Agile, Adaptive Water Allocation Policy

Sustainable Land Management and Climate Change – Adaptation project SLMACC-A 406322

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1 Executive Summary

1.1 Background

The aim of this MPI-funded Agile Adaptive Water Allocation (AAWA) research was to assist the development of policy options that address the question "how might water allocation methods need to change in response to a changing climate to give effect to Te Mana o Te Wai and the National Policy Statement for Freshwater Management 2020." Te Mana o Te Wai prioritises (a) maintaining the health of a water body over (b), providing water to meet human health needs over (c), any "other water uses".

The water allocation policy that is mandatory under the National Policy Statement for Freshwater Management 2020 is to set a minimum flow (i.e., a "cease-take flowrate") or level (for groundwater) and an associated water allocation limit for each water body. Together they define a water allocation band. This policy is given effect to by including conditions in each consent to take water that:

- Limit the maximum rate of take such that the sum of all takes from the water body doesn't exceed its allocation limit. For takes from streams the rate is generally specified in litres per second. For groundwater takes the rate is generally specified in cubic metres per year.
- Require takes from streams, and groundwater takes that have a high "stream depletion" effect, to reduce or cease if continued abstraction would cause the residual flowrate in the stream to drop below a specified "cease take flow" at one or more specified flow-rate monitoring sites.
- Require takes from groundwater to cease once the volume taken reaches the annual take limit.

This method provides sufficient agility for surface water allocation limits to be varied daily in response to day-to-day variations in stream flowrates. In some regions a "cease take flowrate" is specified for each month, and thus can change from month-to-month in a set pattern to meet environmental objectives.

Current groundwater allocation

Current best practice methods for managing groundwater takes from New Zealand's alluvial aquifer systems is to set a limit on the volume (cubic metres) of water that may be taken per year ("annual take limit") and set a limit on the maximum take of take (litres per second). The annual limit is generally fixed for the life of the take consent. For bores located close to rivers or streams, the rate of take (litres per second) for the stream-depleting proportion of the take is further restricted, based on the stream flowrate at the time of abstraction. Some groundwater take rates are managed in relation to groundwater levels in sentinel wells, typically to prevent saltwater intrusion.

Why investigate alternatives to current policy?

There is evidence that the low-flow regime of groundwater-dependent surface waterways is not being maintained by the current approach to managing groundwater allocation. For example, although current best practice methods have been implemented in Canterbury's Selwyn-Waihora Water Management Zone since 2012, there has been a steady decline in summer-time low flows. The magnitude and duration of river flowrates less than the "cease take flowrate" have steadily increased. This suggests that the groundwater allocation rules are ineffective – they are undermining the intent of the surface-water allocation rules. This is understood to be due to increased pumping of groundwater, mainly for irrigation. Climate changes is projected to worsen the situation.

1.2 Project scope and objectives

The purpose of this research project was to identify water allocation policy methods that would have consistently delivered higher low flows in lowland streams than occurred over the last twenty years, and which could be expected to maintain the increases under projected future climates. It has formulated and assessed the effectiveness of a range of water allocation policy methods to identify what type of approach is most effective in limiting changes in low flows in groundwater-dependent streams due to groundwater takes in a representative case study area. The methods were tested using computer simulation models to determine how effective the policy methods would be in raising low flows and what effect they would have on the security of supply for abstractive water uses. While the focus is on groundwater takes, we also discuss surface-water allocation policy responses to climate change.

This project has not attempted to answer the fundamental water allocation question “by how much will society allow the flowrate/water-level regime to be changed from its natural state in exchange for the benefits derived from this change?” To do so would have required consideration of, inter alia, cultural effects, effects on the security of supply for municipal and industrial groundwater takes, technical, social and financial effects on farmers reliant on groundwater for irrigation, and water supply augmentation options, such as managed aquifer recharge, targeted stream augmentation, transferring existing groundwater takes to surface-water supplies (beyond that which has already occurred in the case study area). This was beyond the scope of this project.

The policy options developed and simulated through this project should not, therefore, be incorporated into a Regional Plan variation without further analysis and extensive consultation.

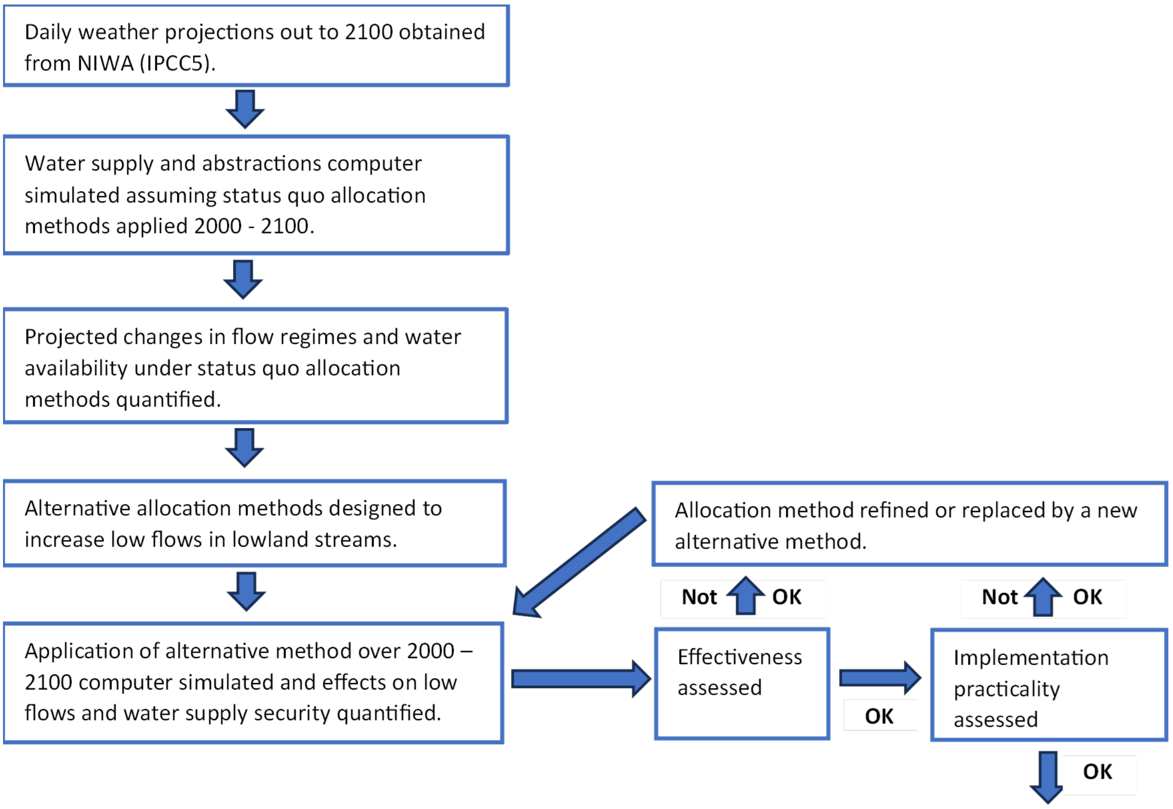
The case-study area

The Selwyn-Waihora water management zone was chosen because it represents various river responses to projected changes in climate change: some benefit, others are adversely affected. It has a significant groundwater system supporting a large irrigated area and pumping is impacting lowland streams and rivers. This zone mirrors most New Zealand catchments with significant groundwater use. Its groundwater allocation policy aligns with national best practices. Moreover, there's a well-calibrated 3D flow model for simulating the effects on flow rates and water levels of different allocation methods, given long periods of daily weather data.

It is therefore an ideal exemplar; the water allocation principles learned through this case study are very likely to be applicable in other areas of New Zealand where water is drawn from alluvial aquifer systems for municipal, industrial, agricultural or horticultural uses.

1.3 Overall approach

We developed and tested alternative water allocation policy methods by applying the following overall approach.



Alternative policy approaches that could potentially increase low flows in groundwater dependent rivers and streams are set out below, grouped under those that are “demand management” focussed and those that are “supply side” focussed.

Policies that reduce demand.

- Reduce the *annual volume limit* on groundwater takes, no year-to-year variation (a simple variation on current policy).
- Vary the *annual volume limit* on groundwater takes based on prior year(s) recharge.
- Vary the *maximum daily rate of take* based on prior year(s) recharge – mimics restrictions on surface-water takes.
- Vary the *maximum daily rate of take* based on the flowrate in the Selwyn River at Coes Ford.
- Shift groundwater takes onto surface water supplies.

Policies that enhance groundwater recharge.

- Increase irrigated area.
- Managed aquifer recharge.

Our research focussed on testing “demand management” policy approaches because the effectiveness of policies that enhance groundwater recharge tend to be very catchment specific. In the case study area, for example, there is limited scope to increase irrigated area (due to water quality constraints) and the real long-term benefits to stream flowrates of managed aquifer recharge are uncertain.

We designed and tested, through computer simulation modelling, many versions of each of the demand management policy approaches. The aim of this experimental development process was to explore the benefits to instream flows and the effects on water supply security of each approach.

1.4 Key results

Surface water allocation

In most areas of New Zealand, water allocation rules for rivers are currently based on the 7 day Mean Annual Low Flow (MALF). Changes in the MALF in the rivers that flow into the case study area are spatially variable. For the Upper Selwyn catchment, the MALF is expected to remain stable or decrease by 5 to 10% by 2100. Over the same period the MALF is expected to remain stable with “overs and unders” for the Rakaia River at the Gorge and southern part of the Upper Waimakariri catchment, while the northern part of the Upper Waimakariri catchment is expected to see a large decrease (up to 40%) under the most extreme radiative forcing scenario (RCP8.5). Under current allocation policy, the average number of days on which water takes are restricted is projected to increase by about 1.5% for the Rakaia at the Gorge under all RCP scenarios modelled. For the Waimakariri at Otarama, the increase is projected to be between 10% (RCP2.6) and 37% (RCP8.5).

If a river or streams MALF increases due to climate change, the cease take flow could increase to secure the stream health benefits, potentially with little impact on abstractors. Such a change could be achieved through the normal 10 yearly regional plan review cycle. A more agile response is unnecessary because the average rate of change is projected to be low. If the MALF is decreasing, there appear to be no significant benefits to low flows in changing the cease-take flow. The only option appears to be flow augmentation if the objective is to maintain or increase future MALF relative to its historic value.

Groundwater allocation: reducing demand by reducing or varying limits on the annual volume taken (cubic metres per year)

Groundwater allocation policies based on setting a limit on the annual volume of water taken are ineffective for meeting ecological aspirations in most years. This is because the limit is set at a level that is generally high enough to fully meet demand in ninety percent of years. Thus, in most years the limit should not be reached. In those years when the limit is reached it is usually late autumn, by which time stresses on river or stream flow rates and ecological quality are often reducing anyway.

Groundwater allocation: reducing demand by varying the maximum rate of take (litres per second) based on groundwater recharge.

Allocation policies that vary the maximum daily rate of take based on an indicator of the state of the aquifer system (land surface recharge in the previous year) was effective in terms of increasing the MALF. However, in some years with very low flow in late summer these policies provided no material increase in flow rate.

Seepage from rivers contributes a high proportion of groundwater recharge in the case study area. Relying on a measure of land surface recharge only as the indicator of aquifer state misses periods with low river recharge.

Water supply security under these policies reduce from 100% to about 80%.

Groundwater allocation: reducing demand by varying the rate of take (litres per second) based on the current flowrate in a sentinel groundwater dependent river or stream.

Allocation policies that vary the maximum daily rate of take of the stream-depleting proportion of a groundwater take based on the current flowrate in a sentinel river were found to be the most effective in terms of increased river and stream flowrates during low flow periods (summer and autumn). This is likely to be the case in most New Zealand alluvial groundwater systems which have groundwater dependent rivers or streams. Our modelling shows this effectiveness will be sustained under future climate.

Water supply security under this type of policy varies depending on the depth of the groundwater take and its proximity to the sentinel river or stream. In the case study area, security of supply reduced from 100% to between 28% (shallow bores) and 82% (deep bores).

1.5 Conclusions

Having the agility to vary allocations on a daily to weekly frequency in response to short-term variations in stream flow is critical to maintaining or improving stream-health and enables adaptation to a changing climate. This is important because short-term variations are expected to become more extreme and current extreme events more frequent.

A groundwater allocation management policy that isolates surface water takes from the cumulative effects of the groundwater takes was not found. Groundwater takes and surface water takes must therefore be managed together – that is, integrated allocation management is required. It is unrealistic to define allocation rules for each independently of the other and expect to be able to prevent surface water allocation limits being breached.

Shifting existing groundwater takes onto surface water supplies permanently reduces the total daily rate of take from groundwater. Though not tested, we expect it to be as effective in raising river and stream flowrates during summer/autumn as the policies that restrict the daily rate of take. The feasibility of implementing this option depends on being able to access a surface water supply that has an acceptable level of water supply security. None are currently available in the case study area.

In the case study area, allocation policies that are the most effective in terms of increasing river and stream flows during summer/autumn significantly reduce groundwater supply security. For takes from deeper aquifers, the security of supply would reduce from 100%, under current policy, to about 80%. This is similar to water supply security from the Waimakariri River. The security of supply of takes from shallower aquifers would reduce to levels that would not be viable for urban, commercial or primary sector water uses.

Changing groundwater water allocation policy to improve stream flows would result in a significant reallocation of climate related risk – more will be borne by the primary sector. This will have economic and social impacts.

The scenario-based approach has identified what we believe to be the most effective type of agile, adaptive groundwater allocation policy for improving low flows in rivers and streams.

While the scenario based approach we took was effective in identifying the most effective demand-management approach to increasing stream flowrates in low flow periods, a more automated way of tuning the parameters is needed to determine the best policy parameters for a specific catchment.

1.6 RECOMMENDATIONS

1. Widen the scope of this policy analysis beyond increasing river and stream flowrates to include quantifying the effects of allocation policy options on:

- The security of supply for municipal and industrial groundwater takes.
- Technical and financial effects on farmers reliant on groundwater for irrigation.

2. Investigate infrastructure based options for increasing stream flows – that is, supply-side options. These could range from storage options for mitigating the effects on water supply security of implementing groundwater allocation options that improve river and stream low flows to options that directly enhance low flows.

3. Develop an automated method for tuning the parameters needed to determine the best policy parameters for the most effective groundwater allocation approach for a specific catchment.

2 INTRODUCTION

The research reported here was funded by Ministry for Primary Industries (MPI) under its Climate Change Adaptation programme (SLMACC) to develop policy options that address the question "How might water allocations need to change in response to a changing climate to give effect to the National Policy Statement for Freshwater Management 2020. This prioritises (a) maintaining the health of a water body over (b), providing water to meet human health needs over (c), any "other water uses".

2.1 Why Investigate Alternatives to Current Policy?

Management of groundwater takes to simultaneously protect the groundwater system and hydraulically connected surface waterways is a challenging, and as yet unsolved problem in New Zealand.

Current best practice methods for managing groundwater abstractions from New Zealand's alluvial aquifer systems is to set a limit on the volume of water that may be taken per year and, for bores located close to rivers or streams, restrict the stream-depleting proportion of the water take based on the current stream flowrate. There is evidence that the health of groundwater-dependent surface waterways is not being maintained by this approach. For example, in spite of this management approach having been implemented in Canterbury's Selwyn-Waihora Water Management Zone since 2012, there has been a steady decline in summer-time low flows, as shown in the following figure. This is understood to be due to increased pumping of groundwater, mainly for irrigation (McKerchar and Schmidt, J. (2007); Weir and Bright, (2017)). Climate changes is projected to worsen the situation due to reduced groundwater recharge (Bright, 2011).

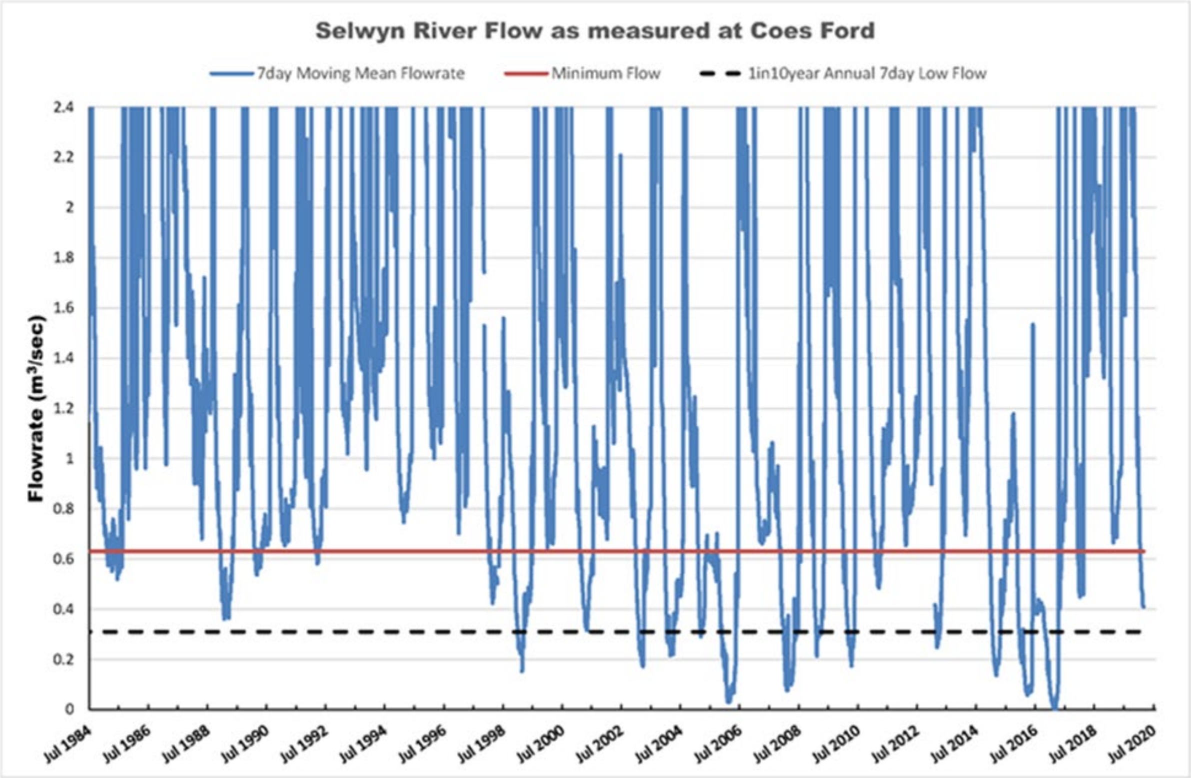


Figure 1: Selwyn River Flowrate at Coes Ford

The magnitude and duration of river flowrates less than the "cease-take flowrate" (at which point all surface water takes must stop) have steadily increased. This indicates that the groundwater allocation rules are ineffective – they are undermining the intent of the surface-water allocation rules.

If current best practice methods for managing groundwater takes are not protecting the low flow part of the flow regime in groundwater-dependent streams sufficiently well to protect stream health, alternatives need to be investigated.

2.2 Focus of this Project: Improving Lowland Stream Flowrates.

The National Policy Statement for Freshwater Management 2020 (NPS-FM) requires Regional Plans to give effect to Te Mana o te Wai.

Te Mana o te Wai prioritises (a) maintaining the health of a water body over (b), providing water to meet human health needs over (c), any “other water uses” (MfE, 2017), (Kāhui Wai Māori, 2019).

The NPS-FM also requires national bottom lines to be met – specifically, objective measures of stream health.

The lower Selwyn River currently does not meet national bottom lines related to stream health (LAWA, 2023).

Under a changing climate, if the allocation rules that provide access to water for “other water uses” remain static, it may not be possible to maintain the health of the water body and provide adequate water to meet human health needs, even if they have been to-date.

Increasing low flows during summer and autumn is potentially part of a solution to the lower Selwyn River stream-health problem.

The purpose of this research project was to formulate a range of water allocation policy methods that would have consistently delivered higher low flows in lowland streams than occurred over the last twenty years, and which could be expected to maintain the increases under projected future climates. The methods were tested to determine how effective they would be in raising low flows and what effect they would have on the security of supply for abstractive water uses.

The Selwyn-Waihora water management zone was chosen as the case-study catchment because:

- It contains examples of the three most prevalent expected river responses to climate change:
  - Mountain rivers that will benefit overall (in terms of mean flow) by the projected changes in climate (E.g. the Waimakariri and Rakaia Rivers).
  - Foothills rivers whose flow rates will be adversely affected by the projected changes in climate (E.g. the Upper Selwyn River)
  - Groundwater-dependent rivers and streams whose flow rates will be adversely affect by the projected changes in climate (E.g., the Lower Selwyn River, Boggy Creek, Harts Creek).
- It has a large groundwater system from which a large, irrigated area is supported and groundwater pumping for irrigation purposes is affecting lowland streams and rivers.
- The range of river and groundwater systems present in the zone are representative of most New Zealand catchments where significant volumes of groundwater are abstracted.
- Current groundwater allocation policy is representative of current best practice in New Zealand for setting groundwater allocation limits.
- There is an existing, well-calibrated, fully integrated 3D flow model of the water management zone’s interconnected groundwater and surface water systems. It has been used to successfully simulate the day-to-day response of flowrates and water levels to daily variation in climate and irrigation demand over a 40+ year period.

It is therefore an ideal exemplar; the water allocation principles learned through this case study are very likely to be applicable in other areas of New Zealand where water is drawn from alluvial aquifer systems for municipal, industrial, agricultural and horticultural uses.

2.3 Key things this Project has not addressed.

The health of rivers and streams requires flow-rate variability (Naiman et al, 2008) – adequate low flows and sufficiently frequent freshes and floods to maintain geomorphological function and habitat suitability. Maintaining the health of a water body therefore requires maintaining a flowrate and water level regime that is not so different from the natural state regime that the health of the water body is compromised.

The fundamental water allocation question then is “by how much will society allow the flowrate/water-level regime to be changed from its natural state in exchange for the benefits derived from this change?”

This project has not attempted to answer this “degree of change” question for the case study area. Rather, it has formulated and assessed the effectiveness of a range of water allocation policy approaches to identify what type of approach is most effective in controlling changes in low flows in groundwater-dependent streams due to groundwater takes. While the focus is on groundwater takes, we also discuss surface-water allocation policy responses to climate change.

We have specifically not assessed:

- Cultural effects.
- Effects on the security of supply for municipal and industrial groundwater takes.
- Technical, social and financial effects on farmers reliant on groundwater for irrigation.
- Water supply augmentation options, such as managed aquifer recharge, targeted stream augmentation, transferring existing groundwater takes to surface-water supplies (beyond that which has already occurred as a result of developing the Central Plains Water Supply system).

The policy options developed and tested through this project should not, therefore, be incorporated into a Regional Plan variation without further analysis and extensive consultation.

3 ALLOCATION POLICY RESEARCH APPROACH

By law water allocation policy must be reviewed on a ten-yearly cycle. We assert that this is frequent enough to adapt policy in anticipation of climate change effects. However, while policies in a plan can be updated this frequently, it can be decades before such changes take effect because effecting change is dependent on changing resource consent conditions via review, which is problematic, or replacement. Resource consents typically have a "life" of between 10 and 35 years. The challenge then, is designing policy that has the agility to effect changes in water allocation quickly enough to respond to climate variability and change, and with minimal regulator input (i.e. low transaction cost).

A water allocation policy that is now mandatory is the setting of a minimum flow (i.e. a "cease take flow") or level and an associated water allocation limit for each water body (MfE, 2017). Together they define a water allocation band. This policy is given effect to by including conditions in each consent to take water that:

- Limit the maximum rate of take such that the sum of all takes from the water body doesn't exceed its allocation limit. For takes from streams the rate is generally specified in litres/second. For groundwater takes the rate is generally specified in cubic metres per year.
- Require takes from streams, and groundwater takes that have a high "stream depletion" effect, to reduce or cease if continued abstraction would cause the residual flowrate in the stream to drop below a specified "minimum flow" at one or more specified flow-rate monitoring sites.
- Require takes from groundwater to cease once the volume taken reaches the annual take limit.

This policy provides sufficient agility for surface water allocation limits to be varied daily in response to day-to-day variations in stream flowrates. In some regions a "minimum flow" (cease-take-flowrate) is specified for each month, and thus can change from month-to-month in a set pattern to meet environmental objectives. Occasionally it is specified for a shorter timeframe (e.g., weekend) to meet specific recreational needs.

In contrast, allocation limits (e.g., the maximum annual take volume) for groundwater are generally fixed for the life of the take consent. Some groundwater take rates (litres/second) are managed in relation to groundwater levels in sentinel wells, typically to prevent saltwater intrusion.

Section 2.1 provided evidence that current implementations of this water allocation policy are ineffective when groundwater takes affect flowrates in hydraulically connected surface waterways, the consequences of which will worsen as our climate changes. This poses the following key questions:

1. To what degree might cease-take-flowrates and allocation limits need to change to maintain the key characteristics of the current flow regime (specifically its changes from 'natural state') and thus the existing level (at least) of water body health under a changing climate?
2. How agile do the cease-take-flowrates and allocation limits need to be?
3. What design changes to the water allocation framework would be necessary to enable agile adaptation to climate variability and change?
4. What would be the impact on the security of supply for abstractive water users of such changes?

We sought answers to these questions by applying the following approach.

Daily weather projections out to 2100 from Collins et.al., 2022 were used with existing models of water flows through soil, groundwater, and rivers to quantify the effects of climate variability and change on irrigation demand, drainage fluxes, groundwater levels, river flows, and lowland stream-flows.

This provided new understanding of the effects of projected climates on water flowrate and level regimes (indicators of stream health), and the availability of water to meet human health needs and the needs of irrigated agriculture, assuming current water allocation policy remains in place.

The nature and scale of projected changes in flow regimes and water availability, relative to historical regimes and availability, were thus identified.

From here we systematically tested the ability of a range of alternative water allocation policies to increase lowland stream flows and maintain the improvements out to 2100. Effects on water availability of each alternative allocation policy were quantified.

We specifically focussed on addressing the unsolved problem of how to manage groundwater takes so that the depletion effect that they have on connected streams and rivers does not cause surface-water allocation limits to be exceeded.

At key points in this experimental development process, we sought feedback from representative regional authority specialist staff on the practicality of implementing the alternative policies.

The primary implementation steps.

Phase 1: Computer simulate mean daily flows for the Waimakariri, Upper Selwyn and Rakaia Rivers under 4 modelled future climate scenarios for the period 1971 to 2100.

> Task 1: Calibrate New Zealand Water Model (NZWaM) (NIWA, 2019) so that simulated mean daily flowrates for the Selwyn River at Whitecliffs and the Waimakariri River at Otarama accurately match the measured flow-rate data for that site over the period 1985 to 2005. This was completed by NIWA.
>
> Canterbury Regional Council had already calibrated their model of the upper Rakaia catchment to the Rakaia River at Fighting Hill flow record.
>
> Task 2: Select a Global Climate Model (GCM) that provides mid-range projections of irrigation demand, drainage (groundwater recharge) and river flow, based on the results of SLMACC project 405213 (Collins et.al., 2022).
>
> NIWA then used the NZWaM to simulate mean daily flow-rates for the Upper Selwyn and Waimakariri sites for the period 1971 to 2100 for each combination of 4 RCP's and the selected GCM. Canterbury Regional Council used their Rakaia model to simulate mean daily flowrates at Fighting Hill using the same combinations of RCP's and GCM.

Phase 2: Computer simulate daily irrigation demand and daily drainage flux from the root-zone across the case study area, for the period 1971 to 2100, taking into account the spatial distribution of soil type, irrigation methods and practices and land use, and the temporal and spatial variation in climate. Aqualinc's irrigation simulation model (IrriCalc) was used for this, using climate data supplied by NIWA.

> Task 3: Divide the case study area into Hydrological Response Units. GIS methods were used with spatial datasets describing soil characteristics, current land-use, and rainfall to define Hydrological Response Units. Soil water storage capacity, land-use, and mean annual rainfall are assumed to be constant within each Hydrological Response Unit.
>
> Task 4: IrriCalc (previously calibrated using CRC lysimeter data) was used to simulate irrigation demand and drainage flux on a daily time-step for each combination of 4 RCP's and the selected GCM over the period 1971 to 2100, for each unique Hydrological Response Unit.

Phase 3: Quantify the magnitude, timing, duration, and frequency of differences between the modelled current flow regimes (1990's) and modelled future flow regimes (2040's, 2090's) for the Waimakariri, Upper Selwyn and Rakaia Rivers, downstream of the main water takes from those rivers (to capture the combined effects on the flow remaining in the river of water allocation rules and water takes to meet irrigation demand). This was done for each combination of 4 RCP's and the selected GCM over the period 1971 to 2100.

> Task 5: Model the water taken from the Waimakariri, Upper Selwyn and Rakaia Rivers on a daily basis to meet modelled irrigation demand in compliance with current water allocation policy and associated plan rules and consent conditions and calculate the flowrate remaining in the rivers immediately downstream of the main takes each day.
>
> Task 6: Quantify the magnitude, timing, duration, and frequency of differences between the modelled current flow regimes (1990's) and modelled future flow regimes (2040's, 2090's) for the Waimakariri, Upper Selwyn and Rakaia Rivers using the following metrics: mean flow, median flow, 7-day MALF, irrigation season median flow; monthly median flows Sept – April. Also quantify the differences for the modelled irrigation takes under each combination of 4 RCPs and the selected GCM, summarising them as changes in the reliability of supply, number and duration of moderate and severe shortfall events per year, and the start and finish dates of severe shortfalls.

Phase 4: Initial re-design water allocation policy so that it can more efficiently adapt to climate change.

Task 7: Determine the changes in minimum flows and allocation limits for the mountain and foothills rivers that would be necessary to maintain the current flow regime downstream of the main water takes and so maintain the health of the waterways at current levels.

Task 8: Assess the feasibility of changes in surface water allocation policy where change is necessary to improve the timeliness and reduce the transaction costs of changing minimum flows and allocation limits to adapt to climate change.

Phase 5: Develop practical methods for managing the cumulative effects of all groundwater takes on surface-water flowrates so that surface-water allocation limits are not exceeded.

Task 9: Set up the existing Selwyn Waihora integrated groundwater / surface-water flow model to simulate the effects of current and future climate on irrigation demand, flowrates, and water levels throughout the case study area.

Task 10: Through several iterations of a scenario based development cycle, experimentally develop practical methods for managing the cumulative effects of all groundwater takes on surface-water flowrates so that surface water allocation limits are not exceeded.

Task 11: Test the effectiveness of new agile, adaptable, integrated allocation methods under the four climate scenarios modelled using 4 RCPs with the selected GCM, over the period 1971 to 2100.

Task 12: At key stages in the development cycle, virtual workshops were held with experienced policy managers from the regions with the most groundwater-supplied irrigation. The workshops reported progress, assessed results, and co-designed the next development iterations to ensure general applicability of the allocation policy throughout New Zealand.

4 HYDROLOGICAL EFFECTS OF CLIMATE CHANGE UNDER CURRENT ALLOCATION POLICY

This section provides a summary of the projected effects of climate change on surface water and groundwater hydrology in the study area.

Comparisons with the historic period are based on the modelled hindcast period (RCPpast), rather than measured historic data. We note that RCPpast is not always a good representation of the historic climate in the study area, for example mean annual land-surface recharge based on hindcast data is 20% lower than that based on historic data (drainage flux from IrriCalc modelling in both cases).

More detailed information is presented in the Appendices.

4.1 Alpine and Foothills Rivers flowrate at key monitoring sites

Modelled flows for the Waimakariri and foothills catchments under future climates were provided by NIWA. Flows for the Rakaia River under future climates were provided by Environment Canterbury.

Mean flows are expected to slightly increase across all Representative emission Concentration Pathways (RCP)s, up to 10% by the end of the century for the Upper Selwyn catchment and up to 5% for the Upper Waimakariri catchment. Median flows are expected to remain stable up to mid-century for both catchments, indicating a potential shift in the overall flow regimes under future climates.

Changes in low flows are not consistent across the low flow range and the catchments. Details are provided in Appendix A.

The frequency and duration of flows below the hindcast 7-day MALF is expected to increase for Waimakariri, which would adversely affect the reliability of surface water takes (discussed further in Section 4.4).

4.2 Irrigation demand

Irrigation demands were modelled on a daily time-step from 1971 – 2100 for each HRU (i.e. combination of soil, land-use and climate), using IrriCalc. Further details are of the modelling are provided in Appendix C and in Weir and Bright (2017).

For each RCP the average annual irrigation demand was calculated for periods representing the mid-century (2040s: 2041 – 2059) and late century (2090s: 2081 – 2099). These values were compared to the modelled historic climate (RCPpast: 1971 – 2005).

Maps showing the spatial distribution of modelled changes in irrigation demand are included in Appendix C.

For RCP2.6, the model outputs show a slight increase (0-5%) in average annual demand across the majority of the plains in the 2040s, with greater increases on parts of the upper Plains and slight reductions on heavier soils on parts of the mid to lower Plains. For the 2090s, relative to the historic period, the modelled shows a slight decrease in average annual demand over a large proportion of the Plains.

Under future climates with higher RCPs there was a more consistent increase in irrigation demand, with greater increases in the 2090s than in the 2040s. For RCP8.5 the percentage change in 2090s was 10-15% across the majority of the Plains, with increases of up to 25% in the upper Plains.

4.3 Drainage

Drainage flux through the soil profile (groundwater recharge) was also modelled in IrriCalc, and changes were calculated for the same time periods (2040s and 2090s).

Maps showing the spatial distribution of modelled changes in drainage flux are included in Appendix C.

For HRUs containing irrigated areas, changes in drainage flux under future climates are more spatially variable than the irrigation, as changes are driven both by changes in rainfall and changes in irrigation water use.

For RCP2.6 – RCP6.0, increases in drainage flux of up to 25% were modelled for irrigated pasture in the 2040s, with smaller increases, and slight decreases in some areas, in the 2090s.

For RCP8.5 the model outputs showed a slight reduction in drainage flux for the 2040s, with increases of 5-10% in most of the study area in the 2090s.

4.4 Flowrates in groundwater-dependent lowland streams

The numerical groundwater model of the study area, with inputs derived from future climate simulations, was used to simulate flows in lowland streams under future climates, under the assumption that there is no change from current land use and irrigated areas, and that current allocation policies remain in force.

Further flow and groundwater level hydrographs, and summary statistics comparing the 2040s and 2090s to the historic period, are included in Appendix B.

Based on flow statistics, both the modelled changes from the historic period to the 2040s, and the differences between RCPs are relatively small. However, Figure 2 and Figure 3, which show modelled flow hydrographs for the Selwyn River in the 2040s and 2090s respectively, reveal significant differences between the RCPs, particularly at the low flow end of the flow regime.

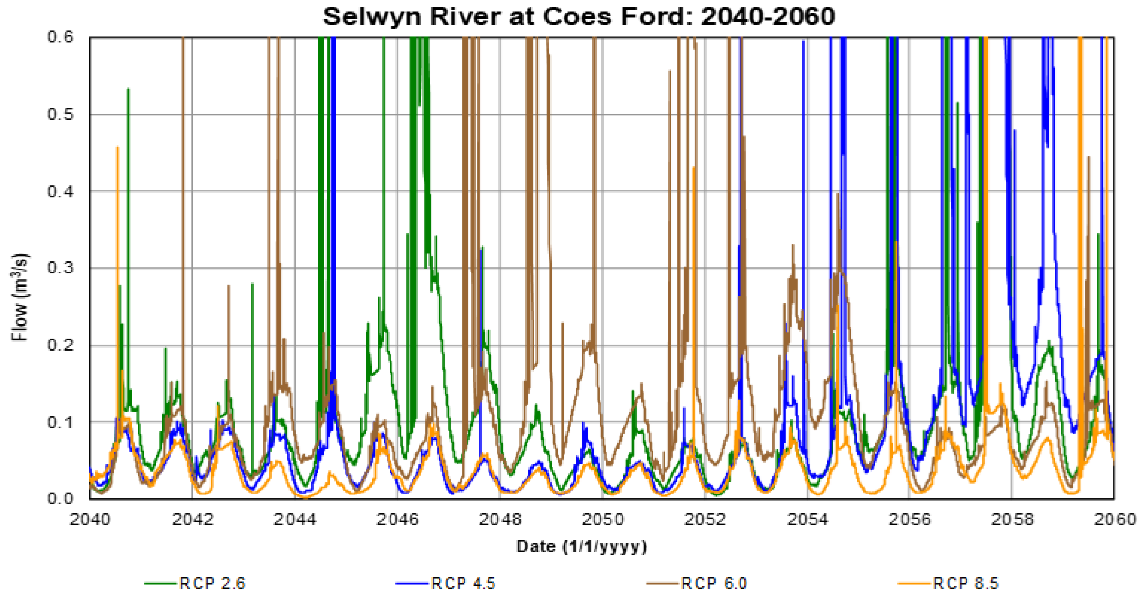


Figure 2: Hydrograph of modelled flows in the Selwyn River at Coes Ford in the 2040s.

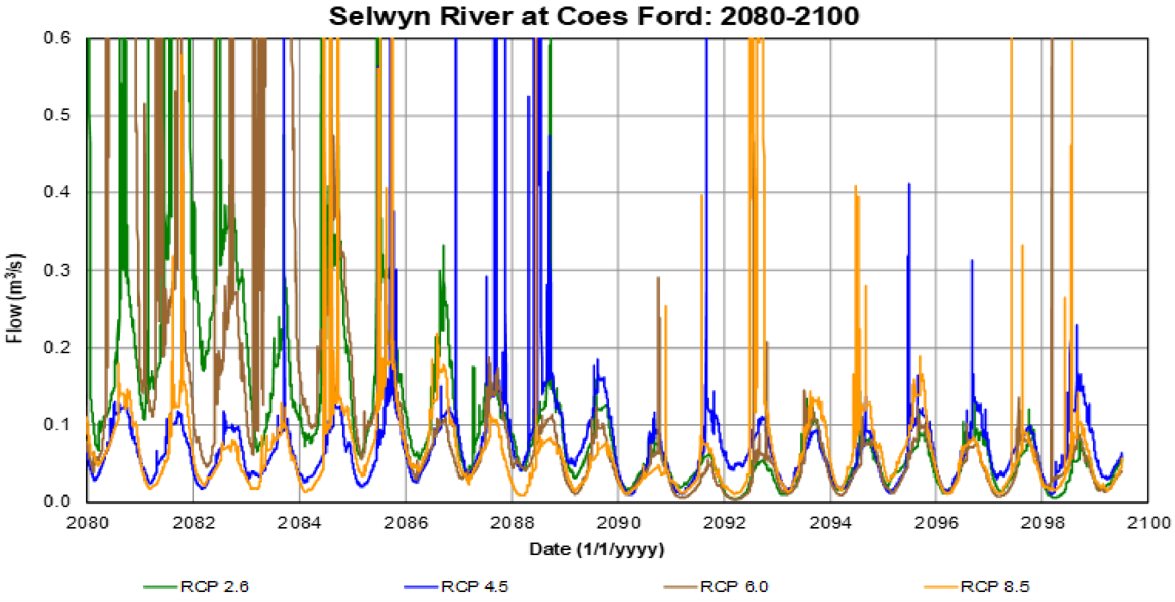


Figure 3: Hydrograph of modelled flows in the Selwyn River at Coes Ford in the 2090s.

4.5 Security of Water Supply from the Alpine Rivers

We modelled water supply security (i.e., water availability over time) and water supply reliability (i.e., considering both the supply and demand) of key surface water takes under future climates for the Waimakariri and Rakaia Rivers. Supply security was expressed as average days per irrigation season with supply restrictions, and the maximum number of consecutive days on restriction per irrigation season. Supply reliability was expressed as the ratio of the volume of water supplied to the water demand volume.

Detailed results are provided in Appendix D.

In both rivers the results showed a reduction overall in both supply security and supply reliability over time, and with increasing RCP. The reduction in supply reliability was more pronounced, indicating that demand side changes are a key driver of reduced supply reliability under future climates.

5 POLICY OPTIONS FOR INCREASING STREAM FLOWS

In most areas of New Zealand, water allocation rules are currently based on flowrate statistics – mean annual seven-day low flow (rivers) and mean annual land-surface recharge (groundwater). These statistics are almost certain to change due to climate change.

If current allocation policies continue, it is to be expected that allocation rules defined by applying these policies would change as the flow statistics change.

Whether such changes are beneficial or detrimental to stream health is context specific.

In this Section we consider the implications of continuing with current water allocation policies and identify alternative policy options where changes appear to be necessary to improve and maintain low flow regimes as climate changes.

5.1 Potential changes in the Implementation of Current Policy due to Climate Change

5.1.1 Surface water

Water allocation rules for water takes from rivers have historically aimed to minimise adverse effects on aquatic ecosystem health ("river health") of making water available for taking.

The setting of a so-called "minimum flow", which is more appropriately labelled the "cease-take flowrate", and an allocation limit are the key allocation policy parameters.

The cease-take flowrate is generally set between 80% and 100% of the mean annual seven-day low flow (MALF). When the river is flowing at or below the cease-take flowrate no water can be taken from the river – it is flowing at its natural rate (unless groundwater takes are depleting stream flows).

Projected changes in climate result in changes in river flow regimes, notably changes to the MALF and the Q95 flowrate (a measure of extremely low flow). If the MALF changes then continued implementation of current policy should result in changes to the cease-take flowrate and, potentially, the allocation limit (if it too is based on the MALF). The effects on allocation rules of climate change, assuming continuation with current policy, differ between river types.

Foothills Rivers (e.g. Selwyn)

Large increases in Q95 are expected under climate change with increases centred around +20% by 2040, rising to +40% by end of century. This is understood to be associated with the expected change in rainfall regimes in the foothills catchment headwaters, such as Selwyn.

Ecological flow characteristics are expected to improve under climate change, due to the improvements in low flows.

If current allocation policy continues to be applied, one would expect the cease-take flowrate for the foothills rivers in the Selwyn-Waihora zone to increase.

This would be considered to be a beneficial change, ecologically, for foothills rivers.

Alpine Rivers (e.g. Rakaia and Waimakariri)

Large decreases in low flow are expected under climate change with the decrease centred around -20% by end of century. Changes in low flows under the highest radiative forcing scenario (RCP8.5) deviate from the other radiative forcing scenarios by the 2050s. This is likely associated with changes in weather patterns in the headwaters of the alpine catchments.

In accordance with the simulated large decrease in the low flow regime for the alpine rivers, the median duration of low flow events is expected to increase across radiative forcing and with time. Low flows are expected to be lower for longer. This is likely associated with changes in weather patterns across the headwaters of the alpine catchments associated with increased temperature across the catchment.

If current allocation policy continues to be applied, one would expect the cease-take flowrate to decrease for the alpine rivers.

This would be considered to be detrimental to the health of alpine rivers.

5.1.2 Groundwater

Water allocation rules for groundwater takes seek to minimise the cumulative effects of all takes on spring-fed streamflows and, to a lesser extent, groundwater levels (thus access to groundwater).

Current policy is to set a limit on the total volume of groundwater that may be taken per hydrological year (July to June). This limit is nominally set at 50% of the long-term average annual land-surface recharge.

It is a constant allocation, there is no variation from year to year.

Projected changes in climate result in changes in average annual land surface recharge. In the Selwyn-Waihora management zone, land surface recharge is projected to increase by 5% to 15%, depending on location and time period (2040’s or 2090’s).

If current groundwater allocation policy continues to be applied, one would expect the annual allocation volume to increase. The resulting increase in groundwater pumping would be considered detrimental from a lowland stream health perspective.

5.2 Alternatives to Current Surface Water Allocation Policy Settings.

5.2.1 Foothills Rivers (e.g. Selwyn)

Given the expected increase in the MALF, there is no apparent need to change from current policy. Application of the current policy of setting the cease-take flowrate at a percentage of MALF would result in an increase in the cease-take flowrate.

5.2.2 Alpine rivers

In order to maintain future river low flow characteristics the same as those observed in the past under current policy settings it would seem appropriate to raise the cease take flow rate because this would appear to result in improved low flows.

However, when the river flow rate is below the cease-take flowrate there can be no abstraction – everyone must shut down their water takes, and all the current flowrate remains in the river. It is flowing at its natural rate.

Raising the cease-take flowrate to a new value should result in slightly higher flowrates when the river flowrate lies between the old and new cease-take flowrates but makes no difference to the river flowrate when it is below the old cease-take flowrate.

The conclusion we draw is that maintaining river low flow statistics in the face of climate change that is causing a reduction in alpine river low flows cannot be achieved by changing water allocation policy.

The only way to increase flowrates when they would naturally be below the cease-take flowrate is to augment river flow. This could come from water stored within the catchment or from another source (i.e., inter-catchment transfer).

5.2.3 In Summary:

If the MALF is increasing the cease take flow could increase to secure the stream health benefits, potentially with little impact on abstractors. Such a change could be achieved through the normal 10 yearly regional plan review cycle. A more agile response is unnecessary.

If the MALF is decreasing, there appear to be no stream health benefits in changing the cease-take flow. The only option appears to be flow augmentation if the objective is to maintain or increase future MALF relative to its historic value.

5.3 Alternatives to Current Groundwater Allocation Policy

The current groundwater allocation policy in the Selwyn-Waihora water management zone enables the taking of groundwater at up to a specified maximum flowrate (litres/sec), provided the annual volume of water taken does not exceed a specified limit. Both parameters – flowrate and seasonal volume taken – are the same each year, regardless of the current state of the groundwater resource.

Previous studies (e.g. Bright (2011)) of the potential effects of climate change on groundwater levels and discharges indicated significant adverse impacts on groundwater dependent streams. This is primarily a consequence of water use increasing as the climate changes.

Application of current policy would raise the allocation limit in line with increased land-surface recharge, thus allowing increased abstraction to meet increased demand. This would be counterproductive because demand is projected to increase more than recharge.

A range of alternative policy approaches are set out below, grouped under those that are "demand management" focussed and those that are "supply side" focussed.

A. Policies that reduce demand.
    - Reduce the annual volume limit on groundwater takes, no year-to-year variation (a simple variation on current policy).
    - Vary the annual volume limit on groundwater takes based on prior year(s) recharge.
    - Shift groundwater takes onto surface water supplies.
    - Vary the maximum daily rate of take based on prior year(s) recharge – mimics restrictions on surface-water takes.
    - Vary the maximum daily rate of take based on the current flowrate in the Selwyn River at Coes Ford.

B. Policies that enhance groundwater recharge.
    - Increase irrigated area.
    - Managed aquifer recharge.

Our research has focussed on the "demand management" policy approaches because of the limited scope to increase irrigated area (due to water quality constraints) and uncertainties about the real benefits of managed aquifer recharge in the study area.

Some farms in the study area are now supplied by Central Plains Water Ltd, and no longer (or rarely) take groundwater. This change started in 2015/16 with the commencement of supply from CPWL's Stage 1. Stage 2 has been operational since October 2019 and has enabled an increase in irrigated area. It is too soon to draw conclusions about the effect of this switch in water source, and increase in irrigated area, from the measured flow record. We have not specifically assessed, through modelling, the effects on stream flow of transferring more water takes from groundwater to surface water supplied by Central Plains Water Ltd, beyond what has already occurred.

We designed and tested, through computer simulation modelling, many versions of each of the remaining demand management policy approaches. The aim of this experimental development process was to explore the benefits to instream flows and the effects on water supply security of each approach. The key results of this process are presented in Sections 6 and 7.

6 EFFECTS OF POLICIES THAT CHANGE ANNUAL TAKE VOLUME LIMITS

The current approach to regional groundwater allocation management in Canterbury sets a fixed limit on the total annual volume of water available for abstraction from a groundwater management zone. This fixed total volume is based on a percentage of the average annual land surface recharge. The percentage currently used is 50%. Section 2 indicates that this approach, or this proportion of land-surface recharge, is not providing sufficient protection of environmental values. It is not clear whether it unnecessarily restricts groundwater takes following periods of high groundwater recharge.

We tested whether low flows in streams could be improved by reducing the fixed allocation limit, to increase protection of stream health. We then tested whether adopting a dynamic allocation limit, changing it from year to year, could increase protection of stream health and increase water availability, depending on the state of the groundwater system. We used groundwater recharge in the immediately preceding years as an indicator of the state of the groundwater system.

The results presented in Sections 6.1 and 6.2 are based on earlier work completed by the project team (Bright et.al., 2008). This work analysed four scenarios: No Limits (Scenario 1), Various Fixed Annual Allocation Limits (Scenario 2) and two forms of Dynamic Annual Take Limits (Scenarios 3 and 4). Results from Scenarios 2 and 4 are included in this report to provide a full picture of the range of policy options we have examined and lay the foundation for the options described in Section 7. The No Limits scenario is no longer relevant. Scenario 3 is not included here because it was less effective than Scenario 4 in raising stream low flows.

6.1 Reducing the maximum annual take volume – fixed for the life of a take consent.

6.1.1 The scenarios assessed.

Three scenarios were developed to test the sensitivity of streamflow and water supply security to the annual allocation limit. These were:

- Scenario 2a: The annual allocation limit was set at 40% of the long-term average land surface recharge.
- Scenario 2b: The annual allocation limit was set at 50% of the long-term average land surface recharge. This represents current groundwater allocation policy in the case study area.
- Scenario 2c: The annual allocation limit was set at 70% of the long-term average land surface recharge

Scenario 2a represents a reduction in annual allocation to 80% of the current (2023) limit.

We assumed that irrigation would be managed as normal until the annual volume was reached, at which point irrigation pumping would cease.

The results presented below focus on Scenario’s 2a and 2b only. We found the consequences of implementing Scenario 2c were almost identical to the option of having no fixed allocation limit at all.

6.1.2 Effect on streamflow

The summary statistics for streamflow in Table 1 show improvements ranging between about 10% for the 7-Day MALF and 4% for the average mean daily flowrate.

Improvement in the 7-Day MALF would improve estimates of stream health indicators that are empirical functions of the 7-Day MALF.

However, figure 4 below shows that increases in streamflow due to reducing the allocation limit may come too late in the summer/autumn period to improve surface water quality during the months it is most stressed.

Water temperature, for example, is most likely on the decline well before the allocation limit materially affected streamflow.

Table 1: Simulated stream flow statistics for the Selwyn River at Coes Ford under two fixed annual allocation policies

Stream name	Flow site	Flow unit	Statistic	**Current Policy**	**Annual Allocation 80% of Current**
Selwyn River	Coes Ford	l/s	7-day MALF	479	525
			Average	2,708	2,809
			Median	1,428	1,515

Figure four, below, shows modelled mean daily river flow for a particularly long, dry summer (1970/71) during which irrigation demand was consistently high, meaning the annual volume limit would be reached sooner than would normally be the case. Although there is a fairly rapid increase in streamflow once pumping stops, there is only a small increase in that season's lowest flow. The increase may benefit fish, from a flow-rate perspective, but probably has very limited benefit in terms of improving water quality.

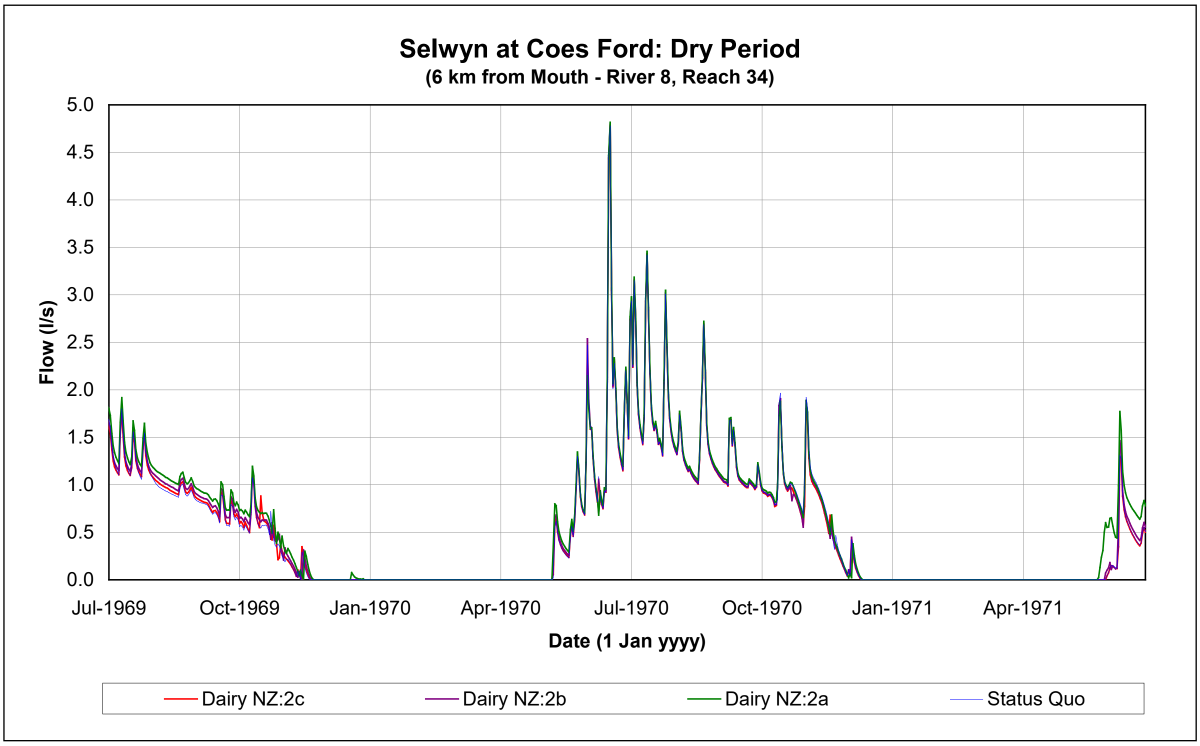


Figure 4: Effect on stream flow of changing annual take volume limit

6.1.3 Effect on groundwater supply security and reliability.

Groundwater supply security under a fixed annual allocation policy is 100% - water can be taken whenever the consent holder wishes to, until the annual allocation limit is reached. No more water can then be taken.

Water supply reliability, which is the ratio of the volume of water supplied (taken) to the volume of water required (demand), varies annually in response to annual variations in water demand. A ratio of 1.0 means supply fully met demand. A ratio of 0.5 means supply was sufficient to meet only half of the water demand.

The figures below show the modelled supply/demand ratio for an area of the Canterbury Plains that includes the case study area, over nearly forty years. This time period includes several seasons at each end of the spectrum – very high demand to very low demand.

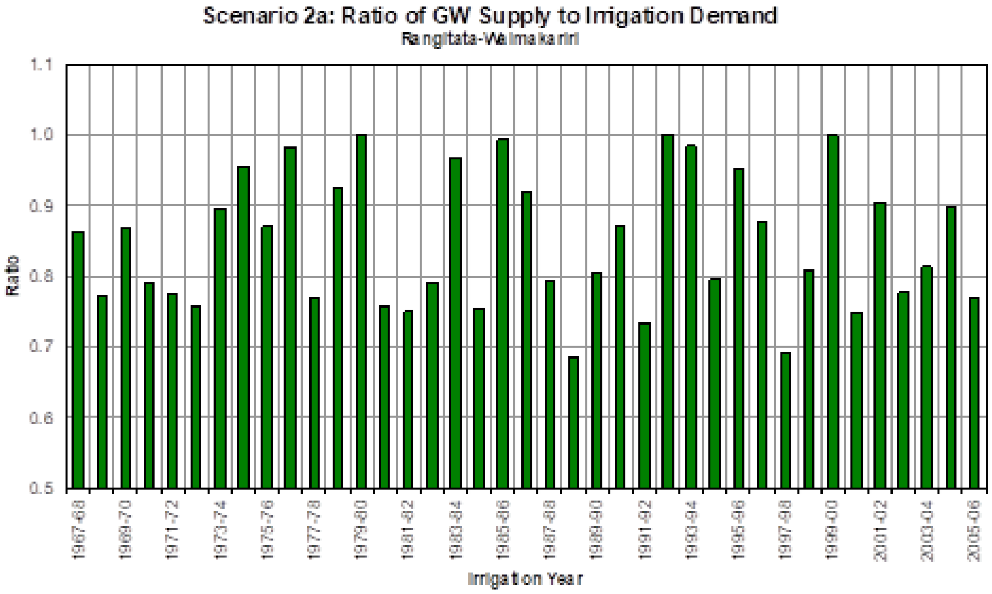


Figure 5: Temporal variation in the supply/demand ratio assuming groundwater allocation limit is reduced to 80% of its current value.

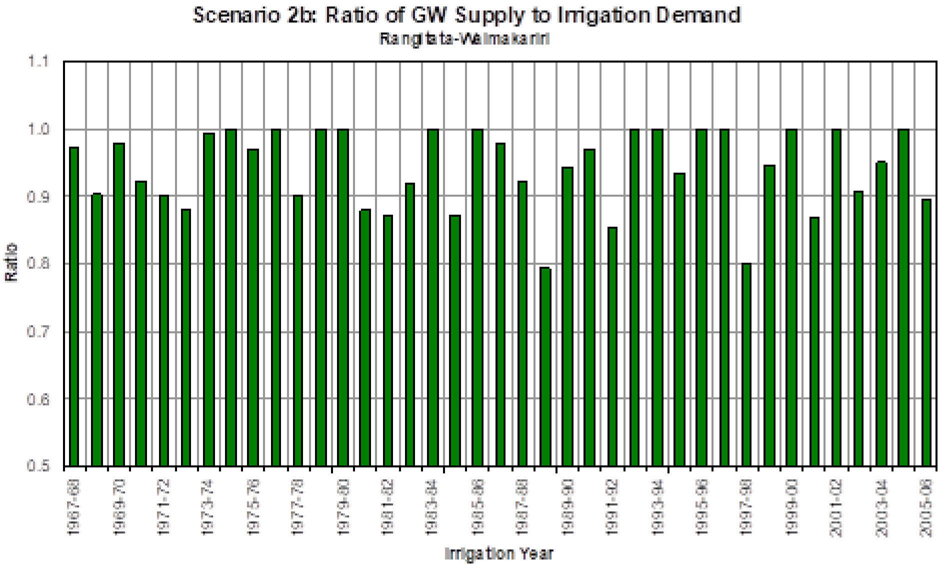


Figure 6: Temporal variation in the supply/demand ratio under the current groundwater allocation limit.

The figures show that the number of years with a supply/demand ratio of less than 1.0 increased as a result of reducing the allocation limit to 80% of the current limit. The minimum supply/demand ratio reduced.

Whenever the supply/demand ratio is less than 1.0, the supply has restricted the users ability to irrigate. When a water user wanted to irrigate but could not because the allocation limit had been reached, a restriction event was considered to have occurred.

The table below provides summary statistics on the frequency and duration of restriction events under each allocation limit. Reducing the allocation limit to 80% of the current limit significantly increases the frequency and duration of restriction events.

Table 2: Modelled water supply reliability metrics under two fixed annual allocation policies.

		Current Annual Volume	Annual Volume 80% of Current
Frequency	Number of restriction events	25	47
	Number of years in which restrictions occur	20	32
	% of years in which restrictions occur	51%	82%
Duration	Average number of days per restriction event	31	41
	Maximum event length over all years modelled (days)	88	116
	Average number of restriction days per irrigation year	39	62

6.1.4 Discussion

Reducing the annual allocation limit to 80% of its current value provided a relatively small benefit to streams, particularly during extreme dry periods such as 1969/70 and 1970/71. Modelling of the flow in the Selwyn River at Coes Ford indicated it would have stopped flowing in each of those summers if groundwater pumping occurred on the scale that it now does. Reducing the groundwater allocation limit would not prevent this happening but would shorten the length of time there was zero flow. Reducing the allocation limit provided little benefit to flow in the river (and adjacent lowland streams) during wet years (Bright et.al., 2008).

In contrast, water supply reliability is highly sensitive to the proportion of land-surface-recharge allocated for abstraction. Reducing the water allocation limit to 80% of its current value reduces water supply reliability to a level that would force changes in farm systems (Ford, 2008). It would disincentivise change to higher value land-uses because the financial cost of water supply shortfalls increases as the value (annual revenue) derived from land-use increases.

6.2 Dynamically adjusting annual take volume limit

A weakness of the fixed annual allocation limit approach is that water can be taken up to the limit every year, regardless of the state of the aquifer system. In principle this would exacerbate the effects on streamflow of a succession of low rainfall recharge years.

6.2.1 Method

We therefore considered varying the annual take-volume limit in response to land-surface recharge in preceding year(s). Thus, a succession of below-average recharge years would result in the progressive reduction in the annual take-volume limit.

A nominal annual groundwater allocation limit was specified. The total land-surface-recharge from the preceding hydrological year was calculated. The difference between this value and the long-term average was shared equally between the environment and water uses. The actual annual allocation for the coming year was thus equal to the nominal allocation limit plus 50% of the difference between last year's recharge and the long-term average. It was constrained to be not less than 50% of the nominal limit, and could rise above the nominal limit following high recharge years.

6.2.2 The scenarios assessed.

Three scenarios were developed to test the sensitivity of streamflow and water supply security to this policy approach. These were:

- Scenario 4a: The nominal annual allocation limit was set at 40% of the long-term average land surface recharge.
- Scenario 4b: The nominal annual allocation limit was set at 50% of the long-term average land surface recharge.
- Scenario 4c: The nominal annual allocation limit was set at 70% of the long-term average land surface recharge

The actual annual allocation limit was calculated by applying the method described in 6.2.1 to these nominal annual allocation limits.

As before, we assumed that irrigation would be managed as normal until the actual annual allocation limit was reached, at which point irrigation pumping would cease.

The results presented below focus on Scenario 4a and Scenario 2b. We found the consequences of implementing Scenario 4c were almost identical to the option of having no fixed allocation limit at all. Scenario 4b did not benefit streamflow as much as Scenario 4a.

6.2.3 Effect on streamflow

The summary statistics for streamflow in Table 3 show improvements ranging from about 7.5% for the 7-Day MALF to 3% for the average mean daily flowrate.

Table 3: Simulated stream flow statistics for Selwyn River flow sites under current policy and a dynamic annual volume allocation policy

Stream name	Flow unit	Statistic	Current Policy	Dynamically Adjusted Nominal Annual Volume Limit of 80% of Current Fixed Limit
Selwyn River at Coes Ford	l/s	7-day MALF	479	515
		Average	2,708	2,796
		Median	1,428	1,547

This is a smaller improvement in the flow statistics than simply reducing the annual allocation limit, but still a worthwhile improvement from the current fixed limit.

Comparison between Figure 7, below, and Figure 4 shows, however, that the dynamic allocation method improves streamflow in the 1970/71 year about two weeks earlier than the fixed allocation limit having the same nominal value. But there is no real difference in streamflow between fixed and dynamic allocation in the previous year.

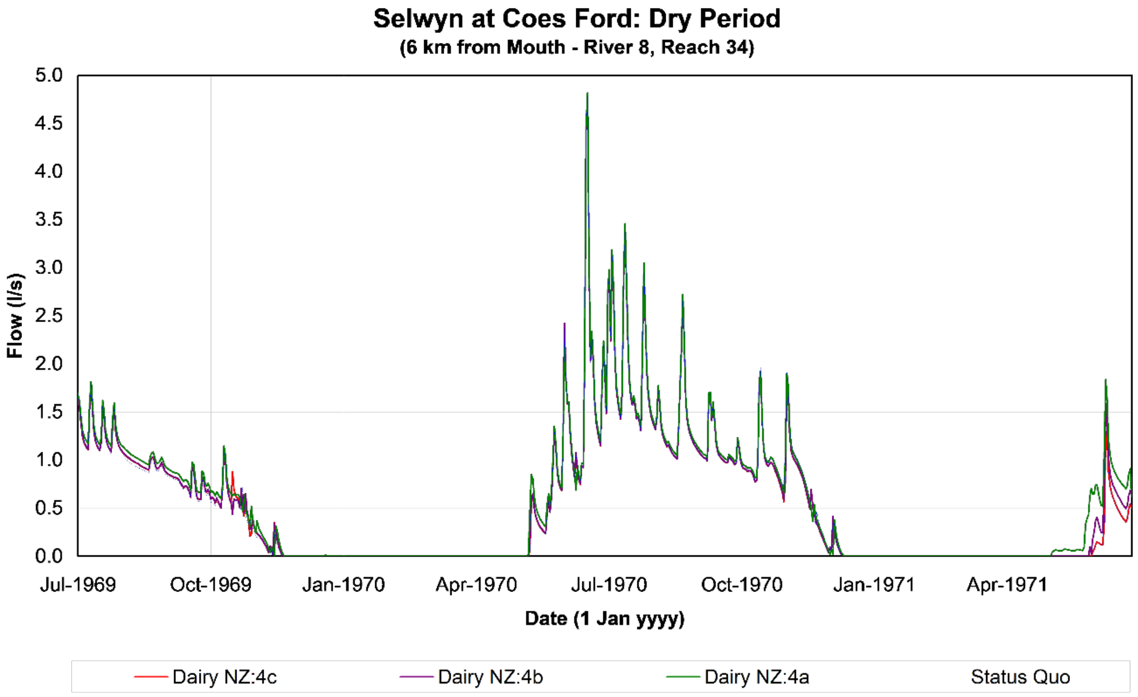


Figure 7: Effect on streamflow of dynamically changing the annual take volume limit.

6.2.4 Effect on groundwater supply reliability.

Figure 8, below, shows the modelled supply/demand ratio for an area of the Canterbury Plains that includes the case study area, over nearly forty years. This time period includes very high demand and low recharge years, such as 1969 to 1971, and very low demand and high recharge years, such as the late 1970's.

The intended effect of the allocation method on the supply/demand ratio of a succession of low recharge years can be seen in the years leading up to the 1972/73 year.

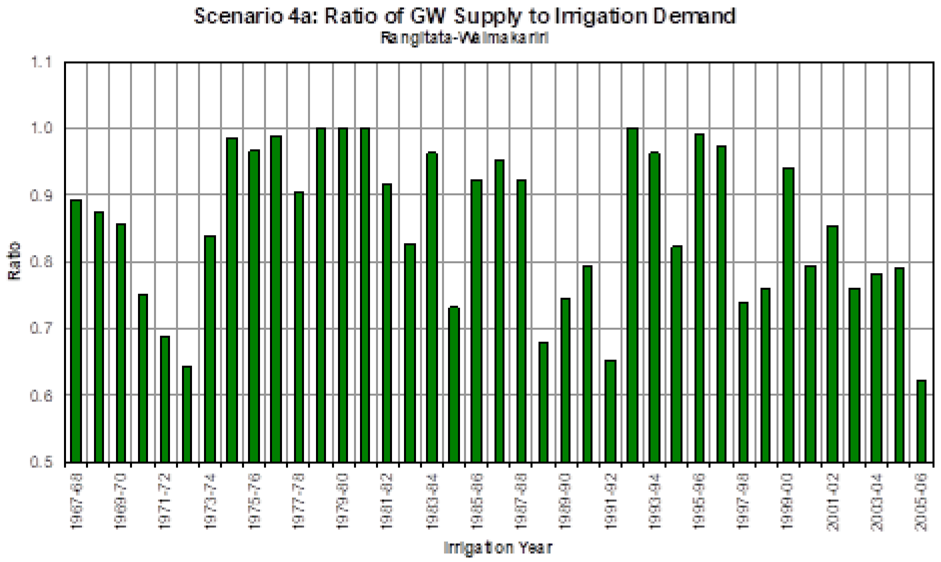


Figure 8: Temporal variation in the supply/demand ratio under a dynamic groundwater allocation regime.

Summary statistics on the frequency and duration of water supply restriction events, when supply did not meet demand, are shown in Table 4 below.

Table 4: Modelled water supply reliability metrics under the current fixed annual allocation policy and dynamic annual allocation.

		Current	Dynamic Allocation (nominal allocation 80% of Current)
Frequency	Number of restriction events	25	42
	Number of years in which restrictions occur	20	28
	% of years in which restrictions occur	51	72
Duration	Average days per event	31	43
	Maximum event length	88	118
	Average days per irrigation year	39	62

6.2.5 Discussion

The benefit of adjusting the annual take-volume limit based on prior year(s) recharge is in bringing the recovery of streamflow forward in some years, relative to the fixed limit scenario. Overall, the improvement in streamflow statistics is not as large as simply reducing the fixed limit, but still an improvement relative to the current fixed limit.

Implementing the dynamic allocation approach reduced the frequency of water supply restriction events, compared to simply reducing the fixed annual allocation. The proportion of years in which restrictions occurred reduced by ten percent.

However, there was no material change in the duration of restrictions, when they occurred.

While each of these policy options does improve stream low flows, the degree and timing of improvement is unlikely to be sufficient to improve the health of the waterway.

The core weakness of allocation approaches that set a limit on total annual water take is that they are reliant on the limit being consumed before it has any effect. This depends on water demand. If it’s a low water demand year the limit might not be reached at all, rendering the policy ineffective that year regardless of the state of the groundwater system. It is noteworthy that the policies tested were not able to prevent extended periods of zero flow in the Selwyn River at Coes Ford during the 1969/70 and 1970/71 summers.

7 EFFECTS OF POLICY OPTIONS THAT LIMIT PUMPING RATES

In an attempt to improve both the magnitude and timing of stream flow increases, we changed the basis of the policy method from an annual volume limit to varying the maximum rate of pumping.

7.1 Restricting the maximum rate of take based on prior groundwater recharge.

7.1.1 Restriction method

Prior to the beginning of each irrigation season, we set the maximum rate of pumping based on land-surface recharge in the preceding year(s). The nominal maximum rate of take was set at the usual irrigation system capacity for the study area (5mm/day or 0.6 litres/sec per hectare irrigated). The actual maximum rate of take was reduced following low recharge years.

The policies that we tested have four parameters:

- The maximum daily rate of water abstraction (expressed in mm/day).
- The allocation ratio, which is the ratio of the land-surface-recharge in the preceding hydrological year to the long-term average annual land-surface-recharge.
- The minimum allocation ratio (this ensures that there is always some allocation available).
- The earliest date in the hydrological year at which restrictions can be applied.

The parameters work together in the following way:

- In July/August each year the land-surface-recharge for the preceding hydrological year (1 July to 30 June) is estimated.
- This quantity is divided by the average annual land-surface-recharge to give the allocation ratio.
- The allowable daily rate of water abstraction for the coming irrigation season is calculated by multiplying the specified maximum daily rate (5 mm/day in our testing) by the allocation ratio, if the latter is at least as great as the minimum allocation ratio. Otherwise, the allowable daily rate is equal to the maximum daily rate multiplied by the minimum allocation ratio.
- The water user is able to take water at the maximum daily rate (e.g. 5 mm/day) up to the earliest date at which restrictions can be applied. Thus, the irrigation season is divided into two parts: the first part is not subject to water take restriction, and the second part is.
- This dynamic or agile groundwater allocation policy was tested for each combination of two parameters:
- Minimum allocation ratio (two values trialled: 0.5 and 0.4).
- Earliest date at which restrictions can be applied (two values trialled: 1 Dec and 1 Jan).

The maximum daily rate of take was set at 5 mm/day to match the design standard centre pivot irrigators are typically designed to meet.

Three different approaches to calculating the allocation ratio were investigated prior to choosing one for the testing outlined above. The simplest is to use the estimated land-surface-recharge for the preceding season. We also tested using the three-year moving average of the annual land-surface-recharge and an alternate “smoothing” method – the exponentially-weighted moving average. Testing showed that the smoothing methods damped out the effects of year-to-year variability too much to adequately protect instream flows.

7.2 Effects on Streamflow

The following table summarises the effects on instream (low) flows of one of the combinations of minimum allocation ratio and date at which restrictions can first be applied. In this case the minimum allocation ratio was 0.4, and 1st December was the earliest date from which restrictions could be applied. This restriction scenario is labelled "Future Restrictions 5" in Figures 9 to 11.

Table 5: Selwyn River modelled baseflow statistics in 2040's and 2080's compared to hindcast baseflow statistics, with and without restrictions. The flow units are cubic metres per second.

Baseflow Statistic	Baseline	RCP 2.6			RCP 4.5		
2040s	**Hindcast 20 years**	**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**	**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**
MALF baseflow	0.376	0.366	0.408	0.033	0.356	0.435	0.059
Median baseflow	1.024	0.989	0.998	-0.026	0.963	0.993	-0.031
Mean baseflow	1.061	1.035	1.051	-0.011	0.999	1.031	-0.031
Irrig season median baseflow	0.817	0.789	0.808	-0.009	0.763	0.816	-0.001
2080s		**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**	**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**
MALF baseflow	0.376	0.357	0.421	0.045	0.328	0.397	0.021
Median baseflow	1.024	0.977	0.995	-0.029	0.981	0.997	-0.027
Mean baseflow	1.061	1.015	1.041	-0.021	0.987	1.009	-0.052
Irrig season median baseflow	0.817	0.796	0.833	0.016	0.766	0.795	-0.022
		RCP 6.0			**RCP 8.5**		
2040s		**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**	**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**
MALF baseflow	0.376	0.341	0.402	0.027	0.317	0.414	0.038
Median baseflow	1.024	0.986	0.997	-0.027	0.901	0.931	-0.093
Mean baseflow	1.061	1.014	1.034	-0.027	0.930	0.971	-0.091
Irrig season median baseflow	0.817	0.750	0.774	-0.043	0.693	0.769	-0.048
2080s		**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**	**No Restriction**	**Restrictions Applied**	**Change from Baseline due to Restrictions**
MALF baseflow	0.376	0.309	0.375	-0.001	0.310	0.374	-0.002
Median baseflow	1.024	0.949	0.968	-0.056	0.919	0.940	-0.083
Mean baseflow	1.061	0.999	1.021	-0.041	0.970	0.993	-0.068
Irrig season median baseflow	0.817	0.735	0.771	-0.046	0.699	0.739	-0.078

The results show that this allocation policy is effective in ensuring that the Mean Annual Low Flow (MALF) is maintained at or above the MALF for the baseline (hindcast) 20-year period under all the RCPs except for RCPs 6.0 and 8.5 in the 2080s. The MALF is a critical statistic because key measures of the health of stream/river ecosystems are positively correlated to it. In summary, this analysis indicates that these policy parameters (0.4 and 1 December) would maintain MALF above recent "historical" values up until the 2080s across all of the RCPs modelled.

While this policy is effective in relation to low flow statistics, there are several low flow years when the policy provides little to no benefits to streamflow, as can be seen in the following figures.

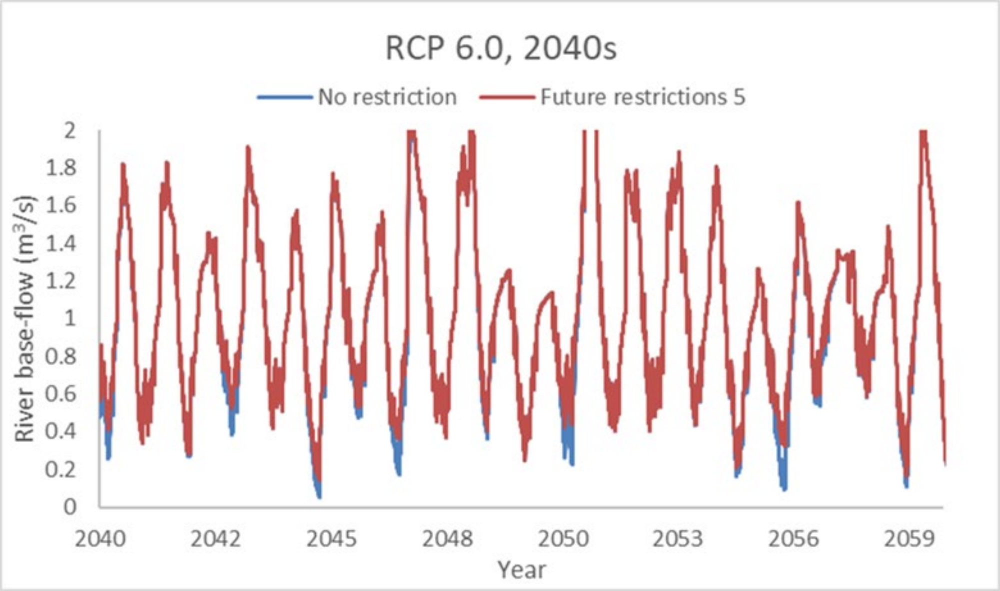


Figure 9: Effect on Selwyn River baseflow in the 2040's of varying the daily rate of water take according to the prior year's recharge.

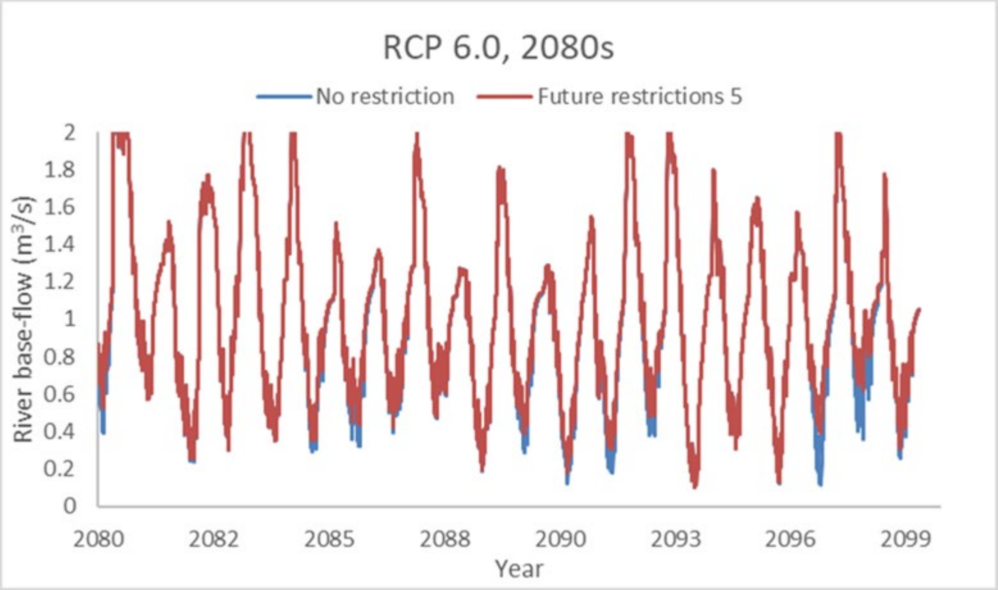


Figure 10: Effect on Selwyn River baseflow in the 2080's of varying the daily rate of water take according to the prior year's recharge.

7.2.1 Effects on Security of Groundwater Supply

The consequences on groundwater users of applying this groundwater allocation policy are indicated in the following allocation ratio time-series graphs, which show results for the scenario as above. Whenever the ratio is less than 1, water users cannot take groundwater at the maximum rate (of 5mm/day) from the restrictions start date.

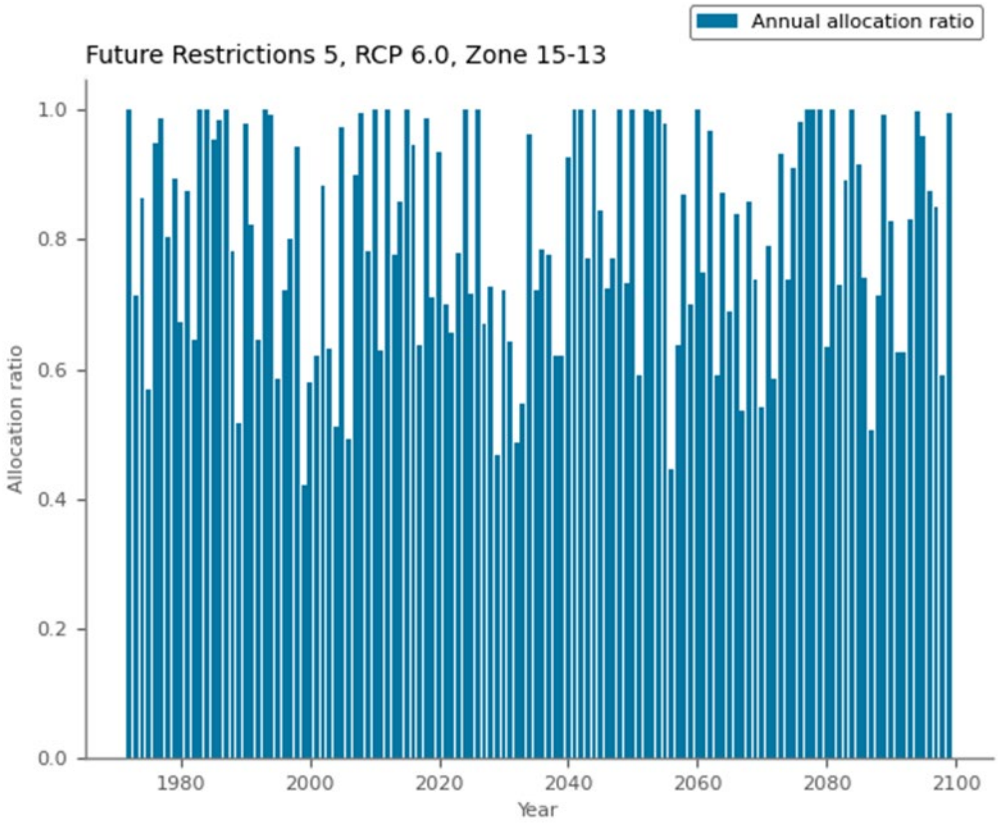


Figure 11: Effect on water supply security of varying the daily rate of water take according to the prior year's recharge.

7.2.2 Discussion

Figure 11 shows that the rate of supply from the restrictions start date (1 December) is less than 75% of the design flow rate in many years. There are very severe restrictions in some years.

The average security of supply over the modelled time-period is 80%.

The magnitude of the restrictions is sufficient to create operational difficulties for irrigated farms unless there are multiple irrigator units, one or more of which can be dropped out of service when a reduction in the pumping rate is required. With the move to centre pivot irrigators this is increasingly difficult – there are few irrigator units per property.

While the policy is effective in improving the MALF and maintaining the improvement out to almost 2080, there is little improvement in some low flow years, as noted in Section 2.2.1. One potential reason for this is that the method is based solely on land-surface-recharge, because it is relatively easily estimated and time-series analysis has shown that temporal variation in land-surface-recharge explains about 75% of the temporal variation in groundwater levels. The largest source of recharge is the Rakaia and Waimakariri Rivers. This is understood to have lower temporal variability than land-surface-recharge. But it is not constant over time. Thus, there is the possibility that this dynamic allocation method is not responding to low total recharge events.

7.3 Restricting the maximum rate of take based on Selwyn River flowrate.

Flowrate in groundwater dependent rivers and streams, such as the lower Selwyn River, respond to the integrated effects of all sources of recharge, and to the cumulative effects of all groundwater takes.

We therefore posed the question:

"What if the proportion of groundwater pumping that affects river flow was restricted on the same basis as surface water takes?"

That is: restrict groundwater takes throughout the Selwyn-Waihora zone based on the current flowrate in the Selwyn River at Coes Ford. Note that this goes beyond current practice, which restricts only those groundwater takes close to the river.

7.3.1 Restriction Method

To determine the proportion of groundwater pumping that affects river flow at the flow monitoring site at Coes Ford we simulated the effect on river flow of an additional groundwater take of 100 litres/second. We systematically varied the location and depth of this additional take to investigate the effects on river flow of distance from the coast (i.e., "allocation zone"), distance from the Selwyn River and pumping depth. The locations of the zones are shown in Figure 12. We used the Selwyn-Waihora groundwater/surface-water flow model in steady state mode to analyse the 45 cases involved.

Results from this steady state analysis suggested the following general responses in stream flows from groundwater abstraction at different distances from the Selwyn River, and at different depths (Table 6).

Table 6: Proportion (%) of groundwater take that depletes stream flow at the monitoring site, based on steady-state analysis. Percent depletion varies with distance from the coast and distance from the river and monitoring site of interest.

River Monitoring Site	Layer 1														
	Coast					Mid Plains					Inland				
Distance from river	100 m	250 m	500 m	1,000 m	2,000 m	100 m	250 m	500 m	1,000 m	2,000 m	100 m	250 m	500 m	1,000 m	2,000 m
Selwyn River Coes Ford	35	28	24	20	17	100	100	93	86	70	61	59	61	59	54
	Layer 2														
Selwyn River Coes Ford	27	25	23	20	16	43	43	43	42	40	35	35	35	36	36
	Layer 3														
Selwyn River Coes Ford	24	23	22	20	17	25	25	25	25	25	27	27	27	27	27

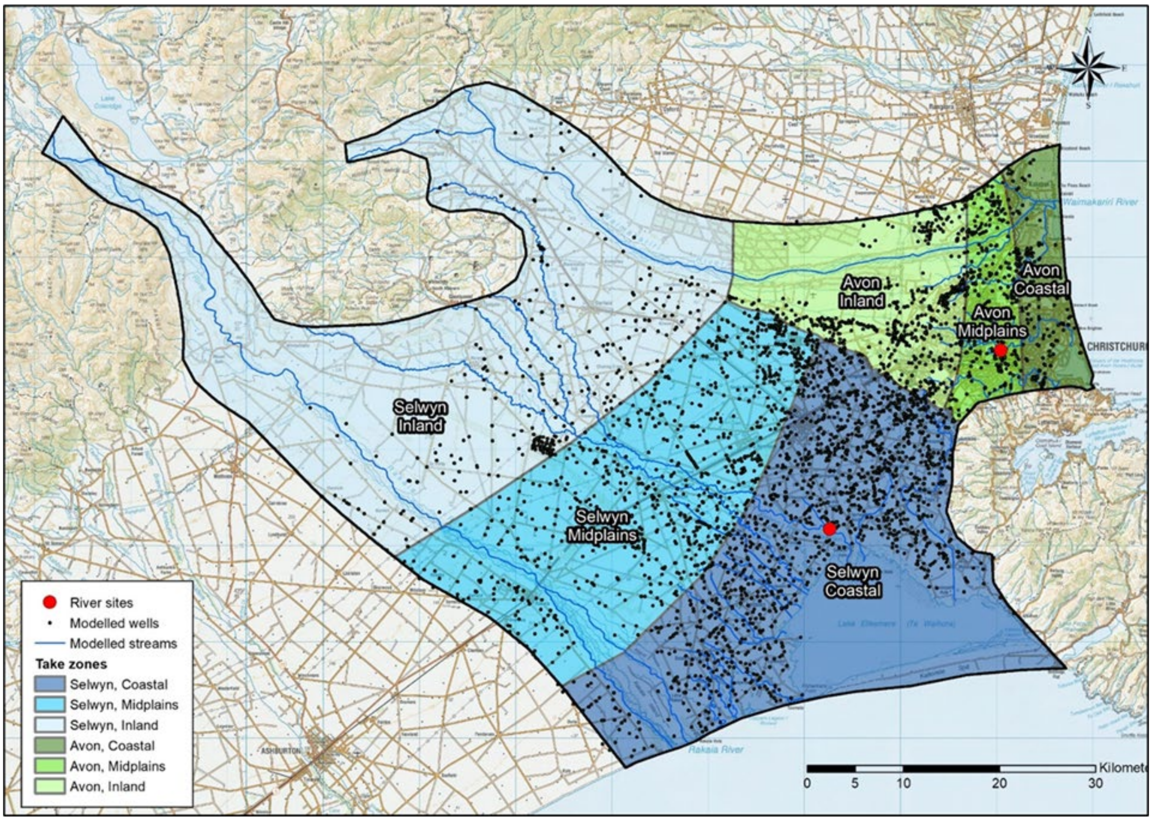


Figure 12: Map showing the location of the allocation zones assumed for scenario analysis.

To simplify the testing of this approach, we simplified the depletion rates in Table 6 with respect to the Selwyn River at Coes Ford to the following:

Layer 1:

- Coastal: Flows are depleted by approximately 30% of the take.
- Mid-plains: Flows are depleted by approximately 100% of the take.
- Inland: Flows are depleted by approximately 60% of the take.

Layer 2:

- Flows are depleted by approximately 40% of the take regardless of the location.

Layer 3 (and below):

- Flows are depleted by approximately 25% of the take regardless of the location.

To test the effectiveness of restricting groundwater takes based on river flow, the above depletion rates were used in our restriction method. For example, takes from Layer 1 wells located in the coastal zone near the Selwyn River were reduced by 30% when surface water takes from the Selwyn River were restricted.

In terms of when restrictions are triggered, Selwyn River flow has been used with the following preliminary cut-back criteria:

Selwyn River: Restrictions have been based on current low flow rules as follows:

• > 1.412 m3/s	No restrictions
• < 1.2 m3/s	Restricted
• 1.412-1.2 m3/s	Pro-rata restriction

The above generalised responses average the effects over different distances from the rivers. This was done to simplify the analysis. Investigating the feasibility and benefits of including distance from the river as a restriction parameter would be an informative next step if this policy approach warrants further development.

We assessed the effect of applying this policy by conducting a transient simulation using our integrated surface-water / groundwater model of the Selwyn-Waihora water management zone.

This was an iterative process, with the restrictions initially being based on measured river-flow time-series data. The second iteration used the modelled river-flow time-series from the initial run. Restrictions for the third run used modelled river-flows from the second iteration. By the end of the third iteration, modelled river-flow had reached a 'converged' solution (i.e., when the differences between subsequent scenario iterations became negligible).

7.3.2 Effect on stream flow.

The modelled flowrate in the Selwyn River at Coes Ford under three main scenarios is shown in Figure 13. The flowrate assuming no groundwater pumping is labelled "NoQ", the flowrate assuming current levels of pumping are labelled "Current", and the flowrate resulting from the application of the trial allocation policy are labelled "Restrictions1 etc." where the number is the iteration number. Thus "Restrictions 3" is the flowrate for the 'converged' solution.

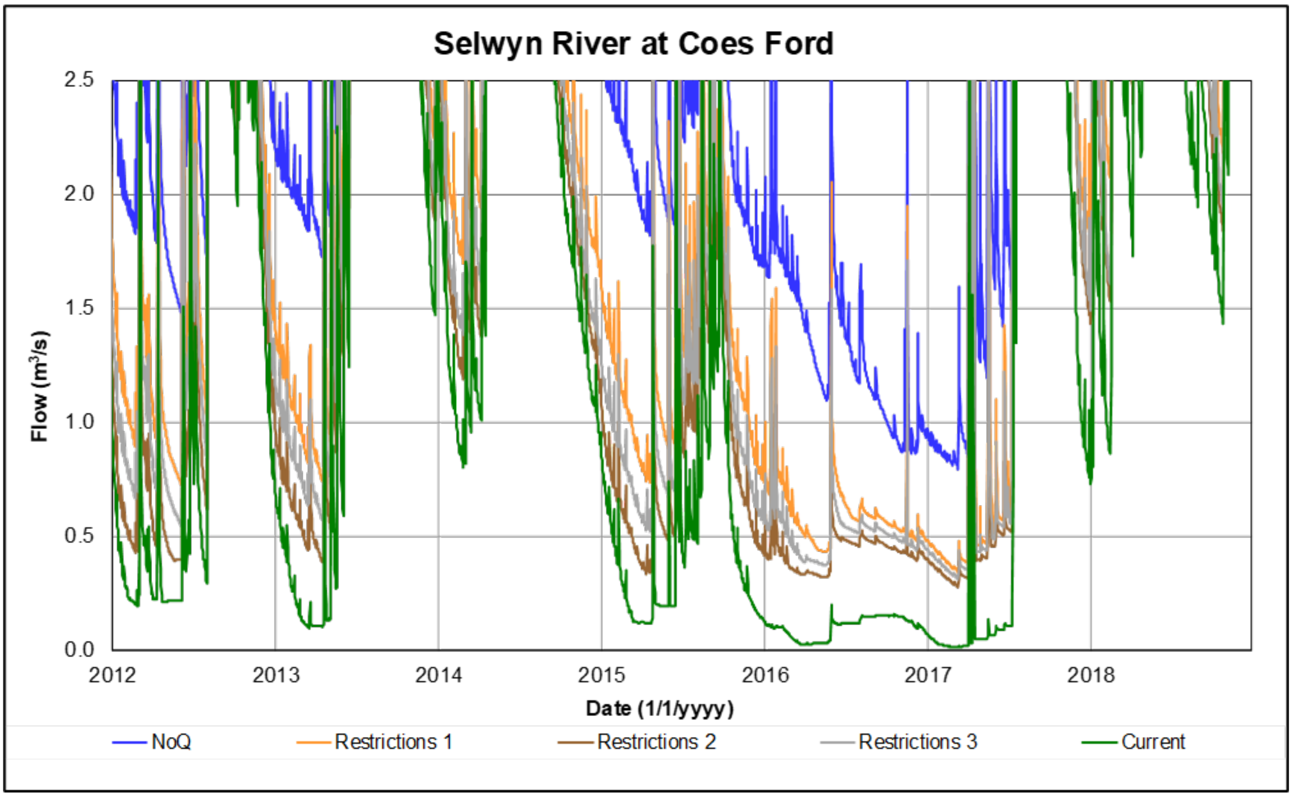


Figure 13: Effect on river flow of varying the daily rate of take from groundwater based on current Selwyn River flow – groundwater takes having the same cease-take-flowrate as surface water takes.

7.3.3 Effects on Security of Groundwater Supply

The effect of this trial policy on groundwater supply security is summarised in Table 7. Note that groundwater supply security is currently 100%.

Table 7: Effect on groundwater supply security of varying the daily rate of take based on current Selwyn River flow.

River site	Layer	Location	Average supply security
Selwyn at Coes Ford	Layer 1	Coastal	79%
		Mid-plains	28%
		Inland	57%
	Layer 2	All	71%
	Layer 3+	All	82%

7.3.4 Policy effectiveness under a future climate

The effectiveness of this policy option under a future climate driven by the RCP6.0 emissions profile was tested by conducting a transient simulation using our integrated surface-water / groundwater model of the Selwyn-Waihora water management zone. The simulated flowrate of the Selwyn River at Coes Ford over two future 20-year time periods is shown in the following figure.

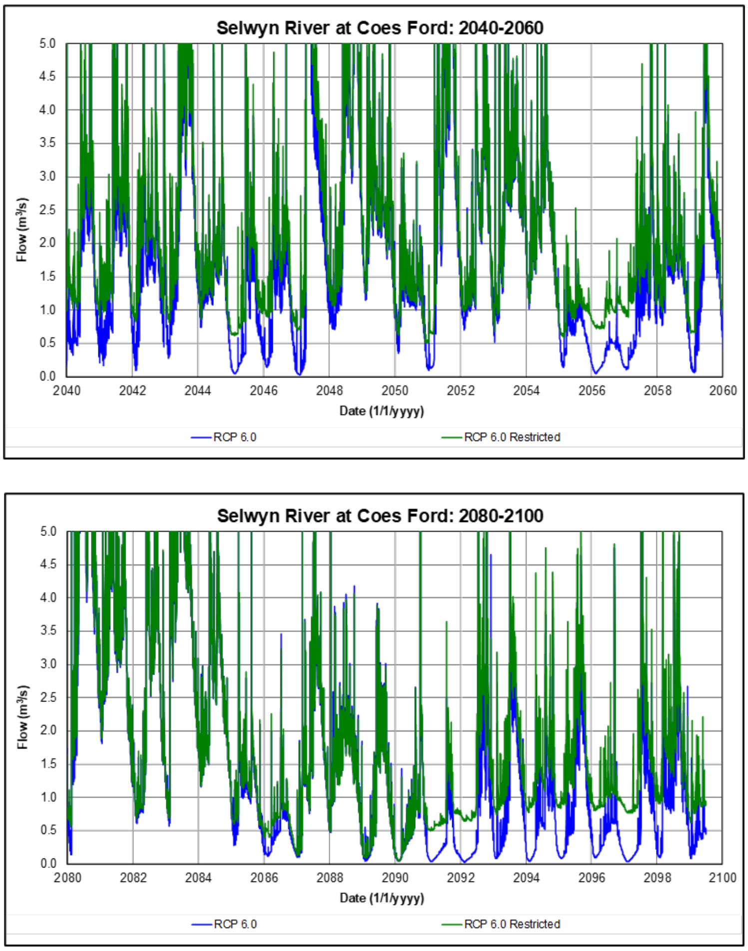


Figure 14: Projected long-term effect on Selwyn River flowrate of subjecting groundwater takes to the same cease-take-flowrate as surface water takes. Current policy: blue line. Flowrate restrictions policy: green line.

The effect of this policy option on average water supply security under a projected future climate is summarised in the following table.

Table 8: Effect on groundwater supply security of varying the daily rate of take based on Selwyn River flow under a projected future climate.

River site	Layer Groundwater taken from	Location	Avg. supply reliability
Selwyn at Coes Ford	Layer 1	Coastal	82%
		Mid-plains	39%
		Inland	63%
	Layer 2	All	76%
	Layer 3+	All	85%

7.3.5 Discussion

Existing groundwater abstraction is predicted to have reduced low flows in the Selwyn River by approximately 800 l/s during the very dry 2016-2017 period. Groundwater abstraction is predicted to have caused the river to stop flowing (or very nearly so), whereas it is predicted to have a minimum flow of around 800 l/s under the No Pumping (NoQ) scenario.

River flows after the third model iteration (i.e., essentially the converged solution) have improved, relative to the current situation, by between 300 and 400 l/s.

For all scenarios and iterations to this point, the land-surface recharge (LSR) remained as specified in the calibrated model (similar to the Current scenario). The effects of abstraction and subsequent water use were therefore overstated. Under the No Abstraction scenario, LSR will be less than under the other irrigated scenarios and therefore groundwater levels and river flows will be correspondingly lower. Consequently, the difference between the No Abstraction and the other scenarios will also be less.

To address this, we recalculated the LSR resulting from the restrictions applied in Iteration 3 and used it instead to update the model's inputs. Iteration 4, shown in Figure 14 below, shows the modelled flowrate after making this adjustment. The restrictions applied under Iteration 4 are predicted to restore approximately half of the pumping-induced effects on low flows in the Selwyn River over the very dry 2016-2017 period. Modelled low flows over this period are predicted to be in the order of 300 l/s whereas they would otherwise be dry (or very nearly so) under current policy (takes not restricted).

7.4 Restricting the maximum rate of take based on Selwyn River flowrate and applying a higher cease-take-flowrate to groundwater takes.

The cumulative effect of all groundwater takes is to reduce the Selwyn River flowrate below what it would otherwise be. The groundwater takes are therefore affecting the security of supply of surface water takes. We therefore posed the question "could the effect of the groundwater takes on surface water takes be eliminated by raising the cease take flow rate for the groundwater takes?"

7.4.1 Method

Following on from Iteration 4, the low flow restrictions were raised under a new scenario (iteration 5) by the approximate difference in low flows between a No Groundwater pumping scenario and Iteration 4. The purpose of this scenario was to test if a higher cease take flow can completely offset the difference in river flows due to groundwater abstraction by restricting groundwater takes during low flow periods.

This scenario is based on iteration 4 but with the cease-take flowrate approximately 300 l/s higher. LSR was recalculated to reflect the new restrictions on the use of groundwater for irrigation.

7.4.2 Effect on streamflow

Figure 15 below compares the flowrate in the Selwyn River at Coes Ford under two different cease-take flowrates for groundwater takes: same as for takes from surface water (Iteration 4) and 300 l/s higher than that for surface water takes (Iteration 5).

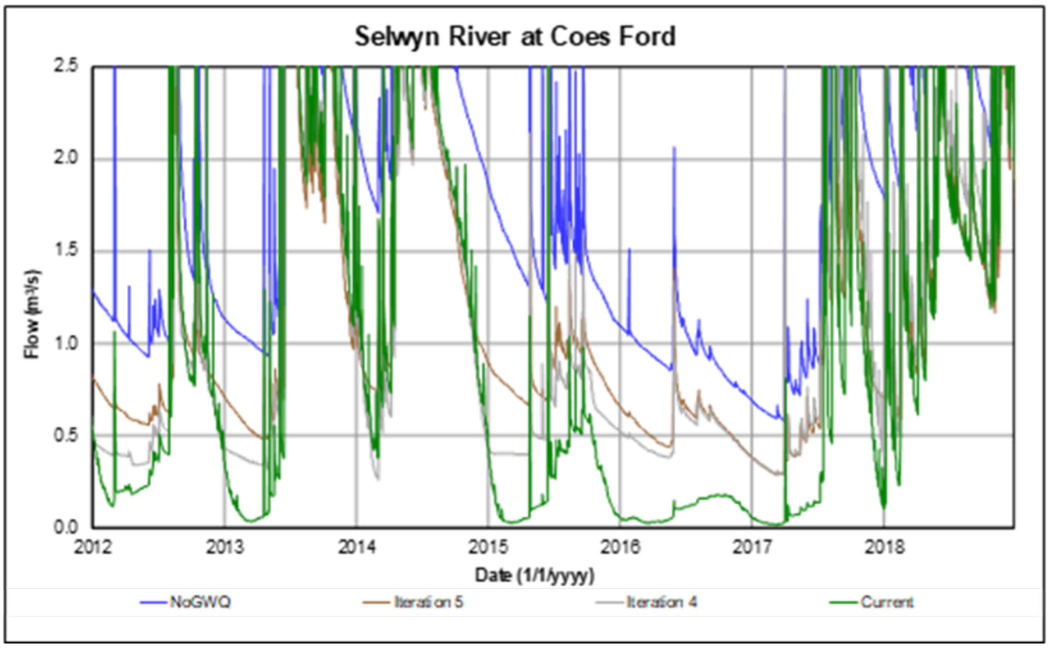


Figure 15: Effect on river flow of varying the daily rate of take from groundwater based on current Selwyn River flow – groundwater takes having a higher cease-take-flowrate than surface water takes.

Under Iteration 5, river flows are generally higher (as restrictions are more frequent and more severe), but river flows during extreme low flow events are predicted to be similar, or only marginally higher, than Iteration 4 (same cease-take flowrate for surface water and groundwater takes). For the Selwyn River, flows are higher (by approximately 150-400 l/s) than Iteration 4 leading into the dry periods, but once the dry summer of 2017 is reached, modelled flows are effectively the same between iterations 4 and 5.

Under Iteration 5, the additional restrictions (compared to Iteration 4) recover approximately half (at most) of the depletion between the No Groundwater Abstraction scenario and Iteration 5. The higher restrictions therefore do not completely offset the differences in river flows due to groundwater abstractions.

The results suggests that the further the natural flow (i.e. unaffected by abstractions) is below the surface water cease take flow, the smaller the increase in river flow due to applying a higher cease-take flowrate for groundwater takes than for surface water takes.

7.4.3 Effect on security of supply

Comparing Table 8, below, with Table 7 above indicates that increasing the cease-take flowrate for groundwater takes by 300 l/s has little effect on average annual groundwater supply security.

Table 9: Effect on groundwater supply security of applying a higher cease-take-flowrate to groundwater takes than to surface water takes.

River site	Layer	Location	Average Supply Security
Selwyn at Coes Ford	Layer 1	Coastal	78%
		Mid-plains	27%
		Inland	56%
	Layer 2	All	71%
	Layer 3+	All	82%

Neither scenario provides sufficient water supply security for high value land uses. For takes from layer 3 or deeper it is barely adequate for pasture-based farm systems, such as dairy farming.

7.4.4 Summary

Under the groundwater allocation policy that restricts all groundwater takes based on the flow in the Selwyn River at Coes Ford, the stream depletion effects of all groundwater takes would be significantly less than in the past, but still about a 400 litres/second reduction in Selwyn R during low flow period.

This policy approach appears to be effective in raising low flows under projected future climate, noting that we have tested it using only one climate projection and there are three summers in the late 2080's that show no improvement. Both aspects warrant further investigation.

Setting the cease-take flowrate for groundwater takes at a higher value than for surface water takes provided limited benefit to streamflow in the years with lowest flows.

While the various types of policy tested do increase the low flow part of the flow regime, we can't eliminate the effect of groundwater takes on surface water flow rates.

We have not found a groundwater take restriction policy that isolates surface water takes from the cumulative effects of the groundwater takes. Groundwater takes and surface water takes must therefore be managed together – that is, integrated management. It is unrealistic to define allocation rules for each independently of the other and expect to be able to prevent surface water allocation limits being breached.

Under this policy approach, reliabilities are barely adequate for takes from layer 3, or deeper. All takes from shallower layers (aquifers) are not sufficiently reliable to sustain current water uses. There may be a small increase in groundwater supply security under future climates – this warrants further investigation.

8 SUMMARY

In most areas of New Zealand, water allocation rules are currently based on flowrate statistics – mean annual seven-day low flow (rivers) and mean annual land-surface recharge (groundwater). These statistics are almost certain to change due to climate change. If current allocation policies continue, it is to be expected that allocation rules defined by applying these policies would change as the flow statistics change.

Changes in the MALF in the rivers that flow into the case study area are spatially variable. For the Upper Selwyn catchment, the MALF is expected to remain stable or decrease by 5 to 10% by 2100. Over the same period the MALF is expected to remain stable with “overs and unders” for the Rakaia River at the Gorge and southern part of the Upper Waimakariri catchment, while the northern part of the Upper Waimakariri catchment is expected to see a large decrease (up to 40%) under the most extreme radiative forcing scenario (RCP8.5). Under current allocation policy, the average number of days on which water takes are restricted is projected to increase by about 1.5% for the Rakaia at the Gorge under all RCP scenarios modelled. For the Waimakariri at Otarama, the increase is projected to be between 10% (RCP2.6) and 37% (RCP8.5).

If a river or streams MALF increases due to climate change, the cease take flow could increase to secure the stream health benefits, potentially with little impact on abstractors. Such a change could be achieved through the normal 10 yearly regional plan review cycle. A more agile response is unnecessary because the average rate of change is projected to be low. If the MALF is decreasing, there appear to be no significant benefits to low flows in changing the cease-take flow. The only option appears to be flow augmentation if the objective is to maintain or increase future MALF relative to its historic value.

The current groundwater allocation policy applied in most regions with alluvial groundwater systems enables the taking of groundwater at up to a specified maximum flowrate (litres/sec), provided the annual volume of water taken does not exceed a specified limit. Both parameters – flowrate and seasonal volume taken – are the same each year, regardless of the current state of the groundwater resource. For groundwater bores close to rivers, the flowrate is usually reduced in a manner consistent with restrictions on takes directly from the river.

Environmental monitoring has provided evidence that the current groundwater allocation policy is not delivering the levels of stream health that were intended, particularly in the lower Selwyn River. Previous studies of the potential effects of climate change on groundwater levels and discharges indicated significant adverse impacts on groundwater dependent streams. Instream health is likely to deteriorate further as the climate changes if the status quo is maintained.

Alternative policy approaches that could potentially increase low flows in groundwater dependent rivers and streams are set out below, grouped under those that are “demand management” focussed and those that are “supply side” focussed.

Policies that reduce demand.

- Reduce the annual volume limit on groundwater takes, no year-to-year variation (a simple variation on current policy).
- Vary the annual volume limit on groundwater takes based on prior year(s) recharge.
- Shift groundwater takes onto surface water supplies.
- Vary the maximum daily rate of take based on prior year(s) recharge – mimics restrictions on surface-water takes.
- Vary the maximum daily rate of take based on the current flowrate in the Selwyn River at Coes Ford.

Policies that enhance groundwater recharge.

- Increase irrigated area.
- Managed aquifer recharge.

Our research focussed on testing “demand management” policy approaches because the effectiveness of policies that enhance groundwater recharge tend to be very catchment specific. In the case study area, for example, there is limited scope to increase irrigated area (due to water quality constraints) and the real long-term benefits to stream flowrates of managed aquifer recharge are uncertain.

We designed and tested, through computer simulation modelling, many versions of each of the demand management policy approaches. The aim of this experimental development process was to explore the benefits to instream flows and the effects on water supply security of each approach.

Allocation policies based on setting a limit on the annual volume of water taken are ineffective for meeting ecological aspirations in most years. This is because the limit is set at a level that is generally high enough to fully meet demand in ninety percent of years. In those years when the limit is reached it is usually late autumn, by which time stresses on river or stream flow rates and ecological quality are often reducing anyway.

Allocation policies that vary the maximum daily rate of take based on the state of the aquifer system or the current flowrate in a sentinel river, such as the Selwyn River at Coes Ford for the case study area, were found to be the most effective in terms of increasing river and stream flowrates during low flow periods (summer and autumn). It appears this effectiveness will be sustained under future climate.

While the scenario based approach we took was effective in identifying the most effective demand-management approach to increasing stream flowrates in low flow periods, a more automated way of tuning the parameters is needed to determine the best policy parameters for a specific catchment.

Shifting existing groundwater takes onto surface water supplies permanently reduces the total daily rate of take from groundwater. Though not tested, we expect it to be as effective in raising river and stream flowrates during summer/autumn as the policies that restrict the daily rate of take. The feasibility of implementing this option depends on being able to access a surface water supply that has an acceptable level of water supply security. None are currently available in the case study area.

A groundwater allocation management policy that isolates surface water takes from the cumulative effects of the groundwater takes was not found. Groundwater takes and surface water takes must therefore be managed together – that is, integrated allocation management is required. It is unrealistic to define allocation rules for each independently of the other and expect to be able to prevent surface water allocation limits being breached.

Having the agility to manage allocations in response to short-term climate variations is critical to maintaining or improving stream-health and enables adaptation to a changing climate. This is important because short-term variations are expected to become more extreme.

In the case study area, allocation policies that are the most effective in terms of increasing river and stream flows during summer/autumn significantly reduce groundwater supply security. For takes from deeper aquifers, the security of supply would reduce from 100%, under current policy, to about 80%. This is similar to water supply security from the Waimakariri River. The security of supply of takes from shallower aquifers would reduce to levels that would not be viable for urban, commercial or primary sector water uses.

Changing groundwater water allocation policy to improve stream flows would result in a significant reallocation of climate related risk – more will be borne by the primary sector. This will have economic and social impacts.

9 CONCLUSIONS

Having the agility to manage allocations in response to short-term climate variations is critical to maintaining or improving stream-health and enables adaptation to a changing climate. This is important because short-term variations are expected to become more extreme.

Allocation policies that vary the maximum daily rate of take based on the state of the aquifer system or the current flowrate in a sentinel river were found to be the most effective in terms of increased river and stream flowrates during low flow periods (summer and autumn). This is likely to be the case in most New Zealand alluvial groundwater systems which have groundwater dependent rivers or streams.

The scenario-based approach has identified what we believe to be the right type of agile, adaptive water allocation policy for improving low flows in rivers and streams.

Integrated management of surface water and groundwater takes is essential to achieving river and stream health objectives.

Allocation policies that are the most effective in terms of increasing river and stream flows during low flow periods significantly reduce groundwater supply security. For takes from deeper aquifers in the case study area, the security of supply would reduce to a level similar to surface water supply security. The security of supply of takes from shallower aquifers would reduce to levels that would not be viable for urban, commercial, or primary sector water uses.

10 RECOMMENDATIONS

1. Widen the scope of this policy analysis beyond increasing river and stream flowrates to include quantifying the effects of allocation policy options on:
    a. The security of supply for municipal and industrial groundwater takes.
    b. Technical and financial effects on farmers reliant on groundwater for irrigation.

2. Investigate infrastructure based options for increasing stream flows – that is, supply-side options. These could range from storage options for mitigating the effects on water supply security of implementing groundwater allocation options that improve river and stream low flows to options that directly enhance low flows.

3. Develop an automated method for tuning the parameters needed to determine the best policy parameters for the most effective groundwater allocation approach for a specific catchment.

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Appendix A: Alpine and Foothills River Flow Modelling

A.1 Introduction

To provide projected future surface water flows to be used as model inputs, NIWA were sub-contracted to calibrate and run TopNet – now the NZ Water Model (NZWaM) – for the four RCPs. This Appendix summarises NIWA's reporting on the model calibration, and the comparison between the baseline and projected climates.

There are three key measures of the quality of the river flow model calibration among the calibration technical summary set out below. These are:

- The mean annual runoff – a comparison of modelled and measured shows whether the model vs measured mass balance match well enough.
- Nash Sutcliffe (NS) calibration statistic – comparison of modelled and measured shows whether the modelled mean daily flows match the measured well enough.
- Modelled vs measured flow duration curves. This is an important visual check of how well the modelled flows match the measured. For this project the match at the low flow end of the range is important because this has a significant effect on run-of-river water supply reliability.

Calibration results for the Upper Selwyn and Waimakariri Rivers are included in the following Sections. Full details of the calibration are provided in Zammit and Shiona (2021)[1].

A.2 Calibration

Upper Selwyn at Whitecliffs

The modelled mean annual runoff (629 mm/yr) matches very closely the observed (634). This is also indicated by the cumulative daily flow curve in Fig 4-2.

The NS statistic indicates a good correlation. It would be nice if it was higher but it is difficult to achieve a close match of both low flows and flood flows.

The modelled flow duration curve is a good match to the observed flow duration curve, as shown in Fig 4-2. There is some departure at very low flows but these aren't likely to have a material effect on modelled water availability from the Selwyn River.

The calibration period was chosen January 2002-December 2010. It is a continuous period that contains the lowest annual average discharge (2005) as well as annual observations above average flow conditions (2008).

Table A.1: Calibration- validation statistics for the Selwyn at Whitecliffs

Location	Calibration (2002-2010)		Validation (1973-2019)			
	NSlog	NS	NSlog	NS	D	VE
Selwyn at Whitecliffs	0.922	0.556	0.913	0.536	0.836	0.536

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[1] Zammit, C. and Siona, H. (2021). Surface water hydrology of the upstream Waimakariri and Selwyn catchments. NIWA report number 2021014CH, prepared for Aqualinc Research Ltd.

Table A.2: Simulated water balance by TopNet for Selwyn at Whitecliffs catchment over the period of observations and simulation (1986-2014) compared with the long term average observed discharge and climatology

Annual Average Flux	TopNet (1973-2014) (mm/yr)	Observed (1973-2014) (mm/yr)	Long term average climatology (mm/yr)
Mean annual precipitation	1224	NA	1364
Mean annual evaporation	594	NA	725
Mean annual runoff	629	634	NA

Table A.3: Simulated and Observed flow characteristics for Selwyn at Whitecliffs catchment over the period 1973-2020

Annual Average hydrological characteristics	TopNet (1973-2020) (m^3/s)	Observed (1973-2020) (m^3/s)
Mean Annual Flow	3.282	3.310
Median Flow (Q50)	2.261	2.053
Q75	1.260	1.187
7dayMALF	0.753	0.760
Q95	0.645	0.704

Table A.4: Simulated and Observed eco-hydrological characteristics for Selwyn at Whitecliffs over the period 1973-2020

Eco-hydrological characteristics	TopNet (1973-2020)	Observations (1973-2020)
Average number of consecutive days below 7day MALF	9.	8
Median number of consecutive days below 7day MALF	6	6
Maximum number of consecutive days below 7day MALF	98	89
Average number of events below 7day MALF for 14 consecutive days over the period 1986-2014	6	6
Median number of events below 7day MALF for 14 consecutive days over the period 1986-2014	0	0
Maximum number of events below 7day MALF for 14 consecutive days over the period 1986-2014	83	74

Table A.5: Simulated and Observed monthly average flows for Selwyn at Whitecliffs catchment over the period 1973-2020

Annual Monthly Flows	Observed (1973-2020) (m^3/s)	TopNet (1973-2020) (m^3/s)
January	1.974	2.003
February	1.813	1.844
March	2.329	2.2784
April	2.757	2.659
May	2.849	3.305
June	3.694	3.865
July	4.569	4.210
August	5.255	5.615
September	4.481	4.919
October	4.241	3.799
November	2.299	2.619
December	2.501	2.169

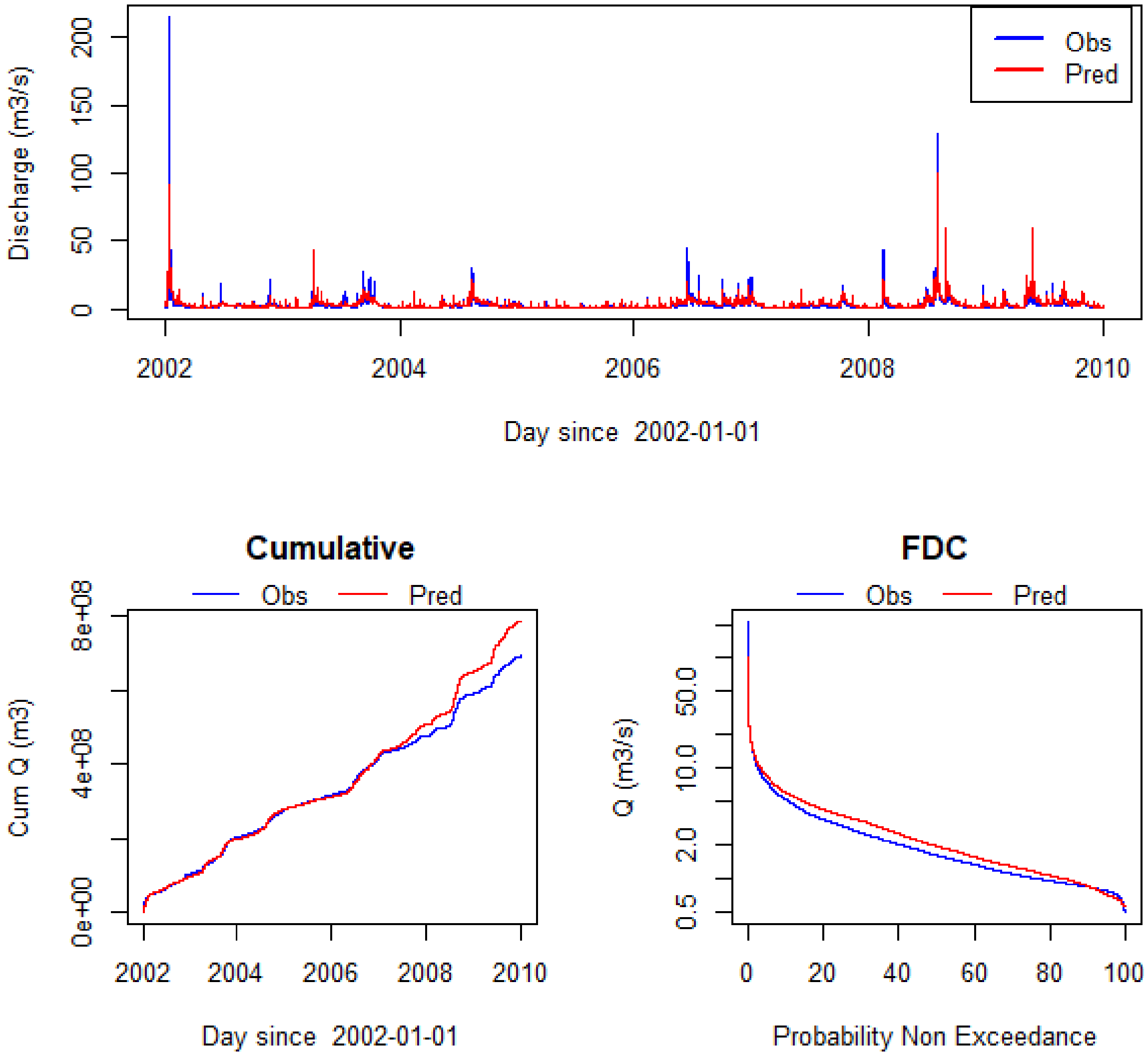


Figure A.1: Calibrated hourly hydrograph, cumulative hydrograph and flow duration curve of Selwyn at Whitecliffs over the calibration period 2002-2010.

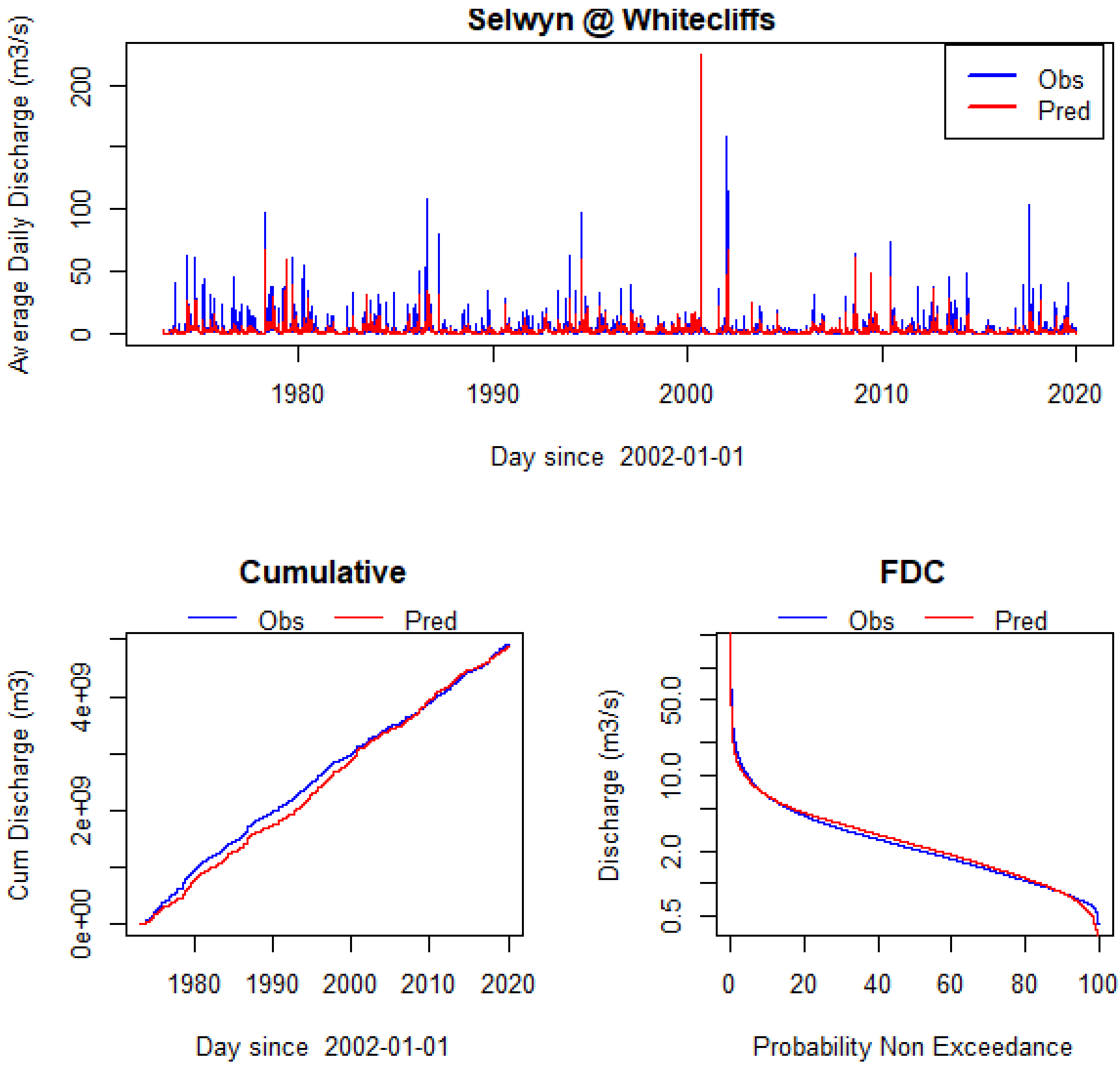


Figure A.2: Simulated daily hydrograph, cumulative hydrograph and flow duration curve of Selwyn at Whitecliffs over the validation period 1973-2020.

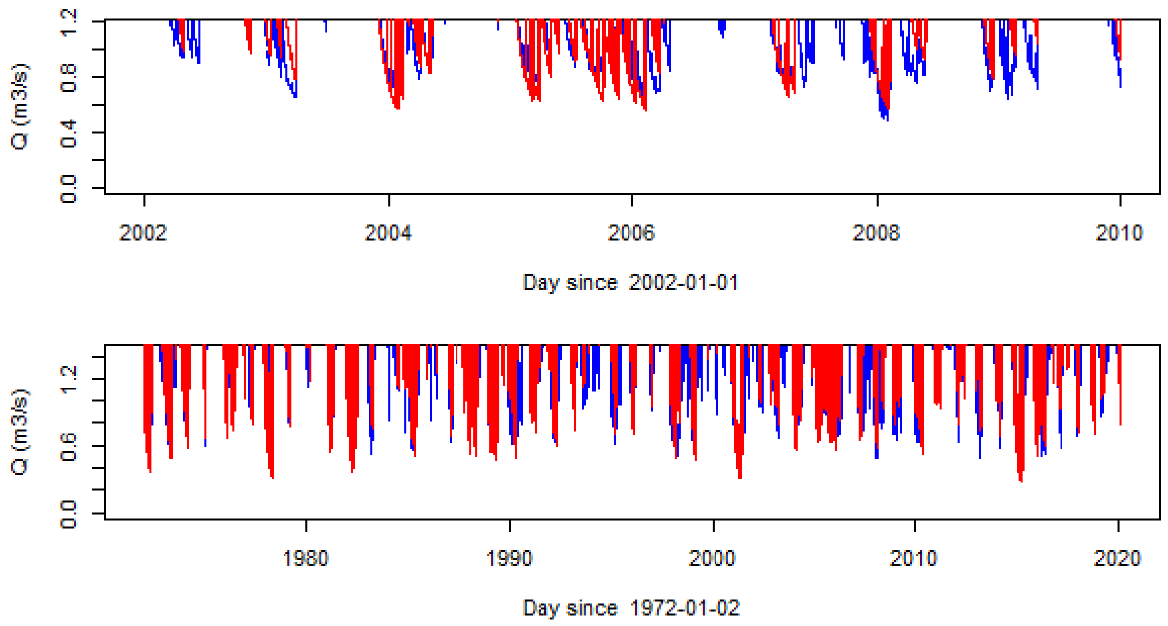


Figure A.3: Observed and simulated hourly low flow hydrograph (i.e., flow below observed Q50) for Selwyn at Whitecliffs over the calibration period (top) and validation period (bottom).

Upper Waimakariri Catchment

The modelled mean annual runoff (1662 mm/yr) matches very closely the observed (1599). This is also indicated by the cumulative daily flow curve in Fig A.4.

The NS statistic indicates a good correlation – better than for the Selwyn at Whitcliffs.

The modelled flow duration curve is a good match to the observed flow duration curve, as shown in Fig A.4. There is some departure at very low flows but this is at flows lower than the current minimum flow so has no effect on water supply reliability.

Note that information is also presented for the Waimakariri at below Otarama. This is for a very short period of record only so, while it is of interest, we put no weight on its values.

Overall, these calibration results are very acceptable for the purposes of the overall project. In fact, they represent a worthwhile improvement on the outputs from the NZ Water Model that we've worked with previously.

The calibration period was chosen January 2011-December 2014. It is a continuous period that contains the lowest annual average discharge (2012) as well as the highest annual average discharge (2013). Due to the short length of observation at that site, the validation period contains the calibration period.

Table A.6: Calibration- validation statistics for the Waimakariri at Otarama.

Location	Calibration (2011-2014)			Validation (2008-2016)		
	NSlog	NS	NSlog	NS	D	VE
Waimakariri at Otarama	0.927	0.639	0.923	0.585	0.863	0.743

Table A.7: Simulated water balance by TopNet for Waimakariri at Otarama catchment over the period of observations and simulation (2008-2016) compared with the long term average observed discharge and climatology

Annual Average Flux	TopNet (2008-2016) (mm/yr)	Observed (2008-2016) (mm/yr)	Long term average climatology (mm/yr)
Mean annual precipitation	2049	NA	2248
Mean annual evaporation	494	NA	650
Mean annual runoff	1662	1599	NA

Table A.8: Simulated and Observed flow characteristics for Waimakariri at Otarama catchment over the period 1973-2020

Annual Average hydrological characteristics	TopNet (1973-2020) (m^3/s)	Observed (1973-2020) (m^3/s)
Mean Annual Flow	113.628	114.000
Median Flow (Q50)	91.327	88.219
Q75	65.589	64.842
7dayMALF	38.475	42.504
Q95	43.813	45.353

Table A.9: Simulated and Observed eco-hydrological characteristics for Waimakariri at Otarama over the period 1973-2020

Eco-hydrological characteristics	Simulated (2008-2016)	Observed (2008-2016)
Average number of consecutive days below 7day MALF	7	6
Median number of consecutive days below 7day MALF	5	4
Maximum number of consecutive days below 7day MALF	20	11
Average number of events below 7day MALF for 14 consecutive days over the period 1986-2014	1	0
Median number of events below 7day MALF for 14 consecutive days over the period 1986-2014	0	0
Maximum number of events below 7day MALF for 14 consecutive days over the period 1986-2014	5	0

Table A.10: Simulated and Observed monthly average flows for Waimakariri at Otarama catchment over the period 2008-2016

Annual Monthly Flows	Observed (2008-2016) (m^3/s)	Simulated (2008-2016) (m^3/s)
January	122.819	132.511
February	69.310	82.681
March	63.392	71.002
April	78.421	99.766
May	136.161	157.806
June	116.289	120.430
July	106.019	91.836
August	118.080	115.227
September	134.690	139.084
October	162.770	146.638
November	128.328	100.431
December	124.679	103.691

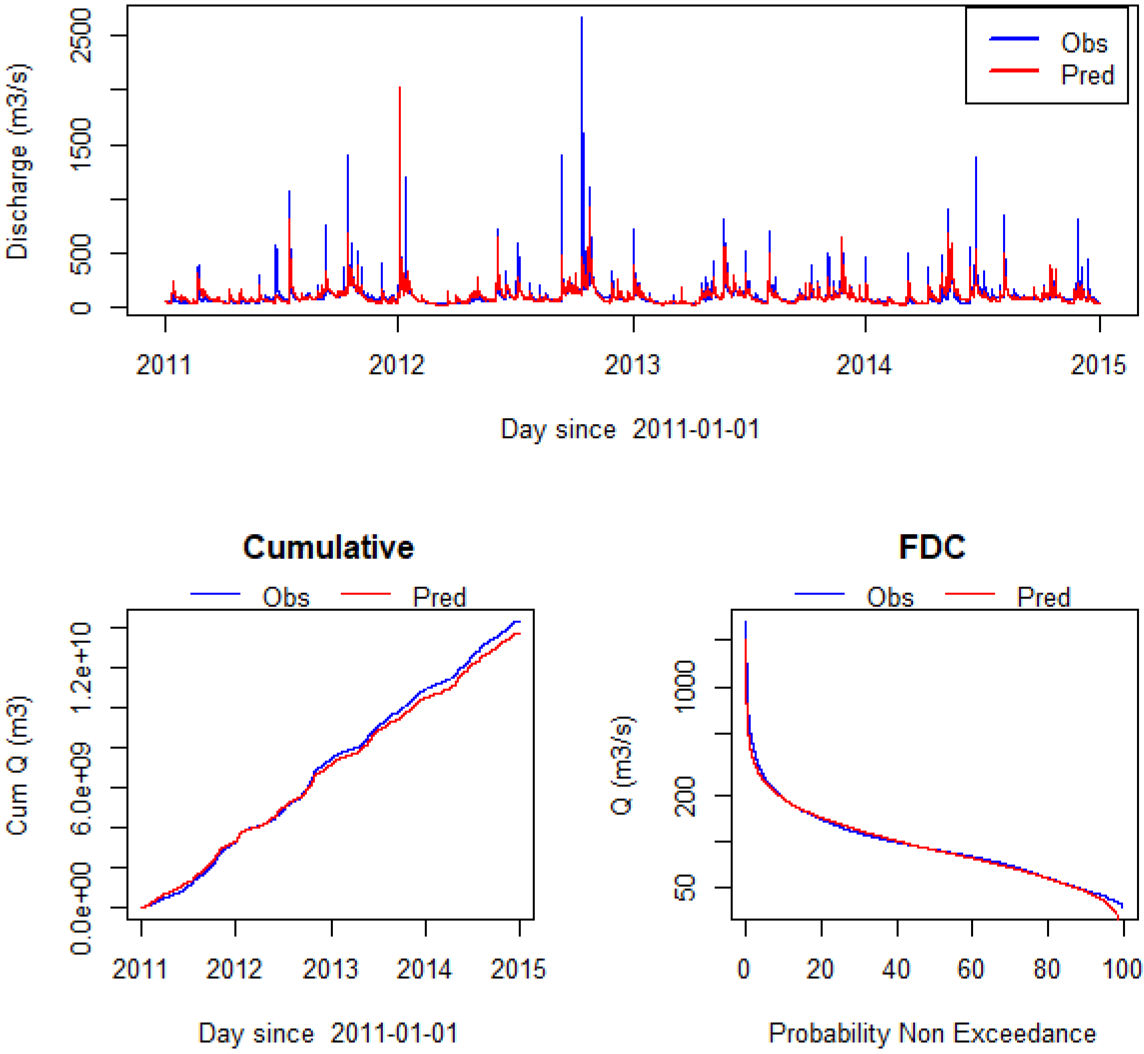


Figure A.4: Calibrated hourly hydrograph, cumulative hydrograph and flow duration curve of Waimakariri at Otarama over the calibration period 2011-2014.

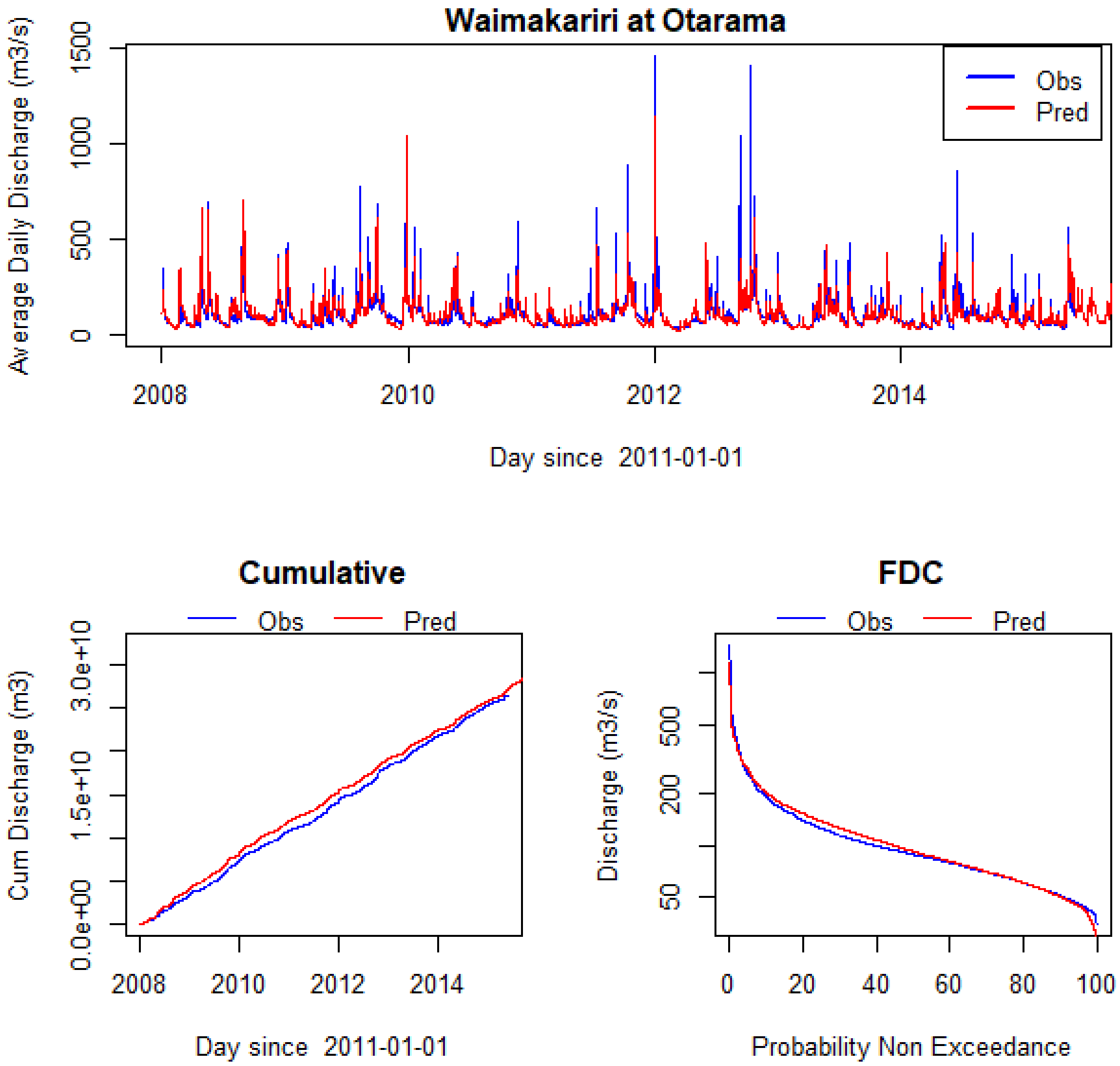
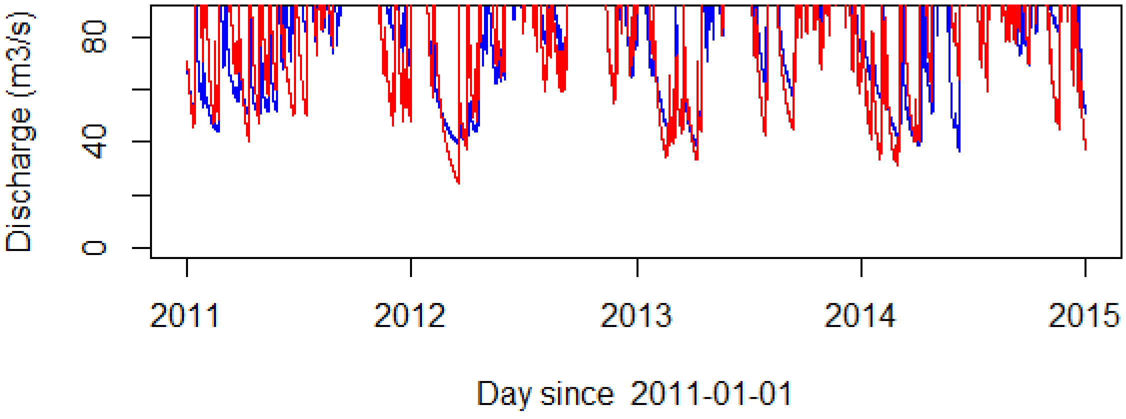


Figure A.5: Simulated daily hydrograph, cumulative hydrograph and flow duration curve of Waimakariri at Otarama over the validation period 2007-2016



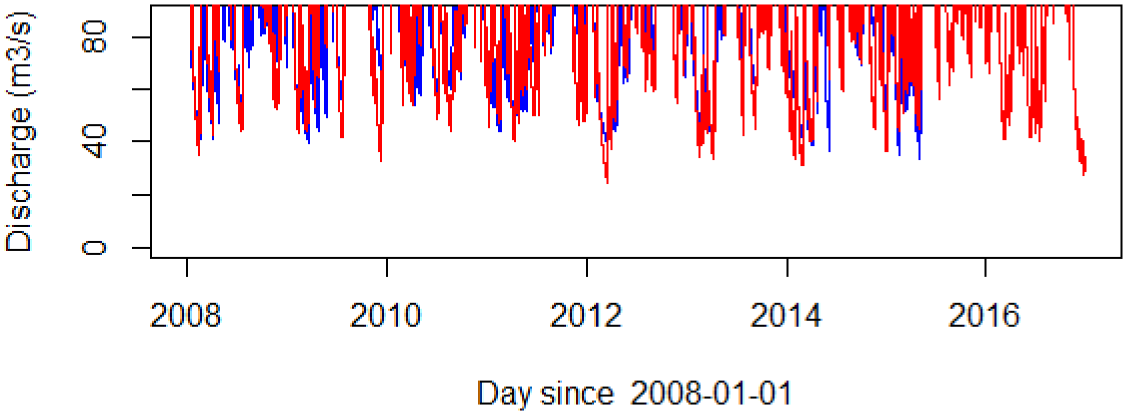


Figure A.6: Observed and simulated hourly low flow hydrograph (i.e., flow below observed Q50) for Waimakariri at Otarama over the calibration period (top) and validation period (bottom).

A.3 Flowrates under future climate scenarios

Following model calibration (as discussed above), flows in the Upper Selwyn and Waimakariri Rivers were modelled by NIWA and provided as daily time-series data for use in subsequent modelling steps. Key results of this work are as follows:

- Average flows are expected to slightly increase up across radiative forcing scenarios to 10% by the end of the century for the Upper Selwyn catchment and up to 5% for the Upper Waimakariri catchments.

- Median flows are expected to remain stable up to mid-century for both catchments. Past mid-century, median flows are expected to increase slightly by 5% by the end of the century for the Upper Selwyn catchment but decrease by 5% in the Upper Waimakariri catchment. The difference in behaviour of the mean and median flows indicates potential shifts in flow regimes under climate change.

- Changes in low flows are not consistent across the low flow range and the catchments. For the Upper Selwyn catchment low flows (defined at Q75) are expected to slightly increase up to 10% by the end the century, while extreme low flows (defined at Q95) are expected to increase by up to 30% over the same time period. For the Upper Waimakariri catchment changes in low flows are consistent across the low flow range with slight increase up to 10% by the end the century.

- Changes in ecologically-important flows (defined as 7-Day Mean Annual Low Flow, or 7-Day MALF) are spatially dependant. For the Upper Selwyn catchment, ecological flows are expected to remain stable or decrease by 5 to 10% by the end of the century. Over the same period ecological flows are expected to remain stable with “overs and unders” for the southern part of the Upper Waimakariri catchment, while the northern part of the Upper Waimakariri catchment is expected to see large decrease in environmental flows (up to 40%) under the most extreme radiative forcing scenario.

- Similar spatial variation is expected for the median number of consecutive events below hindcast 7-Day MALF. A decrease of the median duration of low flow events is expected for the Upper Selwyn catchment, while an increase of this ecological characteristic is expected over the same time frame for the Upper Waimakariri catchment. If 7-Day MALF is used as a water consent threshold, this will point towards a spatially sensitive shift in the distribution of period where water consents will be restricted between the two catchments.

- Changes in discharge modelled are extremely likely to be associated with climate change effects (95% confidence level) for a majority of the overlapping time periods analysed over the period 2006 and 2100 in the Upper Selwyn and the southern part of the Upper Waimakariri catchments, but not for the headwaters of the Upper Waimakariri catchment.

Full results of the flow modelling completed by NIWA are provided in Zammit and Sood (2021)[2]. This includes results for other key sites that are used as input for the Selwyn-Waihora MODFLOW model: Hawkins at Willows and Hororata at Mitchells in the Selwyn catchment; and Coopers Creek at Mountain Road, Kowai at Benmore and Kowai at SH73 in the Waimakariri catchment.

Projected future flows for the Rakaia River were provided by Environment Canterbury. These flows were outputs from ECan’s hydrological model of the upper Rakaia catchment, driven by the same climate inputs as used by NIWA in the NZWaM.

The following figures summarise the projected changes in flows for the Selwyn River at Whitecliffs and the Waimakariri River at Otarama. In each pair of plots the top plot shows the changes under RCP 2.6 radiative forcing scenario, and the bottom plot shows changes under RCP8.5 radiative forcing scenario. The green line indicates results for changes in mean flow, the orange line indicates results for changes in median flows, the black line indicates results for changes in Q75, and the red line indicates results for changes in Q95.

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[2] Zammit, C. and Sood, A. (2021). Potential impact of climate change on river flows in the Selwyn and Waimakariri catchments. NIWA report 2021061CH, prepared for Aqualinc Research Ltd.

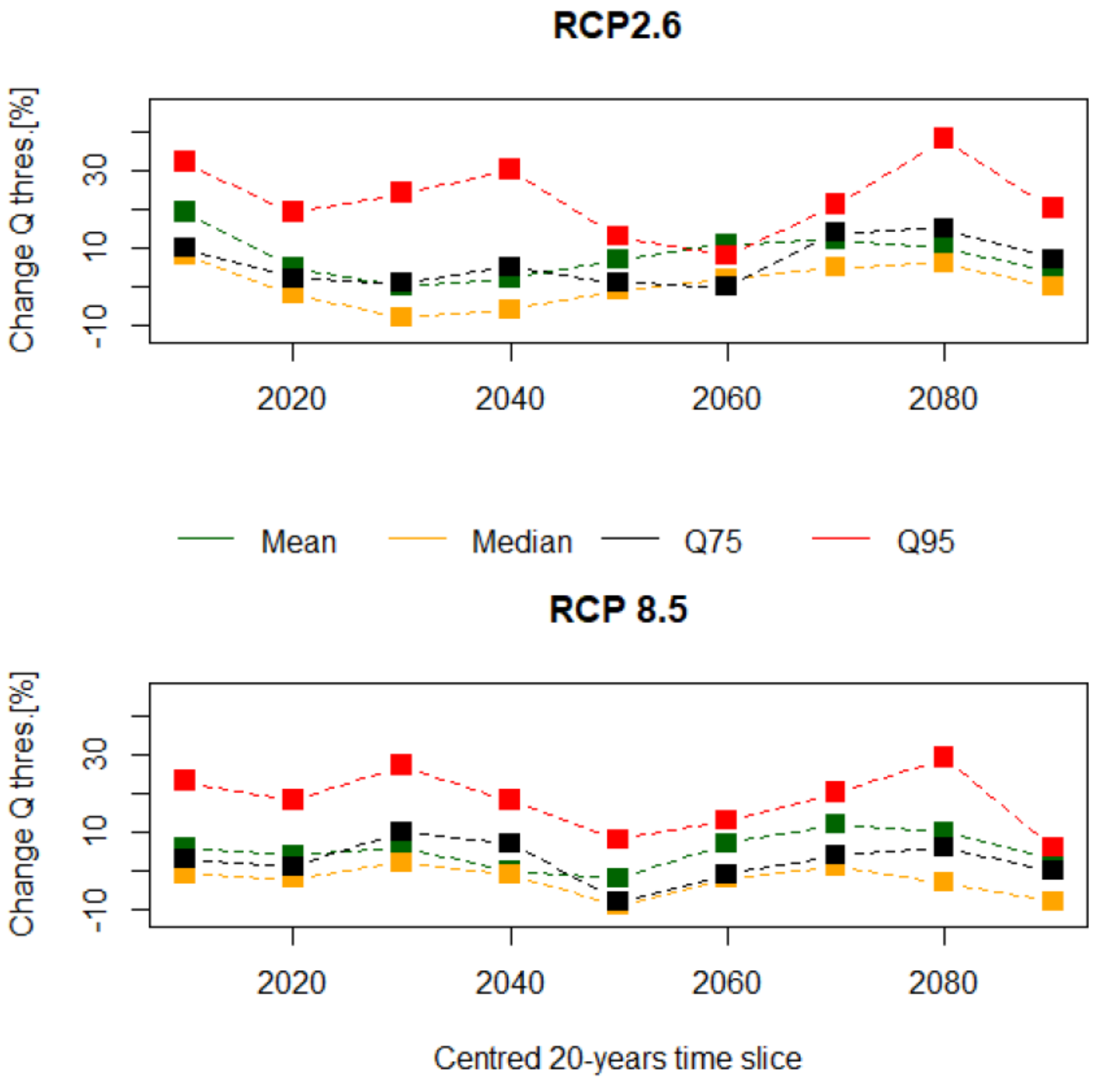

Figure A.7: *20-year centred changes in flow range characteristics for RCP 2.6 and RCP 8.5 across RCPs over the period 2006-2100 for the Selwyn at Whitecliffs.*

Appendix B: Groundwater and Lowland Streams Flow Modelling

B.1 Introduction

The Selwyn Waihora integrated groundwater / surface-water flow model was set up to simulate the effects of current and future climate on irrigation demand, flowrates, and water levels throughout the case study area. Daily irrigation demand was restricted when required by the groundwater allocation policy being tested.

The development of this model is described in Weir and Bright (2017)[3]. The following figure B.1 shows the aerial extent of the groundwater system, and the rivers and streams, represented in the model.

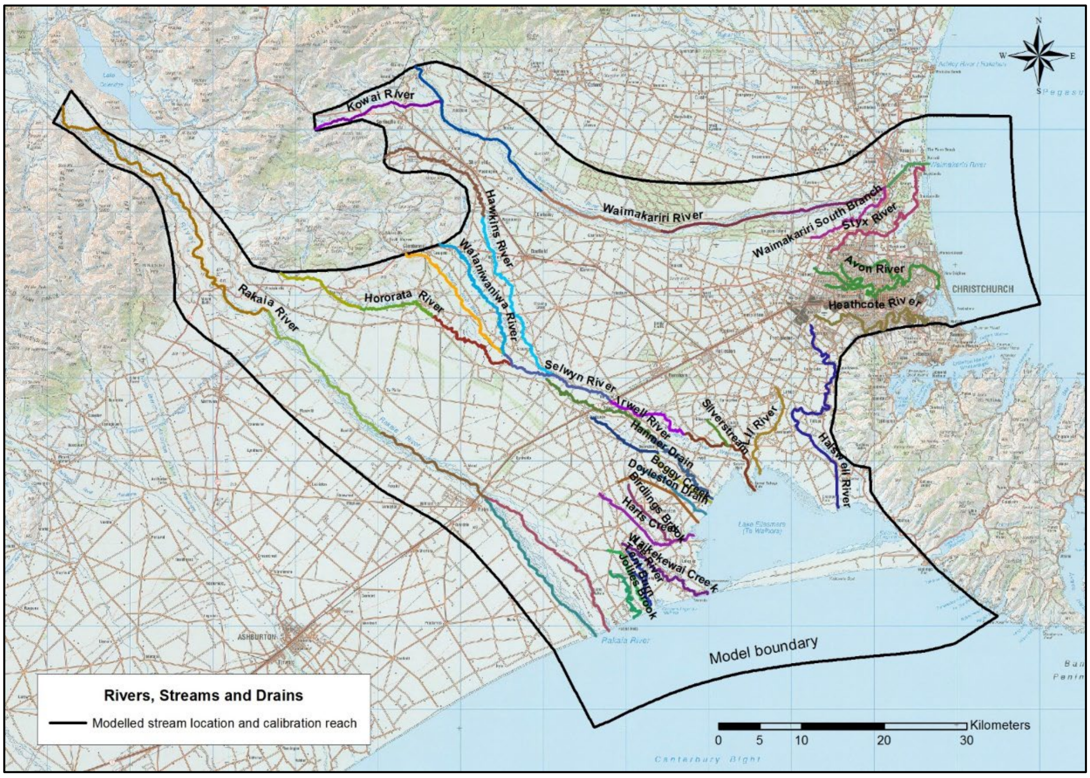

Figure B.1: Spatial extent of the Selwyn-Waihora surface water / groundwater flow model.

B.2 Calibration

The groundwater flow model was calibrated using a combination of groundwater levels and river flows (including river loss measurements).

In total, groundwater levels in the steady state model have been calibrated against measurements from 737 wells. Groundwater levels in the transient model have been calibrated against measurements from 178 wells.

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[3] Weir, J & Bright J, (2017): Canterbury Groundwater Model 3: Model Documentation. MBIE Wheel of Water Research. Aqualinc Research Limited.

The transient model has been calibrated against river flow measurements at sites on 19 different rivers, streams, and drains. Furthermore, modelled river flow gains and losses (from and to groundwater) have been compared to nine sets of estimated gains and losses.

For calibration of the steady state groundwater levels, greater weight was assigned to measurements from calibration wells also used for transient calibration than measurements from other wells.

11.1.1 Simulated Versus Measured Groundwater Levels

Figure B.2 presents a plot of simulated groundwater levels versus average measured groundwater levels for the 737 wells used in calibrating the steady state model. For a perfectly calibrated model, all points would be located exactly along the solid 1:1 line running diagonally through the plot. Some scatter around this line is normal for any model. The amount of scatter either side of this line provides an indication of the goodness of fit. The normalised RMSE and R^2 values are also shown in this figure.

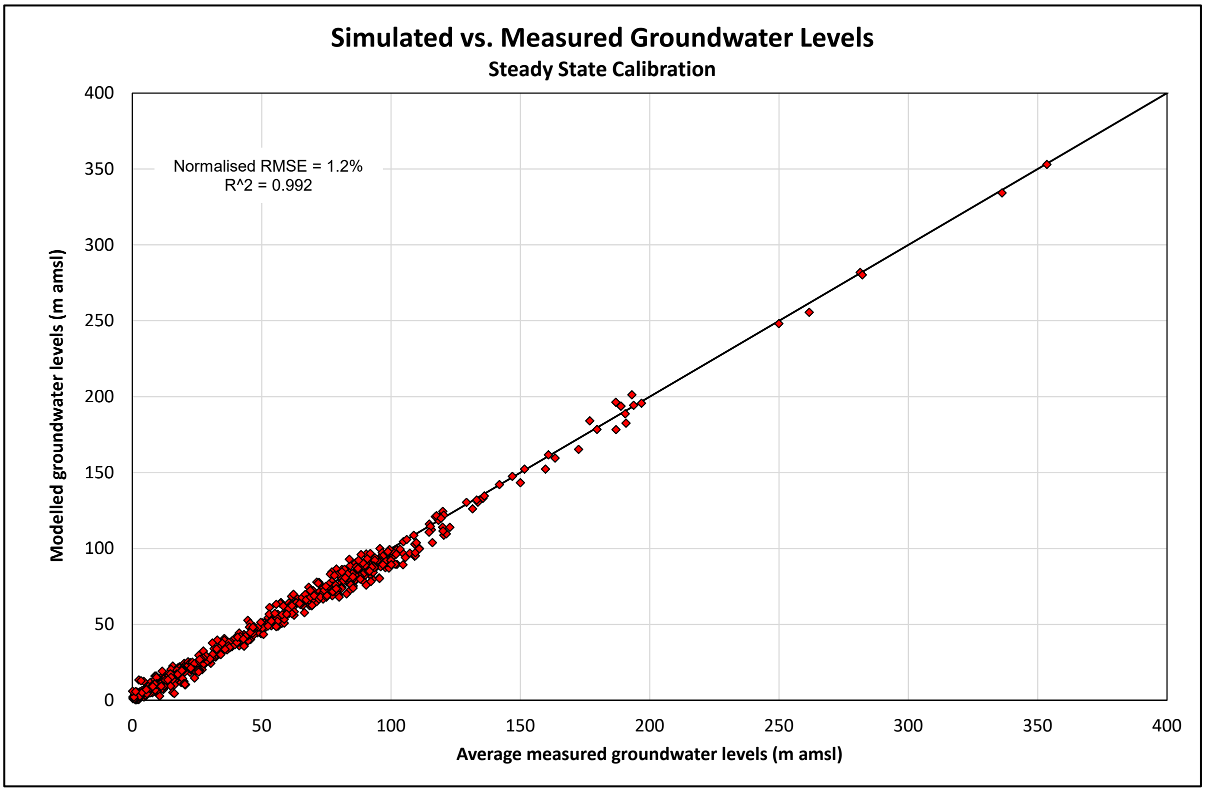
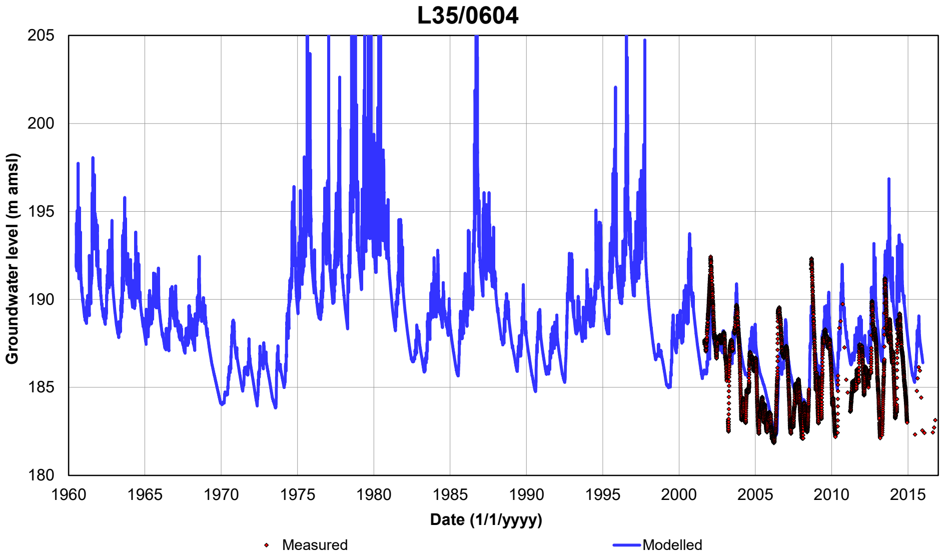
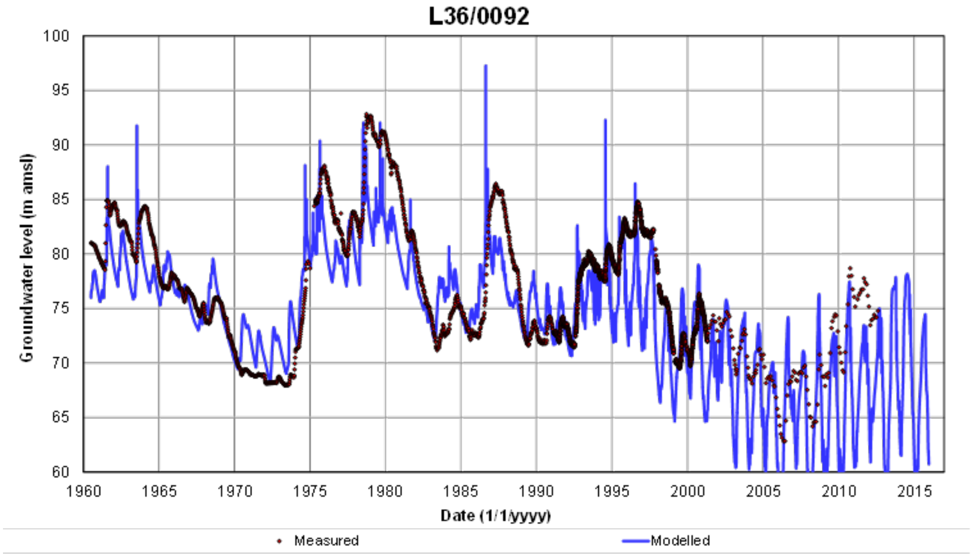


Figure B.2: Simulated versus measured steady state groundwater levels

Visually, a good fit between measured and modelled average groundwater levels was achieved, which is support by the relatively low RMSE and high R^2 values.

The remaining figures in Appendix B show comparisons between measured and modelled mean daily groundwater levels and river flowrates to illustrate the model’s goodness of fit.





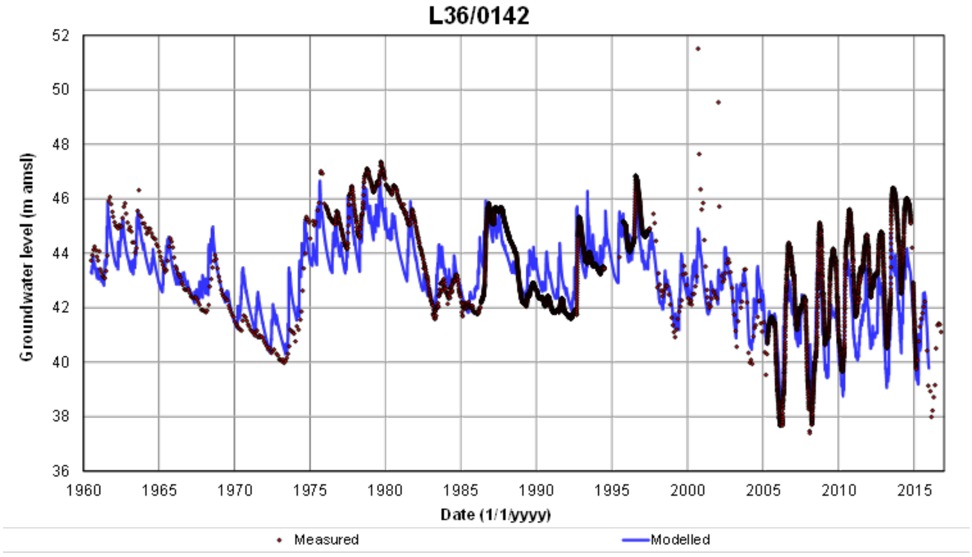
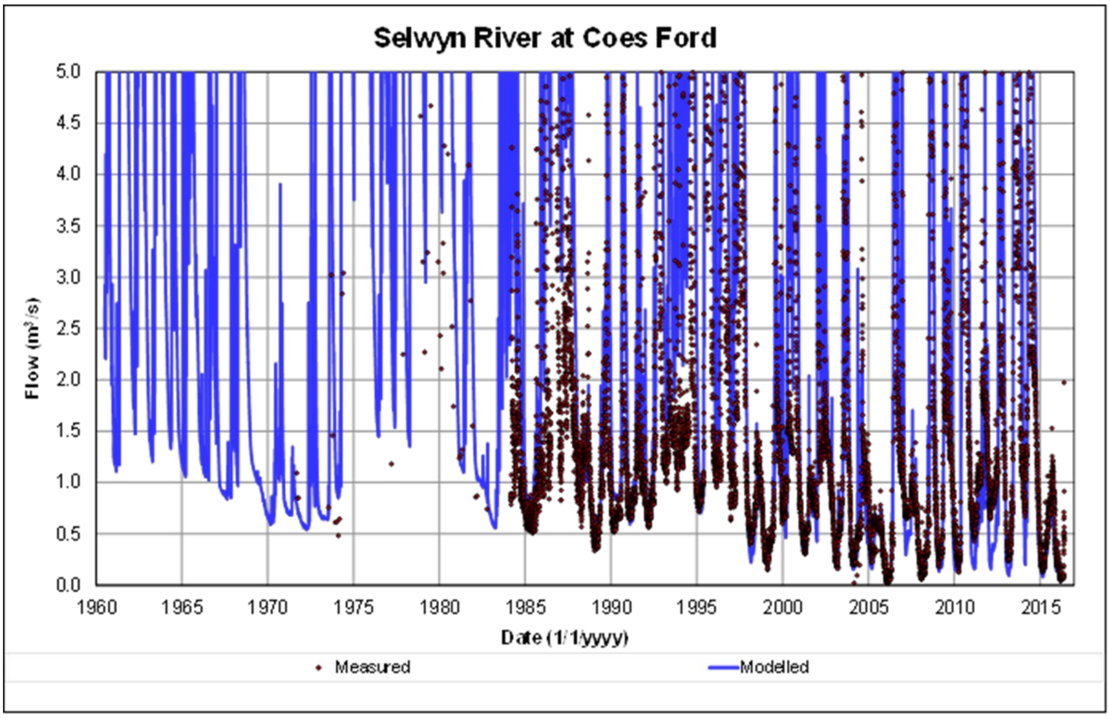


Figure B.3: *Comparisons between measured and modelled groundwater level for bores located in upper, middle and lower Plains.*



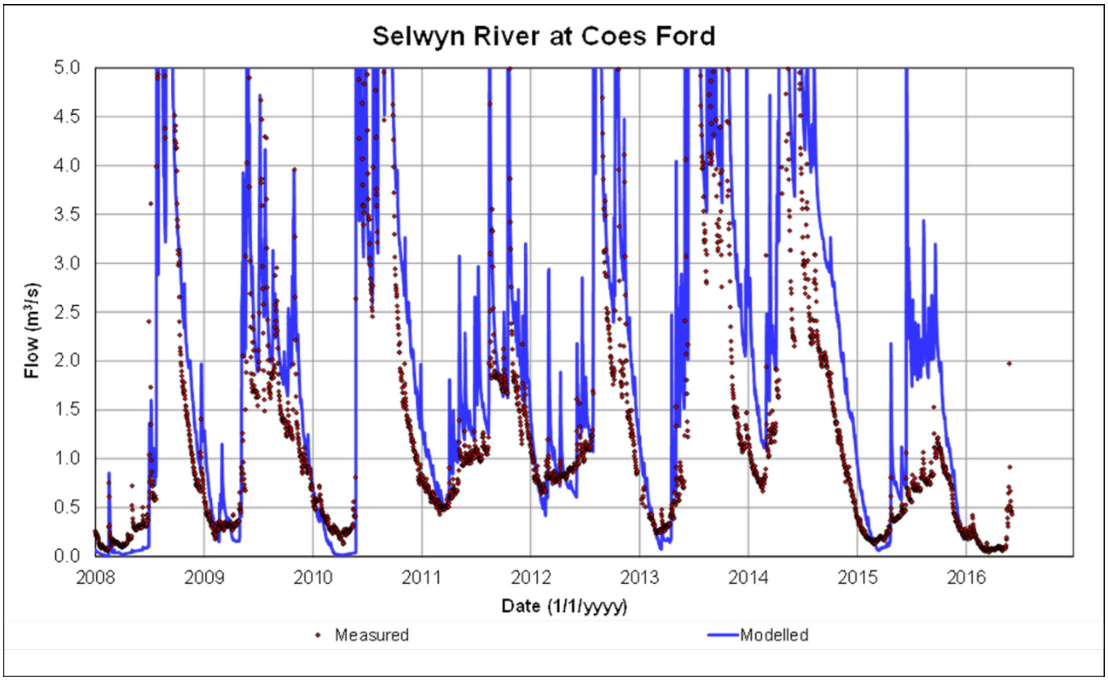
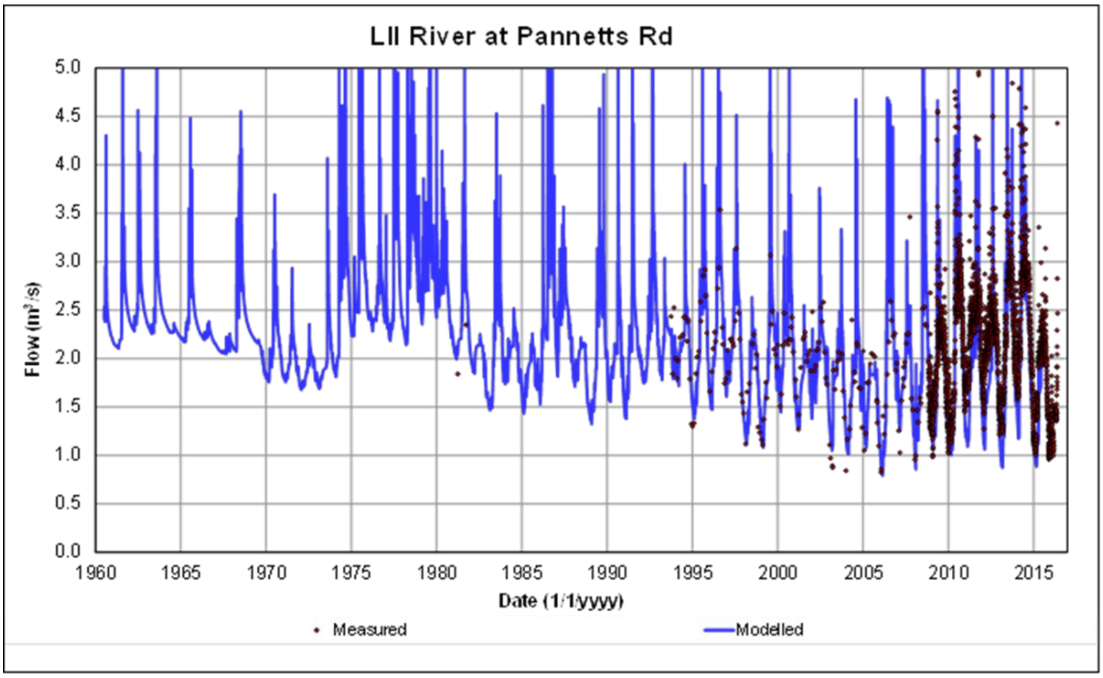


Figure B.4: *Comparisons between measured and modelled flow in the Selwyn River at Coes Ford.*



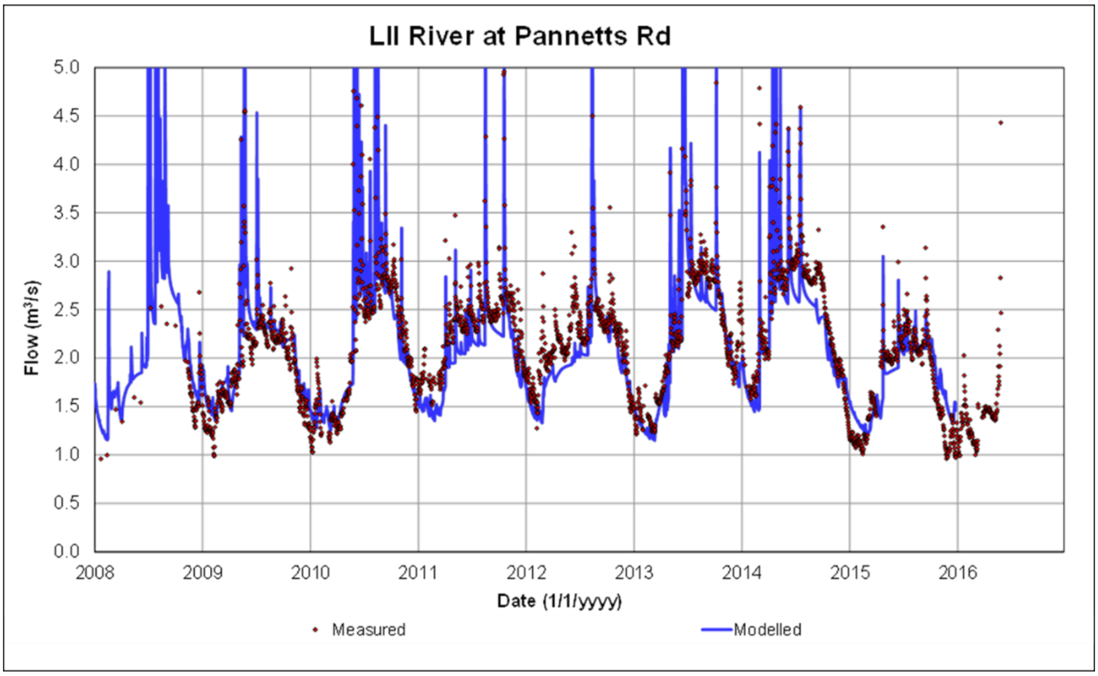


Figure B.5: **Comparisons between measured and modelled flow in the LII River at Pannetts Road.**

B.3 Flowrates and groundwater levels under future climate scenarios

Results of simulated river flowrates under current groundwater allocation policy and alternative policies are shown in Sections 6 and 7 of this report.

Appendix C: Irrigation Demand and Land-Surface-Recharge Modelling

C.1 Introduction

The groundwater level at any location on the plains at any point in time is very dependent on the land surface recharge and groundwater abstraction that has occurred in the catchment previous to that point in time. Therefore, to correctly reproduce transient groundwater levels, it is necessary to include these time varying inputs in the model. To achieve this, the crop-soil water balance model IRRICALC was used to generate time series of spatially varying land surface recharge (from rainfall and irrigation, where applicable) and groundwater abstraction (where applicable).

Details of the model and its application are reported in Weir and Bright (2017)[4]. The primary data inputs used for this project are described in the following Sections.

C.2 Hydrological Response Units

Introduction

Hydrological Response Units (HRU's) are unique combinations of climate (rainfall and potential evapotranpiration), and the soil's capacity to store plant available water (PAW). These vary spatially across the Selwyn-Waihora management zone (SWMZ). The spatial variability is particularly important across the Plains component of the SWMZ because it's this component that drives variation in groundwater levels and flows in lowland streams and river-reaches during the parts of the year when aquatic ecosystem health comes under stress.

The purpose in delineating HRU's is to help build the datasets that encapsulate the temporal (daily) and spatial variation in the hydrological inputs to Aqualinc's integrated groundwater/surface-water flow model. This model was used to quantify the hydrological effects of projected future climate, identify where current water allocation policy is unable to maintain aquatic ecosystem health, and help design and test improved water allocation policy options.

The spatial and temporal variation in the recharge of groundwater from the land-surface and the pumping of groundwater for irrigation (and other uses) was modelled for each 1km x 1km grid cell (100ha) across the SWMZ plains. The rainfall, PET, and soil PAW is specified for each grid cell from an HRU map. Land-use and associated irrigated areas were then specified for each grid cell.

The maps below show the sequence of development of the HRUs and their discretisation into 100ha grid cells. Soil coverages are relatively coarse over the plains. Sensitivity analyses from previous work showed that a finer resolution grid of 500 m x 500 m does not achieve an improved representation for the calculation of irrigation demand and drainage for the SWMZ.

Climate Data

Rainfall and Potential Evapotranspiration (PET) data were obtained from NIWA, then gap filled and extended where necessary to produce a continuous time-series from 1960 on. We used Aqualinc's time series extension software for this. The software analyses all climate data and automatically tests correlations with surrounding sites. Then the best (highest) correlated site is used to fill gaps and extend the series.

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[4] Weir, J & Bright J, (2017): Canterbury Groundwater Model 3: Model Documentation. MBIE Wheel of Water Research. Aqualinc Research Limited.

The correlation method automatically corrects for seasonal differences between sites by calculating a unique correlation relationship for each month of the year. The method interpolates first in time, then spatially.

Rainfall Data

Figure C.1 shows the spatial distribution of mean annual rainfall over the study area. Yearly average rainfall ranges from approximately 500 mm at the coast to approximately 1,000 mm nearer the foothills.

There is good coverage of rainfall sites across the Selwyn-Waihora plains, and individual stations were selected to provide a coverage of sites representing coastal, mid plains and inland areas. Stations were selected for their long length of record and minimal missing data. The rainfall time series (obtained from NIWA) recorded at a station (gap-filled and extended as needed) has been used as the time series to represent the model cell closest to that station. Basic statistics for these rainfall stations are summarised below.

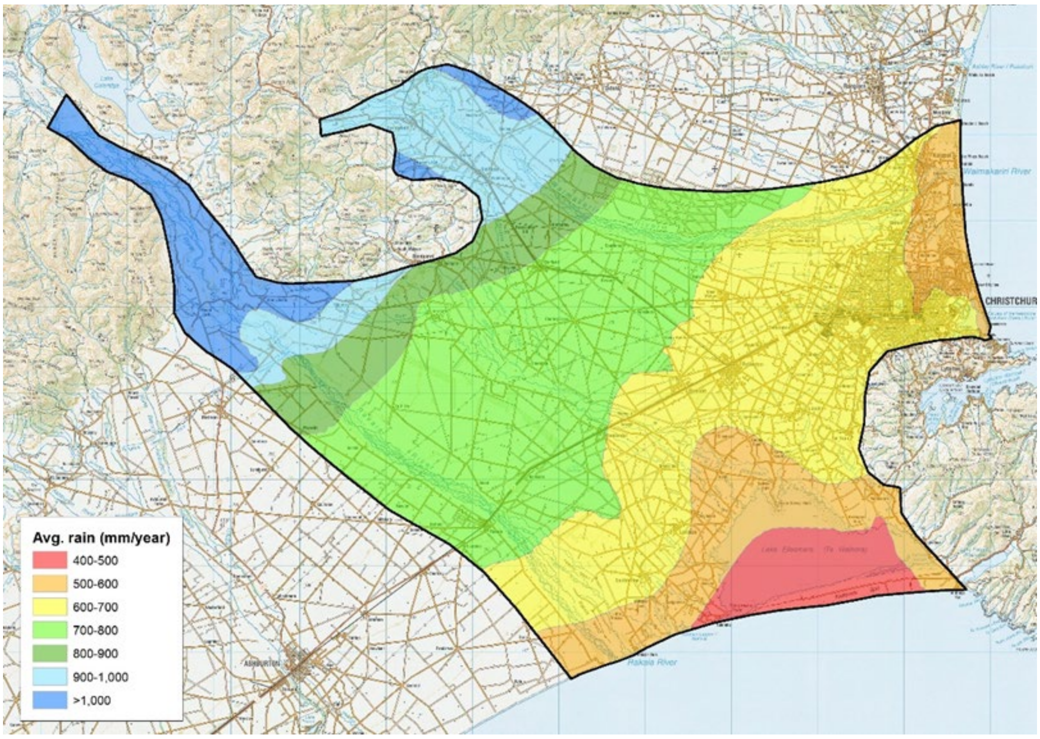


Fig C.1: Rainfall zones derived from daily rainfall time-series data for multiple sites across the area.

Rainfall site	Climate Station network number	Average annual rainfall (mm) (1)
Burnham Sewage Plant	H32631	645
Christchurch Aero	H32451	611
Darfield	H32412	778
Homebush	H32402	855
Hororata	H31591	849
Leeston (Jollies Rd)	H32824	598
Lincoln	H32642, H32643, H32645	591
Rakaia Greenfields	H31671	880
Te Pirita Mead	H31691	710
Winchmore	H31883	729
[1] *For complete time series, gap filled and extended, where applicable*		

PET Data

Figure C.2 shows the spatial distribution of mean annual PET over the study area.

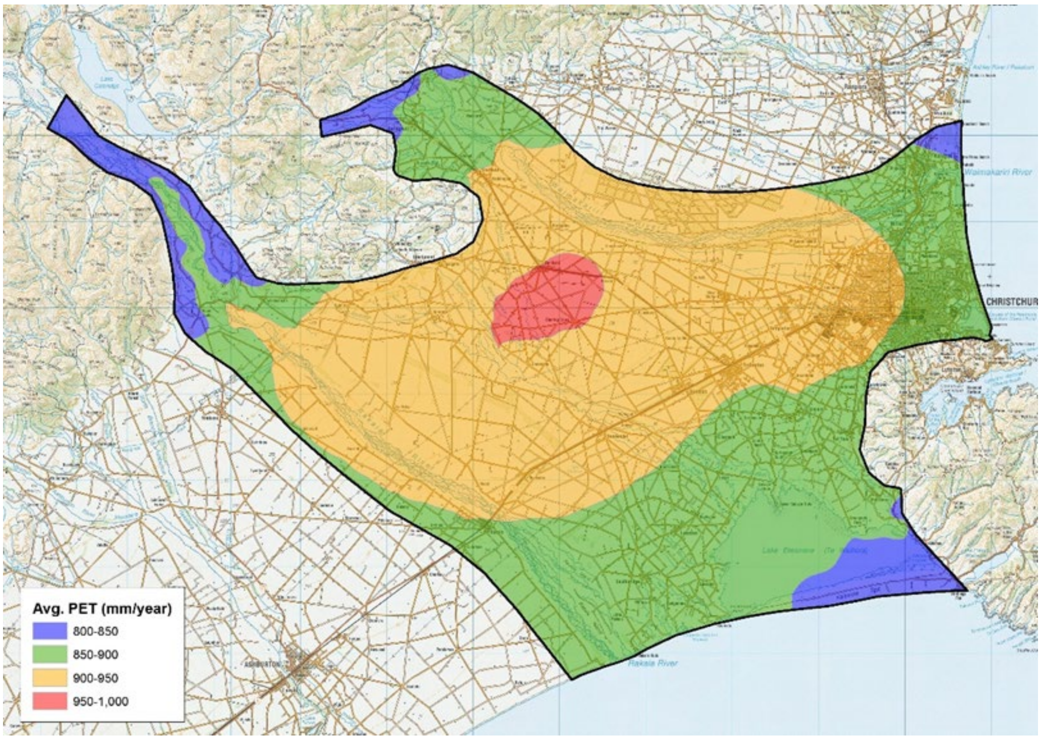


Fig C.2: PET zones derived from daily PET time-series data for accessible climate station sites across the area.

PET has less spatial variability compared to rainfall. The PET time series recorded at a station (gap-filled and extended as needed) has been used as the time series to represent the model cell closest to that station. Basic statistics for these rainfall stations are summarised below.

PET site	Climate Station network number	Average annual PET (mm) (1)
Christchurch Aero	H32451	950
Darfield	H32412	1,000
Highbank	H31572	950
Hororata	H31591	950
Leeston (Harts Creek)	H32734	820
Lincoln	H32642, H32643, H32645	820
Winchmore	H31883	870
[1] *For complete time series, gap filled and extended, where applicable*		

Soils

Data on the soils capacity to store plant available water (PAW) on the Canterbury Plains are required to model the irrigation demand and land surface recharge for each land use category. This information was obtained from Landcare's S-Map coverage. This coverage was adjusted for typical rooting depths of 60 cm for pasture and cropping. Soils were then aggregated into four plant available water (PAW_{60}) classes, as shown in the following table.

Soil PAW range (mm)	PAW category	Representative PAW (mm)
No soil mapped	No soil mapped	0
1-60	Low	40
60-120	Medium	80
> 120	High	140

These simplified categories were chosen based on a sensitivity analysis of the modelled land surface recharge (LSR) for pasture that considered soil PAWs ranging from 30-160 mm. The following was observed from this exercise:

- A 40 mm PAW is adequate to represent shallower soils (1-60 mm PAW);
- There is a break point in the calculated LSR around 80 mm PAW, which suits 60-120 mm PAW soils; and
- Calculated LSR for soils with a PAW greater than approximately 120 mm is relatively insensitive to PAW; a higher PAW has only slightly less LSR than a lower soil PAW within this category.

The spatial distribution of soil PAW categories is shown in Figure C.3.

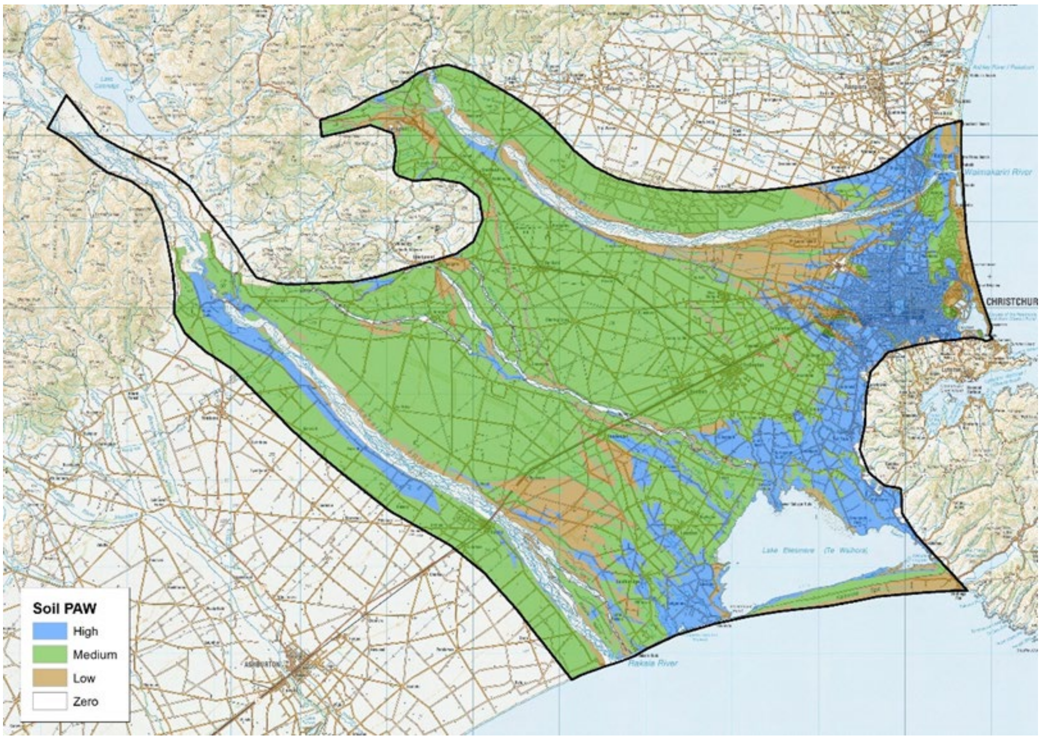


Fig C.3: Soil PAW60 zones across the area, derived from S-Map data.

Hydrological Response Units

The unique HRUs derived by intersecting, using GIS, each of the maps shown in Figures 1-3 are shown in Figure C.4.

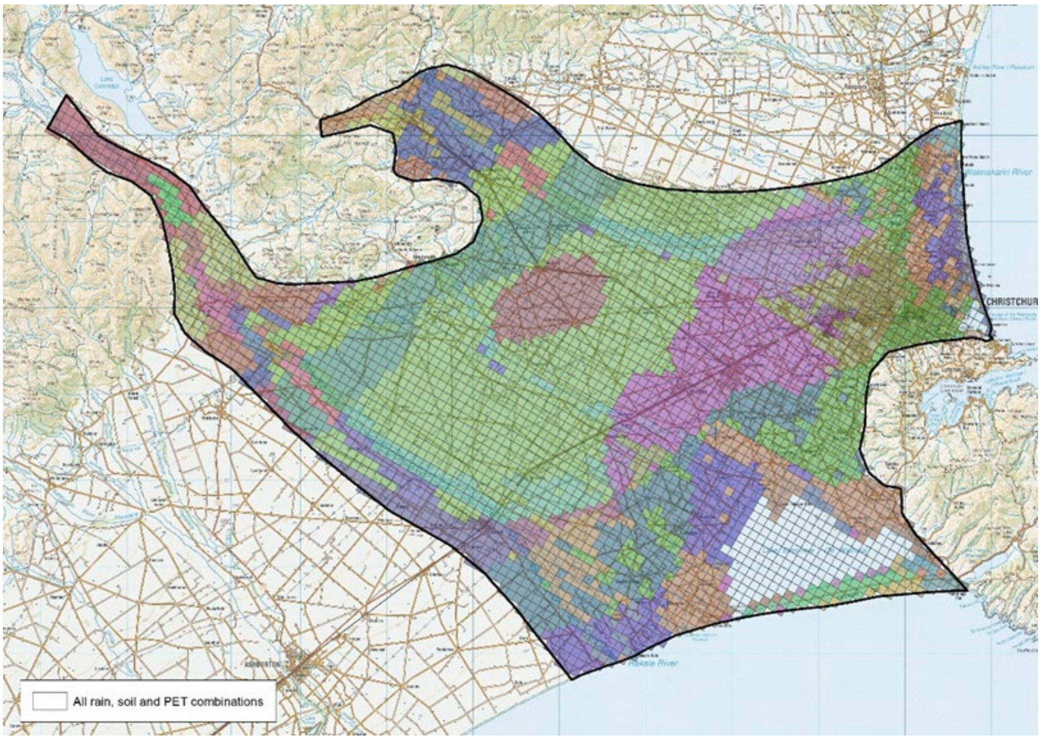


Fig C.4: HRUs derived by combining rainfall, PET and Soil PAW maps, identifying unique combinations and assigning a combination to each 100ha grid cell.

Irrigated Area and Land Use

Land use is an important aspect of any integrated groundwater/surface-water model. The land use and corresponding water use (if any) contributes to how much land surface recharge enters the subsoils (and eventually recharges groundwater) and how much groundwater is pumped. Time-varying and spatially-varying land use is needed to correctly calibrate groundwater/surface-water models against time-varying and spatially varying groundwater levels and surface-water flows. A gridded coverage of irrigated area had been derived in an earlier project, primarily using Canterbury Regional Council's (CRC) consents and wells databases (to provide information on variation over time) and irrigated area mapping previously completed by Aqualinc for CRC and MfE using aerial and satellite imagery from 2015-2016.

Land-use, as identified on CRC's consents database, was categorised into the following:

- Irrigated pasture (e.g. dairying; dairy support)
- Irrigated crops (e.g. arable cropping)
- All non-irrigated land was categorised as dryland pasture.

The proportion of each of these land use categories was determined for each cell. The type of irrigated land use within any cell was assumed to remain constant over time, but the proportion of the cell irrigated varies over time (typically, the irrigated proportion increased over time; but irrigated area in some cells could reduce as consents expire and were not replaced).

Figure C.5 shows the distribution of land-uses for the 2015/16 season.

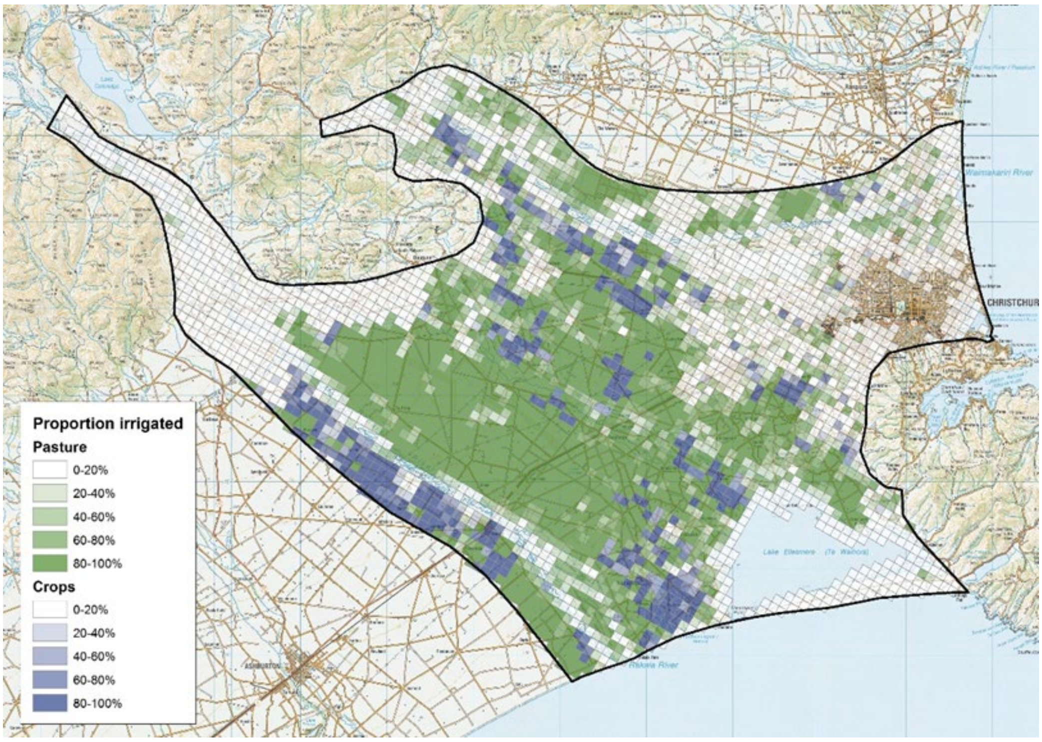


Fig C.5: Proportion of each grid cell that is in irrigated pasture (green), irrigated cropping (blue) and un-irrigated pasture (white cells).

C.5 Calibration

There are various uses for groundwater, which have been categorised as irrigation and non-irrigation uses. These are discussed below.

Irrigation Pumping

Irrigation is the largest abstractive use of water in Canterbury. The amount of water required to adequately irrigate a farm depends on the crop being irrigated, the properties of the soil, the time of the year, climatic conditions (actual evapotranspiration and rainfall) and the irrigation method. The IrriCalc model was used to calculate irrigation demand for each soil and crop type combination within the study area.

The method of applying irrigation water can heavily influence the amount of land surface recharge and resulting irrigation demand. For all spray irrigation areas, the modelled irrigation was triggered-on if the soil moisture in one return period ahead was predicted to fall below 50%. All spray irrigation areas were assumed an irrigation uniformity coefficient of 70% which resulted in an average water use efficiency of approximately 80%, though this varies depending on the soil moisture content.

In total, approximately 8,500 groundwater irrigation takes were modelled over the simulation period.

The calculated demand has been calibrated against measured abstraction data (supplied by Environment Canterbury) for takes that are were monitored for the years 2007-2014. This comparison is shown C.6.

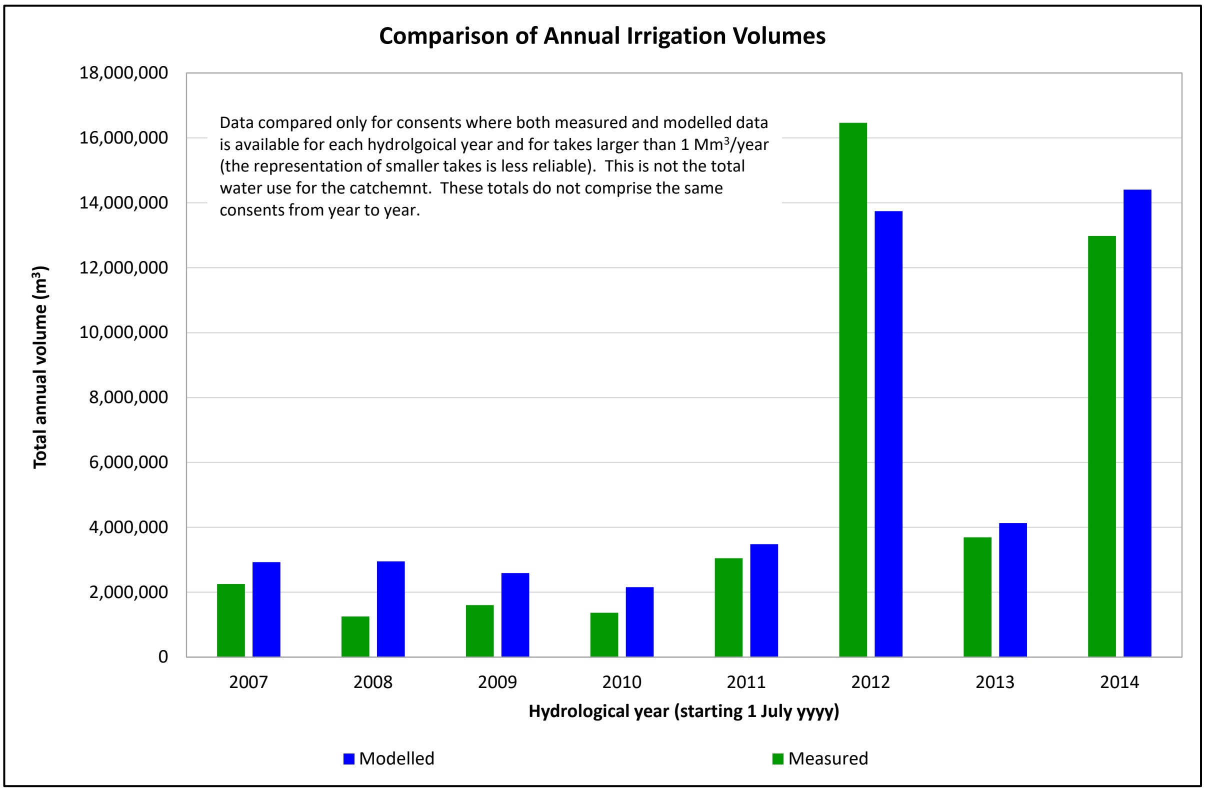


Figure C.6: Comparison of modelled and measured annual irrigation volumes.

A direct comparison between modelled and measured irrigation demand is often difficult for the following reasons:

- Actual irrigated area is often unknown and can be different to the consented irrigated area (this is highly likely).
- Exact farmer operation is unknown.
- Exact soil and irrigation system set up is unknown.
- Missing measured data (e.g., not logged or broken/faulty meters); and
- Partial farm development.

Due to these difficulties, the totals presented in Figure C.6 do not represent all takes within the study area; only takes with measured data are included. Therefore, the large step up in annual volume in 2012 is not solely due to increased irrigation. It is more so a result of the introduction of new regulations requiring consent holders to record and report volumes abstracted.

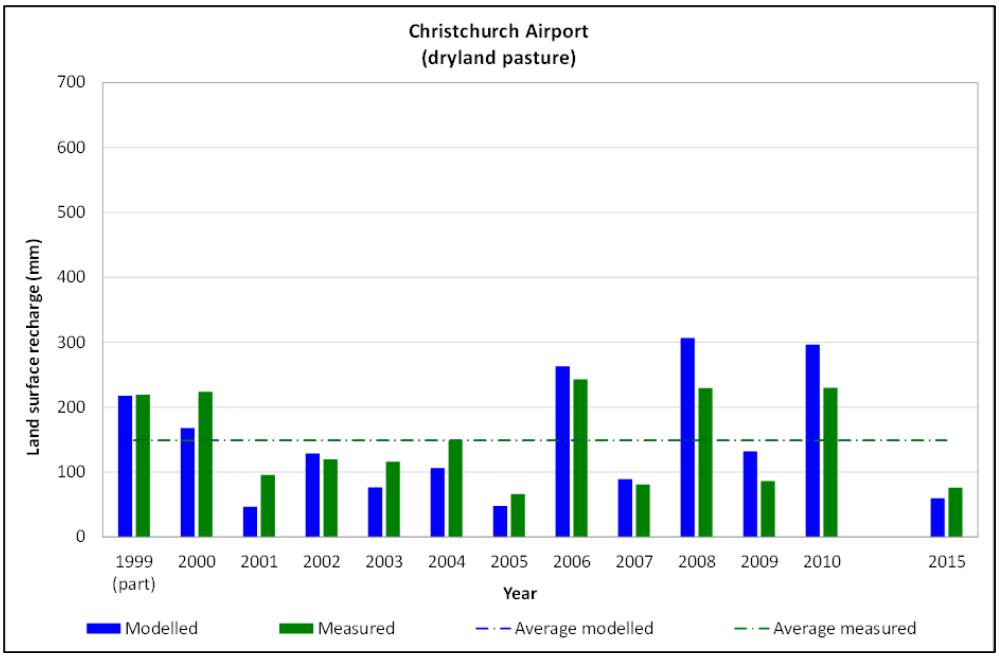
Non-Irrigation Abstraction

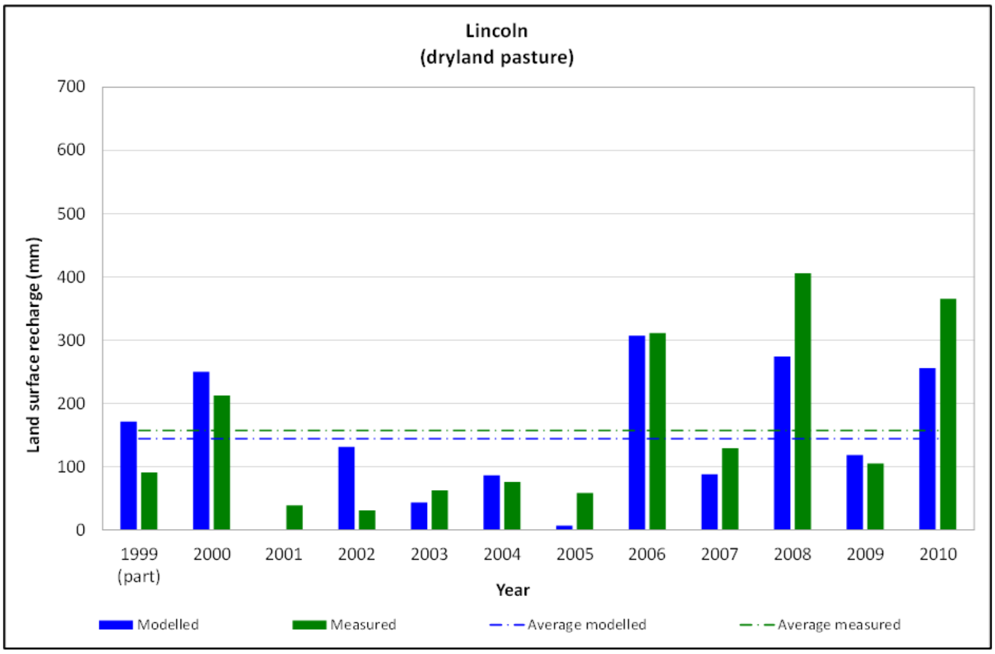
Christchurch city abstracts a considerable amount of groundwater for domestic, commercial and industrial use. These takes have been included in the groundwater model. Other non-irrigation abstractive groundwater uses (such as rural domestic, commercial, stockwater, small-town supply takes and heat exchangers) have been included in the model. They are relatively small and sparsely distributed when compared to the volume of water abstracted for irrigation and for Christchurch city.

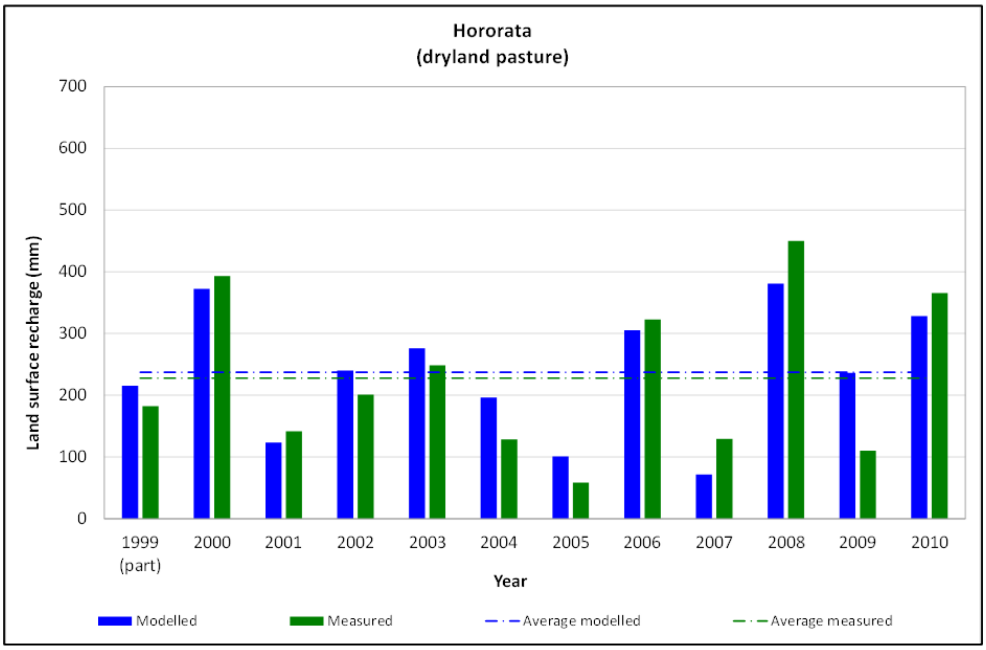
Land-Surface-Recharge

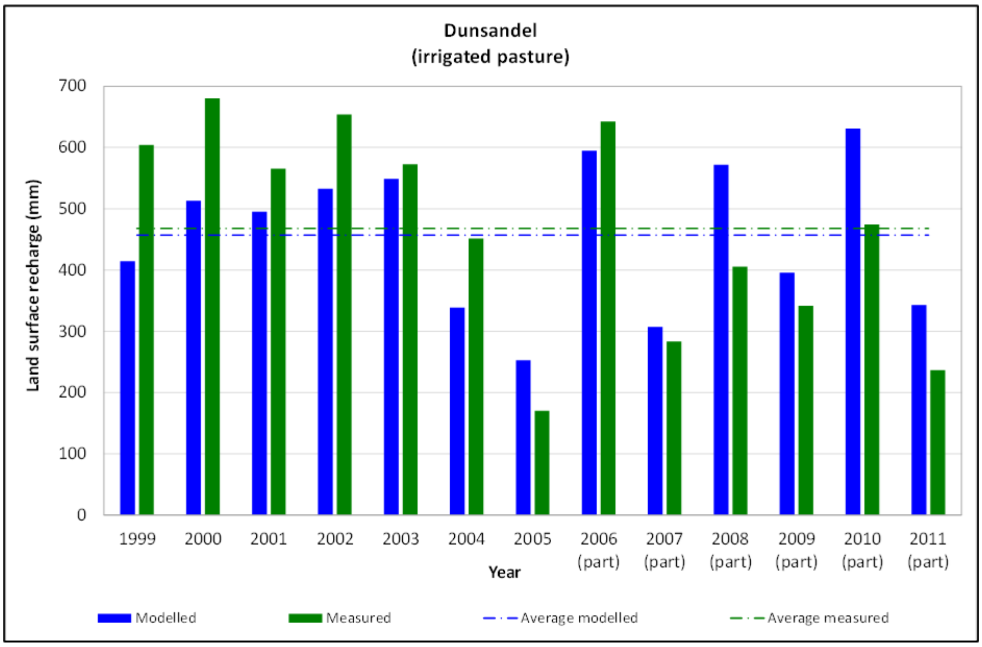
Land surface recharge is calculated each day using the IRRICALC soil-crop-atmosphere water balance model as the excess soil water – i.e., the water incident on the soil surface that exceeds the soils capacity to store water. Excess soil water is partitioned into that which passes through the root zone and eventually recharge groundwater (Land-Surface-Recharge) and that which quickly travels laterally to the nearest stream reach. The proportion of excess soil water that flows to the nearest stream is determined as part of the calibration process.

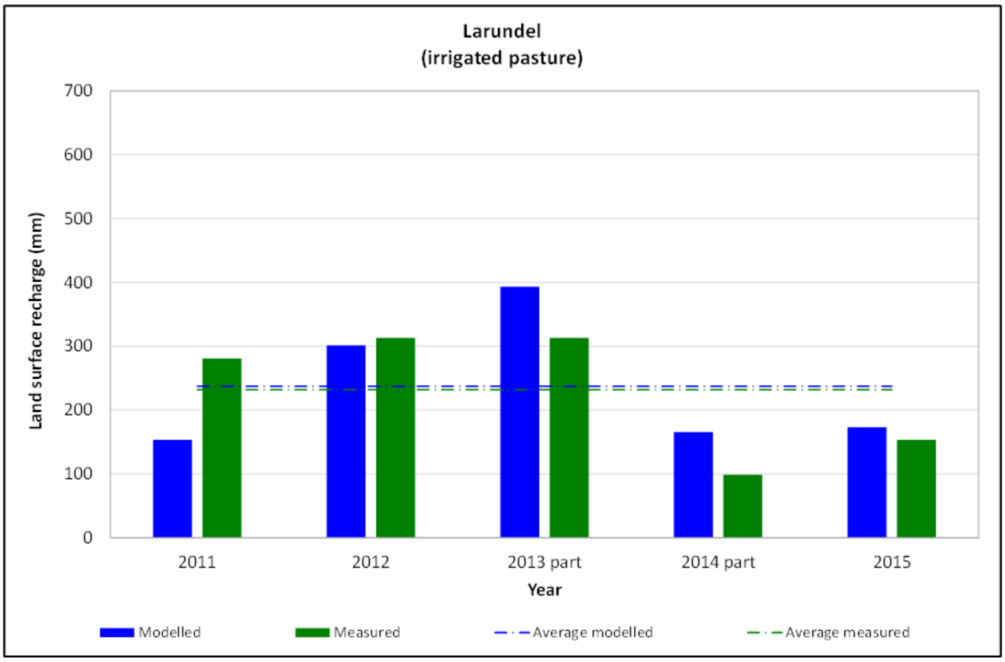
The following figures show a comparison between the modelled soil water excess and drainage measurements obtained by ECan's lysimeter network. The comparison is not always like-for-like because lips around the top of the lysimeters to prevent runoff were not always present.

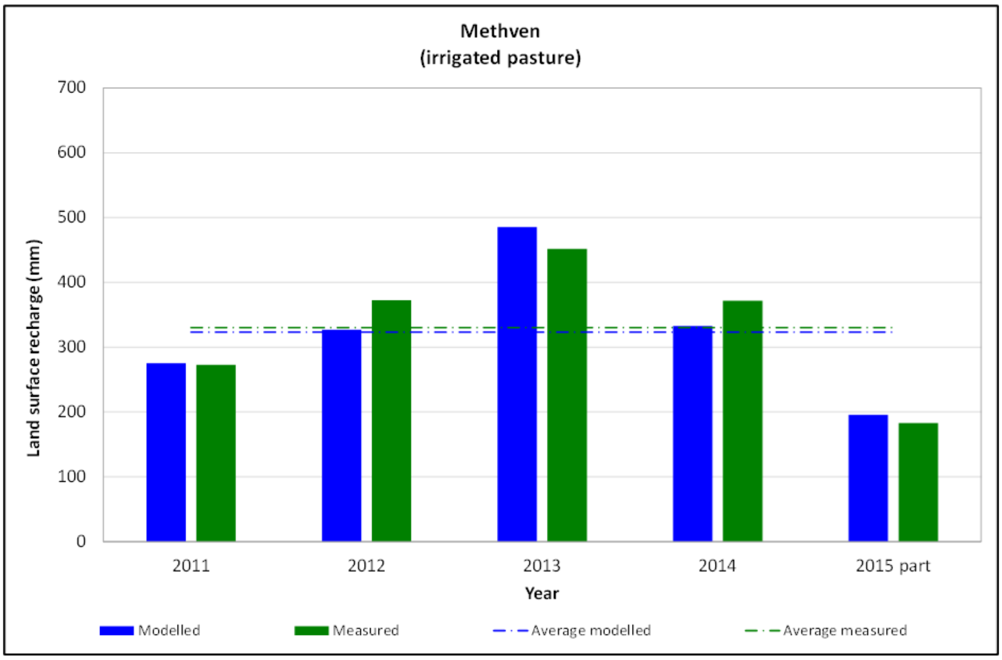





Hororata
(dryland pasture)
Land surface recharge (mm)
700
600
500
400
300
200
100
0
1999 (part)
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Year
Modelled
Measured
Average modelled
Average measured


Dunsandel
(irrigated pasture)
Land surface recharge (mm)
700
600
500
400
300
200
100
0
1999
2000
2001
2002
2003
2004
2005
2006 (part)
2007 (part)
2008 (part)
2009 (part)
2010 (part)
2011 (part)
Year
Modelled
Measured
Average modelled
Average measured





C.6 Irrigation Demand under Future Climate Scenarios

Introduction

Aqualinc's soil moisture and irrigation demand simulation model, IrriCalc, was used to simulate daily irrigation demand and drainage flux, for each combination of four RCPs and the selected Global Climate Models (GCM) (CESM1-CAM5) over the period 1971 – 2100.

Demand and drainage were modelled for each unique HRU. This was done by setting up the simulation model on a gridded basis, with the resultant time-series at each grid cell representing that cell's combination of soil, land-use and climate.

Climate Data

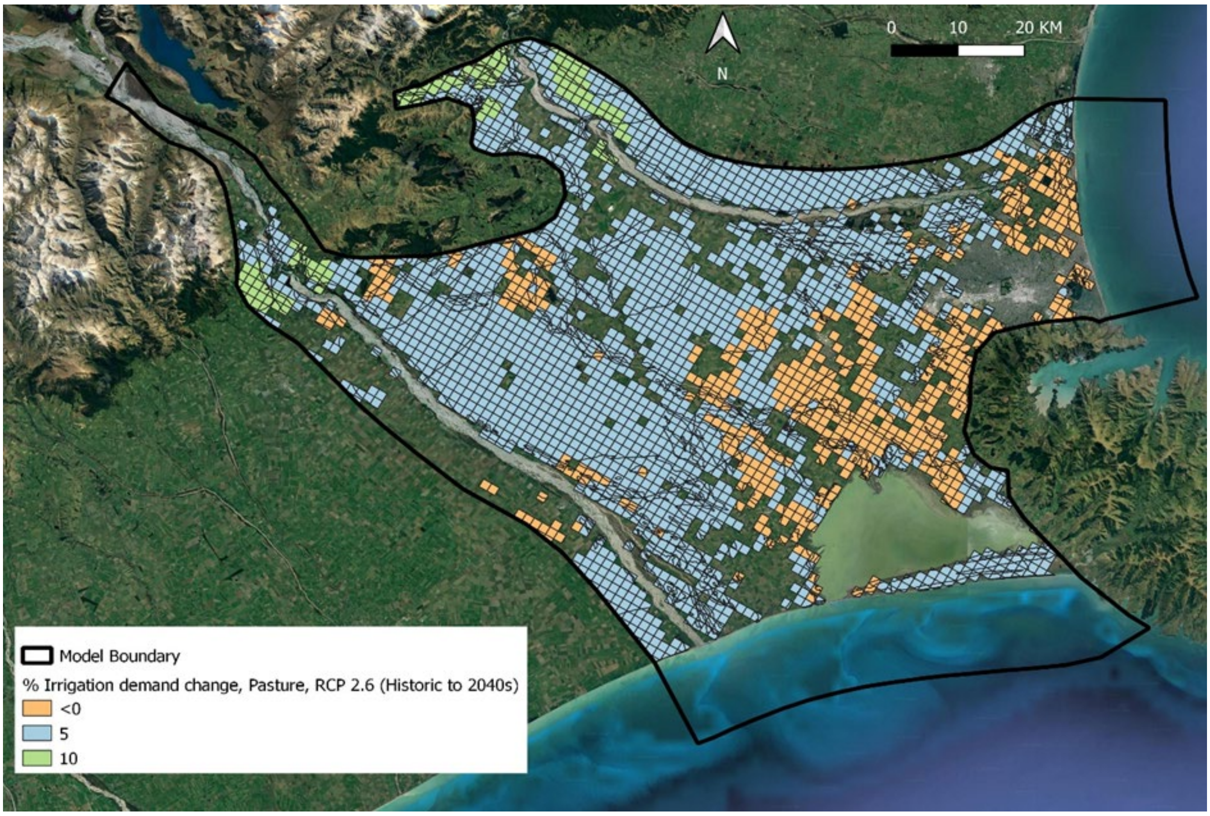
Rainfall and PET data were obtained from NIWA for the selected GCM and each RCP (RCPpast, RCP2.6, RCP4.5, RCP6.0, RCP8.5)

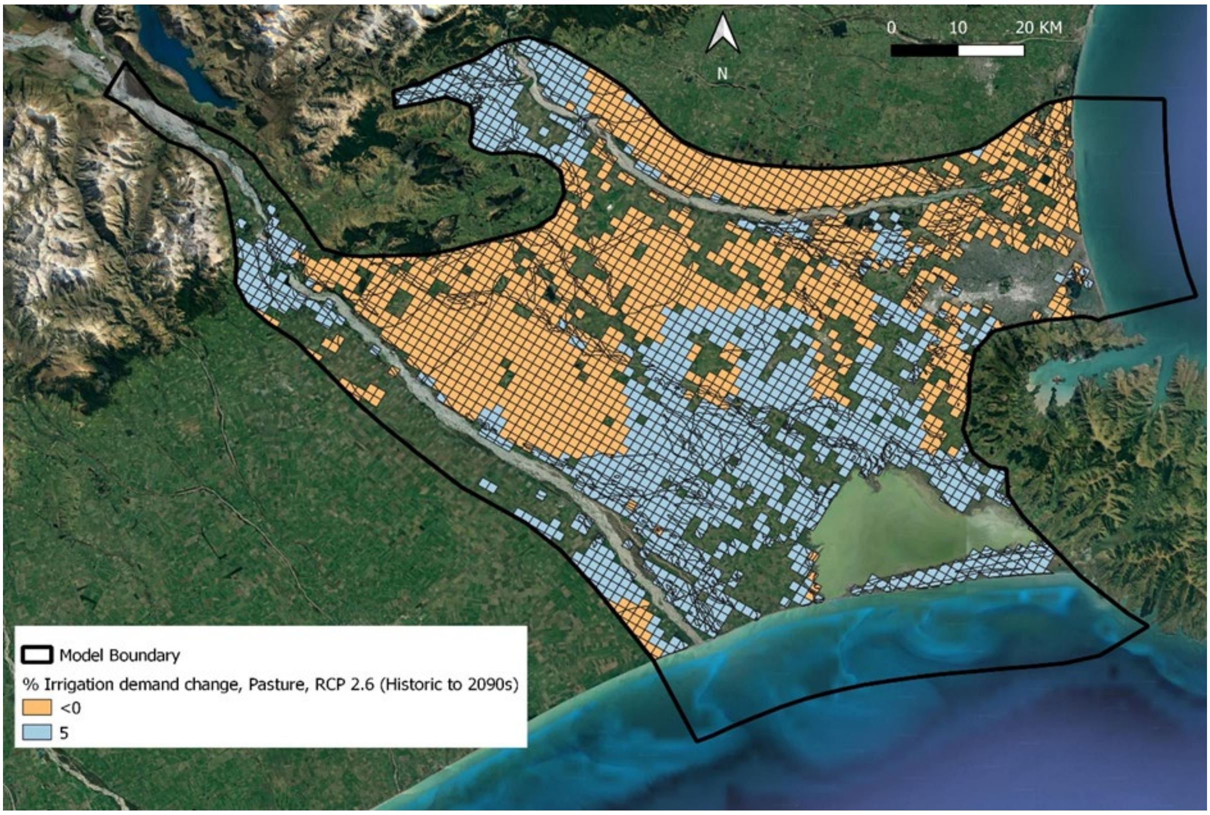
The RCPpast data (1971 – 2005) were combined with each of the other RCPs to create continuous daily time-series from 1971 – 2100 at each Virtual Climate Station Network (VCSN) grid point within the Selwyn-Waihora groundwater model domain.

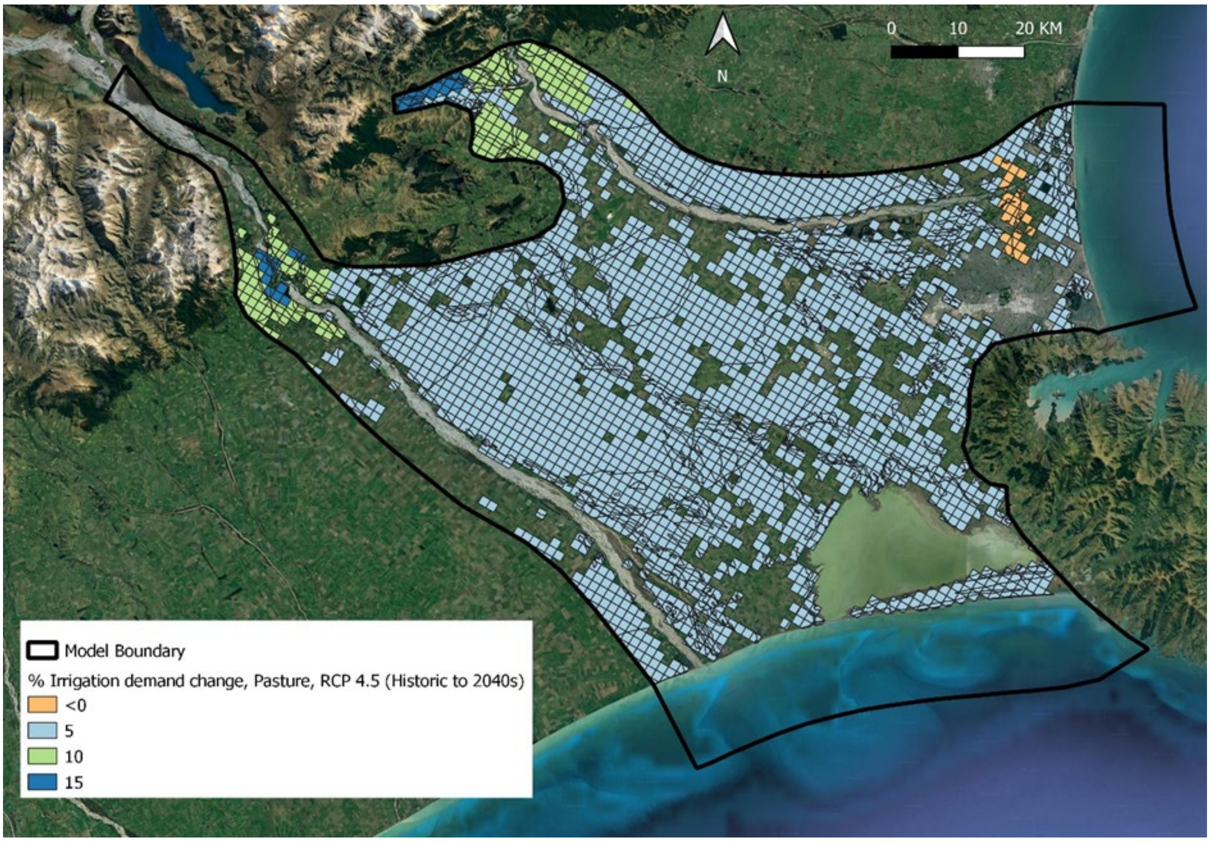
Model outputs

Annual irrigation demand and drainage totals have been calculated at each grid cell from the daily simulation results. Average annual demand and drainage have been calculated for the historic period (1971 – 2005), and periods representing the 2040s (2041 – 2059) and the 2090s (2081 – 2099).

The maps presented below show the percentage changes from the historic period to the 2040s and 2090s respectively, for each RCP. The change in irrigation demand for pasture is shown. Change in demand for irrigation of crops follows the same patterns.




N
0
10
20 KM
Model Boundary
% Irrigation demand change, Pasture, RCP 2.6 (Historic to 2090s)
<0
5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20 KM
Model Boundary
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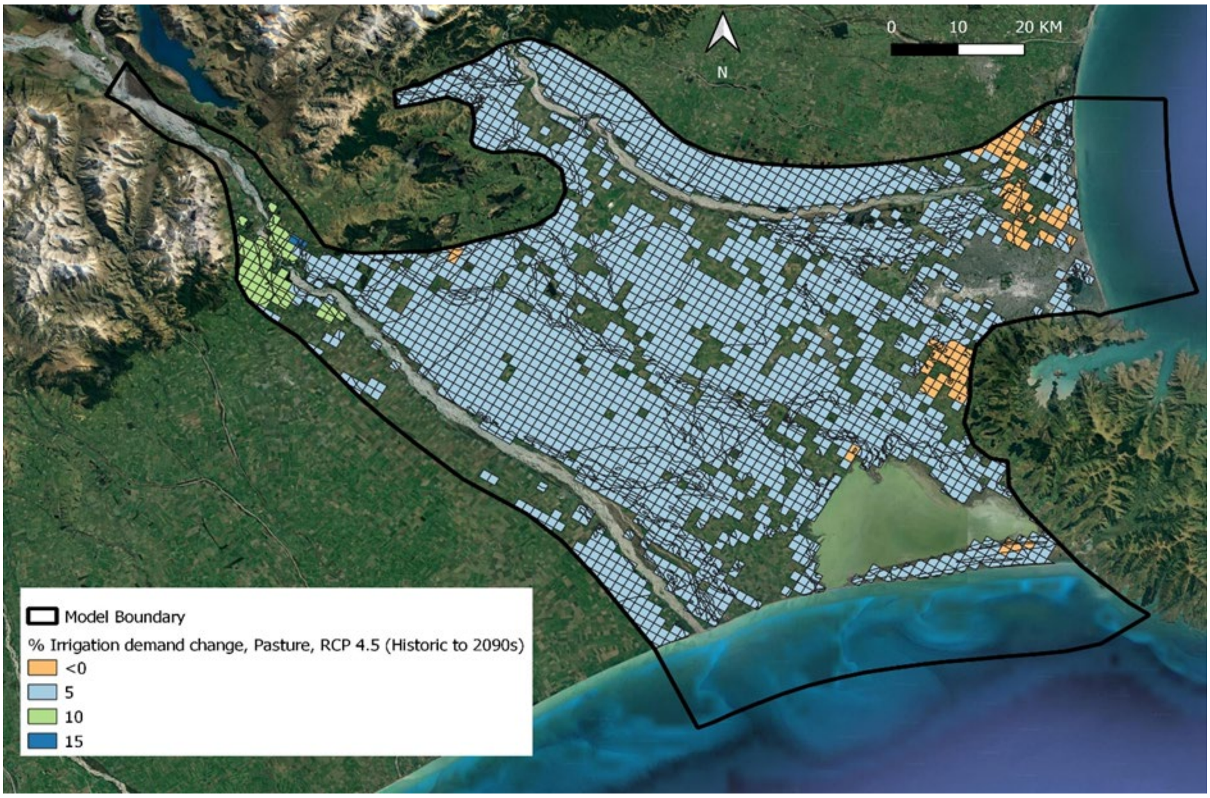
15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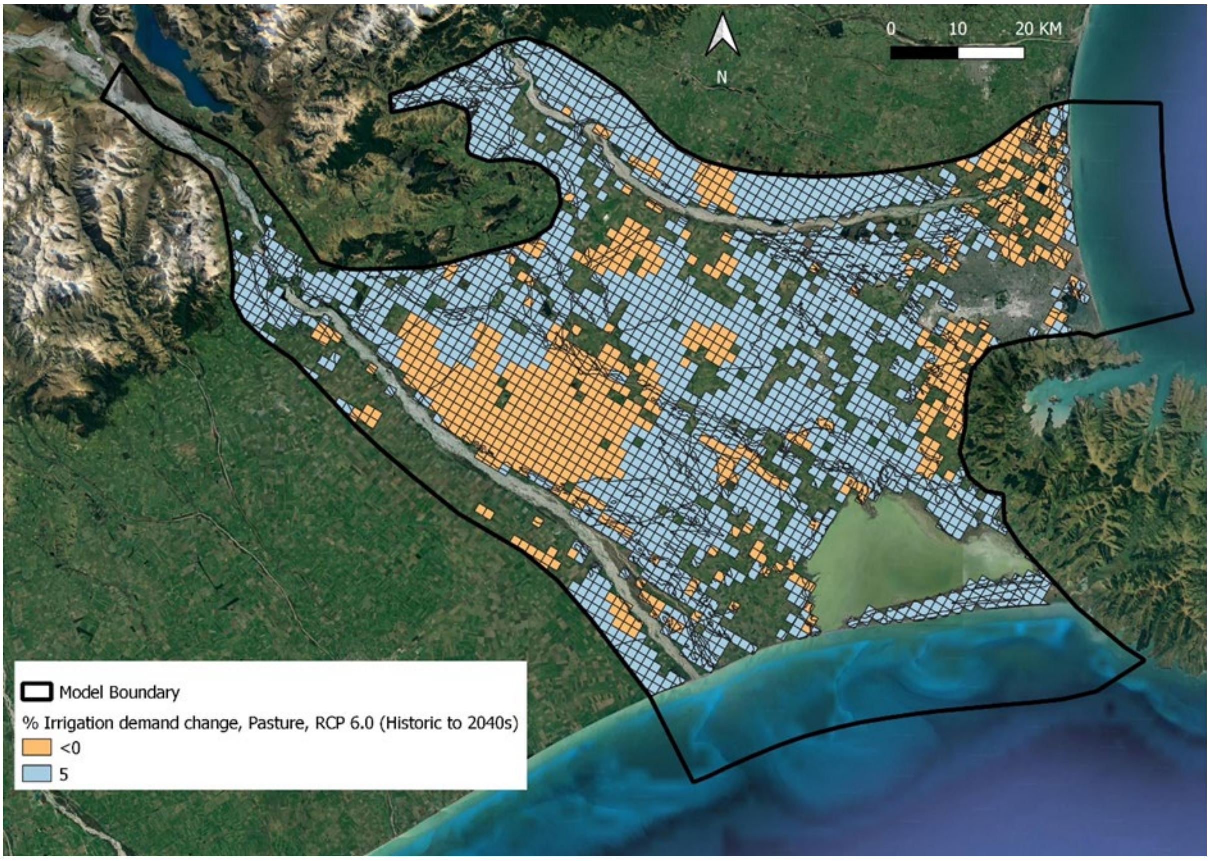
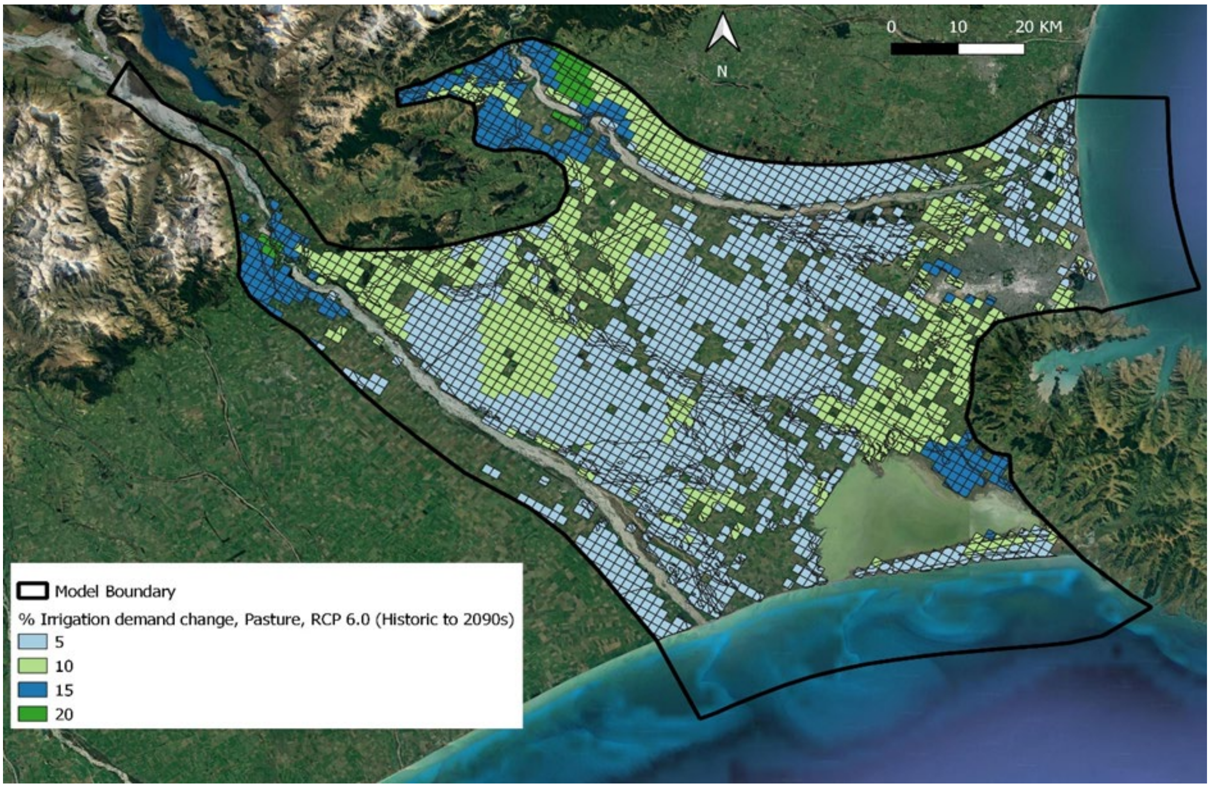

0 10 20 KM
N
Model Boundary
% Irrigation demand change, Pasture, RCP 6.0 (Historic to 2040s)
<0
5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20 KM
Model Boundary
% Irrigation demand change, Pasture, RCP 6.0 (Historic to 2090s)
5
10
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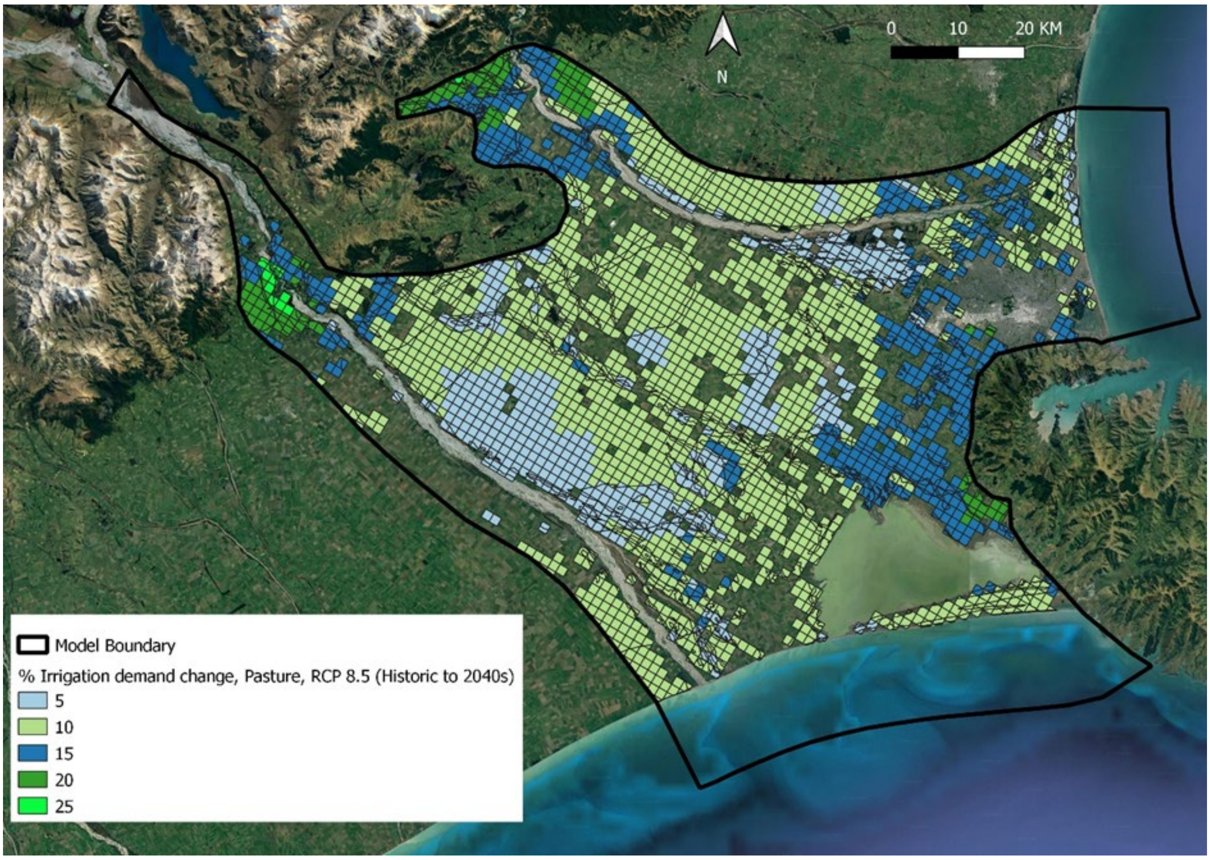
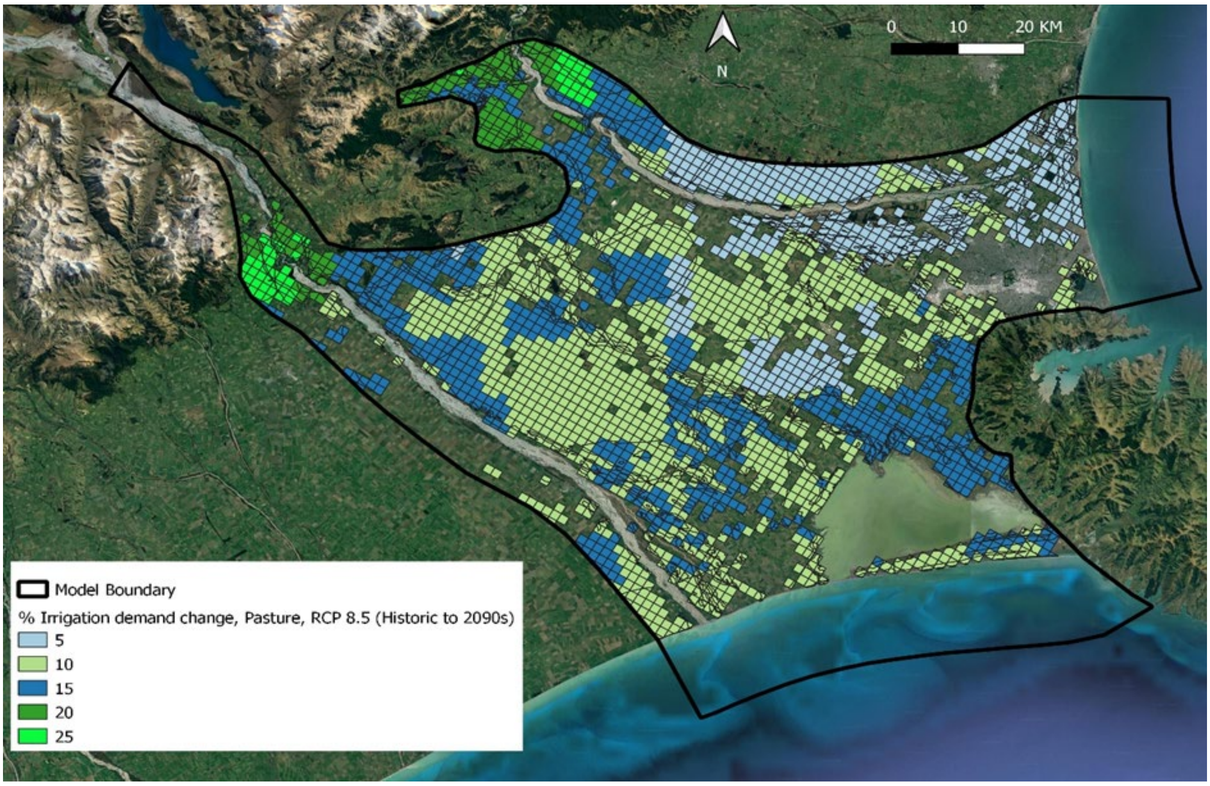
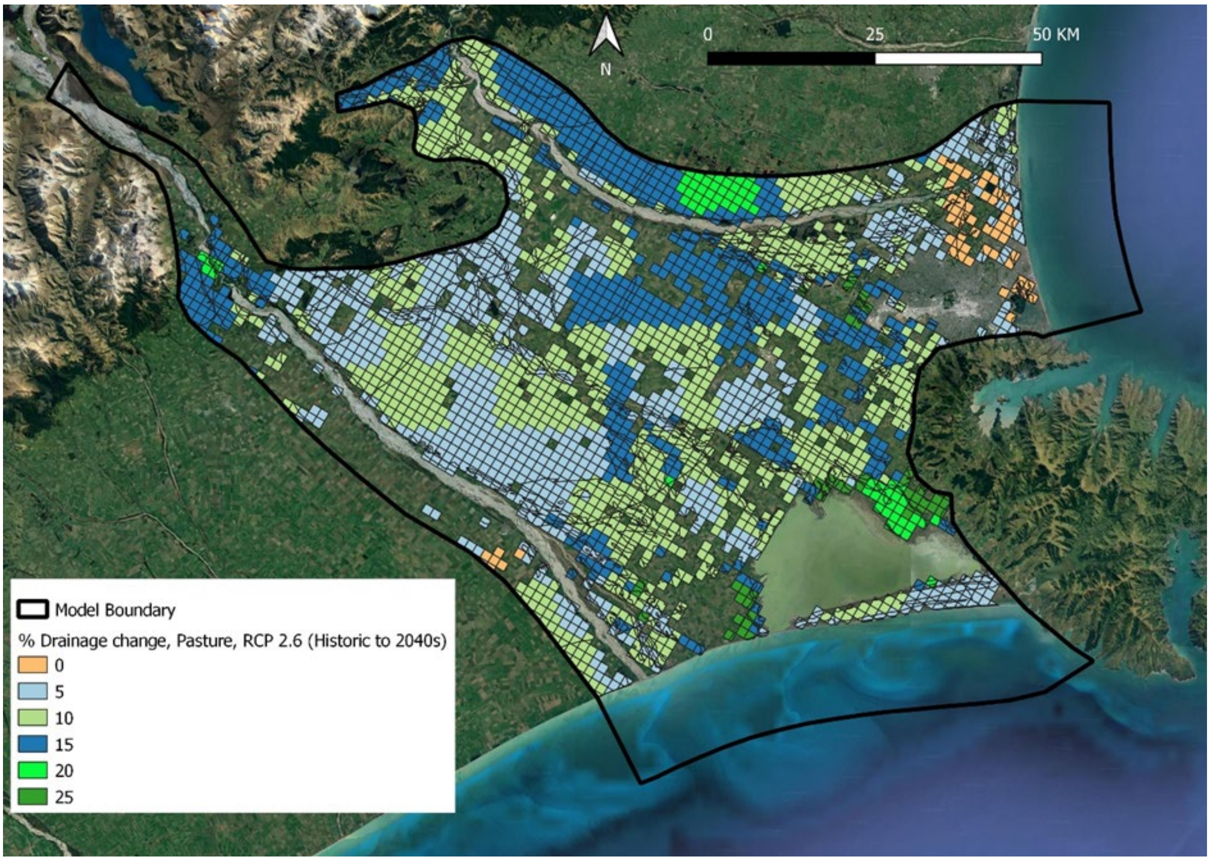
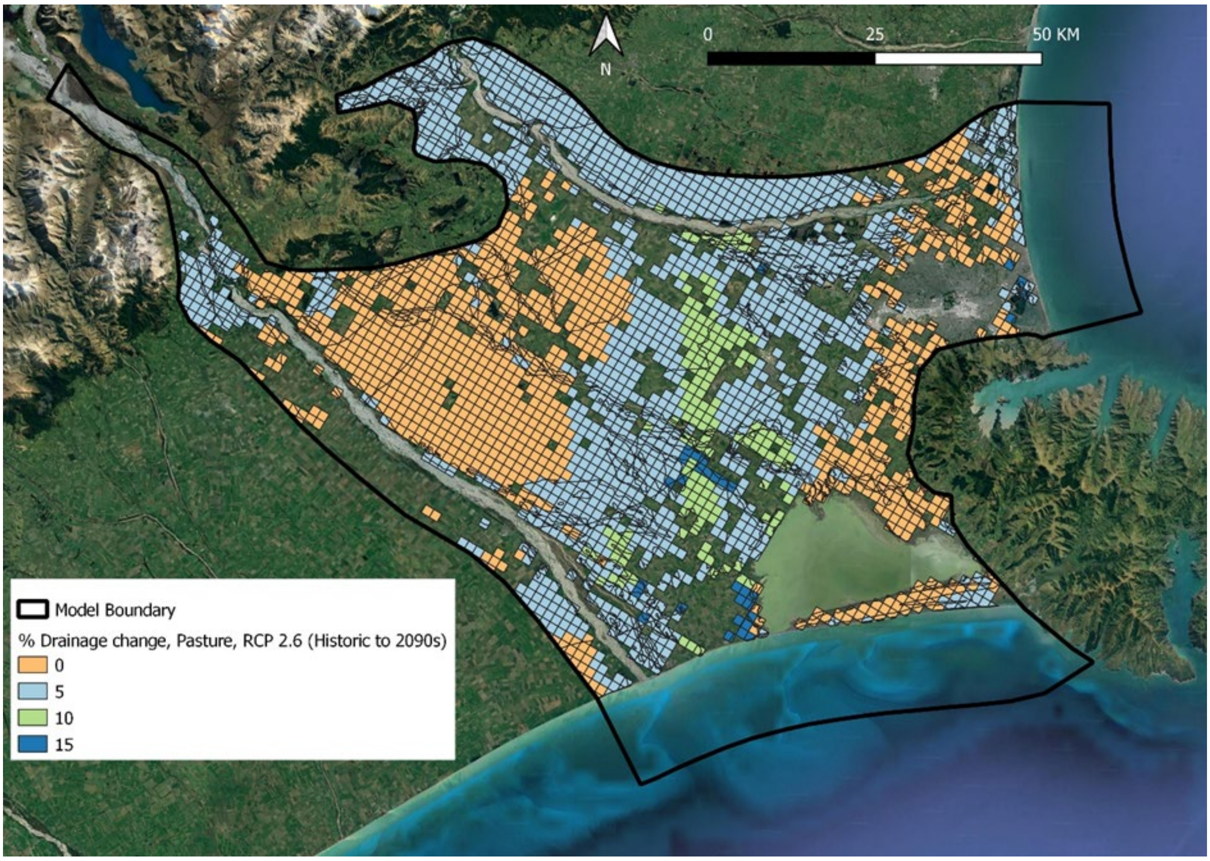
20


N
0
10
20 KM
Model Boundary
% Irrigation demand change, Pasture, RCP 8.5 (Historic to 2040s)
5
10
15
20
25



C.7 Drainage under Future Climate Scenarios




N
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25
50 KM
Model Boundary
% Drainage change, Pasture, RCP 2.6 (Historic to 2090s)
0
5
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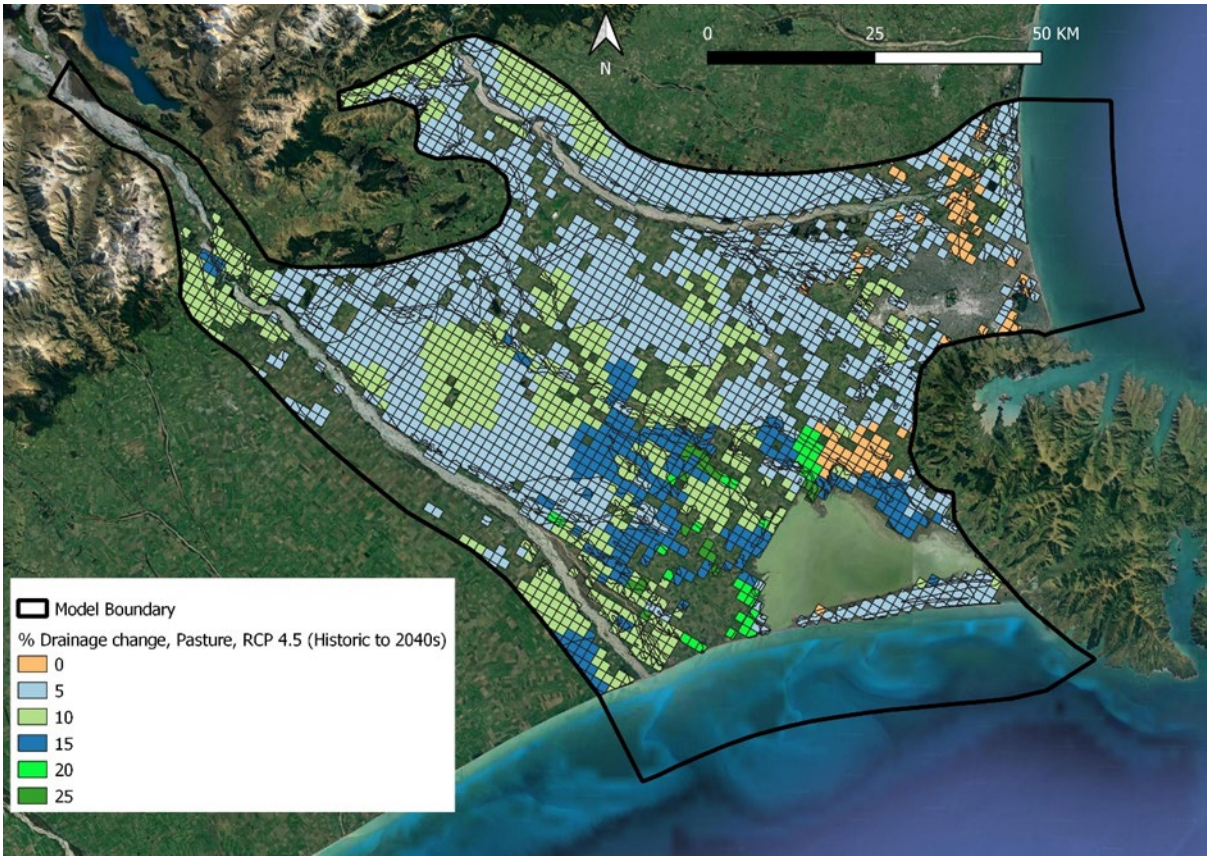
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50 KM
Model Boundary
% Drainage change, Pasture, RCP 4.5 (Historic to 2040s)
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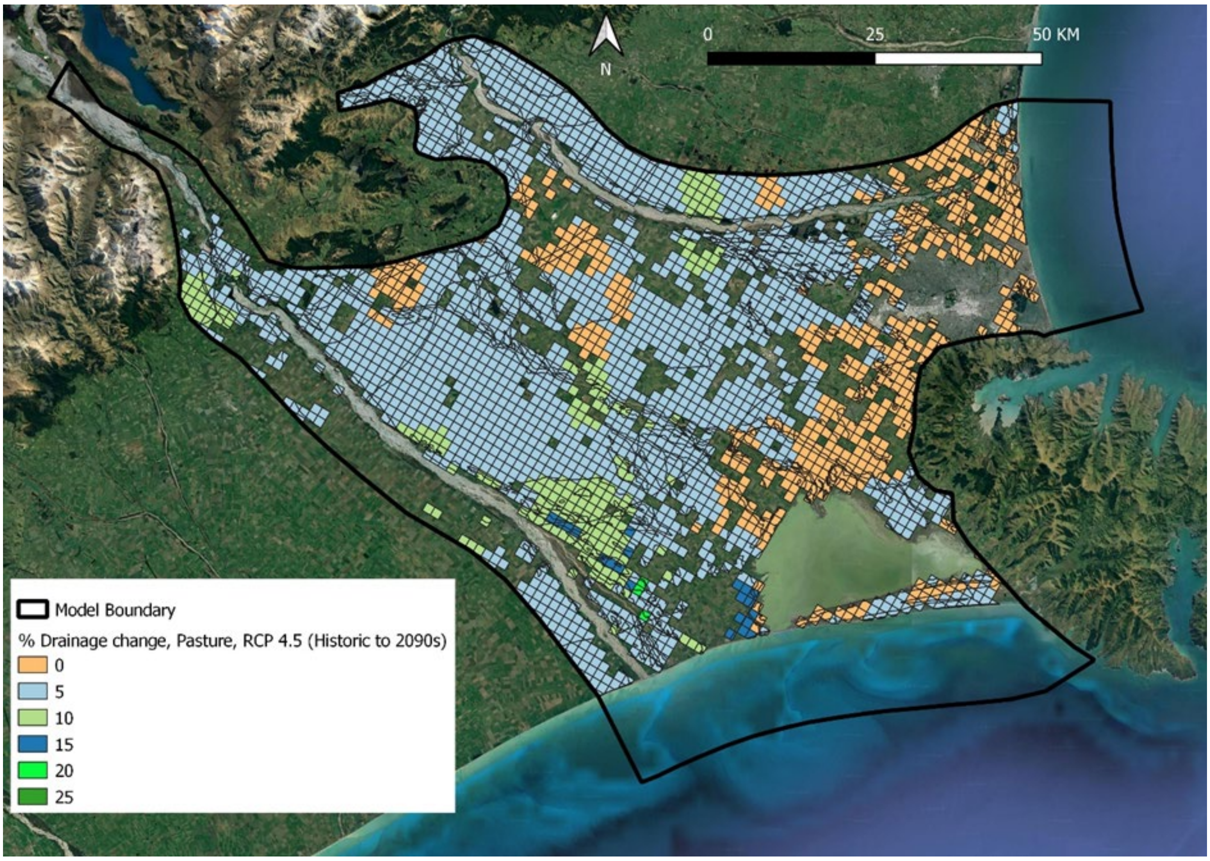
25


N
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50 KM
Model Boundary
% Drainage change, Pasture, RCP 4.5 (Historic to 2090s)
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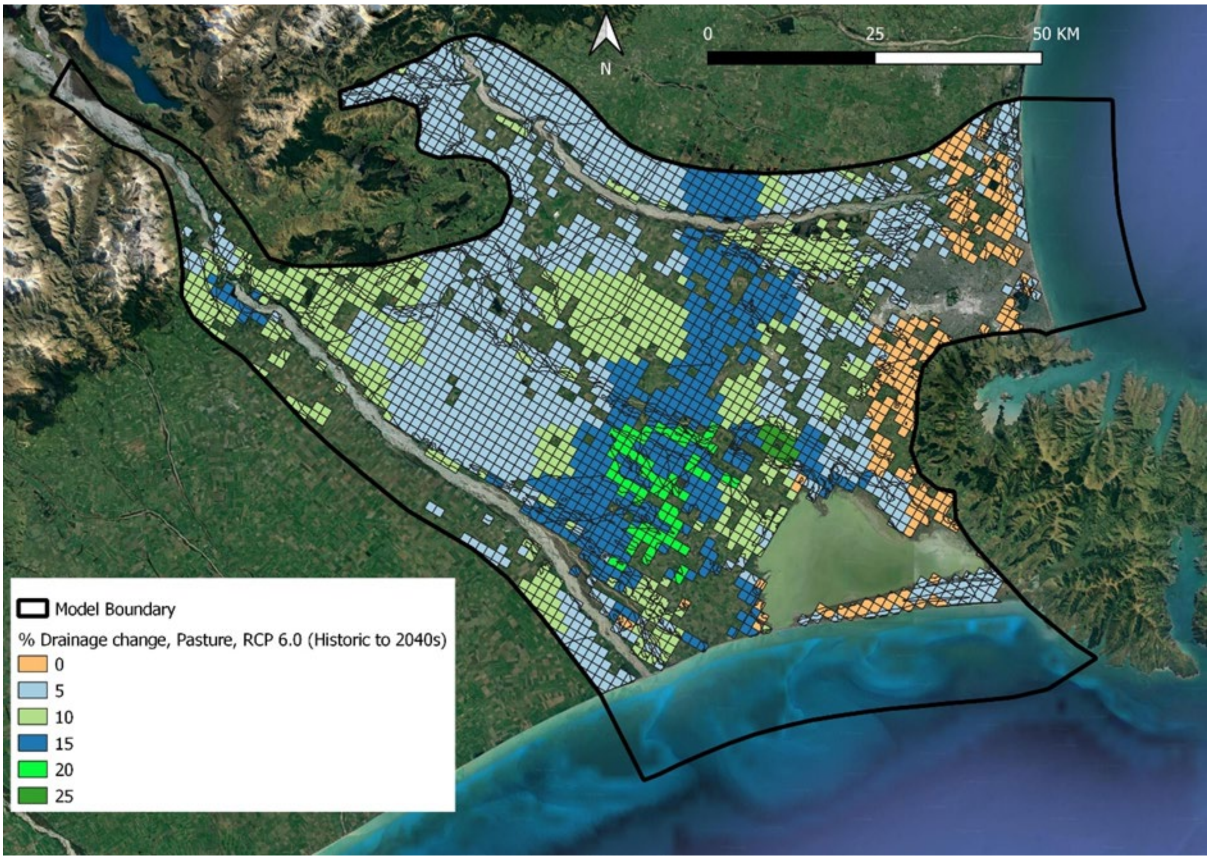
20
25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50 KM
Model Boundary
% Drainage change, Pasture, RCP 6.0 (Historic to 2040s)
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20
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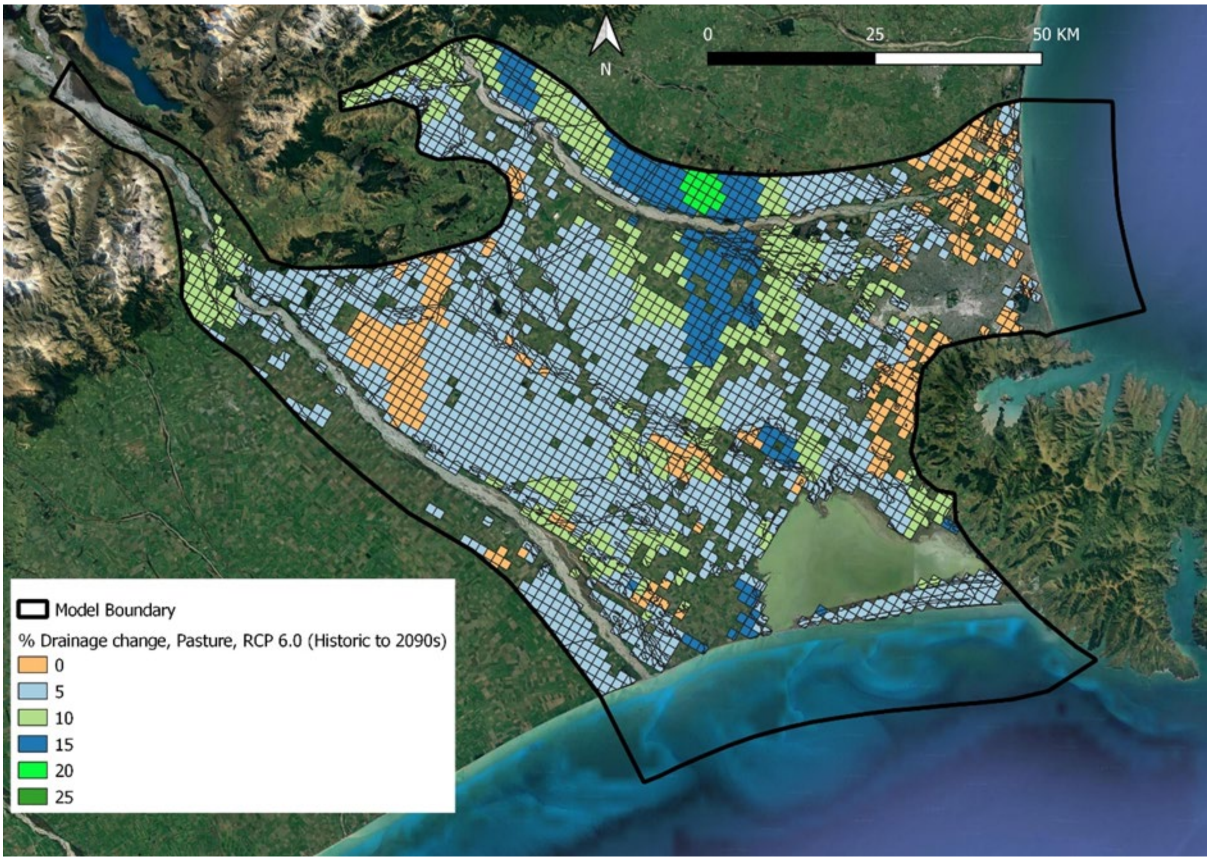
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Model Boundary
% Drainage change, Pasture, RCP 6.0 (Historic to 2090s)
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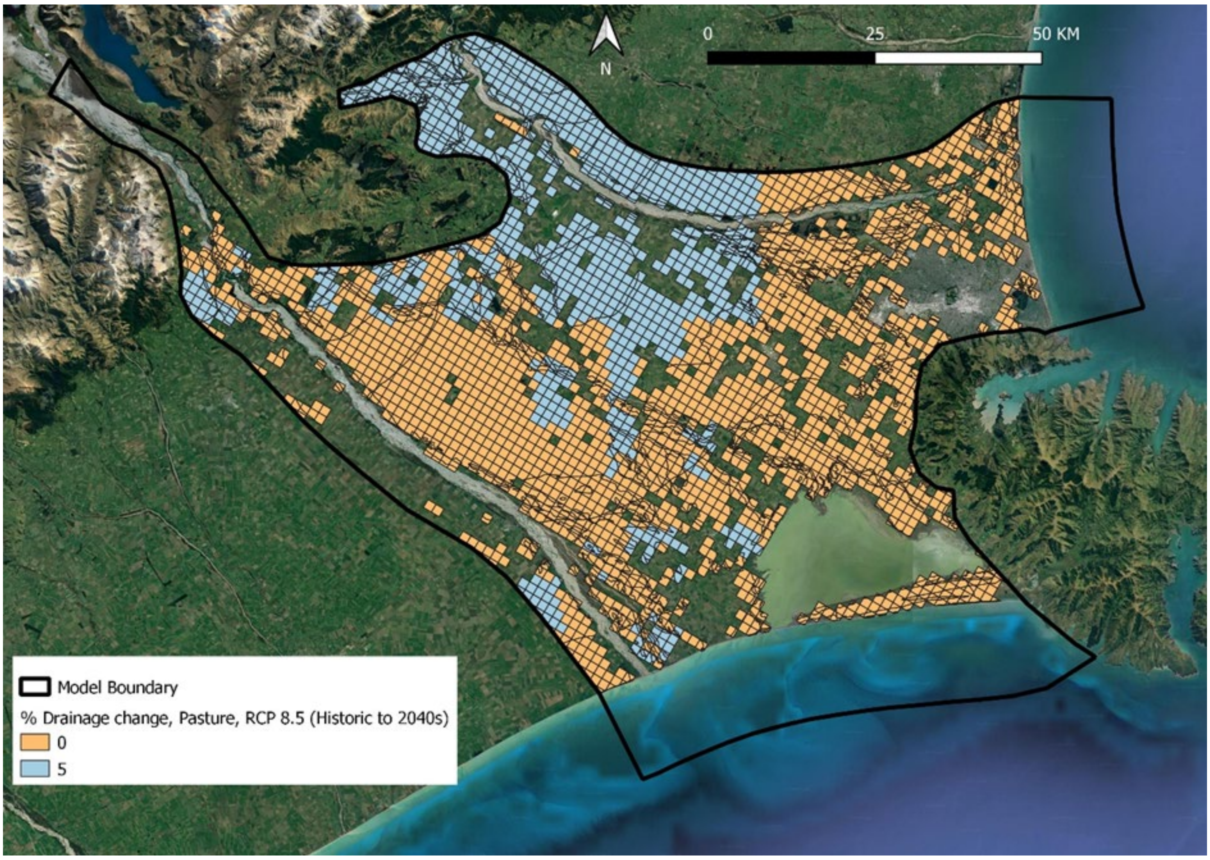
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50 KM
Model Boundary
% Drainage change, Pasture, RCP 8.5 (Historic to 2040s)
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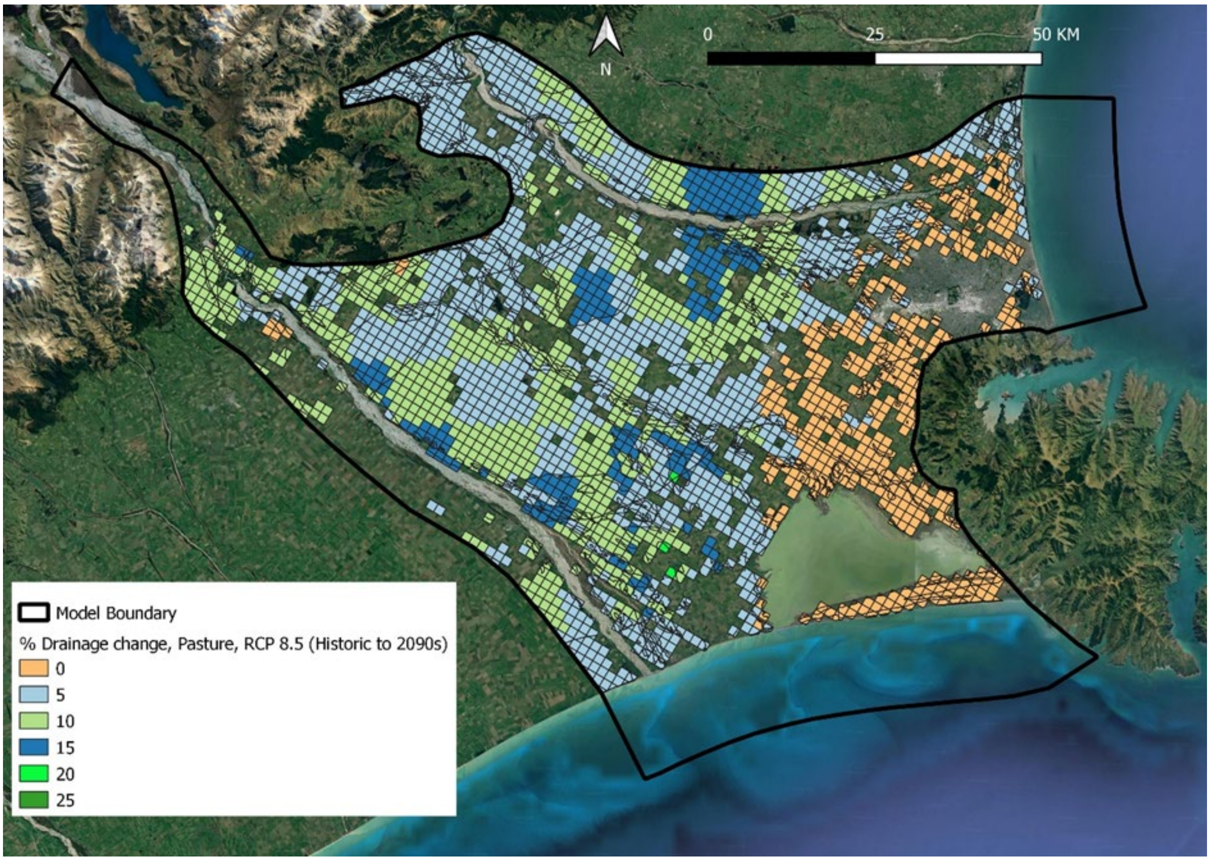
5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50 KM
Model Boundary
% Drainage change, Pasture, RCP 8.5 (Historic to 2090s)
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Appendix D: Surface Water Supply Reliability Under Future Climate Scenarios

The following tables and figures summarise the changes to water supply security (availability over time) and supply reliability for the main CPWL takes from the Rakaia and Waimakariri Rivers, using the following metrics:

- Irrigation-season supply demand ratio
- Average restriction days per month
- Total restriction days per irrigation season
- Consecutive days per irrigation season.

The metrics that are based on number of restriction days are considering water supply security only, i.e. the demand side is not factored in to these. Both full and partial restrictions are counted.

The consent to take water from the Waimakariri River has a condition specifically preventing any water from being taken between 1 May and 30 August. This is reflected in the monthly restriction data.

Overall, there is a reduction in both water supply security and supply reliability. The change in reliability appears to be more pronounced than the change in the number of restriction days, indicating that changes on the demand side are the main driver of the change in supply reliability.

D.1 Rakaia River supply reliability

Supply-demand ratio

Table D.1: Modelled irrigation season supply-demand ratio for three time periods and four RCPs. CPW take from Rakaia River.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	0.36	0.36	0.36	0.36
2040's	0.36	0.30	0.35	0.31
2090's	0.33	0.33	0.33	0.31

Average restriction days per month

Table D.2: Average restriction days per month for modelled baseline period. CPW take from Rakaia River.

RCP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All	28	28	29	27	22	18	22	24	18	17	24	28

Figure D.1: Average number of days with restrictions per month, 2040's. CPWL take from the Rakaia River.

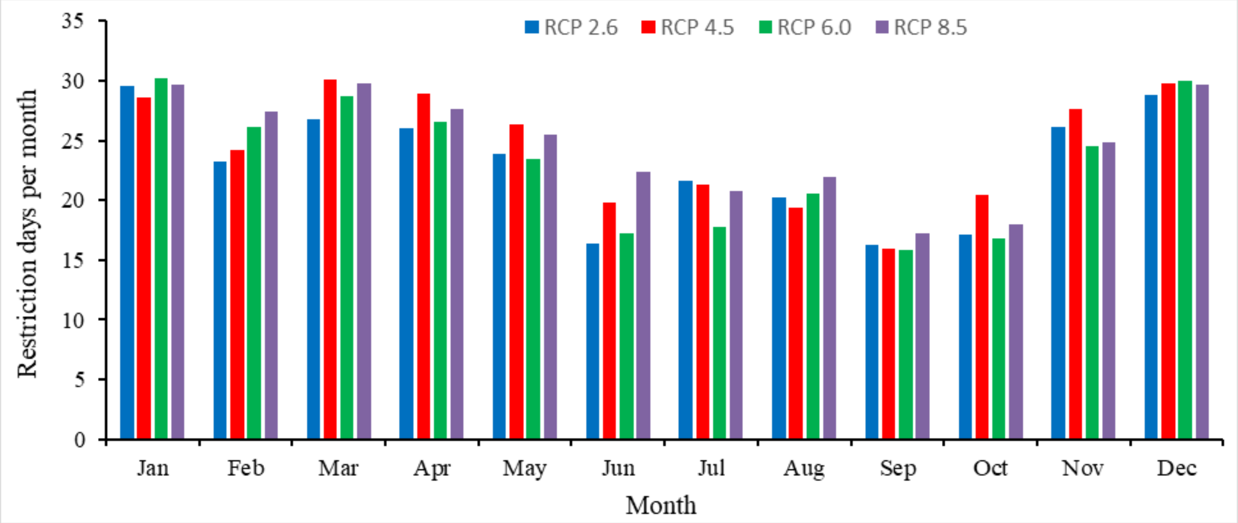
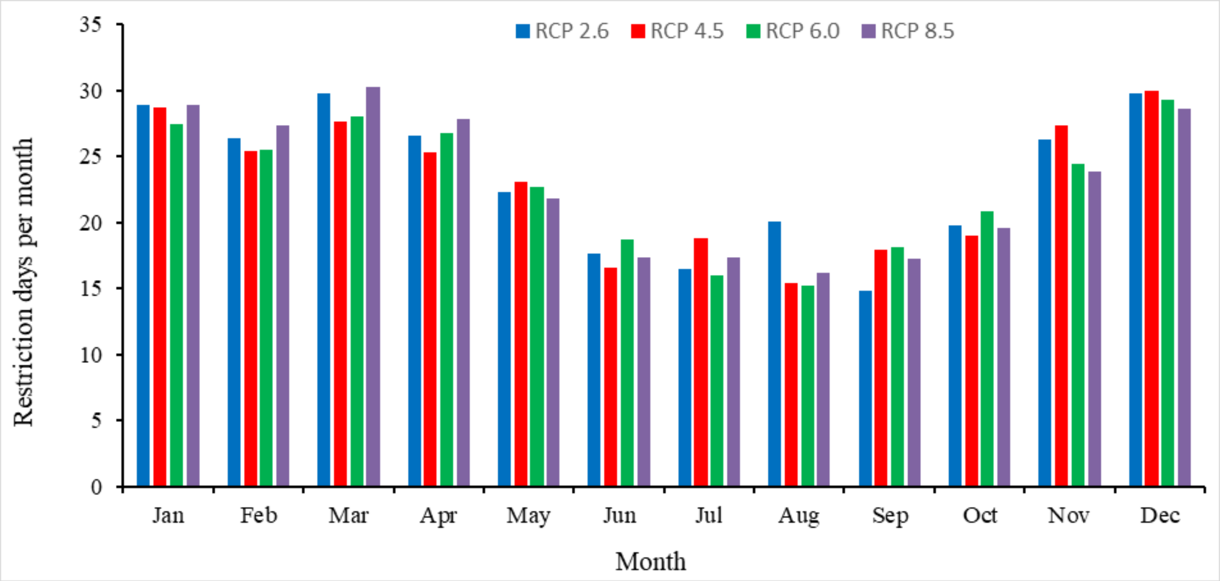


Figure D.2: Average number of days with restrictions per month, 2090's. CPWL take from the Rakaia River.



Number of days with restrictions per irrigation season

Table D.3: Average number of days with supply restrictions per irrigation season for the CPWL take from the Rakaia River.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	199	199	199	199
2040's	194	206	199	204
2090's	202	201	201	204

Maximum consecutive restriction days per irrigation season

Table D.4: Average of the maximum number of consecutive days with supply restrictions per irrigation season. CPWL take from the Rakaia River.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	111.7	111.7	111.7	111.7
2040's	100.4	134.3	123.3	131.8
2090's	133.5	119.6	109.0	116.8

D.2 Waimakariri River supply reliability

Supply-demand ratio

Table D.5: Average supply demand ratio over specified time periods, for four RCPs. CPWL take from Waimakariri River.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	0.90	0.90	0.90	0.90
2040's	0.89	0.87	0.86	0.84
2090's	0.88	0.87	0.86	0.82

Average restriction days per month

Table D.6: Average restriction days per month for modelled baseline period. CPWL take from Waimakariri River.

RCP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All	20	21	21	12	31	30	31	31	0	0	5	16

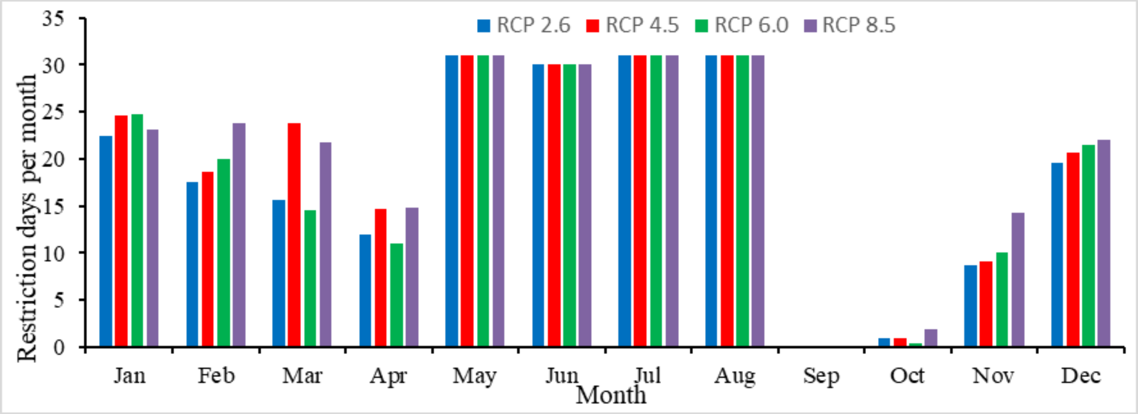


Figure D.3: Average number of days with restrictions per month, 2040’s. CPWL take from Waimakariri River.

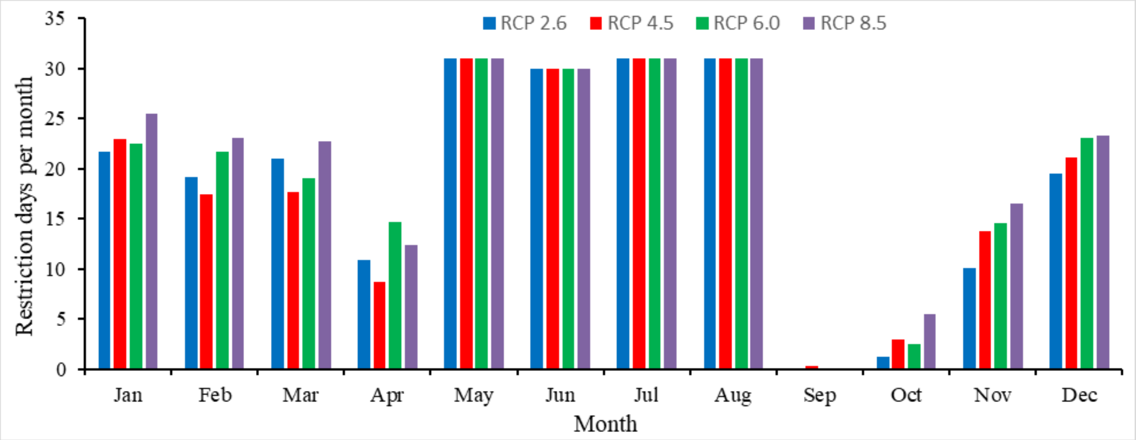


Figure D.4: Average number of days with restrictions per month, 2090's. CPW take from Waimakariri River.

Number of days with restrictions per irrigation season

Table D.7: Average number of days with supply restrictions per irrigation season for CPWL take from Waimakariri River.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	94	94	94	94
2040's	97	113	102	122
2090's	104	105	118	129

Maximum consecutive restriction days per irrigation season

Table D.8: Average of the maximum number of consecutive days with supply restrictions per irrigation season. CPWL take from the Waimakariri River.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	43	43	43	43
2040's	35	44	47	48
2090's	40	42	43	55

Appendix E: River Flow Immediately Downstream of Major Diversions to the Selwyn Waihora Zone

The following tables and figures show projected flow statistics for the Rakaia and Waimakariri Rivers downstream of the major diversions to the CPW water supply scheme for three time periods of interest and four RCPs. These results are the combined effect of changes to the river flows and changes to the modelled demand from the CPW scheme.

E.1 Rakaia River flow statistics downstream of the main CPW take.

Mean Flow

Table E.1: Modelled mean Rakaia River flow downstream of CPW take.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	198.9	198.9	199.0	198.9
2040's	218.3	194.1	220.6	188.3
2090's	207.5	210.4	214.0	215.7

7-Day Mean Annual River Flow

Table E.2: Projected Rakaia River 7-Day MALF downstream of CPW take.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	78.0	78.0	78.1	78.0
2040's	73.1	71.7	71.2	68.5
2090's	72.5	72.0	72.3	66.4

Irrigation Season Median Flow

Table E.3: Projected Rakaia River irrigation-season median flow downstream of CPW take.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	132.9	132.9	132.9	132.9
2040's	131.9	121.2	128.4	119.4
2090's	127.9	131.3	125.5	123.4

E.2 Waimakariri River flow statistics downstream of the CPW take.

Mean Flow

Table E.4: Projected mean Waimakairir River flow downstream of CPW take.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	112.5	112.5	112.5	112.5
2040's	117.7	111.5	115.3	106.7
2090's	114.7	113.9	113.6	110.1

7-Day Mean Annual River Flow

Table E.5: Projected Waimakariri River 7-day MALF flow downstream of the CPW take.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	40.7	40.7	40.7	40.7
2040's	39.3	38.8	37.3	35.5
2090's	38.5	38.0	39.0	34.5

Irrigation Season Median Flow

Table E.6: Projected Waimakariri River irrigation-season median flow downstream of the CPW take.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Historic	78.2	78.2	78.2	78.2
2040's	77.6	70.5	75.5	67.0
2090's	74.1	73.6	68.1	64.4