Zealand information and overseas best practice relevant to climate change impacts on coastal hydrosystems. This study on the impacts and implications of climate change on the Waituna Lagoon, and future work based on a similar methodology, will positively contribute to such a national stocktake.

1.3 Waituna Lagoon

Waituna Lagoon (1350 ha) (Figs 1, 2, 3) is part of the internationally recognised Awarua Wetland Ramsar site (19 500 ha). The lagoon also forms part of the Waituna Wetland Scientific Reserve (Kirk & Lauder 2000). The lagoon is of very high cultural significance for Ngāi Tahu and has important ecological and recreational values (Waituna Lagoon Technical Group 2013).

An initial assessment of the Awarua Wetland Ramsar site confirmed that the ecosystem is likely to undergo significant shifts in composition and habitat quality by 2100 as a result of climate change-related[1] changes in sea level, rainfall, river flows and air and water temperature (Finlayson et al. 2017).

Whakamana te Waituna, a coordinated catchment management effort that aims to maintain and enhance the Waituna Lagoon ecosystem, has been established. This initiative is driven by a partnership between the Department of Conservation (DOC), Environment Southland, Southland District Council, Te Rūnanga o Ngāi Tahu, Fonterra and Te Rūnanga o Awarua.

[1] Workshop on Adapting Wetland Policy and Management for Internationally Important Coastal Wetlands under Climate Change, Brisbane, Australia (31 July – 4 August 2017).

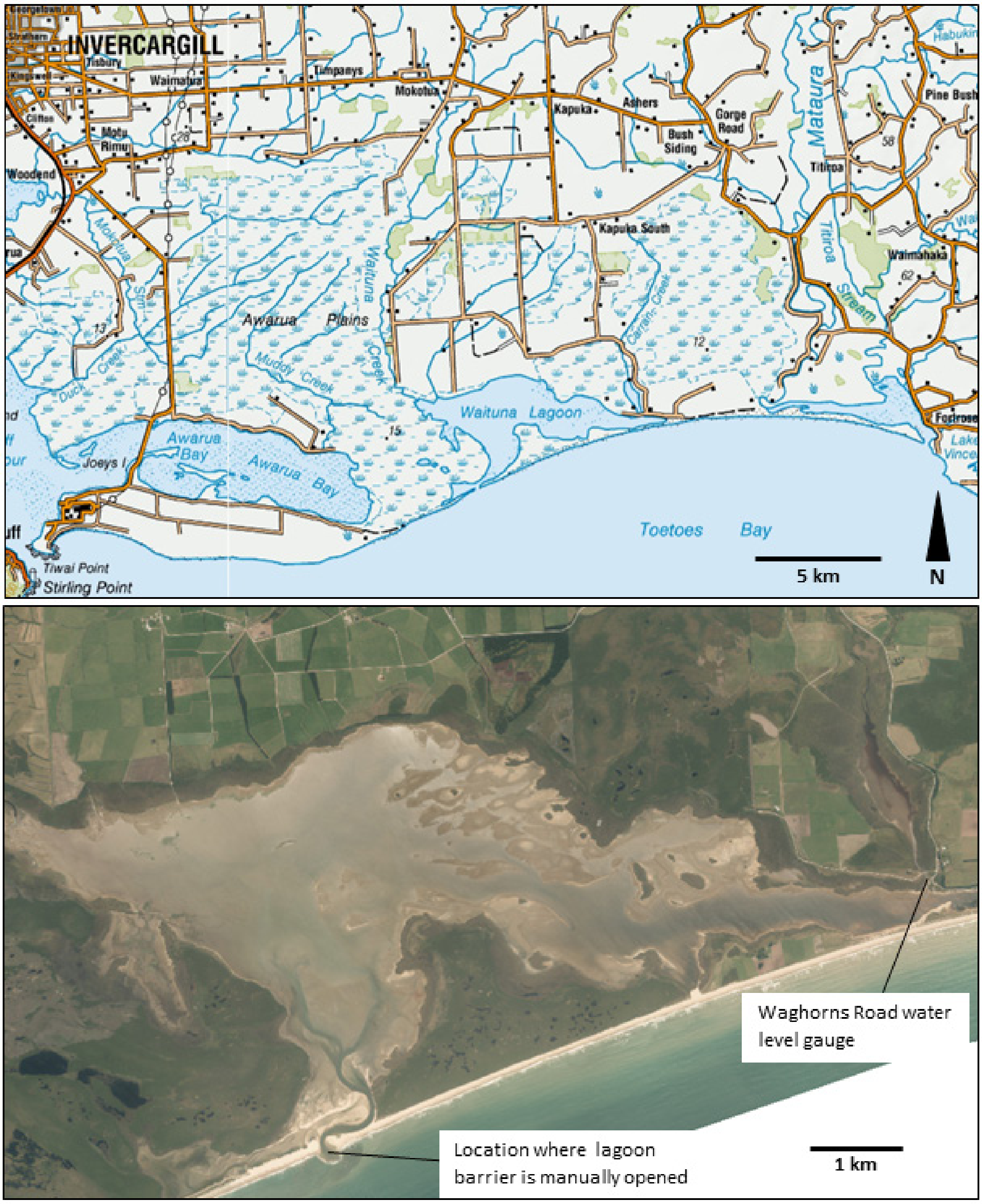

Figure 1. Top: map of the wider area surrounding Waituna Lagoon in Southland, New Zealand. Bottom: aerial photograph of Waituna Lagoon (photo taken when lagoon barrier was open). Source: LINZ.

Whakamana te Waituna also builds on two national freshwater projects DOC is leading in partnership with others: the Living Water[2] programme (a partnership between DOC and Fonterra) which includes the Waituna catchment as well as a number of other estuaries that are downstream of catchments with a high intensity of dairying, and Arawai Kākāriki[3], which encompasses the wider Awarua wetlands, including Waituna Lagoon.

[2] https://www.livingwater.net.nz/

[3] https://www.doc.govt.nz/our-work/arawai-kakariki-wetland-restoration/

Figure 2. Waituna Lagoon in 2015, showing the manually opened gravel barrier in the process of closing by natural wave action. *Photo: Sarah Crump.*

Figure 3. Farmland surrounding Waituna Lagoon in 2015. *Photo: Sarah Crump.*

New Zealand coastal hydrosystems have recently been classified into 11 main types, with Waituna Lagoon assigned the typology of a 'Waituna-type lagoon, sub-class A' (Hume et al. 2016). This type of estuary is reasonably rare, with examples in New Zealand including Lake Ellesmere (Te Waihora), Washdyke and Wainono Lagoons (Canterbury) and Ohuia Lagoon (Hawke's Bay). The distinguishing characteristics of this hydrosystem type are:

- Large (several km^2), shallow (mean depth 2–3 m) coastal lagoons barred from the sea by a barrier or barrier beach (no tidal inflow);

- Typically freshwater, fed by small streams, with brackish pockets in time or space;
- Drainage to the sea is generally by percolation through the barrier;
- Most frequent state is closed to the sea;
- Short-lived openings to the sea occur when water levels build sufficient hydraulic pressure in the lagoon to breach the enclosing barrier, generally due to high river inflows and/or severe storm waves overtopping the barrier;
- Sustained openings to the sea are rare (decadal–century time scales) unless created artificially;
- Tidal inflows may occur for short periods (1–2 tidal cycles) after natural barrier breaches, although recent observations indicate that artificial breaches can result in openings that lead to tidal ingress for up to several weeks (e.g. Lake Ellesmere (Te Waihora));
- Wind waves and wind-induced currents are important agents for water mixing in the lagoon;
- Observations of historical lagoon ridges suggest that these wind-generated agents were even more important in pre-human times when depth and fetch of the waterbodies were greater than today;
- Situated on wave-dominated high-energy mixed sand/gravel coasts;
- Dominant lagoon substrate is very fine sand and mud;
- Sometimes incorrectly labelled as ICOLLs (Intermittently Closed and Opened Lakes and Lagoons, after Haines et al. 2006). However, Waituna barriers typically comprise coarser sediment and are therefore more permeable than those of ICOLLs. This, for most of the time, allows the lake to drain by percolation through the barrier, preventing build-up of water and hydraulic pressure. Hence the barrier breaches less often than in the case of ICOLLs.

The Waituna Lagoon is located within a catchment that has experienced substantial land use intensification over the last century. Large-scale development of the 20000-ha catchment commenced in the 1960s, and dairy farming and other pastoral land uses now use more than 70% of the total land area in the catchment (Fig. 3). Since the early 20th century, local authorities have periodically opened the Waituna Lagoon to the sea. Initially this was to facilitate a productive trout fishery, but since the 1950s the main driver has been drainage of surrounding farmland which has a high natural water table and poor soil permeability, leading to rapid flooding during periods of heavy rain (Jackson et al. 2001; Johnson & Partridge 1998). Lagoon opening also allows for flushing of the increasingly nutrient-rich lagoon water, helping prevent regime shift to an algae-dominated state with even worse water quality. Currently, a resource consent allows manual opening (via excavation) of the gravel lagoon barrier when the water level at the Waghorns Road bridge staff gauge reaches 2.0 m in winter and 2.2 m in spring, summer and autumn (Measures & Horrell 2013; Walsh et al. 2016). Natural coastal sedimentation processes eventually close the opening, with the process taking anywhere from a couple of weeks to a year depending on sediment supply and wave, tide and wind conditions (Larkin 2013). Figure 4 shows the number of days the lagoon has been open per year since 1972. The Whakamana te Waituna partnership aims to remove land drainage as a reason to open the lagoon and manage opening primarily for ecological purposes (i.e. the drainage of nutrient-rich water).

The current trophic level (which reflects water nutrient concentrations) of the Waituna Lagoon coupled with increased land-use intensification in the catchment has raised concern over the potential for the lagoon to switch from a macrophyte (freshwater plants)-dominated state to an algal-dominated state (Sutherland et al. 2014). A macrophyte-dominated state typically has high biodiversity and aesthetic, recreational and tourist values and is usually the desired state. In contrast, an algal-dominated state can often lead to decreased values and increased risk of toxic blooms. The process by which a lagoon moves from one state to the other can be quite rapid and is termed ‘flipping’. Once a lagoon flips from a macrophyte-dominated to an algal-dominated state it is often difficult to reverse and it becomes the new stable state.

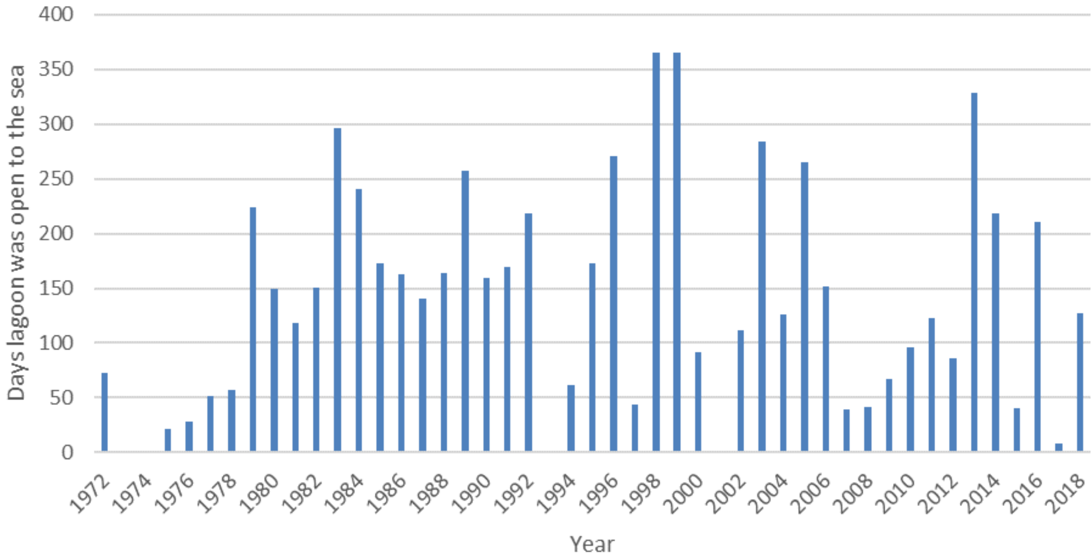

Figure 4. Number of days per year that Waituna Lagoon has been open to the sea since 1972. The days the lagoon is open are sometimes spread over multiple opening events per year. Data source: Environment Southland.

Waituna Lagoon supports beds of the macrophyte ruppia (*Ruppia magacarpa* and *R. polycarpa*), a native freshwater plant that is salt-tolerant (Robertson & Funnell 2012). Ruppia is essential for healthy lagoon functioning, as it holds sediment, absorbs nutrients and releases oxygen. It also creates habitat and a food source for fish and aquatic invertebrates. Ruppia is sensitive to changes in water level and salinity – it requires low salt concentrations during the spring germination period. When the barrier is closed, the lagoon generally has low salinity. However, salinity increases significantly when it is open (Larkin 2013). Therefore, the manual opening regime of the lagoon, which switches it to an estuarine state, threatens the extent of ruppia.

Waituna is an important habitat for waterfowl, migratory birds, coastal birds and native fish. Over 80 different species of birds have been recorded in the Waituna Lagoon and wetland complex, including both internationally and internally migratory waders. A number of nationally threatened species have been recorded in the lagoon area, including the New Zealand dotterel (*Charadrius obscurus*), white heron (*Ardea modesta*), black-fronted tern (*Chlidonias albostriatus*), banded dotterel (*Charadrius bicinctus*) and white-fronted tern (*Sterna striata*) (Rance & Cooper 1997). Some of these birds, such as the eastern bar-tailed godwit (*Limosa lapponica*), migrate from their breeding grounds in western Alaska to seek food in New Zealand during the southern hemisphere summer.

In the past, when the lagoon was open to the sea more frequently, there were considerable intertidal mudflats that provided habitat for waders throughout the year. This key habitat has diminished with build-up of the gravel lagoon barrier. What remain of the intertidal mudflats are therefore particularly important habitat for waders.

Eighteen freshwater and estuarine fish species have been identified in the Waituna catchment and lagoon, including native and introduced species. Common bully (*Gobiomorphus cotidianus*), longfin (*Anguilla dieffenbachia*) and shortfin (*Anguilla australis*) eels, trout, and giant (*Galaxias argenteus*) and banded (*Galaxias fasciatus*) kōkopu have all been found in the catchment (Atkinson 2008).

2. Methodology

This assessment of the impacts of climate change on Waituna Lagoon is based on existing information available in published reports and scientific papers. Primarily, we draw on the climate and sea level rise projections published by the Ministry for the Environment (MfE 2017, 2018) and projections of changes to freshwater inflows to Waituna Lagoon published in Collins & Zammit (2016). Access to these climate and hydrological datasets can be requested by contacting NIWA.

Digital elevation model (DEM) data for the Waituna catchment was derived from LiDAR[4] data and has been made available to DOC under Land Information New Zealand (LINZ) licensing arrangements.

The ecological and water-level management implications of the projected climate change-related impacts are based on current practices, previous modelling results and expert knowledge.

3. Results

3.1 Projected changes to rainfall and temperature

Future projections for climate change were analysed using greenhouse gas emission scenarios, called Representative Concentration Pathways (RCPs), described by the Intergovernmental Panel on Climate Change (IPCC 2013). The four RCPs range from RCP2.6 (strong reduction in global greenhouse gas emissions by 2100) to RCP8.5 (continued growth in emissions at current rates). Six global climate models were downscaled to a 5 km resolution and averaged together to understand potential future changes over New Zealand (MfE 2018).

Mean annual rainfall for Southland is projected to increase by approximately 0–15% (low emissions; RCP2.6) and 5–30% (high emissions, RCP8.5; Fig. 5) by the end of this century, compared with the period 1986–2005 (MfE 2018). For the Waituna catchment, the projected range of increase is 5–10% (low emissions) to 15–20% (high emissions).

Mean annual air temperature for Southland (and the region including Waituna Lagoon) is projected to rise by between approximately 0.5°C (low emissions) and 2.5°C (high emissions; Fig. 6) by the end of this century, compared with the period 1986–2005 (MfE 2018).

3.2 Projected changes to lagoon inflows

Collins and Zammit (2016) assessed climate change impacts on hydrological regimes of rivers and streams throughout New Zealand[5] using downscaled global climate change projections (MfE 2018) and NIWA's national water model (NZWaM-Hydro[6]). Similar to the climate projections discussed above, the assessment was driven by a combination of four emission scenarios (RCPs) and six global climate models, but it was run over the period 1971–2099.

These NZWaM-Hydro projected flows were included in a subsequent report for Environment Southland on Climate Change Impacts for the Southland Region (Zammit et al. 2018). Maps were produced showing colour-coded projected median[7] changes from the baseline period 1986–2005

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4 https://oceanservice.noaa.gov/facts/lidar.html

5 43 862 catchments total with an average catchment area of approximately 6 km^2.

6 https://www.niwa.co.nz/freshwater-and-estuaries/research-projects/nz-water-model-hydrology-nzwam-hydro

7 Changes to inflows are presented based on the median change over the six climate model runs.

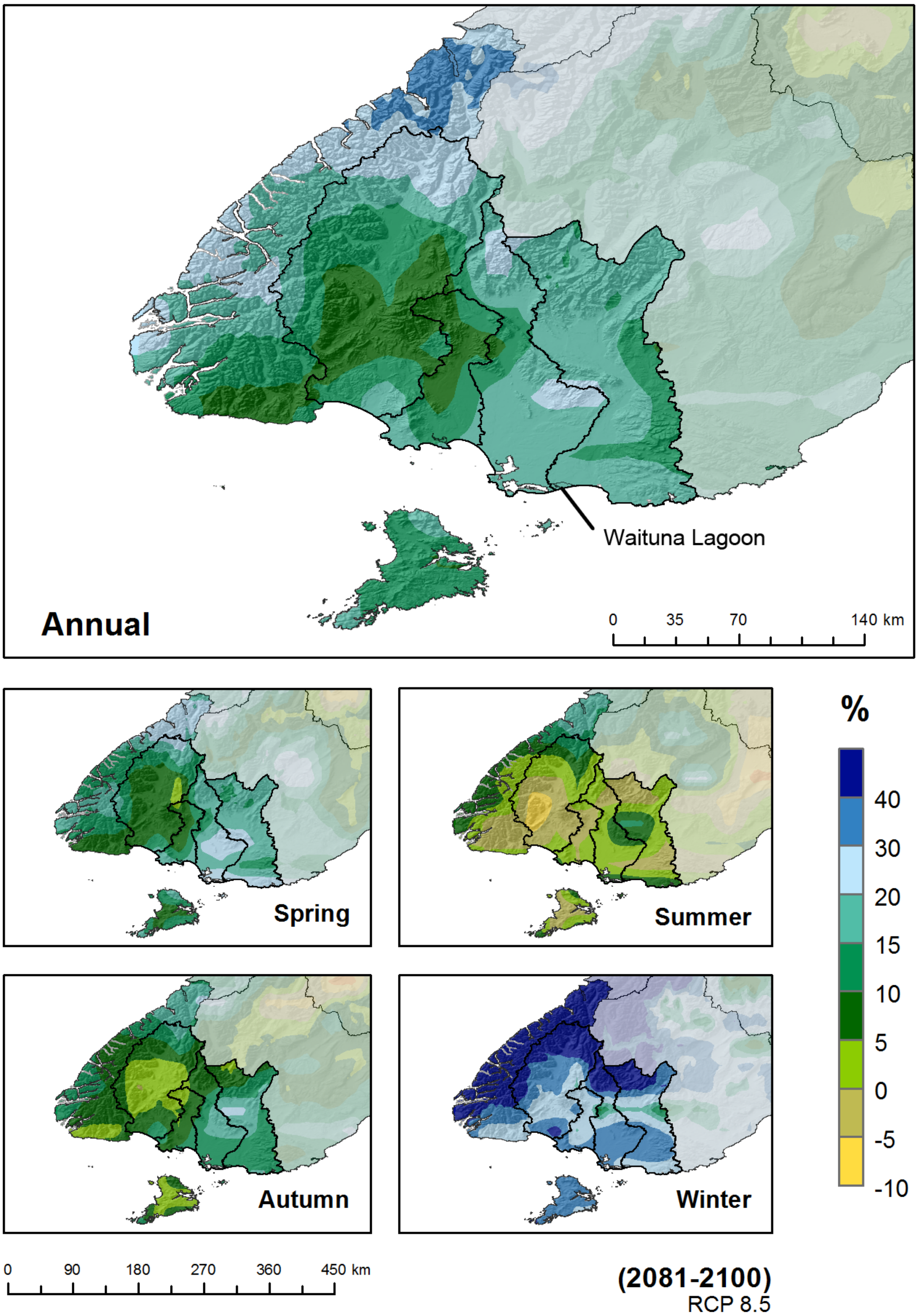

Figure 5. Projected percentage change to Southland mean annual and seasonal rainfall by 2080–99 compared with 1986–2005, based on a high global greenhouse gas emission scenario (RCP8.5) and the average of six global climate models (after Zammit et al. 2018).

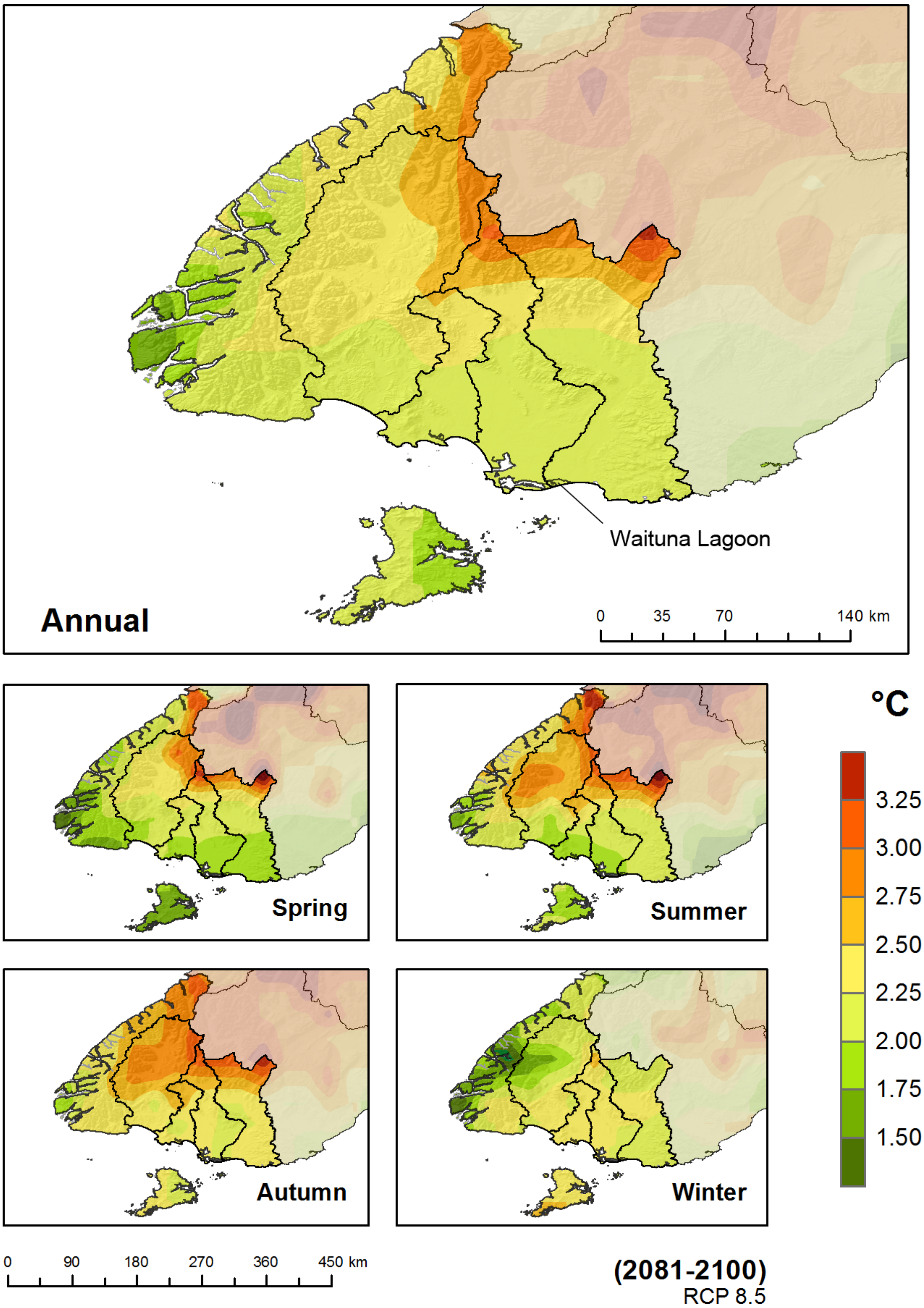

Figure 6. Projected change to Southland mean annual and seasonal temperature (in °C) by 2080–99 compared with 1986–2005, based on a high global greenhouse gas emission scenario (RCP8.5) and the average of six global climate models (after Zammit et al. 2018).

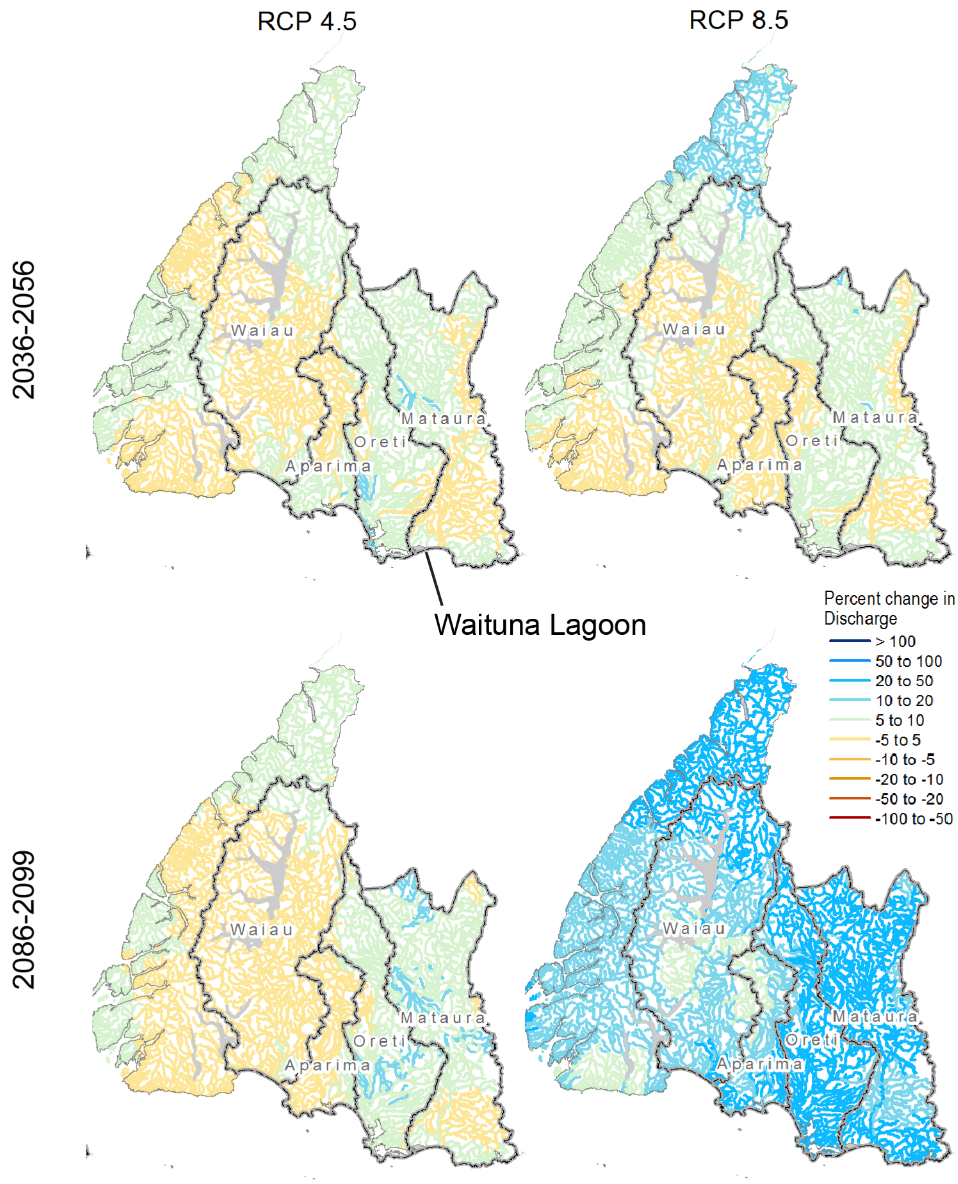

Figure 7. Southland Region multi-model median changes in Mean Annual Discharge (%) for mid (top) and late-century (bottom) and for medium (left) and high (right) emission scenarios (after Zammit et al. 2018).

to mid-century (2036–2056) and end-century (2086–2099), based on two emission scenarios (RCP4.5 = mid-range emissions and RCP8.5 = high emissions), for hydrological parameters of streams and rivers including:

- Mean annual discharge
- The Q95% low flow (flow that is exceeded 95% of the time)
- Mean annual flood (MAF) – the mean of the largest peak flows for each year. For New Zealand rivers, this flow is typically exceeded less than 1% of the time and has a return period of 2–3 years.

For this study, projected changes to the above three parameters associated with inflows to Waituna Lagoon were derived from the Zammit et al. (2018) maps. All changes to the parameters are described as percentage change.

Mean annual water discharge into Waituna Lagoon is projected to increase by up to 10% by the middle of this century and by more than 50% by the end of this century for the high emission scenario, compared with the present-day (Fig. 7). Most of this increase will be in autumn, winter and spring (Zammit et al. 2018). The Q95% low flow for the Waituna catchment is projected to

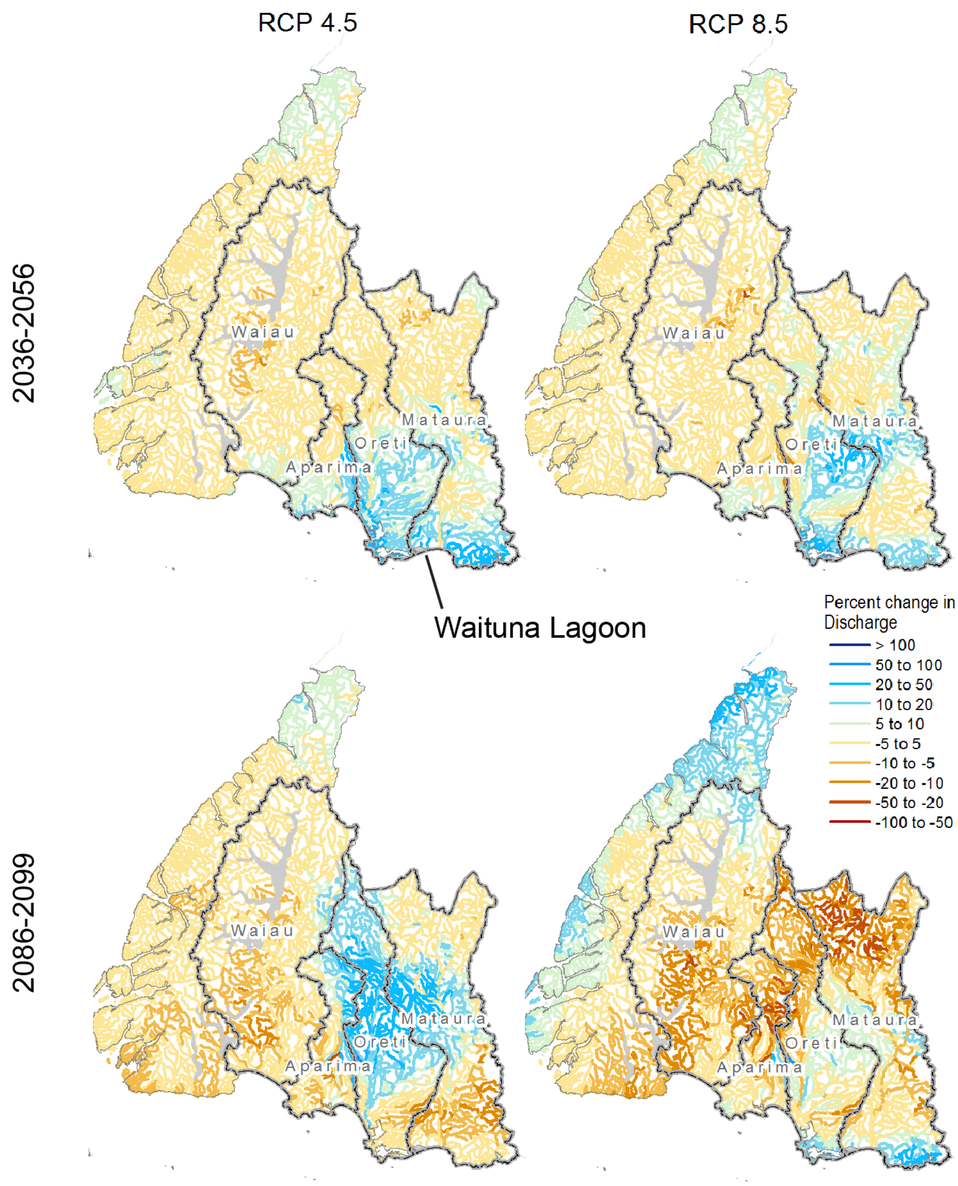

Figure 8. Southland Region multi-model median changes in Mean Summer Discharge (%) for mid (top) and late-century (bottom) and for medium (left) and high (right) emission scenarios (after Zammit et al. 2018).

increase by up to 20% by mid-century but decrease by up to 20% by the end of the century for the high emission scenario, related to drier summers (Figs 5, 8 and 9). Mean annual flood (MAF) is projected to increase for the Waituna catchment, by 20–100% by the end of the century under both medium and high emission scenarios (Fig. 10).

All these projections are dependent upon the greenhouse gas emission scenario. It is also recognised that there is significant uncertainty in the downscaled regionalised precipitation projections from climate models, hence the projected changes in flows are also uncertain (Collins & Zammit 2016).

3.3 Projected sea level rise

Sea level around New Zealand, relative to vertical land movement, has risen by around 0.2 m over the last 100 years. Sea level around New Zealand (including the Southland coast) is expected to continue to rise by an additional 0.2–0.3 m by 2040 and 0.4–0.9 m by 2090, depending upon global greenhouse gas emissions (MfE 2017).

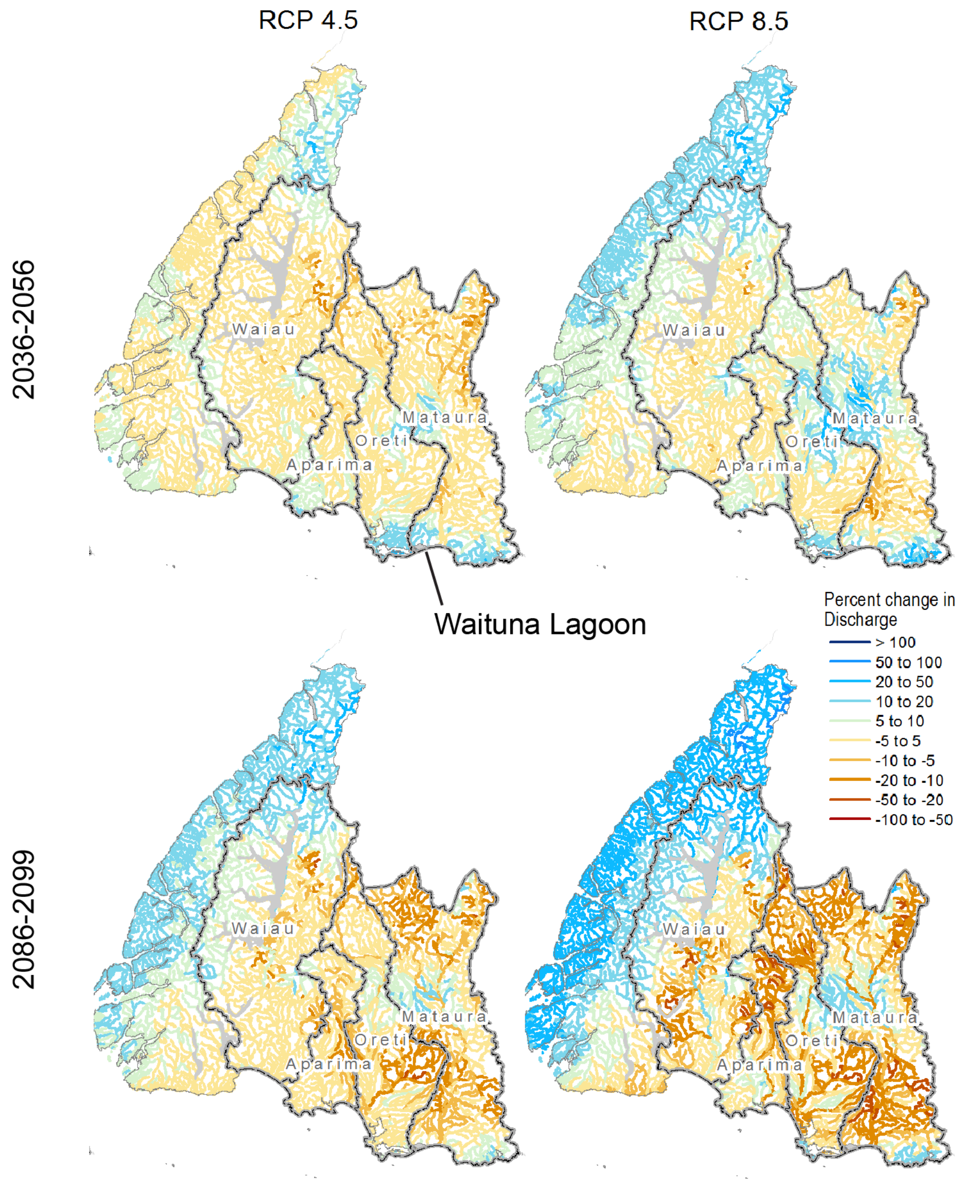

Figure 9. Southland Region multi-model median changes in Q95% Low Flow (%) for mid (top) and late-century (bottom) and for medium (left) and high (right) emission scenarios (after Zammit et al. 2018).

3.4 Impacts of sea level rise on lagoon water levels and intertidal area

Lagoon spatial extent associated with low- and high-tide levels at times when the lagoon is open to the sea were mapped for the current sea level as well as six sea level rise scenarios (Table 1). For each of these seven sea level elevations the lagoon area at low and high tide and the area of the intertidal zone was calculated using GIS software and a LiDAR-based digital elevation model[8] (DEM). The DEM defined the extent of shoreward expansion of the lagoon with different elevations of sea level.

Currently, when the lagoon is manually opened to the sea, the water level drops from the opening threshold of around 2 m above datum to close to sea level within a few days (Schallenberg et al. 2017). The lagoon becomes tidal with water level fluctuations controlled by sea levels and lagoon opening conditions. The lagoon level fluctuates approximately 0.2–0.4 m on each tide, and typically sits in the range 0.2–0.8 m above datum. Water levels are raised as high as 1.1 m above

[8] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/digital-elevation-models

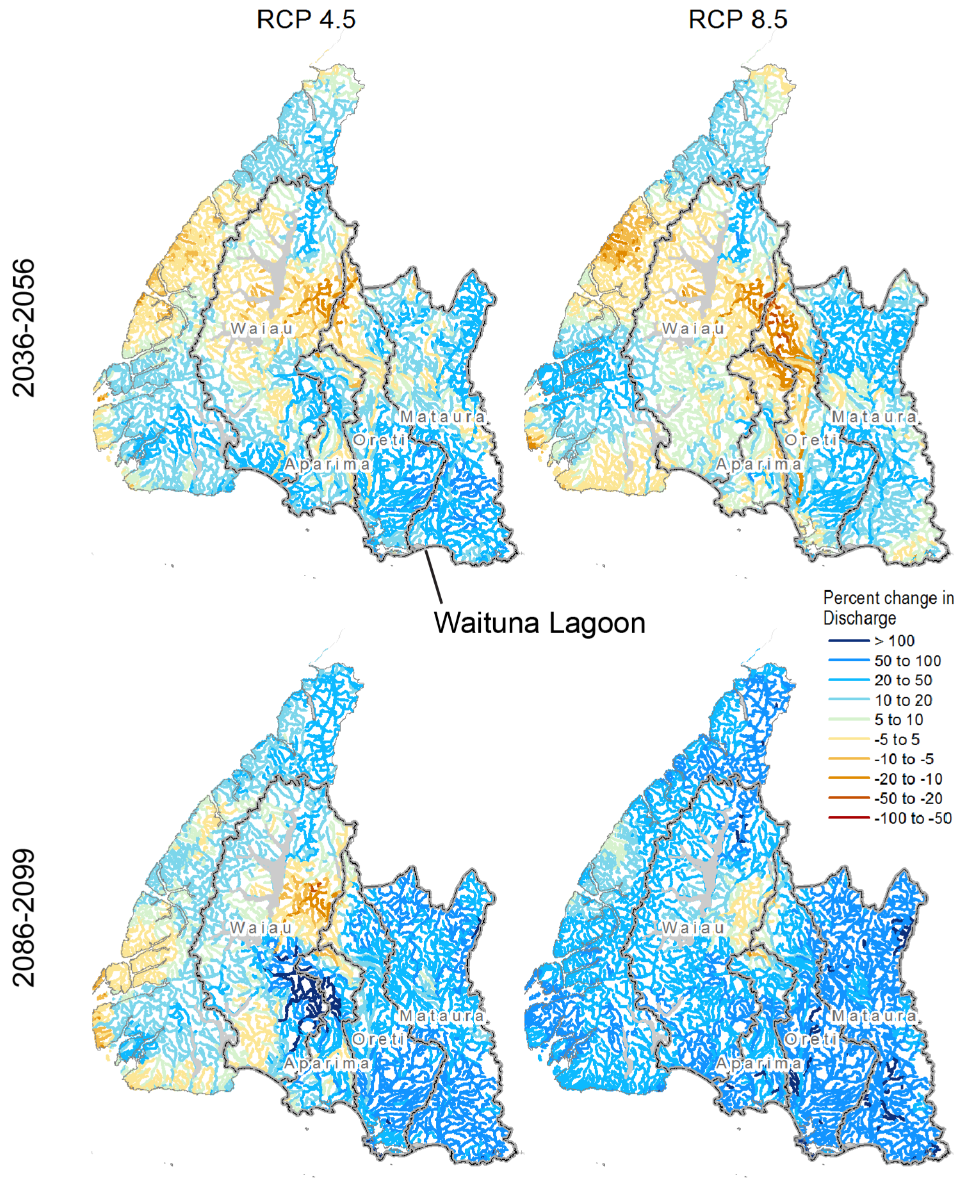

Figure 10. Southland Region multi-model median changes in Mean Annual Flood, MAF (%) for mid (top) and late-century (bottom) and for medium (left) and high (right) emission scenarios (after Zammit et al. 2018).

Table 1. Sea level rise elevations mapped for Waituna Lagoon, and when these elevations may occur under medium-to-high greenhouse gas emission scenarios.

SEA LEVEL RISE ELEVATIONS (m)	WHEN THIS SEA LEVEL RISE MAY OCCUR UNDER MEDIUM-TO-HIGH GREENHOUSE GAS EMISSION SCENARIOS*
+0.2	2040–2050
+0.4	2060–2080
+0.6	2080–2100
+0.8	2100–2120
+1.0	2110–2130
+1.2	2120–2140

* These projected dates are highly dependent the response of large ice masses (e.g. the Greenland ice sheet) to global warming and may be much earlier if the rate of ice melt accelerates.

datum during high winds and when the lagoon opening is constricted by waves. The water levels recorded at Waghorns Road water level recorder during an extended opening in 2013–14 are shown in Figure 11.

For the purposes of this climate change analysis we have assumed that the 0.6 m range from 0.2 to 0.8 m above datum is representative of the typical tidal range. It is assumed that this range will not change with sea level rise, as the height and shape of the coastal barrier will also change in response to sea level rise[9]. However, there will be a rise in the actual low and high tide lagoon levels above datum in accordance with sea level rise. For example, with 0.2 m of sea level rise the new low and high tide lagoon levels will be approximately 0.4 and 1.0 m above datum (i.e. an increase of 0.2 m to both levels, with no change to the tidal vertical level range).

Table 2 and Figure 12 show the projected lagoon area (enclosed water below mean high water springs (MHWS)) and intertidal area (between MHWS and mean low water springs (MLWS)) when the lagoon is open to the sea, associated with the current sea level and six future sea level rise scenarios.

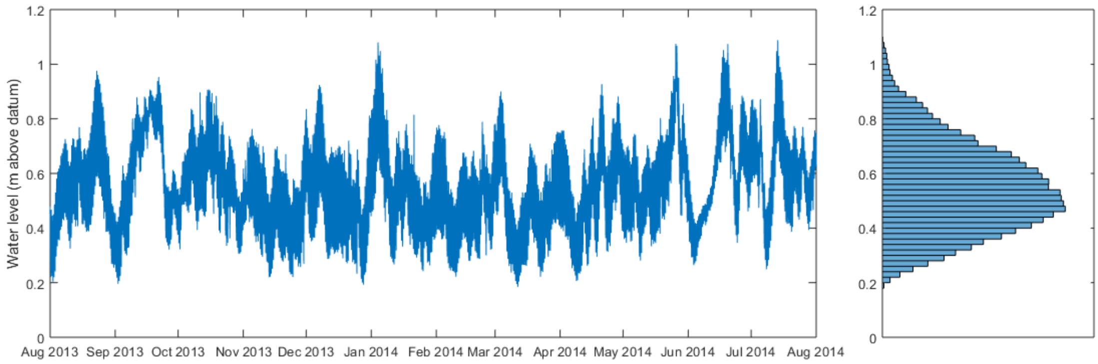

Figure 11. Water level recorded at Waghorns Road water level recorder during an extended lagoon opening in 2013–14. Histogram to the right shows the frequency with which different water levels occur. Levels greater than 0.8 m above datum are generally associated with a constricted lagoon opening.

Table 2. Surface water extent in Waituna Lagoon for approximate average low and high tides and intertidal area under current conditions and six scenarios of sea-level rise (SLR). *Note, these areas are only relevant when the lagoon is open to the sea.*

SCENARIO	TIDE (low or high)	LAGOON LEVEL (m above datum)	LAGOON AREA (ha)	INTERTIDAL AREA (ha)
Current	low	0.2	612.23	687.72
	high	0.8	1299.95	
SLR 0.2 m	low	0.4	812.90	399.62
	high	1.0	1212.53	
SLR 0.4 m	low	0.6	1028.82	405.84
	high	1.2	1434.66	
SLR 0.6 m	low	0.8	1299.95	231.62
	high	1.4	1531.57	
SLR 0.8 m	low	1.0	1212.53	392.50
	high	1.6	1605.03	
SLR 1.0 m	low	1.2	1434.66	250.64
	high	1.8	1685.30	
SLR 1.2 m	low	1.4	1531.57	232.11
	high	2.0	1763.67	

9 The implication of this assumption is that there will continue to be a barrier between the lagoon and the sea at least to the end of this century (i.e. the lagoon is not expected to transition into an estuary). This is a research question that could be further investigated.

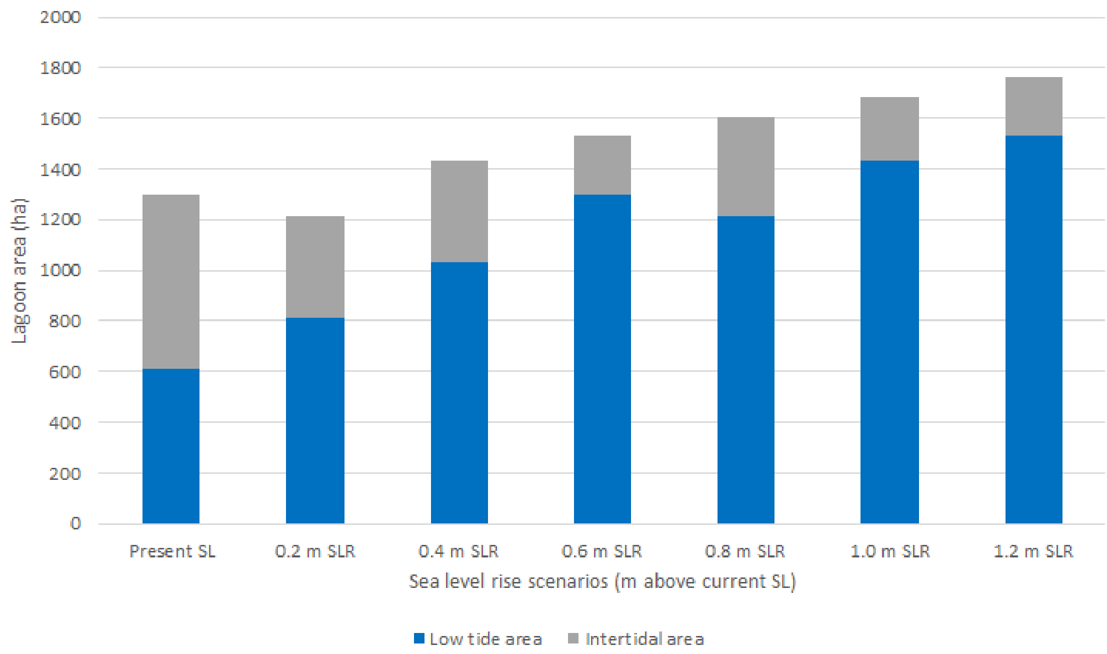

Figure 12. Waituna Lagoon area under current conditions and six scenarios of sea level rise. The average high tide level is the total height of each bar (i.e. low tide area + intertidal area). *Note, these areas are only relevant when the lagoon is open to the sea.*

Lagoon water surface area is projected to increase for both low and high tidal levels under sea level rise, but low tide area is projected to increase more than high tide area, resulting in a decline in the intertidal area from around 700 ha currently to around 400–230 ha, depending upon the sea level rise scenario. Decline in intertidal area occurs even at the modest 0.2 m increase in sea level.

Figure 13 shows the change in intertidal zone with 0.4 m and 1 m of sea level rise[10], compared with present-day conditions. With 1 m of sea level rise the intertidal zone shifts from its current location to beyond the current high tide extent.

4. Discussion

4.1 Implications of changes to inflows

The impact of changes to freshwater inflows depends on whether the lagoon is open to the sea or not. The projected increase in inflows into the lagoon in autumn, winter and spring under both mid range and high emission scenarios, would raise the lagoon level more swiftly when the lagoon is closed to the sea. If the lagoon is open to the sea, the increase in discharge would not impact the lagoon level as this is modulated by the sea level and tide. However, when the lagoon is closed the increased inflow would result in the lagoon being deeper for longer periods, reducing the light environment of the lagoon bed, and likely leading to an increased frequency of manual lagoon opening events (i.e. when the resource consent threshold for manual opening of 2.2 m water depth at the Waghorns Road bridge gauge is reached; see section 4.2).

Increases in the mean annual flood (MAF) of 20–100% by the end of the century under both emission scenarios would greatly increase the risk of inundation of the low-lying land surrounding the lagoon and its tributary creeks. Flooding of this land from the lagoon is only

[10] This analysis can be done for any sea level rise, but here we only show +0.4 m and +1.0 m for demonstration purposes.

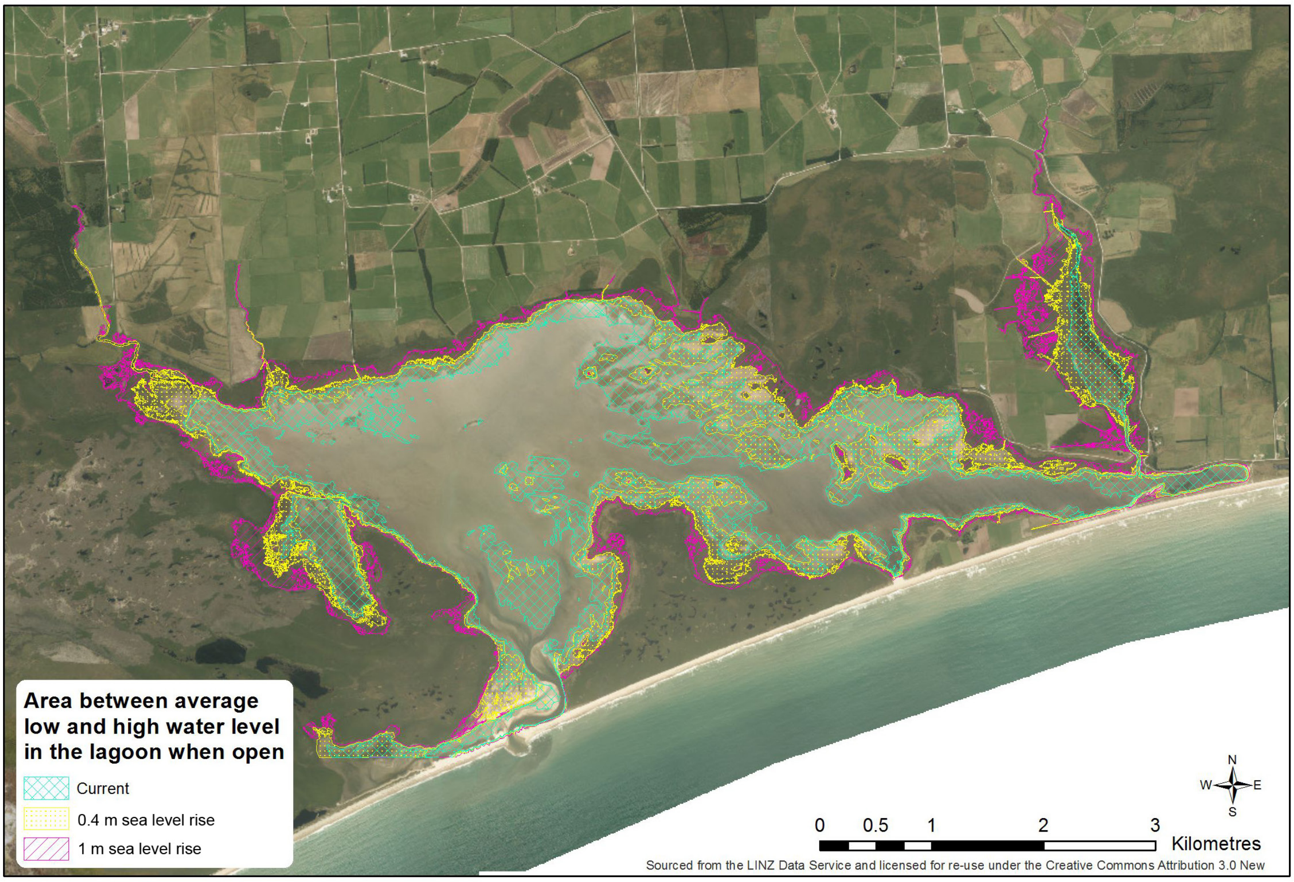

Figure 13. Waituna lagoon intertidal zone for approximate average current conditions plus two sea level rise scenarios of +0.4 m and +1.0 m. *Note, these mapped areas are only relevant when the lagoon is open to the sea.*

likely when the lagoon is closed. Sediment and nutrient transport during flood events would also be increased. Greater flow rates may also increase sedimentation, reduce salinity, lower water temperature and affect turbidity and mixing of the lagoon[11].

Decreases in rainfall and the even lower low inflows projected for summers later in the century would have opposite effects to those associated with increased inflows described above, with lagoon levels rising more slowly, lagoon bed light levels remaining high, and water temperature being higher than for deeper water conditions. An increase in lagoon temperature in summer would likely have a greater ecological impact on the lagoon than the decrease in temperature that may be associated with higher inflows over the winter months. Sea level rise would affect the lagoon level only when the lagoon is open to the sea. The high- and low-tide lagoon water level will rise in accordance with sea level rise. The lagoon area at high and low tide would also increase but the magnitude of change will be affected by the topography of the surrounding land. With 1 m of sea level rise, the high-tide lagoon area is projected to increase by 30%, compared with the high-tide area at present, while the projected increase of the low-tide lagoon area is 134%, compared with the low-tide area at present. This differential increase means that the intertidal lagoon area (i.e. mudflats) would decrease by 64% with a 1 m sea level rise, compared with present. This projected decrease in mudflat area would have considerable impacts on the wading bird population in the lagoon.

[11] Water temperature of lagoons are also highly correlated to the temperature of the overlying air (Schibuola & Tambani 2012). Thus, the Waituna Lagoon water temperature is likely to increase along with projected increases in air temperature. However, deeper water will warm less than shallow water.

4.2 Implications for the lagoon opening/closing regime

The lagoon is currently manually opened by excavation of the gravel barrier when its water level exceeds 2.0 m above a datum at the Waghorns Road bridge gauge during winter and 2.2 m during spring, summer and autumn (Measures & Horrell 2013; Walsh et al. 2016). Currently, this results in an approximately annual opening frequency. If the mean discharge into the lagoon increases, then these two triggering water levels will likely be reached more often (accepting that in summer the mean discharge may decrease). The implication is that the timing of lagoon openings may change, and the lagoon may need to be opened more often. Additional research using detailed modelling is required to fully assess this potential impact (see Appendix 1).

Sea level rise also causes reductions in the efficacy of lagoon openings, due to the following processes:

- When the lagoon is opened, the amount of drawdown of the lagoon water level available would be reduced by sea level rise, because the sea level will be closer to the lagoon water level which is currently higher in elevation.
- With sea level rise the lagoon water level will also rise and the mouth will close at higher lagoon levels than it currently does, increasing the likelihood of more saline intrusion to the lagoon.
- Further, there would be a reduction in storage volume of the lagoon between lagoon mouth closure and the two opening thresholds, reducing the hydraulic gradient between the lagoon and sea[12].
- The reduced hydraulic gradient would also reduce the stored energy available for the water to erode an effective mouth channel (i.e. after a channel is manually cut with a bulldozer the outflow of water widens and deepens the channel).
- Currently it is relatively easy to open the lagoon, but this is likely to become progressively more difficult with sea-level rise as the hydraulic gradient between lagoon level and sea level will be reduced[13].
- In addition, the degree that opening events flush suspended sediment and nutrients will likely be reduced, although this water quality risk may be offset by the increased frequency of opening events.

Eventually (potentially by 2150) the high-tide level may not be much lower than the current lagoon opening threshold. At this time the threshold level would need to be higher than today's level to generate enough hydraulic gradient to flush the lagoon. This, of course, would have significant implications on the spatial extent and depth of the lagoon, leading to surrounding low-lying land being flooded. This highlights the need for efforts (such as those under the Whakamana te Waituna initiative) to explore options to enable this land to be transitioned away from agricultural production.

4.3 Implications for the lagoon ecosystem

Research on the state and functions of, and pressures and impacts on, the Waituna Lagoon ecosystem is ongoing and supported by Whakamana te Waituna, Living Water, Arawai Kākāriki and additional partners. It is undoubtedly a complex ecosystem, particularly due to the interactions between managed land and water uses, human interventions and natural environment variability. There is a pressing need to better understand the potential long-term implications of climate change for this complex system.

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[12] The 'hydraulic gradient' is the amount of water pressure between two bodies of water at different elevations. When the two bodies are connected then the rate of flow of water between them is affected by the magnitude of the hydraulic gradient (i.e. greater pressure results in higher flows, and vice versa).

[13] This is already an issue with manual openings at Lake Ellesmere (Te Waihora).

Here, we summarise the likely[14] response of the ecosystem components to the projected climate changes described above. Our summary is based on published literature and expert opinion and is intended to initiate further discussion and research.

Table 3 presents the potential impacts on a selection of ecosystem components. Three main risks to the lagoon and surrounding farmland can be deduced from this analysis:

- Significant increases in rainfall (autumn-spring), flood events and inundation of surrounding land are likely to contribute higher levels of nutrients and sediment flowing into the lagoon than are currently experienced.
- Decreases in summer rainfall and inflows, as well as increases in temperature, may favour algae growth in the lagoon due to increased water temperature and light levels.
- These changes could both contribute to a regime shift within the lagoon by favouring undesirable algae growth and inhibiting favourable ruppia[15] growth.
- Sea level rise may reduce the available habitat area for species that use the intertidal mudflats and bordering wetland vegetation, as well as cause more regular inundation of surrounding farmland.

Table 3. Summary of likely Waituna Lagoon ecosystem responses to projected climate and sea level changes. Red boxes highlight the impacts that may be severe in nature and contribute or lead to the lagoon ecosystem flipping into an algal-dominated state. Orange boxes highlight impacts that may be moderate, affecting species but unlikely to lead to a regime shift. Green boxes highlight potential benefits to the lagoon ecosystem or species.

ECOSYSTEM COMPONENT	LIKELY RESPONSE TO INCREASE IN WATER INFLOWS AND HIGHER LAGOON WATER LEVELS IN AUTUMN TO SPRING			LIKELY RESPONSE TO DECREASE IN INFLOWS AND LOWER LAGOON WATER LEVELS IN SUMMER		LIKELY RESPONSE TO SEA-LEVEL RISE (WHEN LAGOON IS OPEN)	
	Increased sediment and nutrient loading	**Reduced light levels / deeper water**	**Increased salinity from more frequent lagoon openings**	**Increased water temperature**	**Increased light levels / shallower water**	**Decreased inter-tidal area**	**Increased lagoon area (at high and low tide)**
Ruppia	Reduction in abundance (due to sedimentation of lake bed)	Reduction in growth	Reduction in germination over spring/ summer	Decrease in ruppia biomass due to reduced water depth	Increased growth/ abundance	No impact	Changes in available habitat (based on depth)
Algae	Increased abundance	Decreased abundance	Change in community composition	Increased abundance	Increased abundance	No impact	Increasing available habitat
Fish (native and introduced)	Reduction in habitat quality	Possible reduction in food availability	Reduced larval fish (e.g. giant kōkopu) growth rates†	Reduction in habitat quality (decreased DO)	Possible increase in food availability	Unknown	Increase in available habitat
Wetlands bordering lagoon	Increased abundance of exotic plant species	No impact	Possible change in community composition	No impact	No impact	Loss of intertidal wetland vegetation	Reduced available habitat
Birds (migratory and endemic)	Possible changes to food availability and decreased habitat	Possible changes to food availability and decreased habitat	Possible changes to food availability for some species groups	Possible changes to food availability	Possible changes to food availability	Decreased habitat for waders	Decreased habitat for waders

* Ruppia (*Ruppia* spp.) is a native freshwater plant that is common in Waituna Lagoon. It is tolerant of low levels of salinity. It is desirable that ruppia is able to spread in the lagoon in the future.

† Hicks, A.S.; Jarvis, M.G.; Funnell, E.P.; Closs, G.P. unpubl. data: Non-diadromous recruitment of threatened giant kōkopu (*Galaxias argenteus*) within an intermittently closed and open coastal lagoon: benefits of larval retention and effects of artificial opening.

[14] The IPCC defines 'likely' as having greater than 66% probability of occurrence or outcome. We use this same definition here, with our assessment of likelihood based on expert opinion.

[15] Ruppia (*Ruppia* spp.) is a native freshwater plant that is common in Waituna Lagoon. It is tolerant of low levels of salinity. It is desirable that ruppia is able to spread in the lagoon in the future.

5. Knowledge gaps and lagoon management

This study has highlighted many potential impacts on, and implications for, Waituna Lagoon associated with projected climate change and sea level rise over this century. Table 4 summarises the knowledge gaps identified in previous sections which, together with the information in Appendix 1, should be considered when designing future research projects. Table 4 also provides some considerations of potential management responses which can be used to reduce the uncertainty and proactively adapt to any changes.

Table 4. Summary of future risks and potential management implications for Waituna Lagoon resulting from climate change.

AFFECTED COMPONENT	RISK	CAUSE	CONSIDERATIONS FOR FUTURE MANAGEMENT
Water in lagoon.	Decline in water quality/ regime shift from macrophyte-dominated state to algae-dominated state.	Increased sedimentation and nutrients from high inflows (autumn-spring). Reduced lagoon depth and increased temperature from low inflows (summer). Increased saline incursion. Increase in frequency of lagoon reaching 2 m depth. Reduced ability to open lagoon. Unknown impact of coastal processes on lagoon closing.	Any re-design of the drainage network in the catchment should account for higher freshwater inflows – i.e. increases in flood capacity and nutrient reduction systems are needed. Investigate how opening the lagoon more often will affect salinity levels and ruppia survival. Investigate the impact of potential changes in wave climate and coastal sediment transport on the lagoon's ability to close naturally.
Species, particularly birds, fish and macrophytes, that live in or use the lagoon.	Reduction in numbers able to survive in the lagoon.	Altered food webs. Reduced habitat quality. Less habitat available (particularly intertidal zone).	Need to better understand food web dynamics within the lagoon for zooplankton, fish and birds so that appropriate conservation management actions may be taken. Need to better understand habitat requirements for species, especially those dependent on the intertidal zone (wading birds) and lagoon (macrophytes, fish), so that appropriate conservation management actions can be taken.
Adjoining land owners/ managers.	Flooding hazard.	Increased inflows and higher frequency of inundation of surrounding land with sea level rise.	A buffer zone immediately adjacent to the lagoon should be developed by retiring land from agricultural production. Inundation modelling of the lagoon and surrounding land that includes future rainfall predictions is needed (update Walsh et al. (2016)).

6. Similar assessments for other coastal hydrosystems

Coastal hydrosystems, such as wetlands, estuaries and lagoons, are especially sensitive to climate change, as they can be affected both by changes to freshwater inflows and changes to sea level (Rodríguez et al. 2017). This has implications for threatened native species that use these ecosystems. This desktop study of the Waituna Lagoon in Southland has shown the potential for exploring these projected changes for any coastal location using existing hydrological projections in tandem with GIS-based mapping techniques. Critical to the assessment is the availability of LiDAR-based digital elevation data.

Each hydrosystem may be affected by climate change quite differently depending upon its type, local topography and hydrological regime. Ecological and management implications of any changes would also vary with location. A recommended course of action for central and local government agencies is to identify key coastal sites with available LiDAR data and carry out similar assessments to that described in this report, taking the additional research areas flagged (Appendix 1) into consideration. If necessary and if possible, more detailed studies could be undertaken using localised hydrological models and site-based assessments.

7. Conclusions

The climate of Southland (including the region around Waituna Lagoon) is projected to become wetter (except in summer, when drier conditions are predicted) and warmer over the coming several decades. These changes are likely to result in higher freshwater inflows in autumn, winter and spring and lower inflows in summer (when low flows are projected to be even lower than at present). Floods are generally expected to be larger all year round.

Increases in rainfall, freshwater inflows, flood events and inundation of surrounding land are likely to contribute to lower lagoon-bed light levels and higher levels of nutrient and sediment entering Waituna Lagoon than are currently experienced. Consequently, increased algae growth and inhibit Ruppia growth are predicted. These are known components that contribute to regime shift from a desirable macrophyte-dominated state to an undesirable algal-dominated state and are closely linked to declines in water quality. This shift would fundamentally change the ecology of the lagoon and create unsuitable habitat for many of the species that currently exist there.

With the projected increases in inflows (except in summer), the lagoon water level would increase more rapidly than under present conditions. The implication is that the lagoon would either have to be manually opened more frequently (if the present threshold depths for opening are maintained) or the thresholds for opening would need to be raised (if the opening frequency is maintained). If the latter, then more of the land surrounding the lagoon would be subject to inundation before the lagoon would be opened.

Regular opening of the lagoon to lower the water level and flush nutrients out is likely to become more difficult with sea level rise and the loss of hydraulic pressure to aid opening. Sea level rise and more frequent openings of the lagoon barrier would have significant impacts on the biodiversity of the lagoon area, particularly in relation to decreasing intertidal habitat detrimentally affecting wading birds and increased salinity reducing the abundance of the macrophytes that currently support the food web of the lagoon.

These projected changes pose a major risk to a wide variety of plants, birds and fish, many of which are threatened endemic species and a fundamental part of what gives Waituna Lagoon its high ecological status.

8. Recommendations

Based on this study we recommend the following actions:

- Climate change impacts and implications should be factored into future ecological research plans for Waituna Lagoon.
- Ongoing monitoring and research is needed to address knowledge gaps concerning the possible ecological dynamics resulting from reduced habitat quality and extent at Waituna Lagoon.
- Management and research efforts should also focus on the catchment and drainage network at Waituna Lagoon and seek to reduce the impacts of high flows and nutrient leaching on water quality within the catchment.
- All lagoon management plans for Waituna Lagoon and elsewhere should be reviewed and reassessed at least every 10 years using the latest data, research and climate projections. A 10-year rolling review should be part of a long-term strategy for the remainder of this century and potentially beyond.

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Appendix 1 – Additional research

Hydrological modelling

A distributed hydrological model for the Waituna catchment and lagoon has been developed and validated by Deltares and DairyNZ[A1]. The model is called WFLOW[A2], and has been integrated with a nutrient model (OVERSEER) to model water quality and nutrient loads flowing into the lagoon.

Projected daily rainfall and evapotranspiration data from NIWA's Regional Climate Model could be incorporated into the WFLOW model and the impact on water quality, nutrient loads (given no other changes), and lagoon water depth could be assessed in more detail than in the desktop study addressed in this report. This information will be useful for long-term strategies for enhancing water quality in the catchment and lagoon, and for assessing ecological impacts.

NIWA is currently enhancing the TopNet hydrological model in a project commissioned by Environment Southland in association with their Source and Flows programme. The objective of the work is to develop two hydrological models (1. A surface+simple groundwater conceptualisation – TopNet0 and 2. A coupled surface-groundwater model – TopNet-GW) for the Waituna catchment to assess:

- Water transfer between the Mataura catchment (through the Edendale area) to the Waituna catchment;
- Use of hydrogeochemistry to better inform water flux understanding across the Waituna catchment;
- Model conceptualisation impact on decision making (water allocation and ecological decision making through coupling TopNet suite and CHES tool);
- Coupling hydrological model (TopNet suite) with water quality model (CLUES suite[A3]) to provide temporal disaggregation of simple coupled quantity-quality models and integration with Freshwater Management Unit models suite (Mid Mataura model being currently developed in parallel).
- As suggested above, NIWA Regional Climate Model output could also be incorporated into these surface+groundwater models to improve the projections of potential changes to surface and groundwater flows and their impact on water quality in the Waituna Lagoon.

Changes in lagoon water level

There is potential to use lagoon water level data in combination with inflow data to model what the projected reduced flows over summer would do to water levels[A4]. The potential rate of water level rise/fall in the lagoon could also be modelled, providing valuable guidance on how much more frequently the water level would hit the trigger for opening.

[A1] van den Roovaart et al. 2014. Contact person is David Burger, Environment Manager, DairyNZ, Hamilton.

[A2] https://oss.deltares.nl/web/wflow/why-wflow

[A3] https://www.niwa.co.nz/freshwater-and-estuaries/our-services/catchment-modelling/clues-catchment-land-use-for-environmental-sustainability-model

[A4] Environment Southland may have the capacity to do this work.

Changes in wave climate

NIWA performed and updated models to project changes in the significant wave height around New Zealand (Law et al. 2016). Figure A1 shows the projected percent changes between the present-day and the end of this century for a mid-range emission scenario (RCP4.5, left) and a high-range scenario (RCP8.5, right). Both scenarios show an increase in significant wave height is projected for the south coast of New Zealand of 2–5% (noting that there is much variability between climate models). As the lagoon mouth closure process is driven by wave-driven coastal sediment transport, it would be fundamental to model how these projected changes in significant wave height could affect the mouth closure process.

Physiographic modelling

Rissmann et al. (2018) describe the application of a high-resolution physiographic approach to modelling water quality controls for the Waituna catchment. A physiographic approach seeks to understand the pathways of water through a catchment, over land and through the ground, under different rainfall conditions. The Living Water partnership is currently undertaking research on this[A5]. The approach could be expanded to estimate the effect of climate change on water quality (e.g. eutrophication (shift of the lagoon to an algae-dominated state), turbidity) and seabed (sedimentation) outcomes by deriving equations to explain the relationships between climatic drivers (e.g. soil moisture, soil temperature and rainfall) and inflows, water quality and hydrochemistry. The model could then be used to assess farmer adaptation options to mitigate any changes to water quality associated with climate changes.

Extreme events

The frequency and intensity of extreme events (e.g. storm surge, high winds, droughts and flood events in the catchment) are likely to be affected by climate change. Changes to these events would be a major factor for the long-term sustainability of the opening and closing regime at the lagoon mouth and are also likely to significantly impact on the lagoon ecosystem.

Influence of tectonics and lagoon sediment budget on relative sea-level rise

The actual impact of sea-level rise is dependent on coincident changes in land elevation and the sediment budget (from the catchment and the sea). Areas where subsidence is occurring have faster relative sea level rises than stable areas, whereas land undergoing uplift may not be impacted by sea level rise to the same extent. Sediment supply to the coast also has an impact on relative sea level rise through impacts on coastal erosion or accretion. How this applies at Waituna and elsewhere needs more study.

Changes to the lagoon typology due to climate change

It would be good to explore the potential for the typology of the hydrosystem[A6] (Hume et al. 2016) to change, e.g. an increased connection with the sea resulting from barrier erosion or more frequent overtopping with sea-level rise and increased freshwater inflows, and what this might mean for the lagoon ecosystem if it changes; for example, from a system typology of a Waituna lagoon to an ICOLL (Intermittently Closed and Open Lakes and Lagoons).

[A5] https://www.livingwater.net.nz/catchment/waituna-lagoon/physiographics-project/

[A6] http://www.mfe.govt.nz/publications/marine/classification-of-new-zealands-coastal-hydrosystems

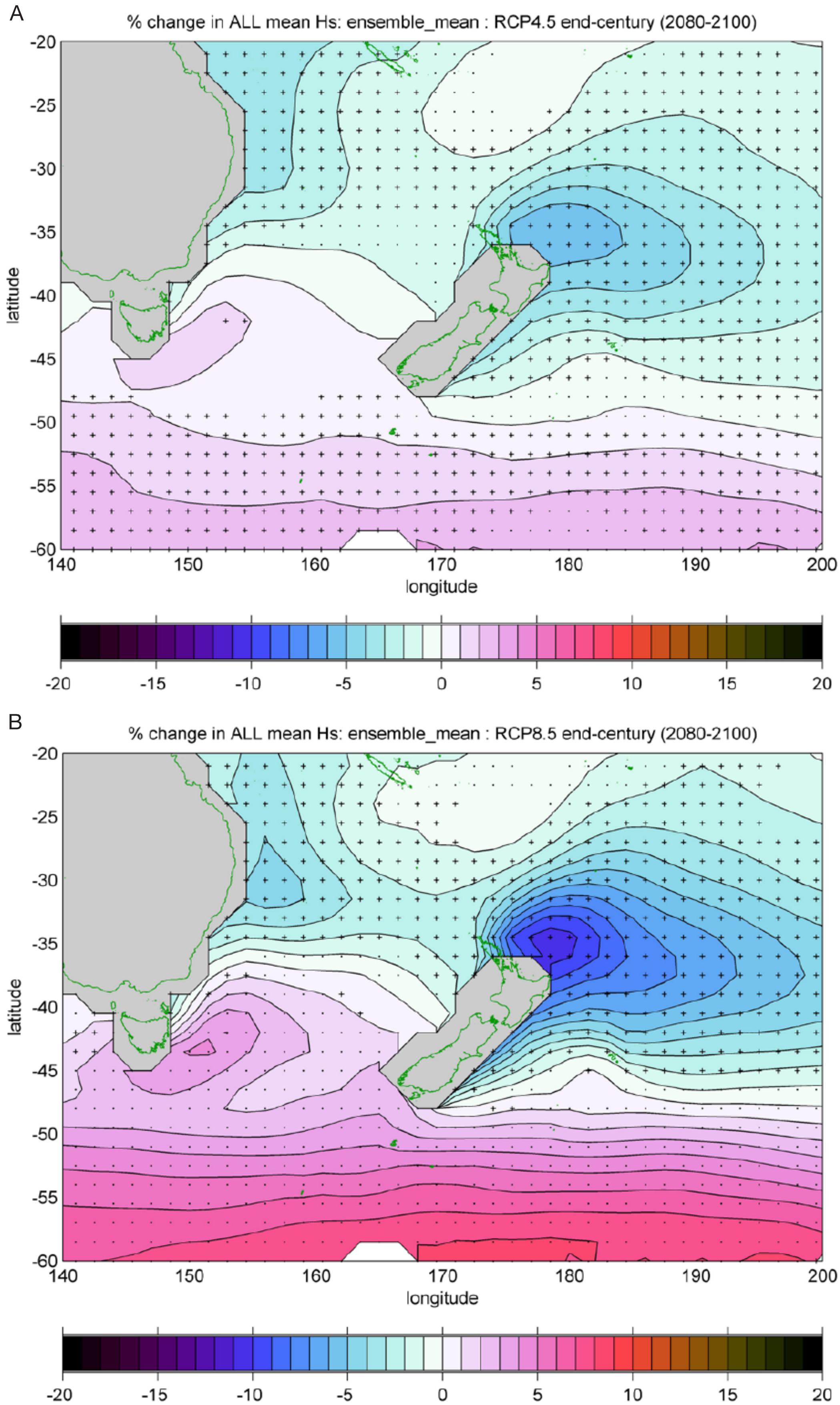

Figure A1. Multi-model average percentage change in significant wave height for mid-range emission scenario RCP4.5 (A) and high-range emission scenario RCP8.5 (B) for 2100 relative to present-day. The heavy- and lightly-stippled areas indicate respectively where all four, and three out of four, models show the same sign of change as the multi-model mean, and so indicate greater confidence in projections, whereas lack of stipules implies little confidence in either direction or magnitude of change (i.e. the Tasman Sea).