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Groundwater REPORT

GROUNDWATER RECHARGE AND IRRIGATION DEMAND MODELLING

Ruamahanga Collaborative Modelling Project

PREPARED FOR
Greater Wellington Regional Council

C15050-03

3/12/2017

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TABLE OF CONTENTS

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1 EXECUTIVE SUMMARY

Daily time-series datasets for status-quo irrigation and drainage were developed for the Wairarapa Plains for the historical period (1972 – 2015). The datasets were generated on a 500 m x 500 m spatial grid using IrriCalc, Aqualinc's soil-moisture balance and irrigation simulation model.

Climate data for each grid square were obtained from NIWA's virtual climate station database and used as inputs to the status-quo model. The soil water-holding capacity in each grid square was obtained from Landcare Research's S-Map database.

Drainage outputs from IrriCalc were partitioned into recharge and quickflow. Results from irrigated and dryland model runs were combined based on estimates of actual irrigated area to give time-series datasets representing the irrigation demand, recharge and quickflow in each grid square. These results were provided as inputs to the MODFLOW/SFR model for the Wairarapa Plains.

The IrriCalc modelling was repeated using climate data from the GFDL-CM3 climate model, with an RCP (representative concentration pathway) value of +6.0 W/m^2. Three 20-year sub-sets of this data were used, representing the historical period, the 2040s, and the 2090s, respectively.

Drainage and irrigation outputs based on the climate model data were processed in the same way as the status-quo outputs. Maps showing the predicted percentage change in rainfall, irrigation demand, actual evapotranspiration, and drainage, relative to the historical period of the climate model, are included in this report.

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2 MODELLING OBJECTIVES

The objectives of the modelling described in this report were as follows:

1. To develop irrigation and drainage time-series datasets for the 1972 to 2015 time period, across the whole of the Wairarapa Plains, and to provide these data for use in an integrated groundwater – surface-water flow model (MODFLOW/SFR) for this area.
2. To investigate the likely changes in irrigation demand and recharge across the Wairarapa Plains for the 2040's and 2090's, and to develop irrigation and drainage time-series datasets for these future periods.

3 CONCEPTUAL MODEL

3.1 Overview

Seasonal irrigation water use and drainage is primarily a function of rainfall, plant water use and irrigation management. Soil hydraulic properties indirectly affect irrigation water use. Interactions between these soil properties, rainfall, irrigation application system characteristics, and irrigation management determine how much of the applied water (including rainfall) is retained in the root zone of the soil, and thus how much drainage occurs and how soon the next irrigation will be required.

The method used by Aqualinc to estimate irrigation water use is an implementation of the internationally accepted approach described by Allen et al. (1998). Aqualinc's implementation uses IrriCalc to simulate the day-to-day operation of an irrigation system to avoid yield loss due to water stress. A rule-based approach to irrigation management is simulated. Application of the irrigation management rule on a daily basis, in response to modelled soil water balance status, determines the timing of irrigation and the amount to be applied. The various components of the rule are described in Section 3.3. The result of applying the irrigation rule in concert with a daily water balance model is a daily time series of drainage volume and irrigation application depth. The total amount of irrigation water used over a user specified irrigation season is summed.

The time series of seasonal irrigation water use is then analysed to determine the seasonal irrigation water use that would avoid crop yield loss, to a specified level of reliability – such as fully meeting irrigation requirements eight years out of ten years on average.

Computer modelling of irrigation system operation is a transparent method for estimating seasonal irrigation demand, based on use of a validated soil water balance model, defined irrigation management rules, and climate data.

In particular, it is a method that preserves the correlation between daily rainfall and other daily climate data, and it avoids the need to make major assumptions about the effectiveness of rainfall and efficiency of irrigation. The volume of drainage from each rainfall and irrigation event is an output – a result that depends on the soil water deficit at the time of the event and on the characteristics of the irrigation or rainfall event.

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3.2 Summary of Key Assumptions

The key assumptions on which Aqualinc's method for estimating irrigation water use and drainage is based on are:

- The irrigation actions determined by the irrigation system model are practical;
- Irrigation rules are consistently followed – for some rules, this implies that soil water content in the root zone is continuously monitored and used for irrigation decision making;
- Water is always available for irrigation, at the rate required, when irrigation is required according to the decision rule being used (note that actual water availability can be used but for the purpose of estimating potential water demand 100% availability is assumed);
- Assumptions specific to the soil-plant-atmosphere model used (see Section 4.1 for assumptions pertinent to the IrriCalc model); and
- Assumptions specific to the irrigation system model and irrigation management rules used (see Section 4.3 for assumptions pertinent to the IrriCalc model).

3.3 Information Required to Apply the Method

The information required to apply this method depend on the information requirements of the model(s) used. Section 3 describes IrriCalc model and the information required to use it.

4 MODEL DESIGN

4.1 Description of IrriCalc's Soil Water Balance Model

The version of IrriCalc used for this project is a single-layer soil water balance model that uses the following equation to update the calculated soil water content on a daily basis given daily measurements or estimates of rainfall, irrigation, drainage and actual evapotranspiration.

$$S_{t_2} = S_{t_1} + R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - AET_{(t_2-t_1)} \quad \text{(Equation 4-1)}$$

Where:

$AET_{(t_2-t_1)}$	=	Actual evapotranspiration between time t_2 and t_1
$R_{(t_2-t_1)}$	=	Rain between time t_2 and t_1
$I_{(t_2-t_1)}$	=	Irrigation between time t_2 and t_1
$D_{(t_2-t_1)}$	=	Drainage between time t_2 and t_1
S_{t_2}	=	Soil water content at time t_2
S_{t_1}	=	Soil water content at time t_1

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$$AET_{(t_2-t_1)} = K_c \times f(S_{t_1}, a) \times ETref_{(t_2-t_1)}$$

K_c = Crop factor applicable over time t_1 to t_2

$f(S_{t_1}, a)$ = Evapotranspiration reduction function

$ETref$ = Evapotranspiration for a well-watered reference crop

The evapotranspiration reduction function is an empirical function that takes a value in the range 0 to 1, depending on the ratio of soil water content on day t_1 to the “field capacity” and the parameter “a”. The parameter “a” is related to the volume of soil water that is readily available to the plant. The particular empirical function used in IrriCalc is described in Minhas *et al.* (1974), and has been used in New Zealand by Heiler (1981) and Bright (1986).

Drainage is assumed to occur whenever the soil water content is calculated to be greater than “field capacity”. The volume of drainage is set equal to the volume required to reduce the soil water content to “field capacity”, and it is assumed that drainage occurs within the same daily time period as the rainfall or irrigation that raised soil water content above “field capacity”.

Reference crop evapotranspiration is calculated from daily climate measurements using the Penman-Monteith method (FAO-56), with parameters appropriate for estimating evapotranspiration from a well-watered grass sward of 120 mm height.

Irrigation amounts are either calculated by an irrigation system model on each day of a defined irrigation season or are input as time series measurements. The irrigation system model is described in Section 4.3.

IrriCalc outputs each component of the soil water balance on each day of the simulation, along with a check-sum that indicates whether mass has been conserved and the accumulated volume of water used for irrigation.

4.2 The Crop Factor

The Crop Factor is a plant structure parameter that specifies the evapotranspiration of a plant population relative to a reference evapotranspiration.

Usually the reference evapotranspiration is that of a well-watered pasture with canopy characteristics that are constant throughout the year. The key canopy characteristics are plant height, leaf area index, and the stomata resistance and canopy resistance to vapour transport.

The assumption that the reference crop is “well-watered” implies that there is a good store of water in the soil. It also implies that the form and hydraulic resistances of the plant’s root system are such that the root system is capable of supplying water at the flow rate required to meet the atmosphere’s capacity to evaporate and transport water away from the plant canopy.

The crop factor used in this project varies throughout the year. The temporal variation in the crop factor changes throughout the year because of changes in the height, leaf area index, and form of real pasture canopies. The crop factor for pasture has been derived from data from Canterbury Regional Council’s lysimeter network (see Section 5).

4.3 Description of IrriCalc’s Irrigation System Model

The irrigation system model enables key irrigation system design and irrigation management parameters or constraints to be specified. These are the depth and spatial uniformity of irrigation applications, the return period, the soil water level at which irrigation is triggered, the beginning and end of the irrigation season, and the maximum seasonal irrigation water use.

Table 1 shows the various combinations of irrigation system parameters that can be applied to replicate a wide range of irrigation systems and practices.

Table 1: Irrigation management options available in IrriCalc

Application depth	When to irrigate			
	Never	Every X days, where X = Return Period	Trigger on soil moisture, providing the days since the last irrigation equal or exceed the Return Period	User supplied time series
Zero	✓			
Fixed depth (user defined)		✓	✓	
Variable depth (return soil moisture to a specified level)		✓	✓	
User supplied time series				✓

4.3.1 Irrigation applications

These are either input as a time series of actual application depths or are determined by the application of irrigation management rules.

The application depth specified by the user, or calculated by the irrigation model, is the spatial average of the water depth applied across the wetted width and run length of the irrigation application device. The spatial uniformity of the irrigation application is specified by Christiansen’s Uniformity Coefficient.

The amount of water that is retained in the soil due to an irrigation event is calculated using the method described in Bright (1986). Implicit in this calculation is the assumption that the spatial distribution of application depth can be represented by the Normal distribution. The amount retained, and thus the amount of irrigation water that drains, is a function of the soil water deficit at the time of irrigation, the average application depth, and the spatial uniformity of the irrigation application. The relationship between application efficiency (which is the ratio of volume of water retained to volume of water applied), average application depth, and uniformity is illustrated in the following figure:

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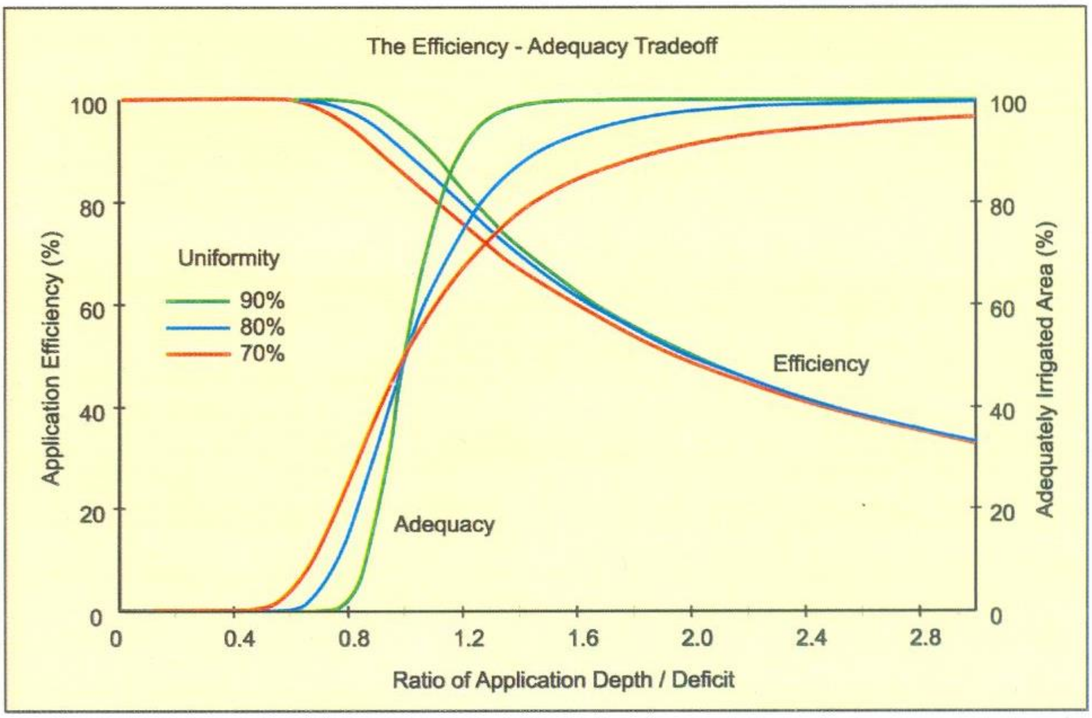

Figure 1: Relationship between application efficiency, application uniformity and application depth (source: Bright, 1986)

4.3.2 Application efficiency

Application efficiency is defined as the ratio of the volume of irrigation water retained in the root zone of the soil to the volume of irrigation water applied to the land surface. The application efficiency varies from application event to application event.

Application efficiency is not a direct output of an IrriCalc simulation, but can be calculated for each irrigation event by opening the IrriCalc output file in Excel and doing the calculation in Excel.

4.3.3 Irrigation system capacity

Irrigation system capacity is an implicit constraint in IrriCalc. The combination of application depth and return period constrains irrigation system capacity according to the following:

$$\textit{Maximum flow rate} = (\textit{Application depth} \times 10{,}000) \div (\textit{Return period} \times 86{,}400)\ \ell/s/ha$$

where Application depth is in millimetres and Return period is in days.

4.3.4 Maximum seasonal irrigation water use

The total amount of irrigation water used in any irrigation season is constrained to be less than the user-specified maximum seasonal irrigation water use. If the specified maximum is reached during an irrigation season, then irrigation is prevented for the remainder of that season. No attempt is made, in this version of IrriCalc, to optimise the use of the limited volume of water. The total volume of irrigation water used is re-set prior to beginning of the next irrigation season.

To investigate how much irrigation water would have been used over a sequence of many years in the absence of a cap on total use, the specified maximum seasonal irrigation water use is simply set to a very large number.

4.4 Summary of Key Assumptions

- The soil is free draining.
- Crop canopy development is sufficiently consistent across years to enable use of a crop factor time series to transform evapotranspiration for a reference crop into evapotranspiration from the crop or pasture of interest.
- All rainfall and irrigation intercepted and retained on leaf and stem surfaces is effective in meeting the evapotranspiration load.
- The spatial distribution of irrigation application depth can be represented by the Normal Distribution.

4.5 Data Needed to Use IrriCalc to Estimate Seasonal Irrigation Demand

The information required to apply IrriCalc is summarised in the following sub-sections. The climate and soils data required are available throughout New Zealand, courtesy of fundamental databases maintained by the National Institute for Water and Atmospheric Research Ltd. and Landcare Research Ltd.

4.5.1 Climate, Crop and Soils Data Required

- Daily time series for rainfall and potential evapotranspiration for the site of interest. These can be measured data or data from NIWA's virtual climate network.
- Crop factor time series (one year). For irrigated pasture, the crop factor time series is based on Van Housen (2015). Crop factors for other crops are generally sourced from FAO 56.
- Crop root depth (or depth of soil that supplies water to meet crop needs).
- Water holding capacity of the soil to crop root depth (mm per mm of soil depth).
- Dates the crop or pasture is sown and harvested.

4.5.2 Irrigation System Data Required

- The type of irrigator to be modelled and some understanding of its operating requirements.
- The maximum and minimum average application depth that is practical to apply for the particular irrigator.
- The uniformity of irrigation applications (Christiansen's Uniformity Coefficient).

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- The length of the irrigation rotation (days).
- The soil water content at which irrigation is initiated (if irrigation timing is determined by measured soil water content).
- Maximum seasonal irrigation water use.
- Beginning and end dates for the irrigation season.

5 MODEL CALIBRATION

There are no data from the Wairarapa area that is suitable for calibrating the soil water balance model. The primary calibration parameter is the crop factor time series, followed by the capacity of the soil to store plant available water.

A crop factor time series has been calibrated for use in Canterbury, using data obtained from Canterbury Regional Council's (CRC) lysimeter network (Van Housen, 2015). Figure 2 shows that the drainage modelled using this crop factor time series with IrriCalc matches closely that measured at CRC's Methven lysimeter site. This crop factor has been used with IrriCalc to model irrigation water use and drainage for this project. The assumption is that the pasture species, growth rates and management used in the Wairarapa are the same as, or very similar to, those used in Canterbury.

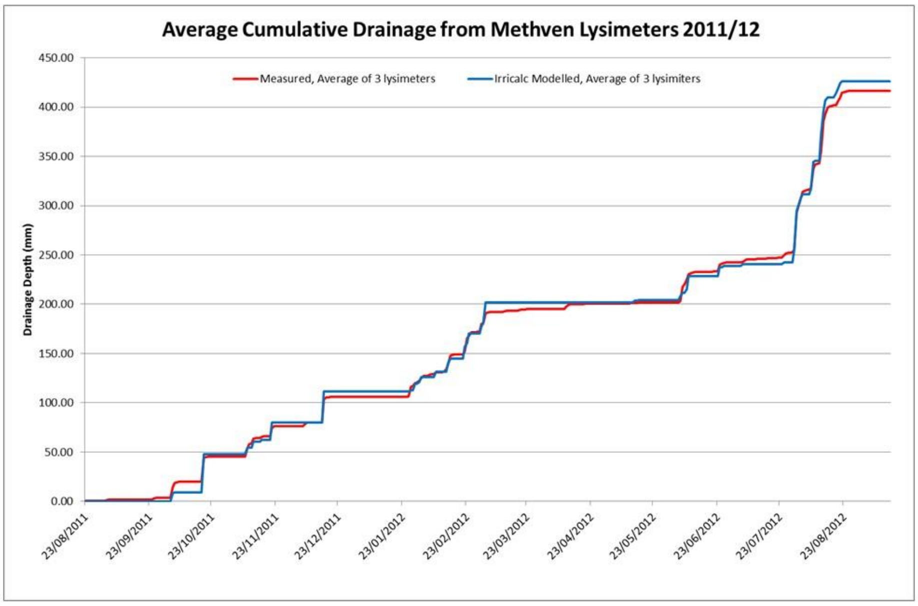

Figure 2: Comparison between measured and IrriCalc modelled drainage

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6 MODELLING STATUS QUO

The Wairarapa Plains area was divided up into 500m x 500m grid-squares based on the NIWA Virtual Climate Station grid. The area covered matches the area covered by the MODFLOW/SFR computational grid, although the spatial discretisation of the MODFLOW model is finer.

Daily climate data for each grid square for the period 1 Jan 1972 to 31 December 2015 was supplied by NIWA from their Virtual Climate Station database.

The most prevalent soil type in each grid square was determined by intersecting this grid with a copy of S-Map provided by Landcare Research Ltd. for this area. The water holding capacity to 600mm depth was obtained for each of these soil types from S-Map.

IrriCalc was used to simulate changes in the soil water balance from day-to-day in response to rainfall, irrigation, actual evapotranspiration and drainage, for each grid-square over the period 1972 to 2015. The simulations were repeated assuming no irrigation so that for each grid-square three key time-series datasets were developed: potential irrigation demand, drainage under irrigated conditions, and drainage from unirrigated land.

Estimates of the proportion of irrigated land in each grid square, and the year in which irrigation first occurred, were used to generate time-series data-sets of actual irrigation demand and drainage for each grid square.

The key time-series datasets for each grid-square were provided to the MODFLOW/SFR modelling team as an input to their groundwater – surface water flow modelling.

Some results of the IrriCalc modelling are presented in summary form in the figures below.

Figures 3 and 4 illustrate the modelled average annual water flows into and out of the soil under dryland (i.e. unirrigated) and irrigated conditions for two areas on the Wairarapa Plain.

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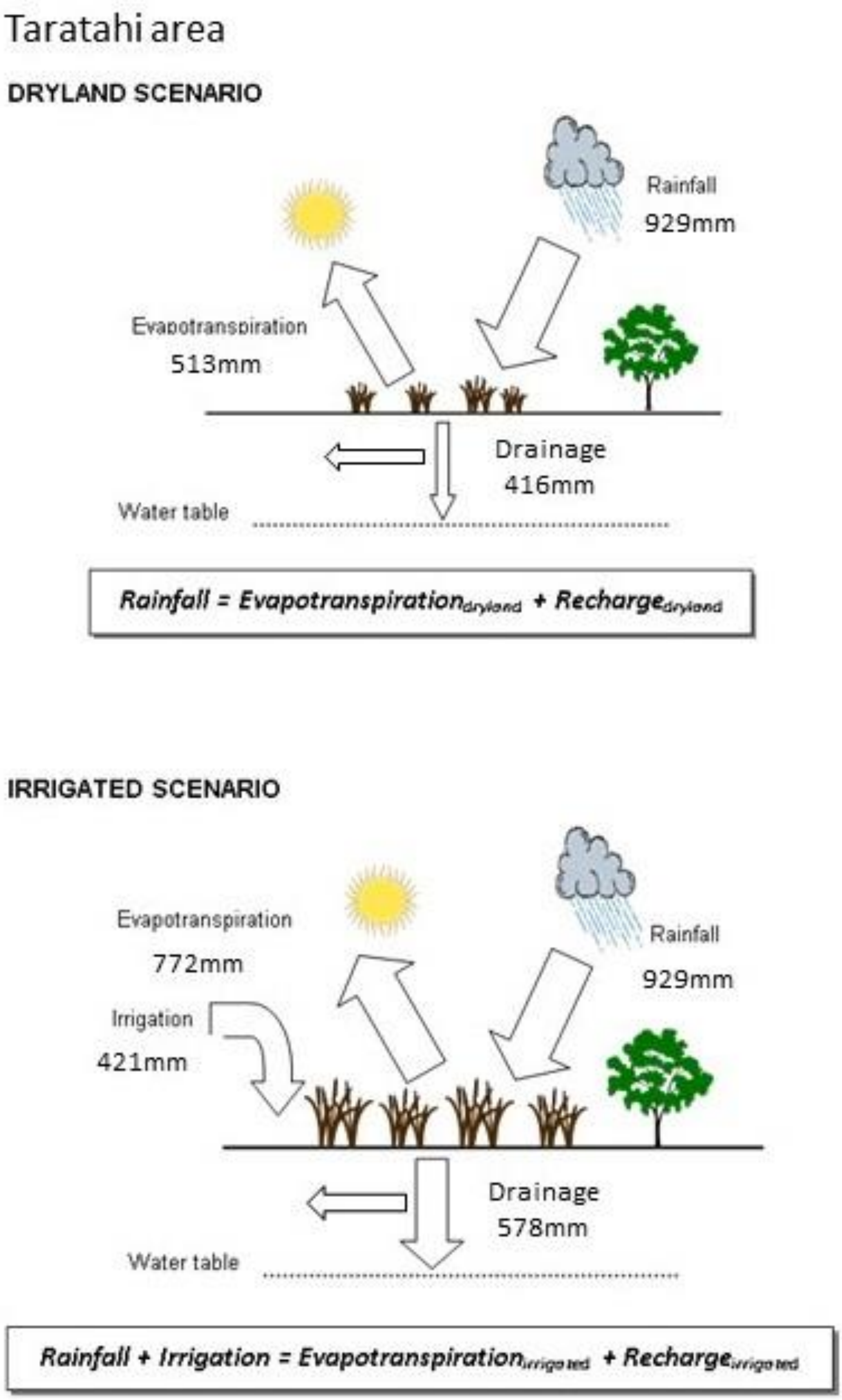

Figure 3: Average annual water inputs and outputs to soil in the Taratahi area

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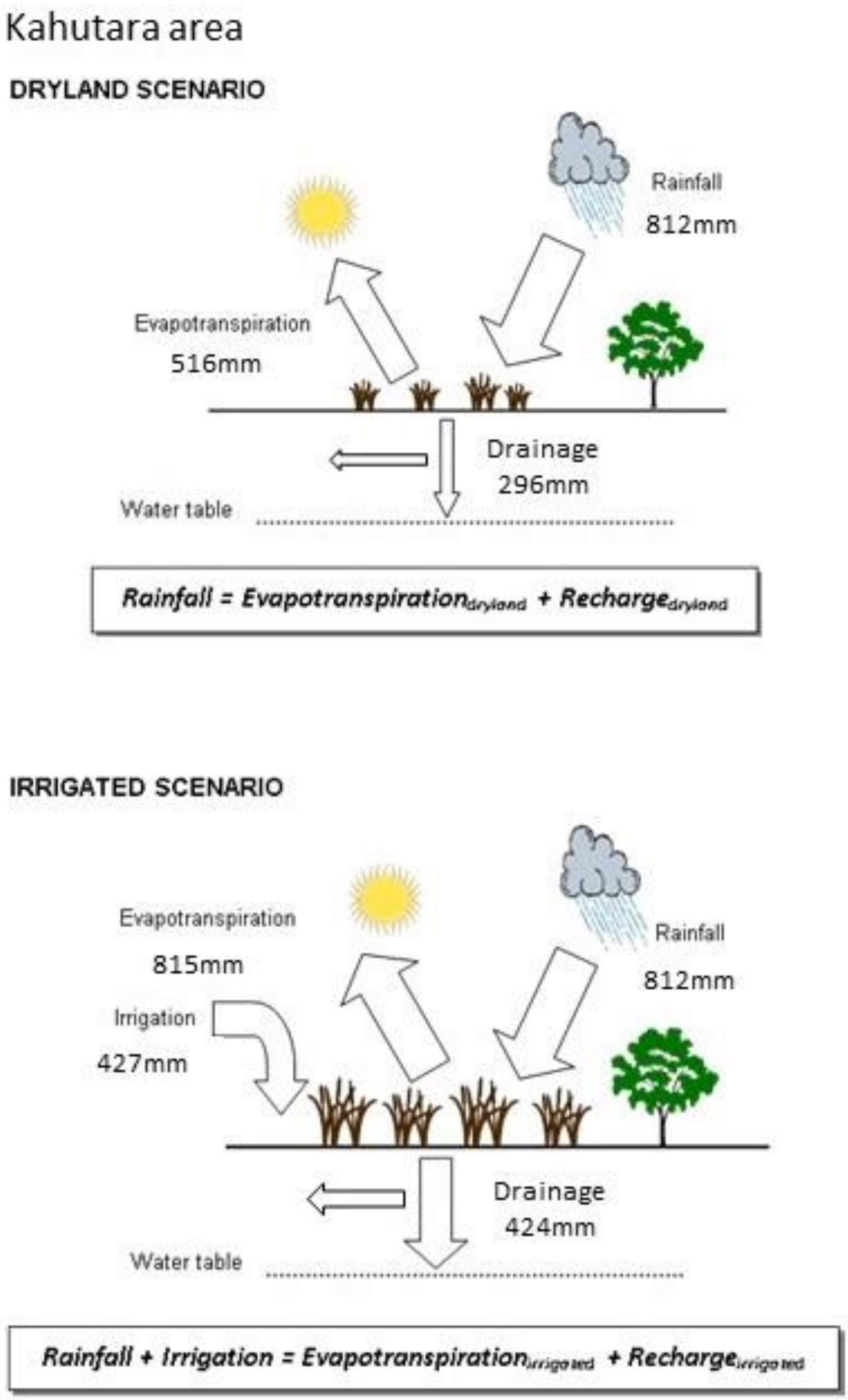

Figure 4: Average annual water inputs and outputs to soil in the Kahutara area

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6.1 Partitioning of drainage

Not all of the amount of drainage shown in the figures above goes to groundwater. A portion of the drainage moves laterally to rivers and streams, generally below the soil surface but at times as surface run-off. The partitioning of the drainage amount calculated by IrriCalc into groundwater recharge and near-surface lateral flow to streams is calculated separate from the IrriCalc modelling process.

The drainage amount calculated by IrriCalc is partitioned into near-surface lateral flow to streams and drainage to groundwater using a simplification of Woodward et al's (2013) method. Their conceptual model of stream-flow generation has three flowpaths to streams – surface run-off, shallow sub-surface lateral flow and deeper groundwater flow. Their analysis showed that for the Toenepi catchment, which is predominantly used for dairy farming, run-off contributed only 5% of stream flow. Therefore our approach has further simplified the conceptual model by lumping the surface run-off and shallow sub-surface flow path into one – the 'near-surface lateral flow path'. The mechanics of approach is a threshold-based mass balance approach. It assumes that when the drainage depth calculated by IrriCalc exceeds a specified value, the drainage in excess of this threshold is quickly flows to the nearest appropriate stream as near-surface lateral flow. This implicitly assumes that the soil water content must exceed a threshold value, between 'field capacity' and saturation, before near-surface lateral flow occurs.

For each grid-square the 95th percentile of the daily modelled dryland drainage time-series was calculated and used as the drainage threshold. The maximum daily recharge to the groundwater system, for both the irrigated and dryland cases, was capped at this value. Drainage in excess of the 95th percentile was classified as quickflow (i.e. near-surface lateral flow), and a separate time-series of this was generated. The quickflow from each grid-square was assigned to the closest stream reach in the MODFLOW/STR model. The drainage threshold is a calibration parameter. The 95th percentile was chosen because we have found in prior studies that this resulted in a good match between measured stream flows and those modelled using the MODFLOW/SFR software.

6.2 Annual variation in irrigation demand and drainage

Irrigation demand and drainage vary considerably from year to year. The following figures illustrate the degree of annual variation for the Taratahi and Kahutara areas, for irrigated pasture.

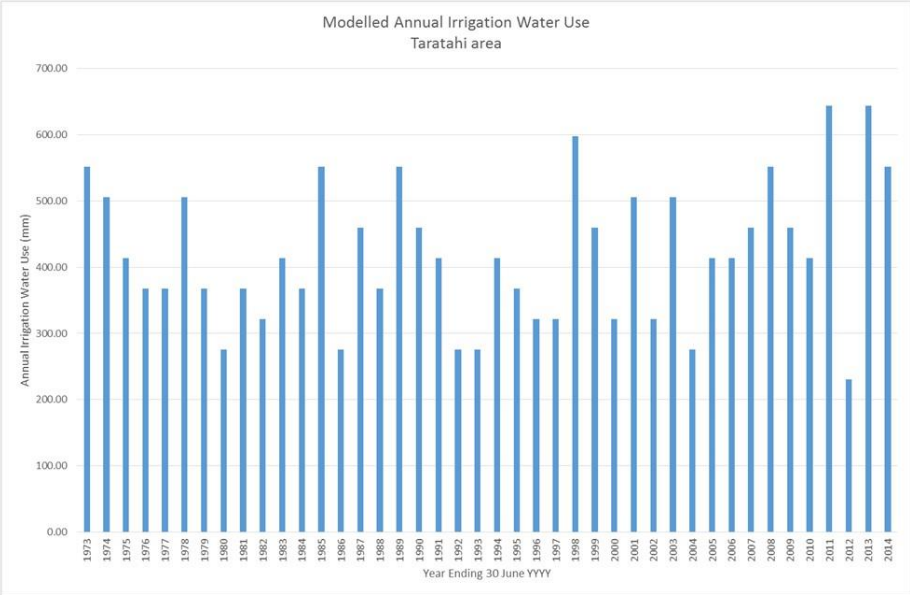

Figure 5: Modelled annual water use for irrigation of pasture in the Taratahi area

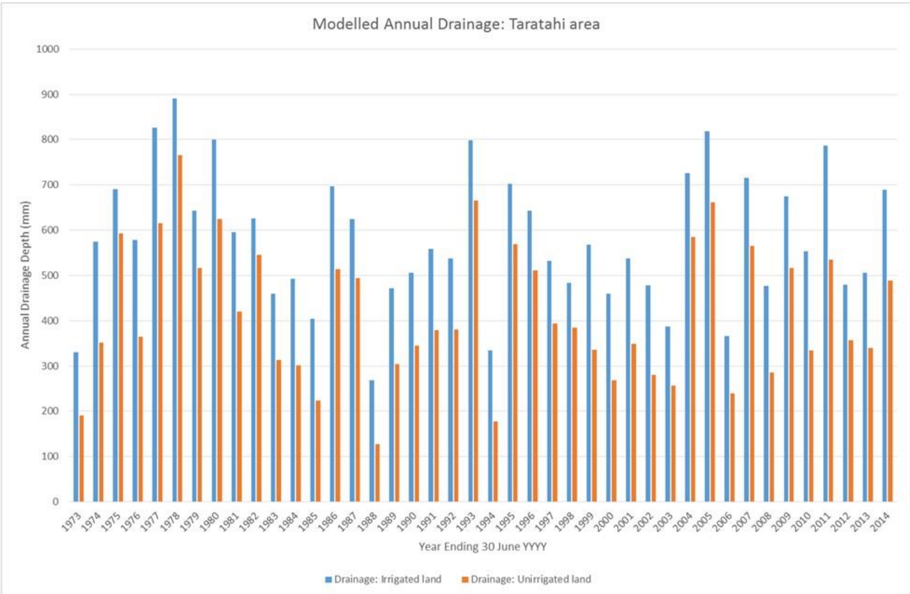

Figure 6: Modelled annual drainage depths under irrigated and unirrigated pasture in the Taratahi area

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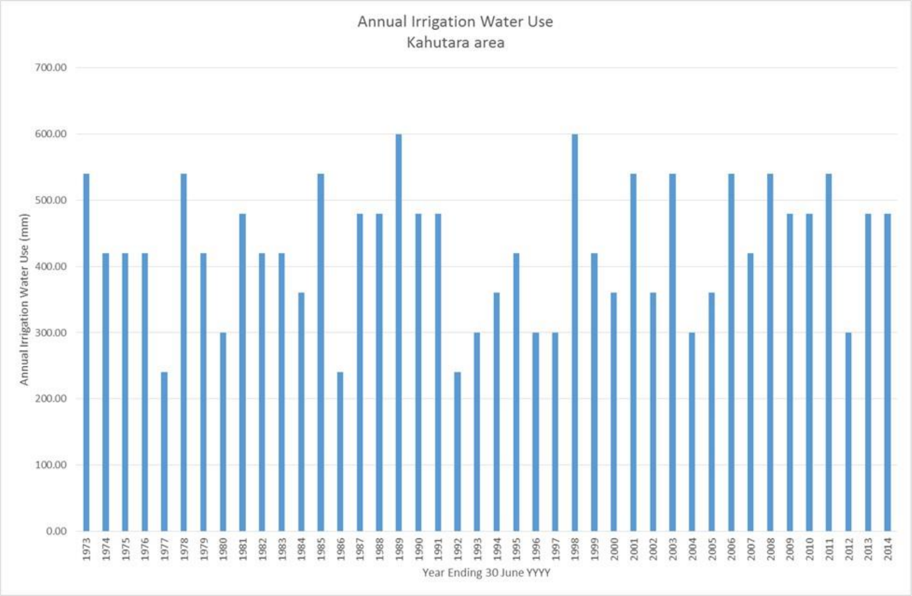

Figure 7: Modelled annual water use for irrigation of pasture in the Kahutara area

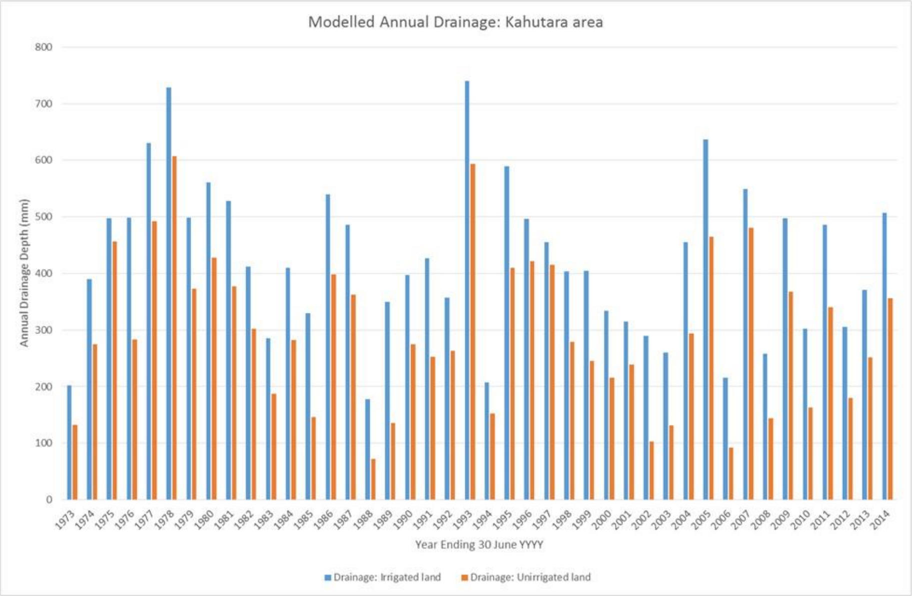

Figure 8: Modelled annual drainage depths under irrigated and unirrigated pasture in the Kahutara area

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6.3 Spatial distribution of status quo results

There is considerable spatial variability in the IrriCalc inputs and results across the model area. The spatial variation in average annual values for the status quo scenario is shown in the following maps.

6.3.1 Rainfall

Average annual rainfall contours (based on the VCN dataset) are shown in Figure 9. The rainfall is highest in the west, with a relatively strong gradient from west to east.

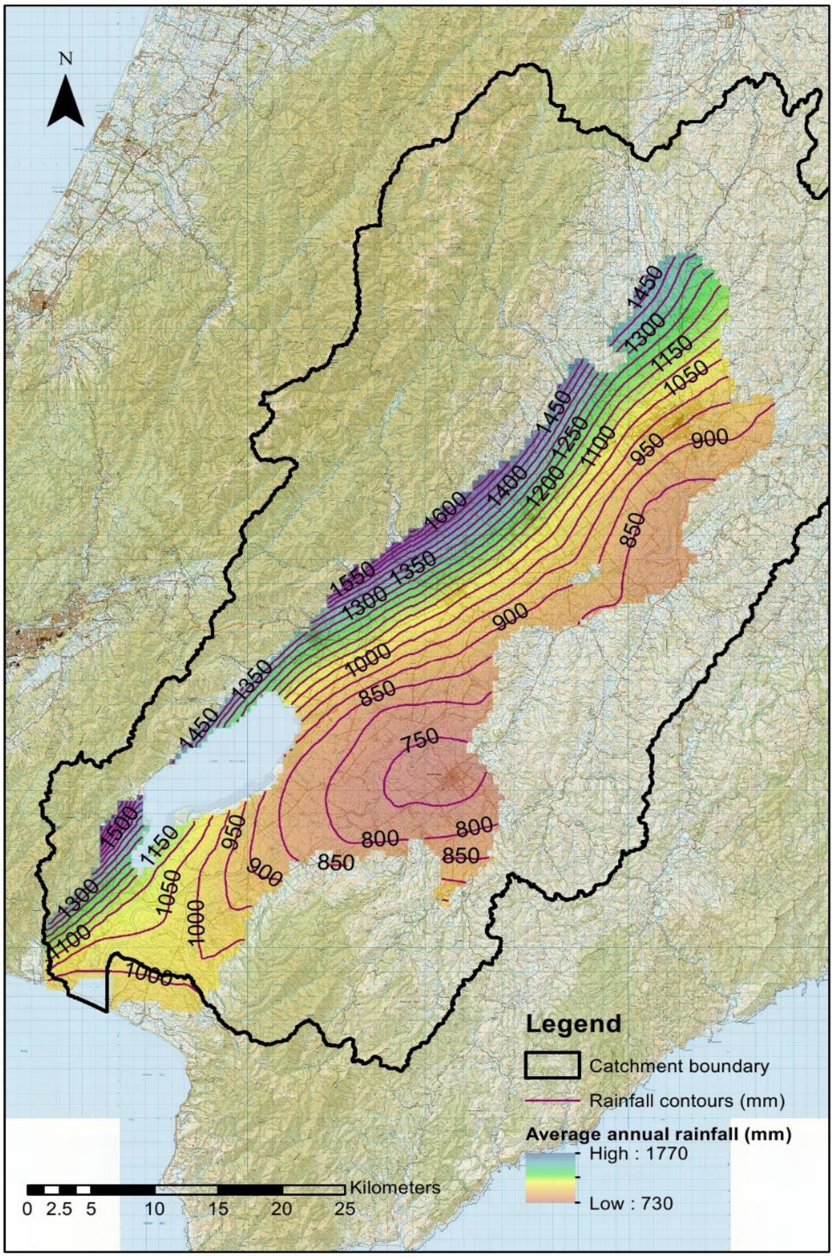

Figure 9: Average annual rainfall for historical period (VCN data)

6.3.2 Irrigation demand

The modelled average annual potential irrigation demand (i.e. not taking into account the actual irrigated area in a grid square) is shown in Figure 10. The highest irrigation demand (561 mm/yr) is in the eastern part of the catchment, the lowest in the west.

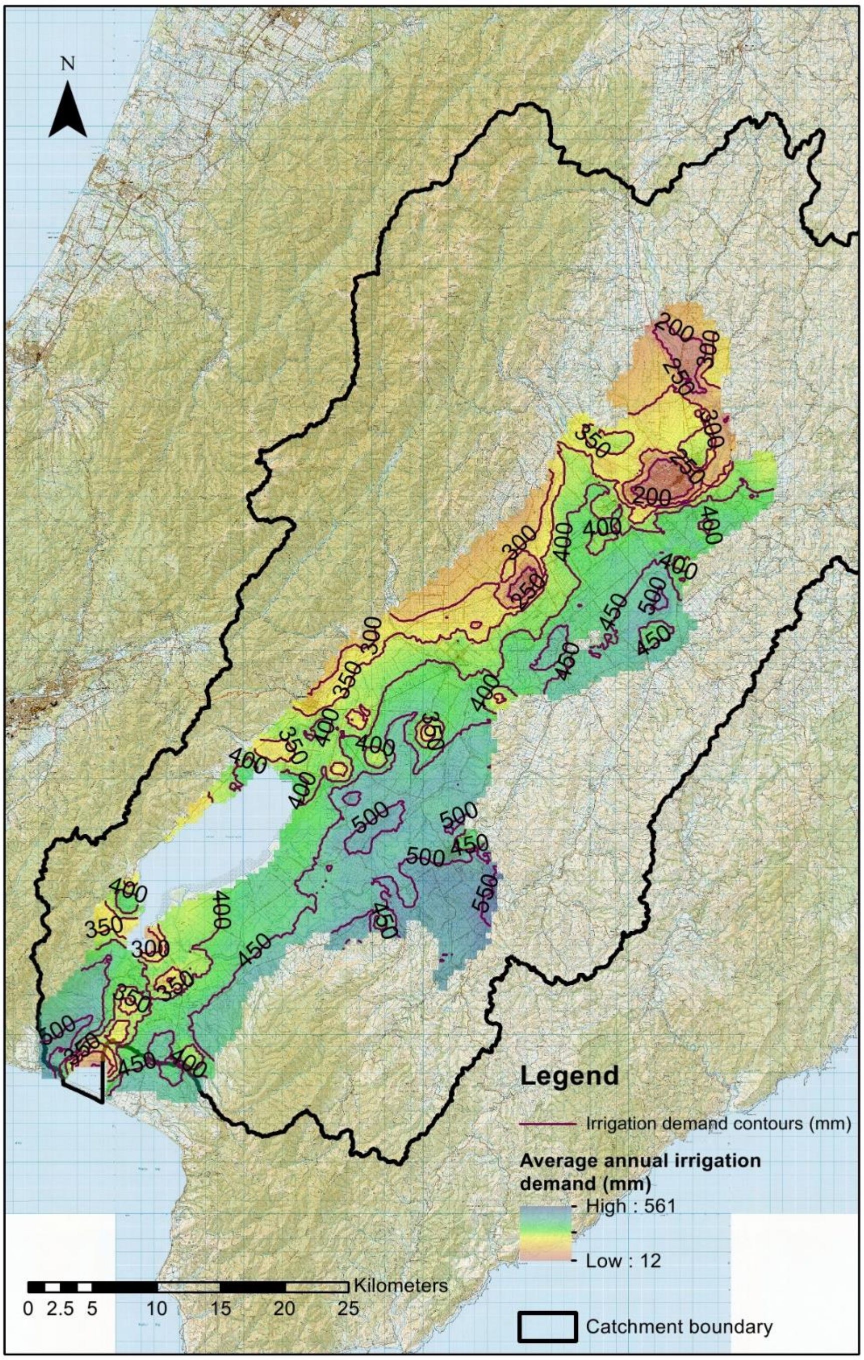

Figure 10: Average annual irrigation demand for status quo (VCN data).

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6.3.3 Actual evapotranspiration

The modelled actual evapotranspiration (AET) is shown in Figure 11 for the irrigated scenario, and in Figure 12 for the dryland scenario. The irrigated AET has a relatively smooth gradient from north to south. This is due to the irrigation applications filling in the rainfall deficit; spatial variability in soils is smoothed out by the different irrigation strategies defined for each soil type in the model. The variability in soils is much more evident in the dryland results, which have an east-west gradient.

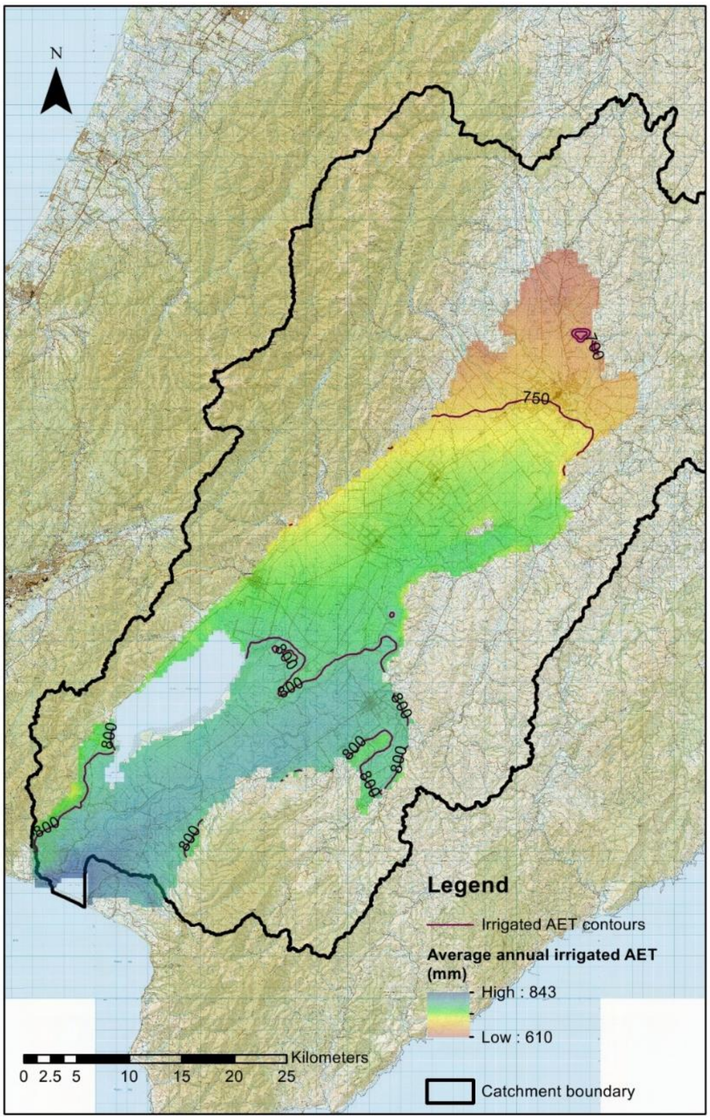

Figure 11: Average annual irrigated AET for status quo

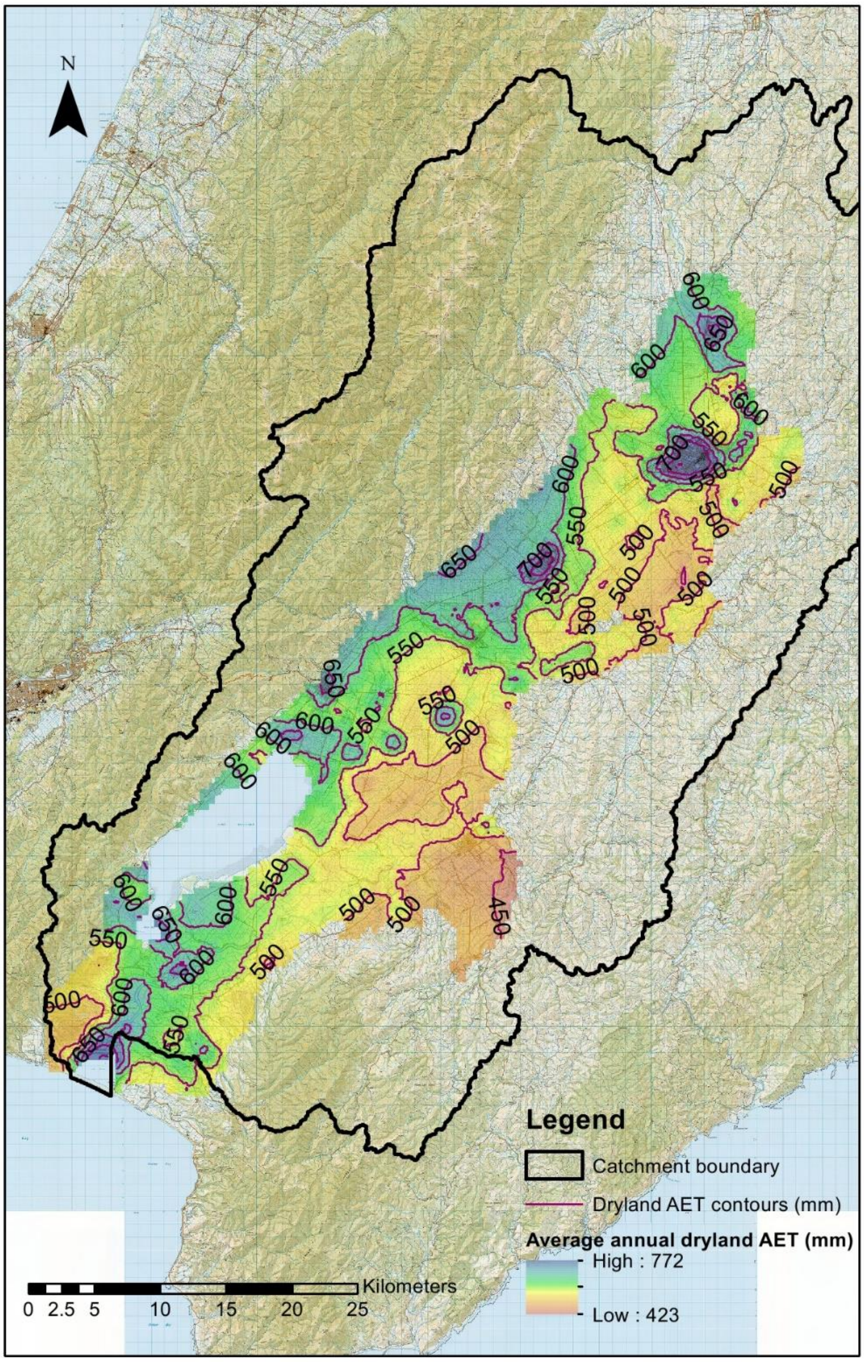

Figure 12: Average annual dryland AET for status quo

6.3.4 Drainage

The modelled average annual irrigated drainage for the status quo is shown in Figure 13, and the dryland drainage is shown in Figure 14. The results shown in both figures are the total drainage, before partitioning into recharge and quickflow. The spatial variability in the irrigated and dryland results is similar, with an east-west gradient.

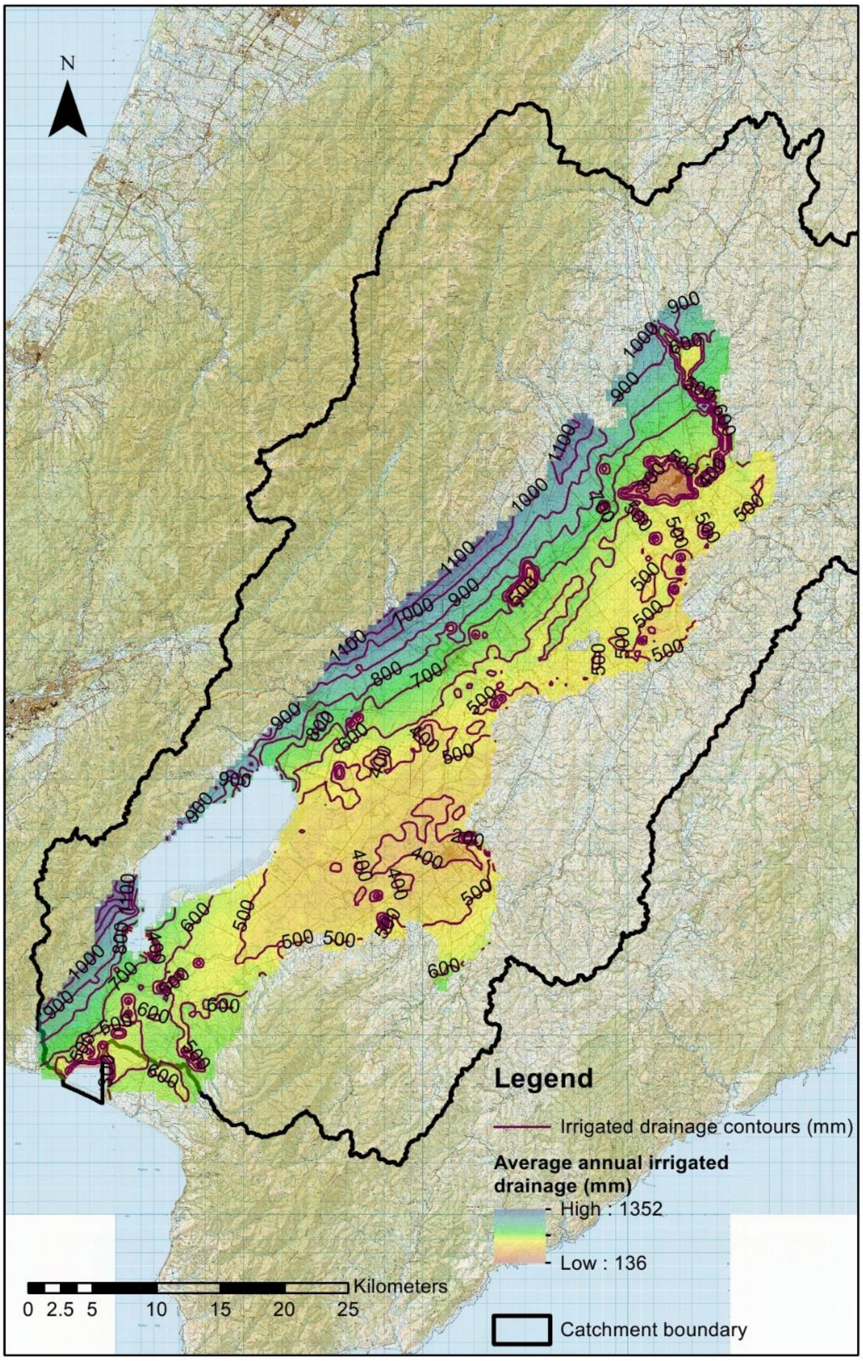

Figure 13: Average annual irrigated drainage for status quo

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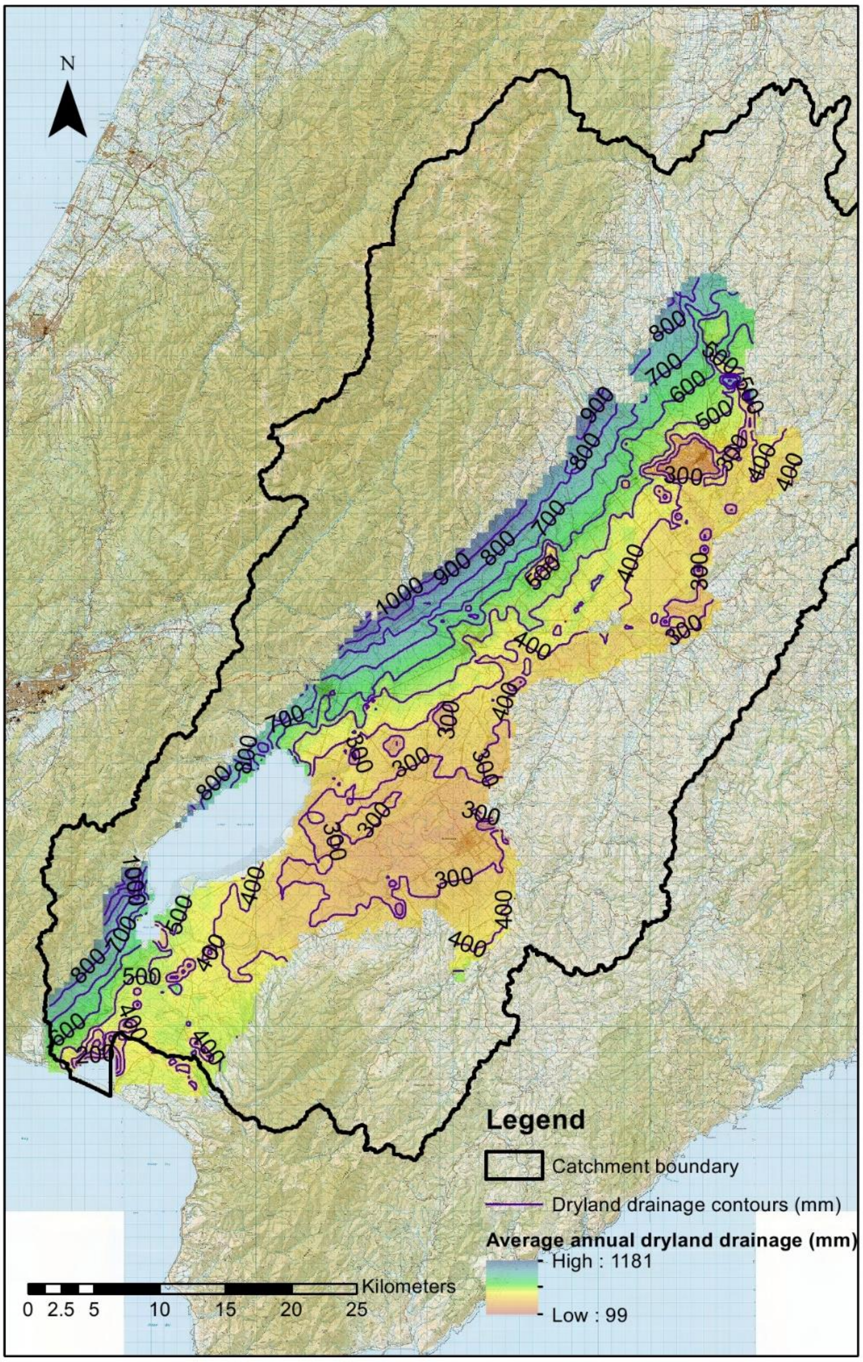

Figure 14: Average annual dryland drainage for status quo

7 CLIMATE CHANGE SCENARIOS

To investigate potential future changes in irrigation demand and drainage, IrriCalc was re-run with climate inputs from the GFDL-CM3 climate model, with an RCP (representative concentration pathway) value of +6.0 W/m^2. This dataset was provided by NIWA.

The climate model outputs are spatially distributed on a 0.05° latitude and longitude grid. This is coarser than the Virtual Climate Station grid. The 500 m x 500 m grid cells that were used for the status quo model were joined in GIS to the climate model grid, so that each cell in the finer grid was assigned the closest grid point from the climate model output. Approximately 100 cells in the fine grid were represented by each climate model grid point.

The climate model outputs run from 1 January 1971 to 31 December 2100. Three 20-year sub-sets of this data were used: 1 July 1986 – 30 June 2006, 1 July 2030 – 30 June 2050, and 1 July 2080 – 30 June 2100. Results for these periods are referred to as “historical”, “2040”, and “2090” respectively.

The soils, crop-types and irrigation rules in IrriCalc were unchanged from the status quo simulation.

The results from the climate-change model runs were processed in the same way as the status quo results to generate daily modelled irrigation, recharge and quickflow data-sets for each computational cell in the MODFLOW model, which were provided to the modelling team. For partitioning the drainage into recharge and quickflow, the 95th percentile drainage was calculated from the dryland drainage results for each climate period. The proportion of irrigated land in each cell was assumed to remain constant for the future climate scenarios.

The irrigation demands shown in the figures in this section are the potential irrigation demands, regardless of whether irrigation occurs at a given location. The drainage results are the total drainage, prior to partitioning into recharge and quickflow.

7.1 Comparison of VCN and climate model data for historical period.

The percentage difference between the average annual rainfall from measured data (VCN) and the climate model outputs is shown in Figure 15. Averages for both datasets were calculated over the “historical” period (1987 – 2006). On average the mean rainfall from the climate model was 11% higher than the VCN data. The general trend is for the average annual rainfall from the climate model to be lower than the VCN data in the north of the catchment and higher in the south.

The chequered pattern in Figure 15 is due to the coarse climate model grid being mapped to the finer VCN grid.

The modelled rainfall for the historical period has been used as the baseline value for calculating percentage changes in the future scenarios.

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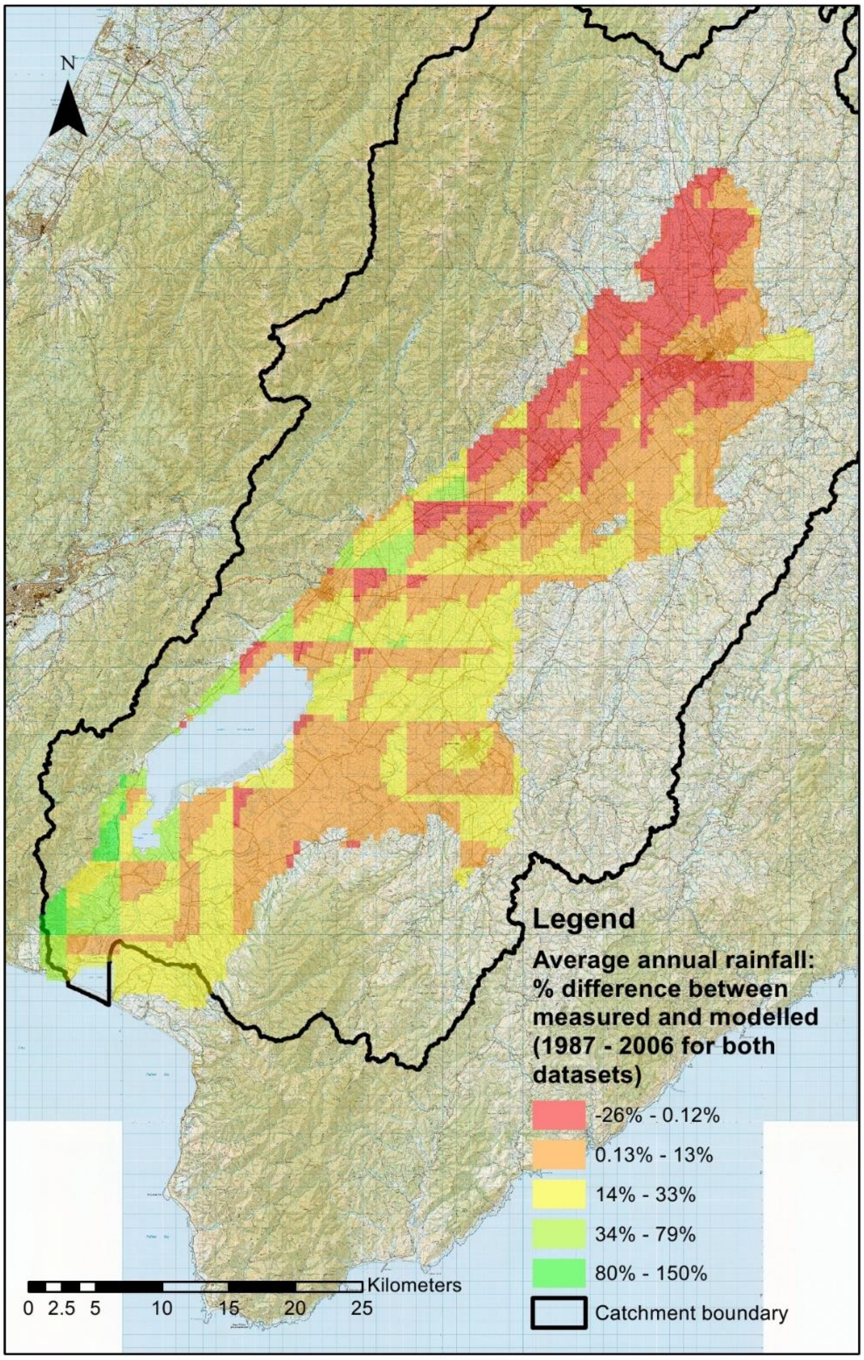

Figure 15: Comparison of average annual rainfall from VCN and climate model, 1987 - 2006

7.2 Future rainfall

The percentage difference between the 2040 average annual rainfall and the historical period is shown in Figure 16. In all parts of the catchment the average annual rainfall is predicted to be lower than the historical period, with a maximum reduction of 6.4% in the west of the catchment.

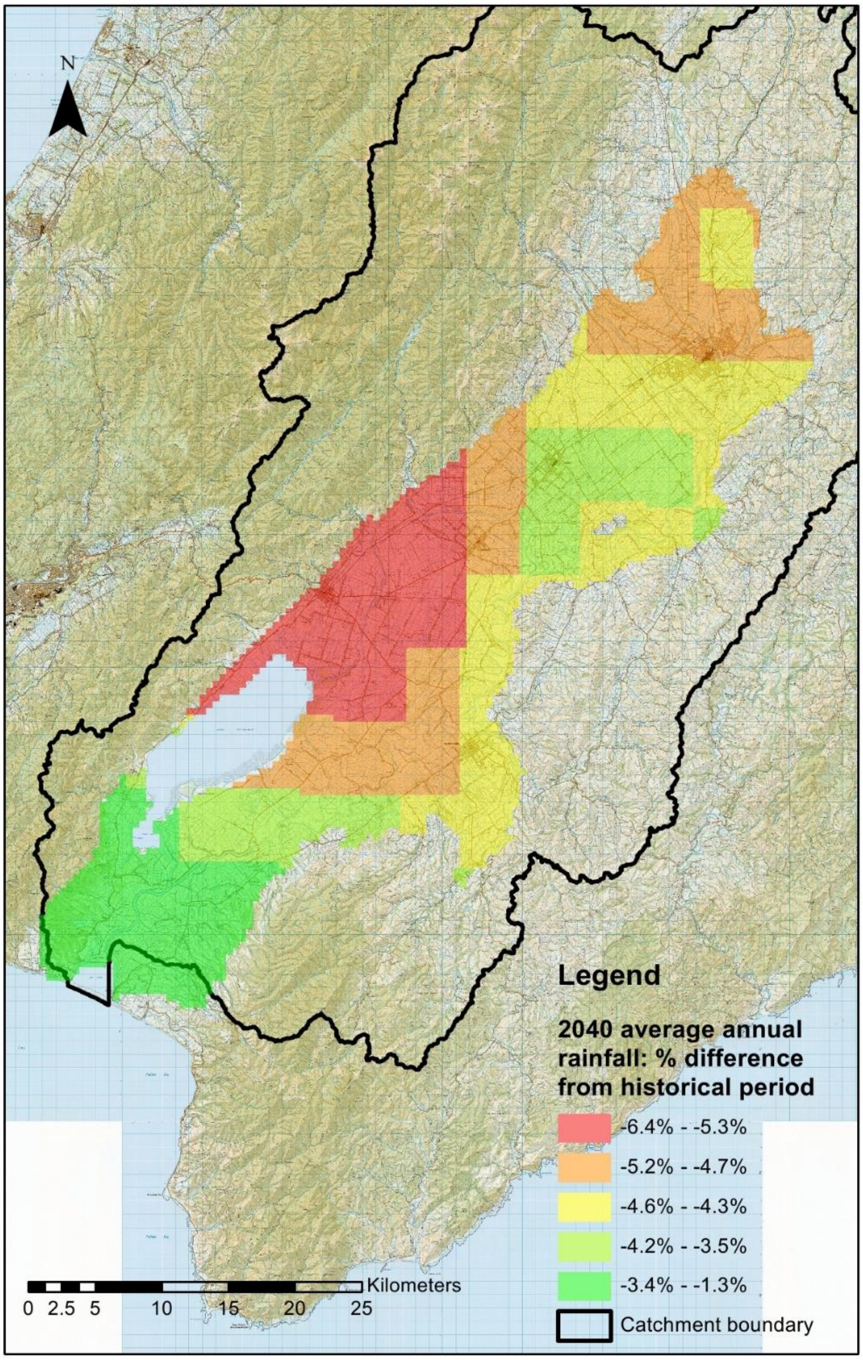

Figure 16: Percentage difference between 2040 rainfall and historical period.

The percentage difference between the 2090 rainfall and the modelled historical period is shown in Figure 16. A reduction in rainfall is predicted in all parts of the catchment, ranging from 6% in the east to 12% in the west.

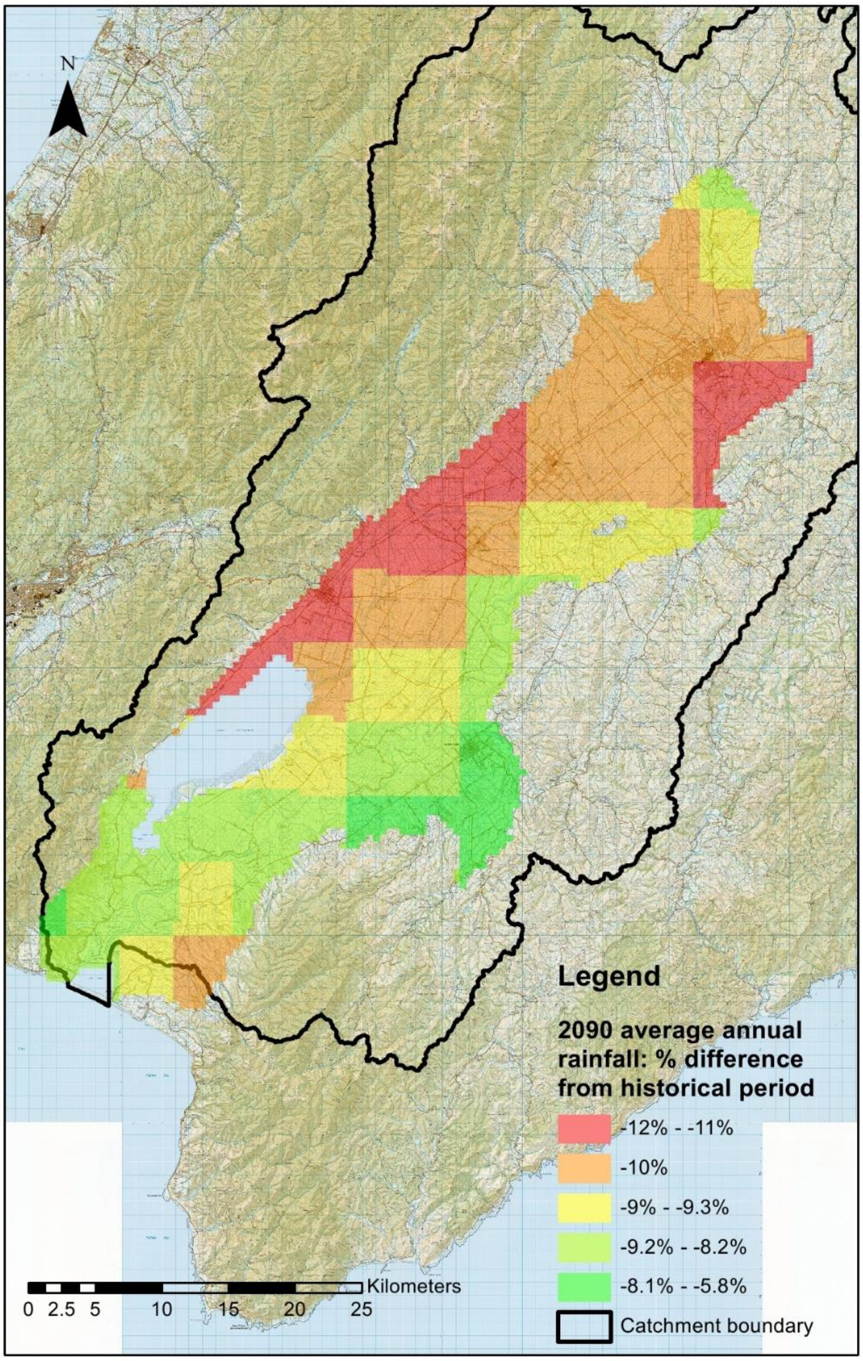

Figure 17: Percentage difference between 2090 rainfall and historical period

7.3 Future irrigation demand

The modelled percentage change in average annual irrigation demand between 2040 and the modelled historical period is shown in Figure 18, and the percentage change between 2090 and the modelled historical period is shown in Figure 19.

For the 2040 period the model results show an increase of up to 25% in the north and west of the catchment, with smaller increases in the south and east. For the 2090 period the spatial pattern of increases is similar, but the magnitude is greater, with an increase of up to 46% predicted.

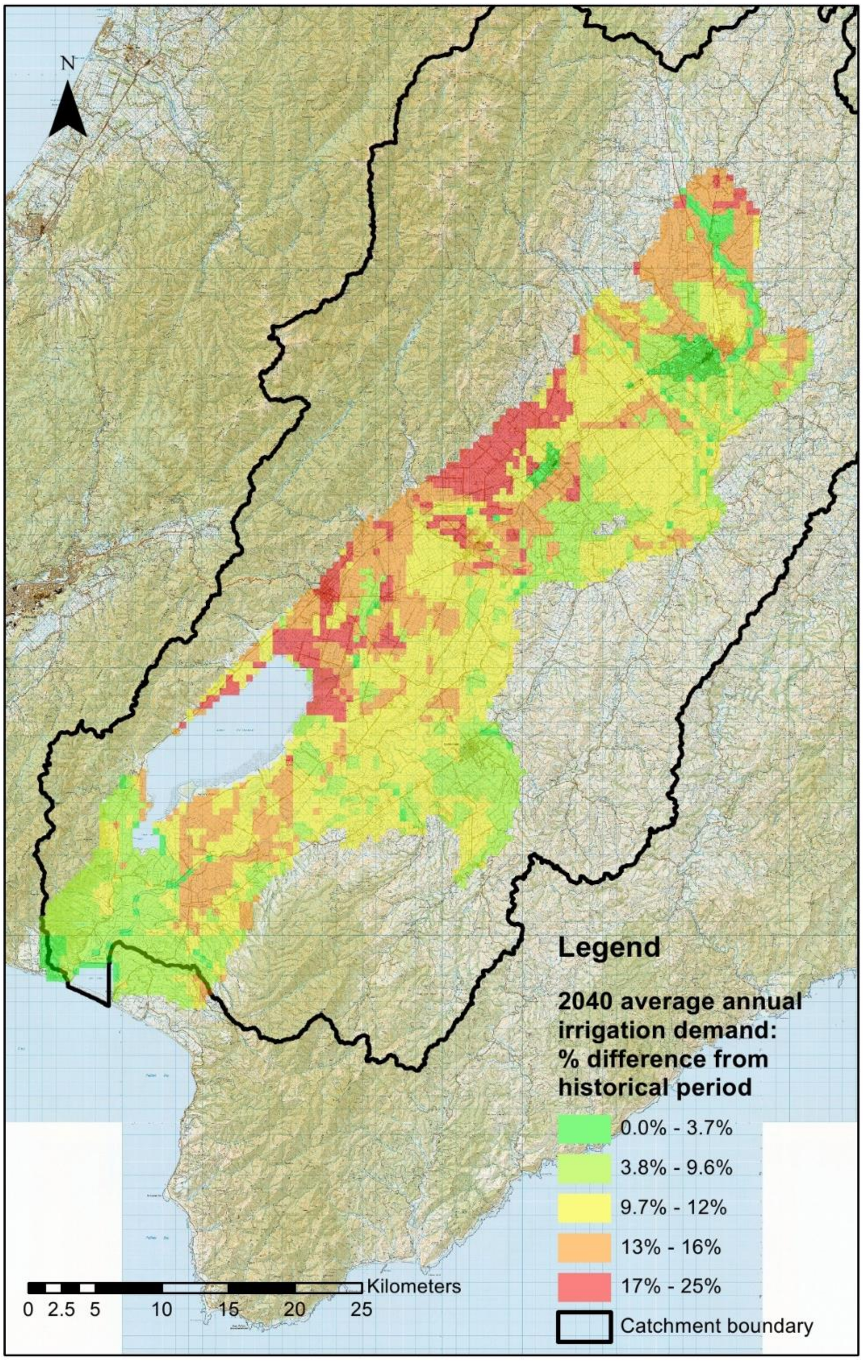

Figure 18: 2040 average annual irrigation demand: percent difference from historical period

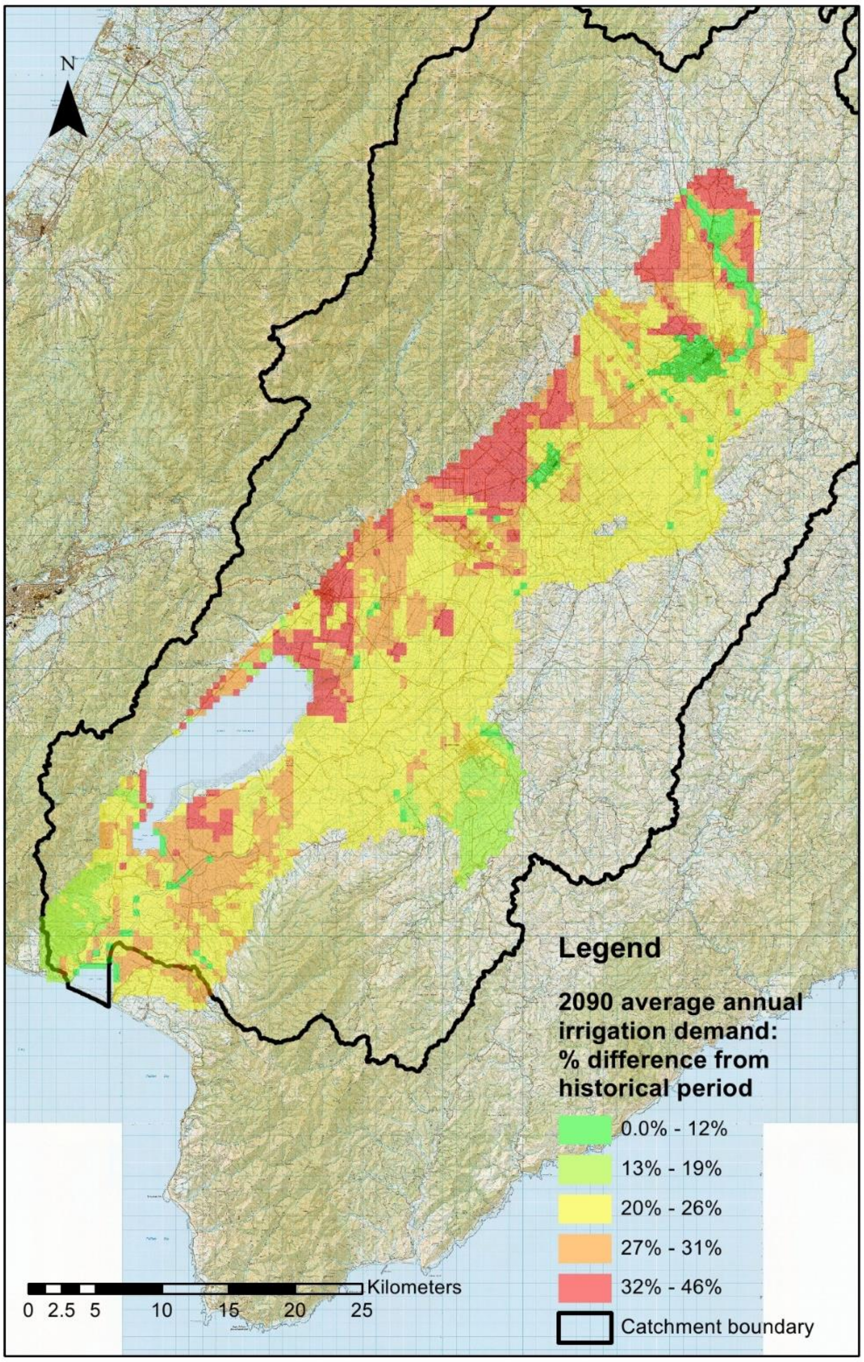

Figure 19: 2090 average annual irrigation demand: percent difference from historical period

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7.4 Future AET

7.4.1 Irrigated AET

The modelled percentage change in the irrigated actual evapotranspiration (AET) between 2040 and the historical period is shown in Figure 20. An increase in AET was predicted across the majority of the catchment, with a trend towards greater increases (up to 4.8%) in the north.

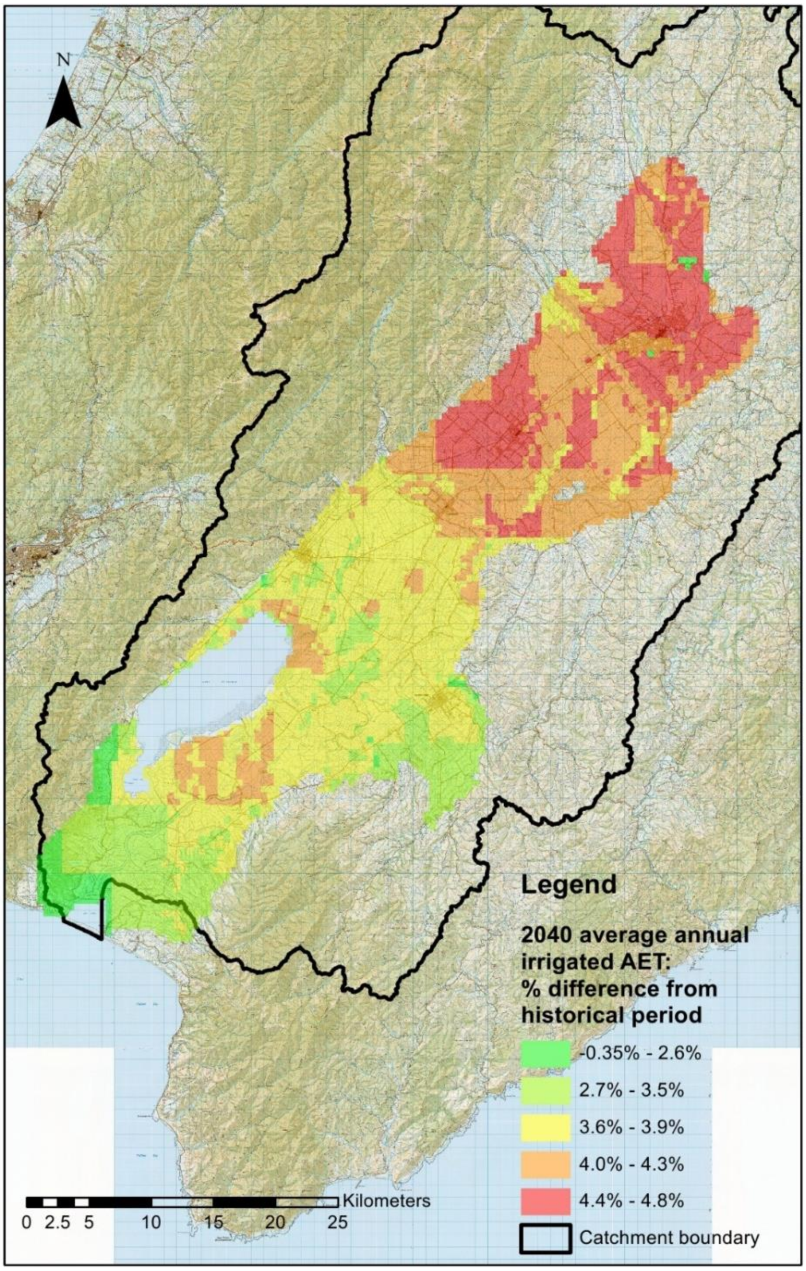

Figure 20: 2040 average annual irrigated AET: percent difference from historical period

The modelled percentage change in irrigated AET between 2090 and the historical period is shown in Figure 21. The general spatial trend is similar to the 2040 results, with an increase of up to 11% predicted in the north of the catchment.

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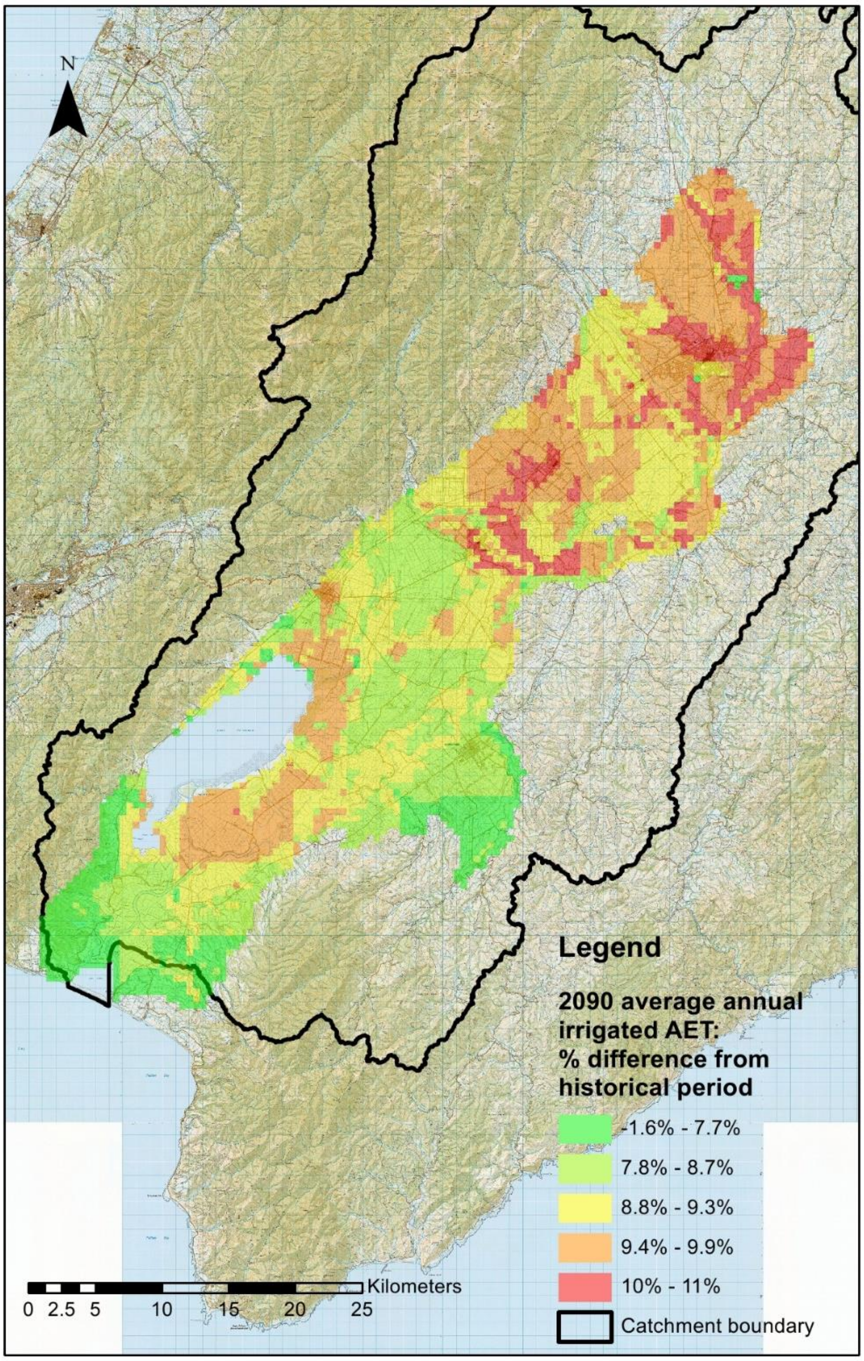

Figure 21: 2090 average annual irrigated AET: percent difference from historical period

7.4.2 Dryland AET

The percentage difference between the average annual dryland AET for 2040 and the historical period is shown in Figure 22. In the southern part of the catchment (with the exception of the area south of Lake Wairarapa, a reduction in AET of up to 4.1% relative to the historical period is predicted. In the northern part of the catchment an increase of up to 4.6% is predicted. Over the majority of the catchment smaller differences in AET are expected.

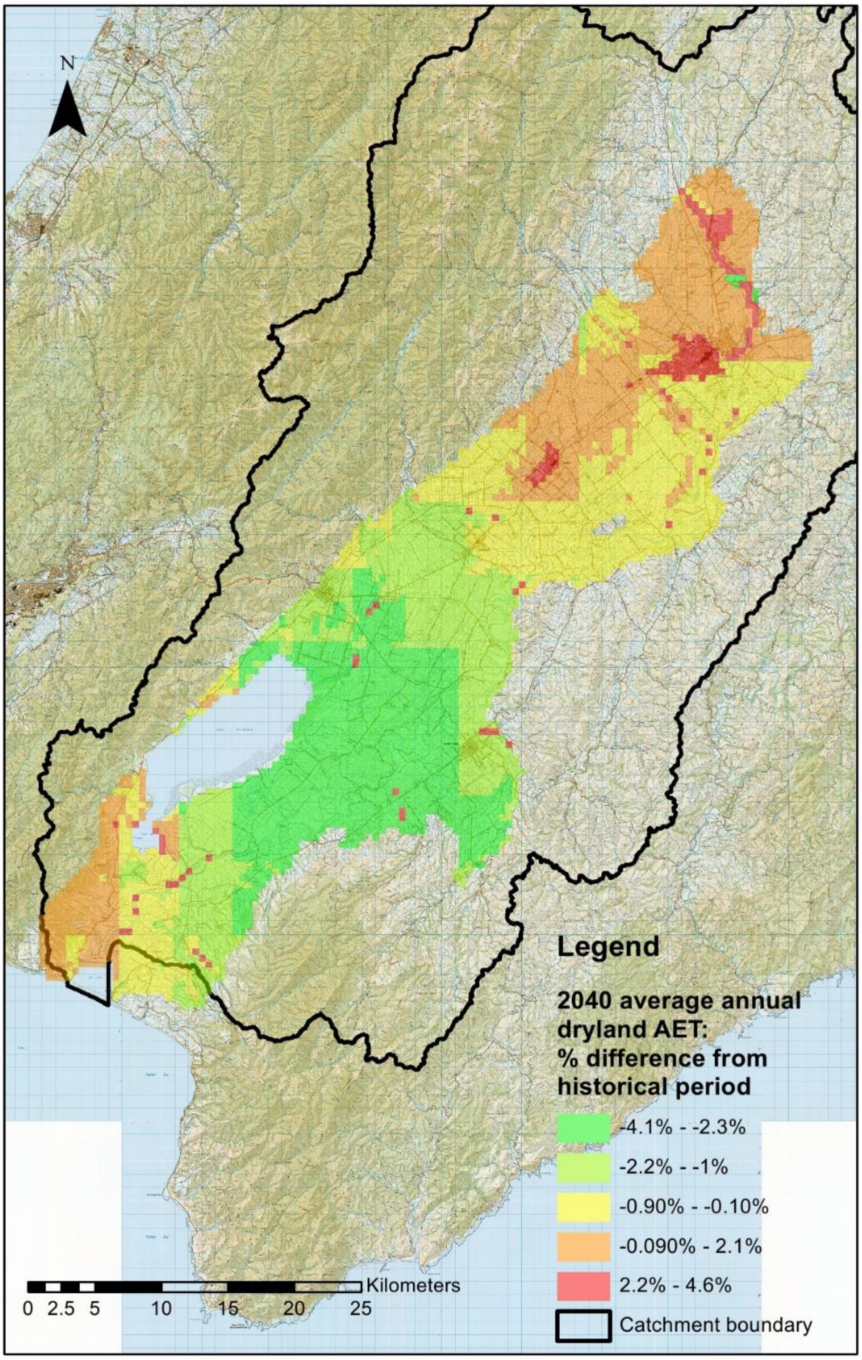

Figure 22: 2040 average annual dryland AET: percent difference from historical period

The modelled percentage difference in dryland AET between 2090 and the historical period is shown in Figure 23. A reduction of up to 6.3% is predicted in the south of the catchment, and an increase of up to 11% in the north. As for the 2040 results, however, smaller changes are predicted over the majority of the catchment.

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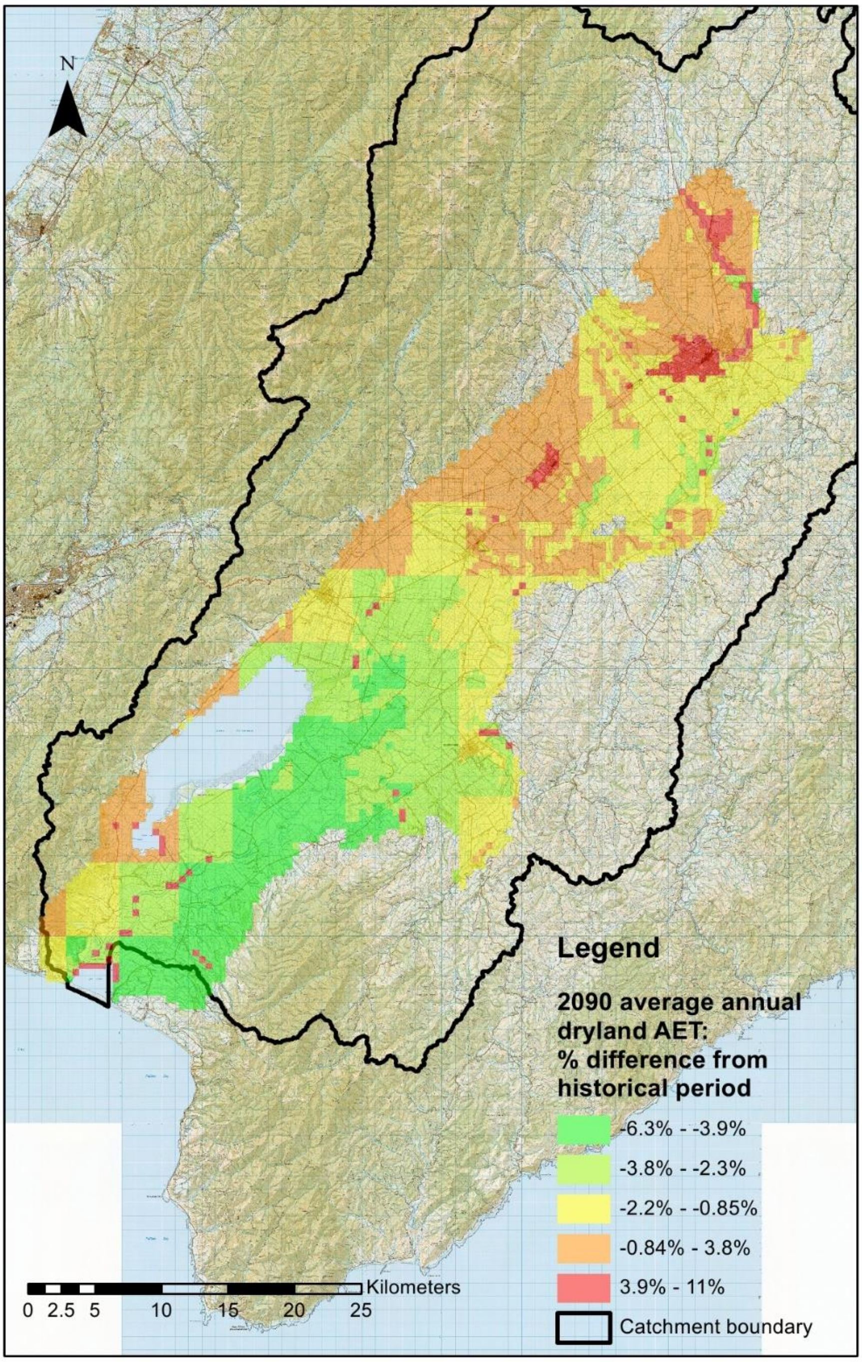

Figure 23: 2090 average annual dryland AET: percent difference from historical period

7.5 Future drainage

7.5.1 Irrigated drainage

The modelled percentage change in irrigated drainage between 2040 and the historical period is shown in Figure 24. A reduction in irrigated drainage is predicted across the majority of the catchment. Although maximum reductions of 61% were predicted, changes of this magnitude were limited to a relatively small area; over the majority of the catchment the predicted reduction was less than 30%.

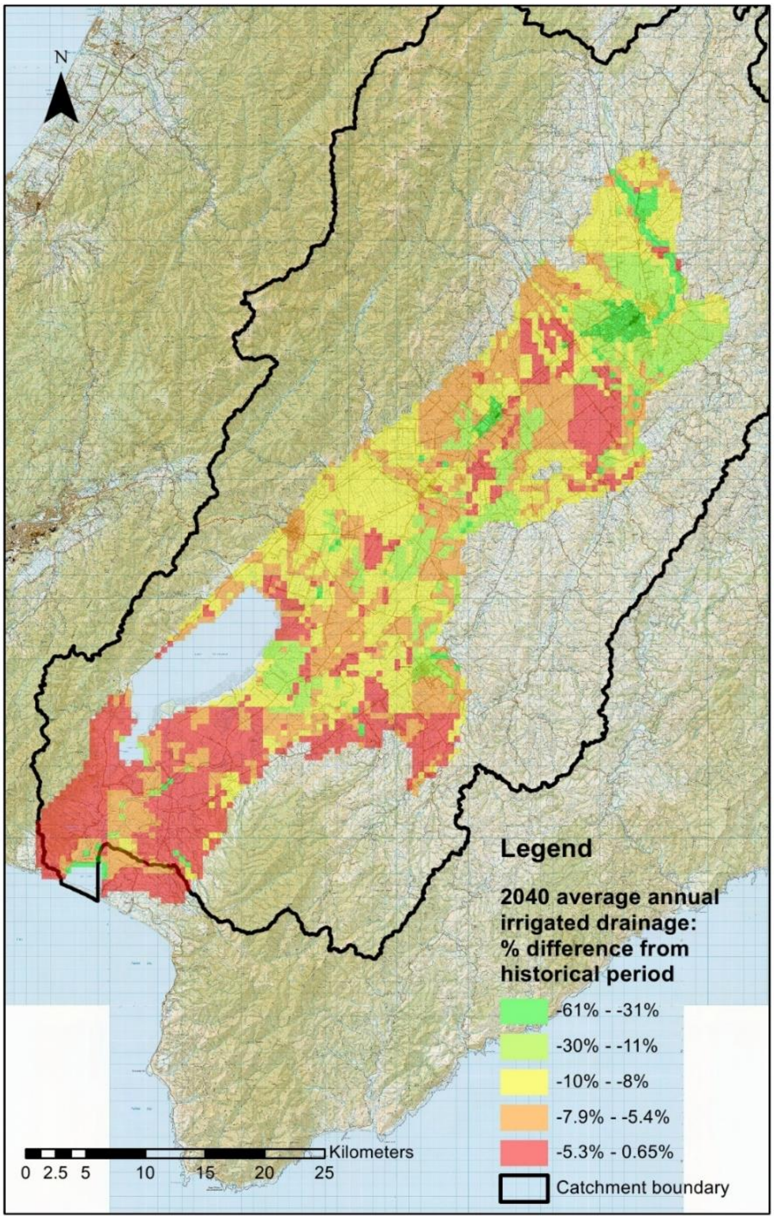

Figure 24: 2040 average annual irrigated drainage: percent difference from historical period

The modelled percentage change in irrigated drainage between 2090 and the historical period is shown in Figure 25. Drainage is predicted to decrease throughout the catchment, with a maximum reduction of 67%. Over the majority of the catchment, however, the reduction was less than 46%.

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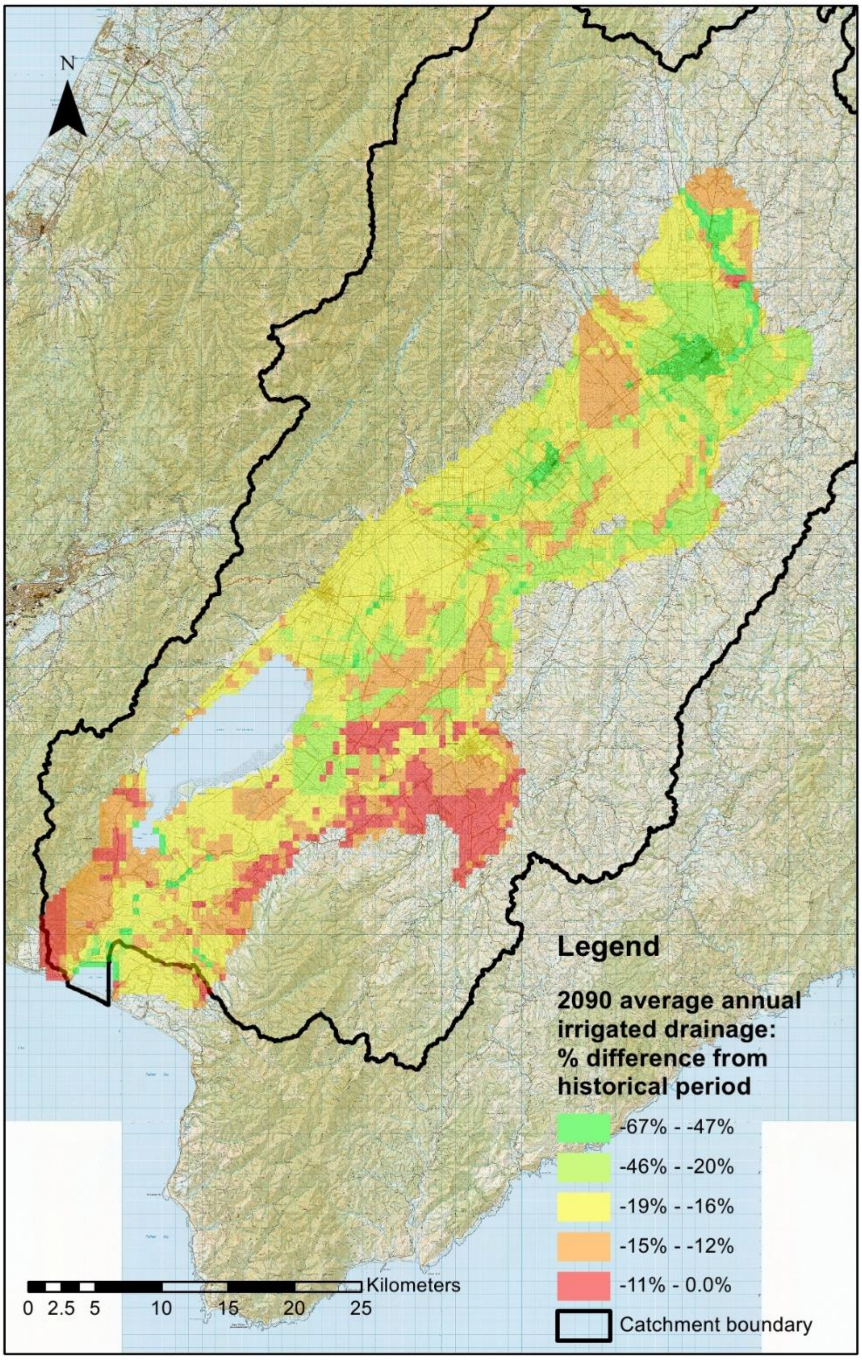

Figure 25: 2090 average annual irrigated drainage: percent difference from historical period

7.5.2 Dryland drainage

The modelled percentage difference in the average annual dryland drainage between 2040 and the historical period is shown in Figure 26. Reductions in dryland drainage, relative to the historical period, are predicted throughout the catchment. Spatially, the general trend is a smaller reduction in the south, and up to a 61% reduction in the north. As for the irrigated drainage results, the greatest reductions are confined to a relatively small area, and over the majority of the catchment area the reduction was less than 34%.

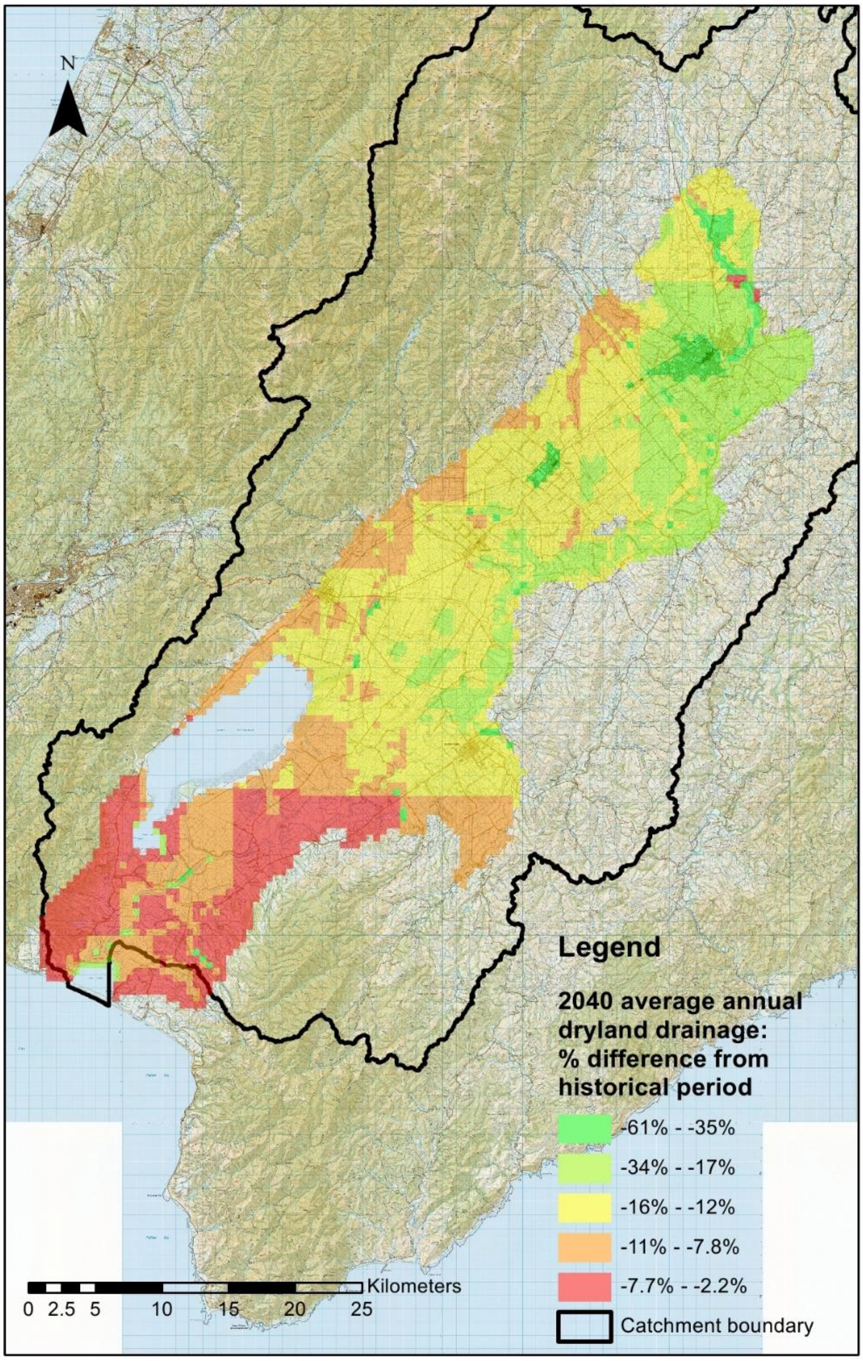

Figure 26: 2040 average annual dryland drainage: percent difference from historical period

Percentage changes in dryland drainage for 2090 are shown in Figure 27. The spatial trend is similar to the 2040 dryland drainage results, and the maximum reduction predicted is 67%. Over the majority of the catchment area the predicted reduction, relative to the historical period, is less than 49%.

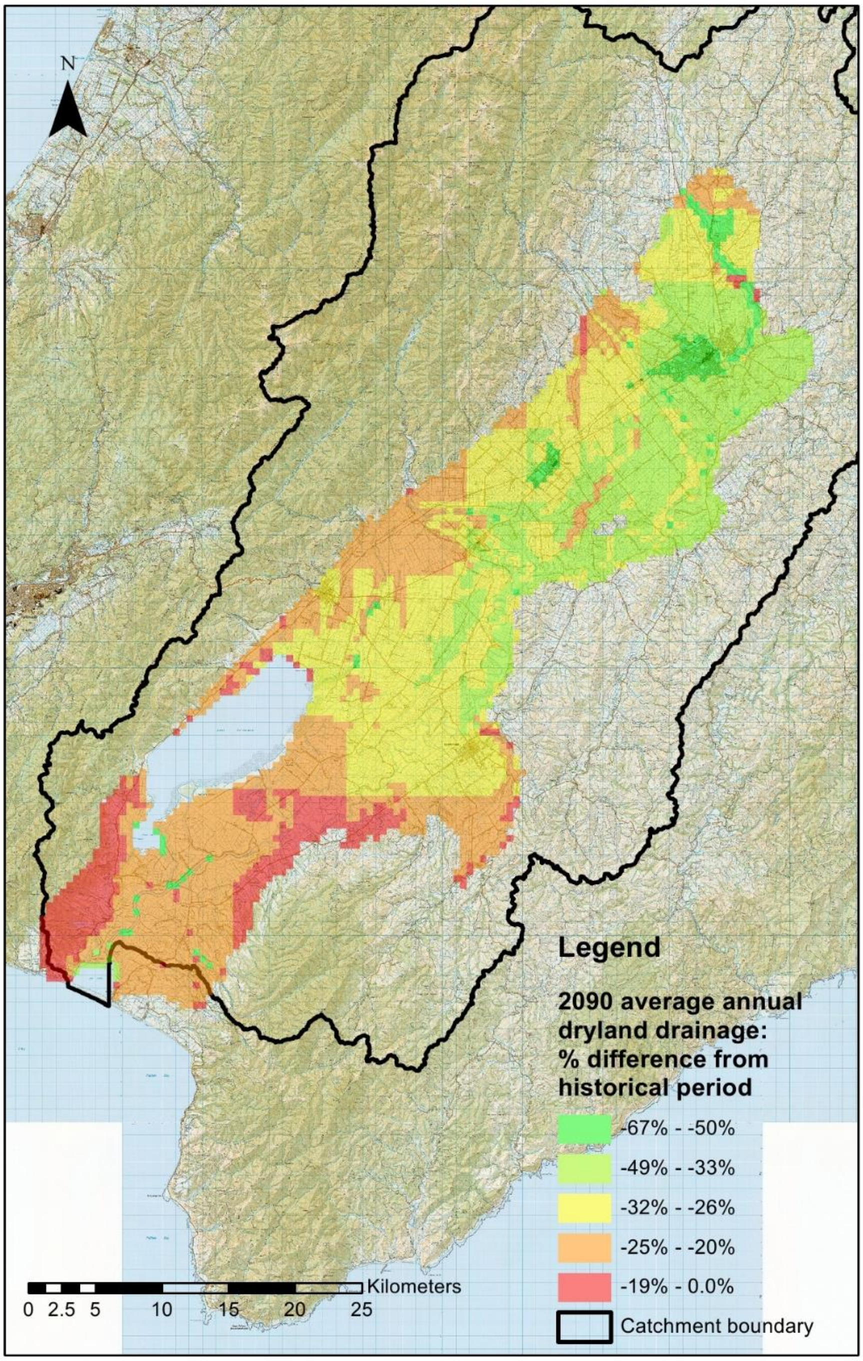

Figure 27: 2090 average annual dryland drainage: percent difference from historical period

8 UNCERTAINTY ANALYSIS

A formal, mathematical uncertainty analysis of the soil water balance modelling is not possible because of the lack of relevant measurements.

There are two distinctly different areas of uncertainty in the modelling of irrigation water use and drainage. These areas are technical and behavioural. Uncertainties of a technical nature include measurement error, parameter uncertainty and the extent to which the conceptual model and associated mathematics deviate from the real world. Behavioural uncertainty exists because the model's irrigation decision making rule attempts to mimic farmer decision making about when to irrigate and how much to apply. The model assumes that irrigation decision making is based on information about the current soil water content. In practice other factors also play a part, but it's not yet practical to build these into a computer simulation model.

Recent research indicates that irrigation water use and drainage can be modelled to within 3% of true values for a specific farm if highly detailed information about that specific farm is available as model inputs (Van Housen, 2015). On the other hand, if generally applicable farm information is used to model irrigation and drainage for a specific farm then errors in the range 10% - 15% are to be expected (Van Housen, 2015). For studies involving scores of farms, modelling will very likely provide both over and underestimates of irrigation water use and drainage. In aggregate, errors of the order of 10% are likely.

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