New Zealand Groundwater Atlas: Groundwater Fluxes

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GLOSSARY

AET: Actual Evapotranspiration; the combined effect of evaporation from vegetation, soils and transpiration from vegetation

ANUSPLIN: a software package to perform a spline interpolation. See details at https://fennerschool.anu.edu.au/research/products/anusplin

Aquifer: an underground geologic layer that contains significant quantities of water and has sufficient internal flow of water to be productive

ASCII: a character encoded standard used in many simple text files

Bias: the difference between the probability-weighted average of all possible values for a modelled parameter and the true value of the parameter being estimated (ie a systematic [built-in] error that makes all values wrong by a certain amount)

Calibration: the process of adjusting model inputs and parameters to match model outputs to desired values, for example, historic observations

Drainage: the amount of water leaving the soil to recharge to groundwater. Also called ‘recharge’ or ‘groundwater recharge’

Element: a small area or volume within a model domain in which equations are solved

Error: the difference between a measured value and a true value, where the true value can be known

Flux: the action or process of flowing in or flowing out (describing the magnitude and direction of flow)

Gaining reach: a reach where groundwater is discharging to surface

Head (hydraulic): the elevation of groundwater relative to a chosen level

Hydraulic conductivity: a parameter that describes the rate of flow of water in a geologic layer (the ease with which a water can move through pore spaces or fractures). Units are length/time, for example, m/day

IrriCalc: the recharge model used by Aqualinc

Iteration: a mathematical approach implemented within a numerical model in which a series of approximations are used to achieve a best solution

Losing reach: a reach where surface water is infiltrating to groundwater

Model domain: the space (area and thickness) and time represented within the model

NetCDF: a binary array-oriented scientific file format

NGRM: National Groundwater Recharge Model

NWT: National Water Table; a model that calculates a New Zealand-wide water table surface

Observation: a quantifiable measurement that can be used as a target for matching in a calibration

Parameter: a numerical input that defines characteristics of the model and can be adjusted by the user or calibration software

Permeability: a number (units L^2) that describes how easily a fluid can pass through a geological unit (eg a sandstone). In many numerical models, permeability is incorporated into hydraulic conductivity

PET: Potential Evapotranspiration; the amount of evapotranspiration if ample water is available, that is, no water deficit

QMAP: the digital geological map of New Zealand, provided at the scale of 1:250,000

Reach: a section of a stream or river along which similar hydrologic conditions exist, for example, discharge, depth, slope

Recharge: the rainfall or surface water that recharges to groundwater, also called 'groundwater recharge' or 'drainage'

Saturated: the state of all porosity within an area being filled with water

Seepage: the flow of groundwater to the surface, also called 'upwelling', 'saturated upwelling', 'groundwater seepage' or 'groundwater discharge to surface'

TopNet: the NIWA hydrological model

Uncertainty: a measurement of the possible variation of model inputs and/or outputs based on available information. The 'true' value is not known but is assumed to be within this range of values

Upwelling: also known as 'saturated upwelling'. See *Seepage*

EXECUTIVE SUMMARY

This report describes national data sets related to groundwater flux estimation, including the methodologies used to undertake this work and the resultant digital data sets. This work was completed by GNS Science (GNS), Aqualinc Research Ltd (Aqualinc) and the National Institute of Water and Atmospheric Research (NIWA) under commission to the Ministry for the Environment (the Ministry) as part of the Ministry's New Zealand Groundwater Atlas programme.

The work here-in includes the following components:

1. Groundwater recharge: development of nationwide mean (daily and seasonal) groundwater recharge data sets through the combination of three pre-existing groundwater recharge models (separately developed by GNS, Aqualinc and NIWA)
2. Groundwater–surface water exchange: development of a national indicative groundwater discharge data set using an existing national groundwater flow model, as well as comparison with a pre-existing gaining/losing stream prediction data set
3. Groundwater flow: development of a national groundwater flow data set using an existing national groundwater flow model.

Three underlying groundwater recharge models (TopNet, IrriCalc and the National Groundwater Model [NGRM]) were used to develop a Model Mean, that is, the mean of the three models, for the 2000–2015 period. This Model Mean shows that recharge for 2000–2015 varies spatially over the nation, depending on climate and landscape conditions. An inter-model comparison shows that all three models show the same spatial and temporal trends but with consistently different magnitudes: TopNet is the lowest, IrriCalc is the highest and NGRM is the closest to the Model Mean. Inter-model differences are mainly caused by the bias within each model caused by different model assumptions, mainly through subtly differing definitions of recharge and different model input variables, for example, evapotranspiration.

A nationwide map of groundwater discharge probability was developed with a nationwide groundwater model, National Water Table (NWT). This shows that groundwater discharge has a high probability in foothills to plains and a low probability in areas where geology is less permeable, for example, impermeable rock or near-surface clay layers. Comparison of NWT discharge outputs with another national approach (National Classification [NC]: based on observations and a machine learning algorithm) is complex because the two approaches produce different output variables and locations of groundwater discharge. Initial insight from local studies indicate that the NWT model correctly identifies the reduced groundwater discharge in near-coastal clays and the existence of groundwater discharge close to or in the foothills. However, it overestimates the number of streams with groundwater discharge when compared with some local studies and NC predictions.

The NWT model was also used to develop a rough indication of nationwide estimates of near-surface groundwater flow amplitudes. The results support existing understanding that flows are highest in areas that are very hydraulically conductive (eg gravels in plains) or are gravity-driven by a large and high upstream catchment (eg Taranaki) or both (eg the Canterbury Plains).

Results and discussion of this report lead to the following recommendations:

- National approaches as described in this report can be a framework to obtain seamless and consistent overviews of groundwater from the national to the local scale, where more regional and local data should be included at a later date
- Inter-comparisons between recharge and discharge models demonstrate that different models have different variables and definitions of fluxes, which may have significant impacts on how the data are utilised. Future research should aim for more coherence between recharge and discharge models in New Zealand
- There is currently no robust coupled national model of surface water and groundwater in New Zealand, causing inter-model differences caused by model assumptions and input and output variables. To further improve consistency of groundwater–surface water exchanges, we recommend continuing and extending inter-organisational model coupling approaches
- Finally, this study showed long-term recharge trends at a nationwide scale; it is advised to have a more extensive study on long-term recharge trends that also looks at regional long-term trend analyses.

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1.0 INTRODUCTION

This report describes national data sets related to groundwater flux estimation, including the methodologies used to undertake this work and the resultant digital data sets. This work was completed by GNS Science (GNS), Aqualinc Research Ltd (Aqualinc) and the National Institute of Water and Atmospheric Research (NIWA) under commission to the Ministry for the Environment (the Ministry) as part of the Ministry's New Zealand Groundwater Atlas programme.

The Ministry requires national-scale groundwater data sets to inform groundwater work streams related to the Environmental Reporting Act (2015) and the National Policy Statement for Management (2014, 2017), as well as to increase public awareness about groundwater. To that end, the work here-in includes the following components:

1. Groundwater recharge: development of nationwide mean (daily and seasonal) groundwater recharge data sets through the combination of three pre-existing groundwater recharge models (separately developed by GNS, Aqualinc and NIWA)
2. Groundwater–surface water exchange: development of a national indicative groundwater discharge data set using an existing national groundwater flow model, as well as comparison with a pre-existing gaining/losing stream prediction data set
3. Groundwater flow: development of a national groundwater flow data set using an existing national groundwater flow model.

The scope of this work is to use pre-existing data only, using information already held by the authors in most cases. It is not in scope to compile and quality-check large amounts of data held by regional authorities (for example, borehole monitoring data) or to undertake detailed regional assessments. Due to the coverage of existing national data sets, the geographic scope of this work encompasses the contiguous land masses of the North and South islands of New Zealand. All data sets are developed in a nationally-consistent manner (no difference between regions) and are provided in a digital format that facilitates future improvements and online access. Guidance around uncertainty of the data is also provided, as well as recommendations about how these data sets could be improved in the future.

2.0 INPUT DATA

2.1 Groundwater Recharge Data

Three models were compared in this study: The National Groundwater Recharge Model (NGRM), TopNet and IrriCalc. General model specifications on the three individual models that were used are summarised in Sections 2.1.1–2.1.3 and are compared in Table 2.1.

Table 2.1 Model specifications for each of the three recharge models used. VCSN = Virtual Climate Station Network, FSL = Fundamental Soil Layer, S-Map: most up-to-date soil map from Landcare Research, AET: actual evapotranspiration; LRIS: Land Resource Information Systems Portal: https://lris.scinfo.org.nz/.

	NGRM	TopNet	IrriCalc
Model Cell Resolution	1 km x 1 km	Strahler three polygons of Digital Network catchments.	0.05 x 0.05 lat. lon. arc degrees
Period	2000–2015	2000–2015	2000–2015
Rainfall Input	VCSN	VCSN	VCSN
Soil and Permeability Information	FSL and QMAP	FSL	S-Map/FSL
Elevation Model	Geographx (2012)	LRIS 30 m digital elevation model	LRIS Land Slope Classes
Theoretical Model	Only estimates of rainfall recharge are considered to contribute to groundwater recharge; AET is based on satellite observations.	Estimations of discharge of groundwater to surface water near riparian zones are removed from the rainfall recharge to provide groundwater recharge.	Estimations of the contribution of irrigation are included along with rainfall recharge to provide the groundwater recharge.

2.1.1 National Groundwater Recharge Model

The NGRM was developed to demonstrate the utility of satellite data and global models by development of a rainfall recharge model that is consistent over all regions of New Zealand. The NGRM has a 1 km × 1 km model grid that covers most of New Zealand and uses a cell-by-cell soil water balance approach to estimate rainfall recharge. The NGRM model is inspired by a global coarse-resolution recharge model (WaterGAP: Döll and Fiedler 2008), but uses higher resolution input data, that is, Moderate Resolution Imaging Spectroradiometer (MODIS) derived evapotranspiration and vegetation data, as well as the available nationwide data sets on rainfall, elevation, soil and geology.

The model uses daily rainfall input from the Virtual Climate Station Network (VCSN), as described by Tait et al (2006), from which it compiles monthly values before running the model, and also uses the Fundamental Soil Layer (FSL)[1], freely available information from

[1] https://soils.landcareresearch.co.nz/soil-data/fundamental-soil-layers/, Manaaki Whenua Landcare Research.

the Land Resource Information Systems (LRIS) portal.[2] A possibly superior and newer product for soil information (S-Map)[3] is also available through Landcare Research but was not used, as it is not freely available and not consistently available across all regions of New Zealand.

Compared with other recharge models, a different approach is taken by the NGRM in terms of using the national geological map QMAP (Heron 2014) to indicate where recharge is limited due to the permeability of the subsurface.

The NGRM model calculates actual evapotranspiration (AET) by inferring vegetation health from satellite data, from which plant water stress is estimated. AET equals potential evaporation (PET) when plants and soil have an abundance of water available, whereas AET is less than PET when the soil or plants have a deficit of water. While the NGRM model derives AET from satellite observations, the other two models in this study use model assumptions to estimate AET.

The NGRM uses mean slope from a digital elevation model to calculate a run-off ratio. Furthermore, the NGRM model does not include a river recharge module: it only catches rainfall recharge on river areas. A detailed description of NGRM input components and the model algorithm is described in Westerhoff et al (2018a).

2.1.2 TopNet Recharge

NIWA's hydrological model, TopNet, provides sub-catchment recharge to groundwater at each time step. For this study, TopNet hydrological simulations were based on the River Environment Classification 2 network aggregated up to Strahler[4] catchment order three (approximate average catchment area of 7 km^2) used within previous national and regional scale assessments. The simulation results comprise hourly time series of various catchment scale hydrological variables for each reach. TopNet catchment scale recharge estimates were provided to this study as a NetCDF formatted file defining reach IDs and their locations and as space separated ASCII files compiled to monthly timeseries of recharge. Further details on the TopNet modules used for this project are described in Appendix 3.

During this study, it became apparent that the definition of recharge given by NIWA is different than used by other studies. This is due to the difference in model conceptualisation (ie distributed physically based catchment scale areal average versus spatially distributed physically based model). TopNet catchment average recharge is defined as 'net drainage': an areal integration per catchment of the recharge from the uninfluenced zone and the influence and saturated upwelling into the soil zone as formulated by Bandaragoda et al (2004) and Clark et al (2008) – see Appendix 3 for pictorial definitions of these zones. In areas where there is little interaction of groundwater to surface water, net drainage will likely be equal to recharge. However, in catchments where groundwater–surface water interaction is significant, a component of net drainage will be groundwater discharge to surface. This deficiency is currently being improved by NIWA so that the two components of net drainage (total drainage and saturated upwelling) can be separated into recharge and discharge. Therefore, the NIWA recharge estimate is likely to give lower values than other recharge models in many catchments.

[2] Land Resource Information Systems Portal: https://lris.scinfo.org.nz/

[3] https://smap.landcareresearch.co.nz/, Manaaki Whenua Landcare Research.

[4] Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order one, second order streams develop at the confluence of two first order tributaries, stream order increases by one where two tributaries of the same order converge.

The digital elevation model used is identified as the digital elevation model of New Zealand with 30 m resolution, available from the LRIS portal.

2.1.3 IrriCalc

Recharge was calculated using Aqualinc's soil moisture and irrigation simulation model, IrriCalc. The IrriCalc model estimates groundwater recharge with a daily time step for each VCSN point in potentially irrigable areas, allowing for the soils, land use and irrigated area in a rectangular cell surrounding that point. Model results for the dominant soil and irrigated land use combination for each mesh cell were assumed to represent irrigated recharge in that cell. Dryland (non-irrigated) areas were all assumed to be pasture. Land uses and irrigation systems were broadly categorised, as it is not practical to represent all crops and irrigation types at a national scale. IrriCalc does not cover the nation entirely: cells with land predominantly steeper than 15° (ie mountainous terrain) are not modelled and are left as empty cells.

The model was applied, using the mesh of the VCSN stations, in both irrigated and dryland (non-irrigated) areas. For dryland areas, IrriCalc was set to never irrigate, and therefore recharge resulted from rainfall alone. In irrigated areas, estimates of irrigation contributed to the groundwater recharge. As many cells contain both dryland and irrigated areas, the total recharge in each mesh cell was calculated from the combination of irrigated (if applicable) and dryland model outputs, proportioned according to the mapped irrigated area in the cell.

IrriCalc does not use an elevation model as input; instead it uses 'run-off ratios' that are estimated through a national data set on slope classes.

All IrriCalc model description and assumptions used for this project are described in Appendices 1 and 2.

2.2 Groundwater Flow and Groundwater–Surface Water Exchange Data

2.2.1 National Water Table (NWT) Model

The NWT model was developed by Westerhoff et al (2018b) to obtain a nationwide overview of groundwater levels that bridges the gap between the too-expensive advanced local models and the too-simple global-scale models. Westerhoff et al (2018b) applied an existing global-scale groundwater flow model and improved it by incorporating national input data of New Zealand terrain, geology and recharge, and by making slight adjustments to model parametrisation and model testing. The resulting nationwide maps of hydraulic head and water table depths showed that the NWT is capable of defining the main alluvial aquifers with fine spatial detail (the current application is on a 250 m grid). In two regional case studies in New Zealand, the hydraulic head showed high correlation with the available groundwater level data. The NWT can aid in provision of water table estimates in data-sparse regions and can also be used to solve inconsistencies between models in areas of trans-boundary aquifers, that is, aquifers that cover more than one region in New Zealand.

One of the model's principal inputs is the recharge estimates from the NGRM (Section 2.1.1). The model's principal outcomes are a water table elevation (metres above sea level) and a water table depth (metres below ground level, Figure 2.1). Westerhoff (2017) also showed that intermediate outcomes are likely to add value to hydrogeological research, for example, the model contains a nationwide estimate of hydraulic properties; it can provide groundwater flow directions and fluxes; and it can provide groundwater discharge to surface (example shown in Figure 2.2).

The NWT model is simplified: it does not contain information on confining layers and also contains only simple calibration modules. More details on the NWT are in Westerhoff et al (2018b).

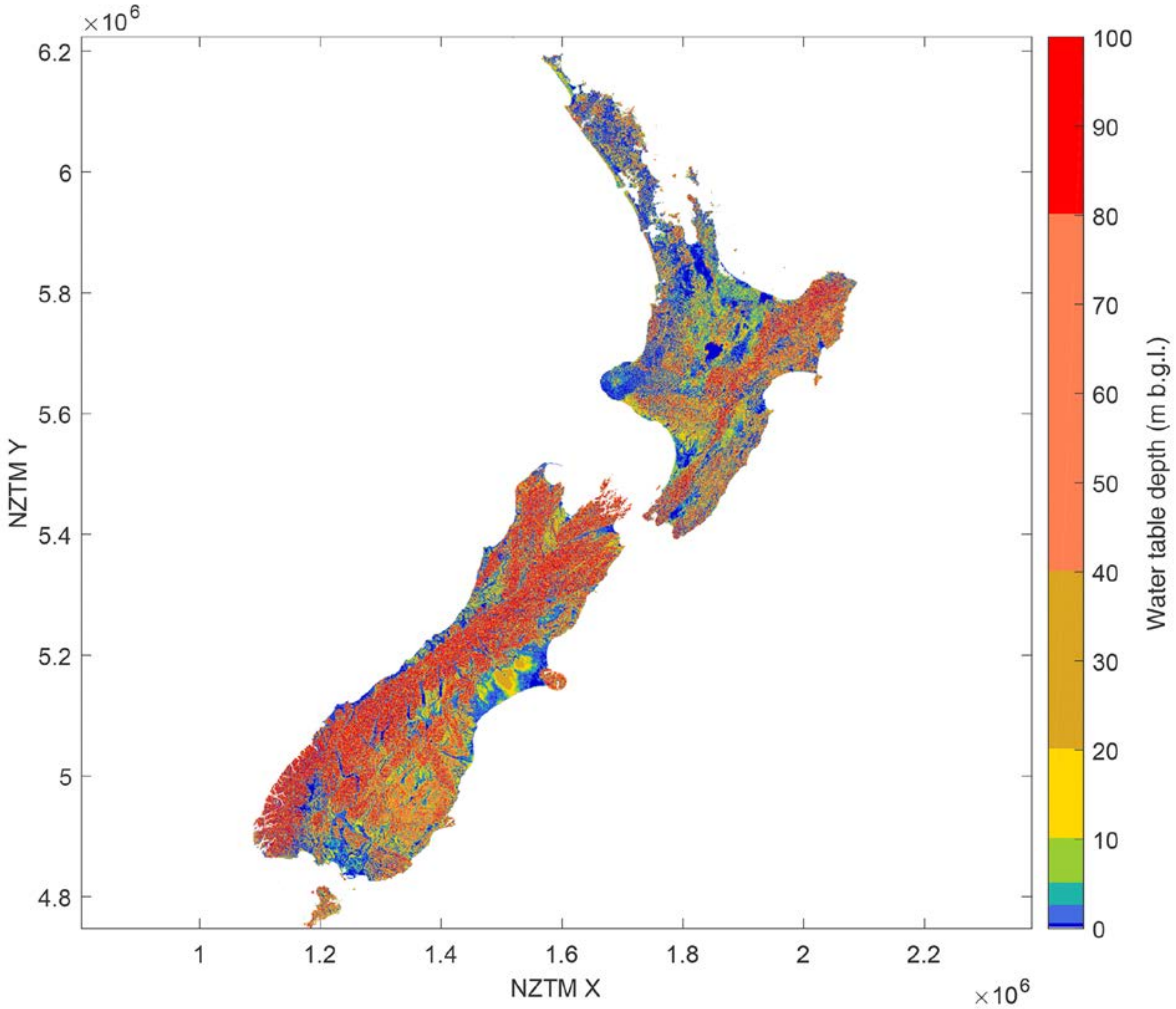

Figure 2.1 National Water Table (Westerhoff et al 2018): water table depth.

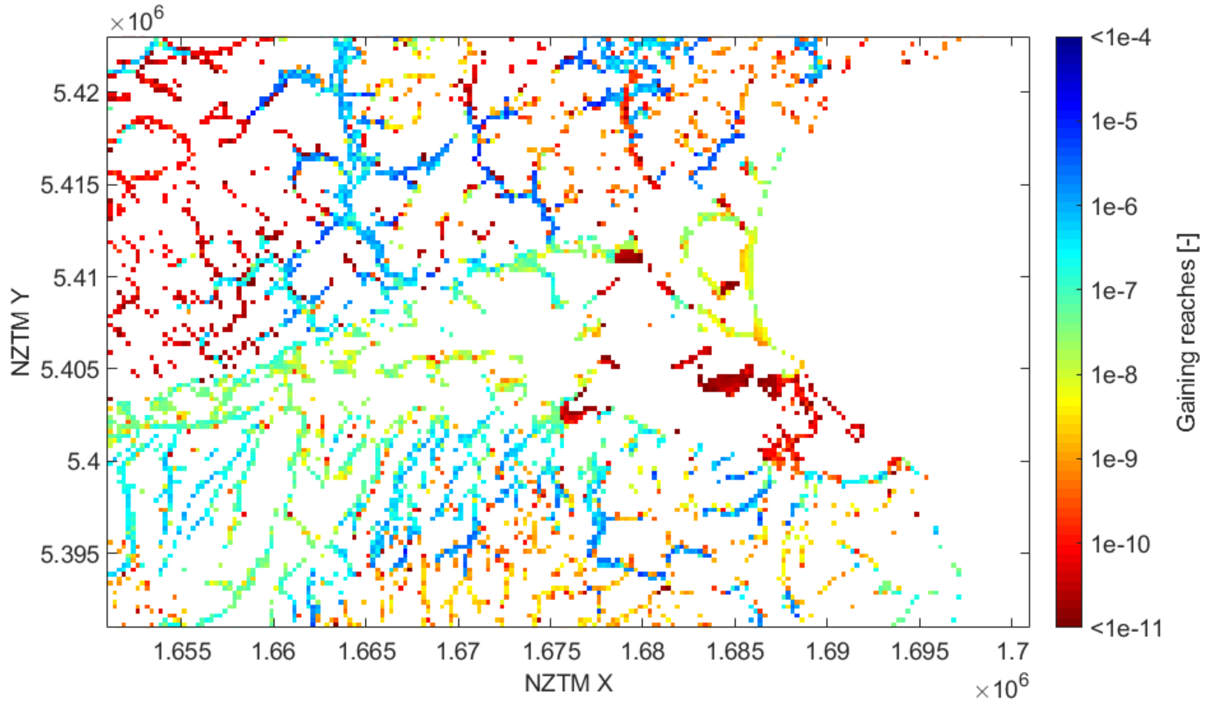

Figure 2.2 Groundwater discharge example outputs from the NWT model. Zoom in the Wairau Plains; volumes are normalised to the total of all model pixels.

2.2.2 National Classification of Gaining and Losing Stream Prediction

The National Classification (NC) of gaining and losing stream prediction was released to the public in December 2017. This data set classifies each of NIWA's defined reaches (having similar polygons as described in Section 2.1.2) into four qualitative classes (described in Yang et al 2017):

- 'Losing': the reach is always losing (ie surface water is infiltrating to groundwater)
- 'Gaining': the reach is always gaining (ie groundwater is discharging to surface water)
- 'Gain_loss': the reach is both gaining and losing
- 'Uncertain': gaining and/or losing in the reach is unknown.

These predictions are based on a machine-learning algorithm called Random Forest: a supervised classification with observations from regional councils in the North Island (see Yang and Griffiths 2017; Griffiths and Yang 2017) and in the South Island (from Horrell et al 2014, 2015a, 2015b) as training sets. The applied classification is nationwide and was given as input for this study in the form of a GIS PolyLine shapefile, with each line representing a reach (Figure 2.3).

The following limitations are to be taken into account when using this data set:

- Due to the paucity of river classification observations above 500 m above sea level, prediction of the river classes is limited to 500 m elevation
- Most of the regional councils in the North Island (except Greater Wellington) classify streams based on a regional approach instead of a stream-by-stream approach (which is the approach taken in South Island regions). As a result, North Island classification was extrapolated from the South Island classification model that was merged with the Greater Wellington classification data set.

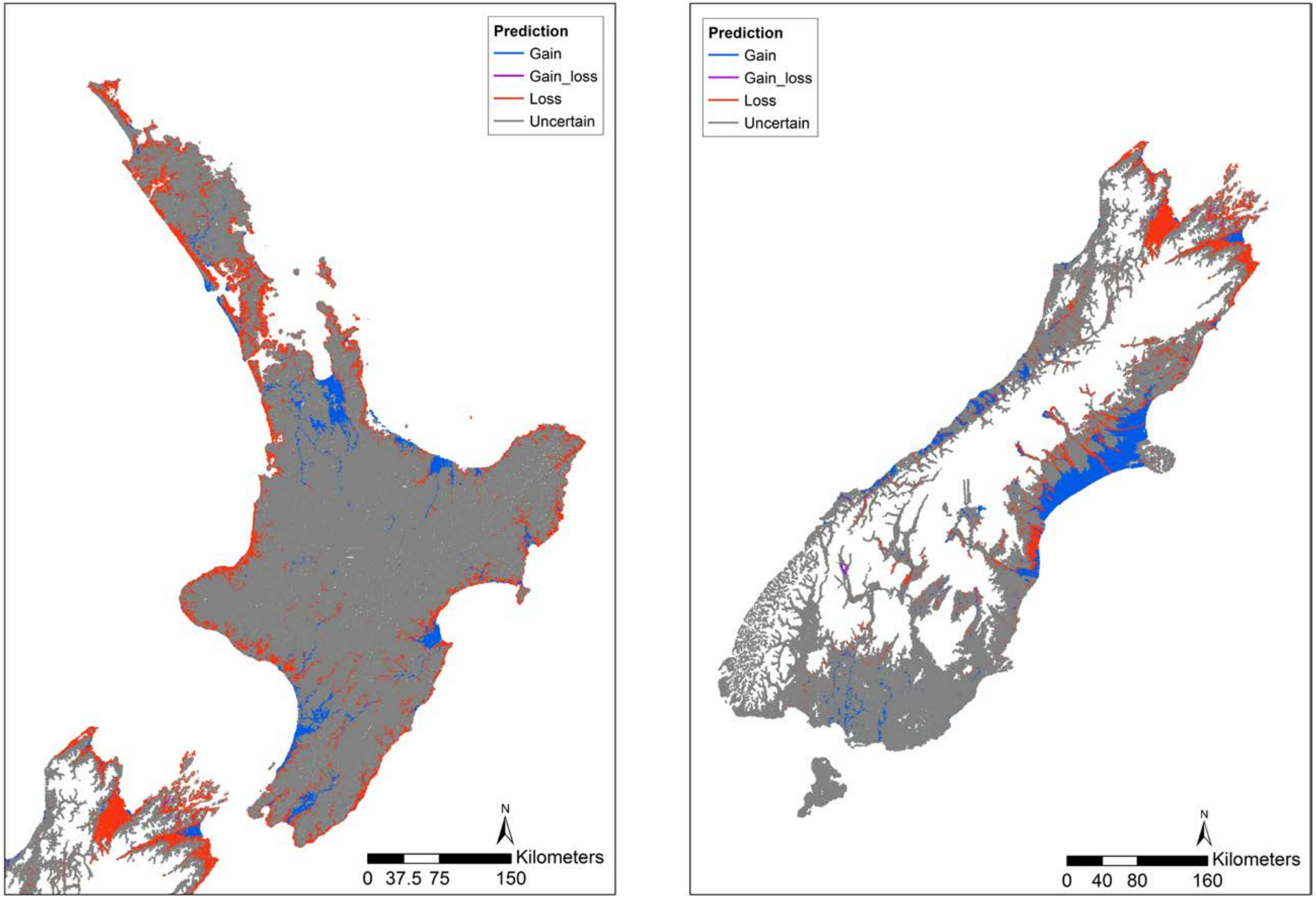

Figure 2.3 National Classification of gaining and losing stream predictions.

3.0 METHOD

3.1 Development of a Model Mean of Three Groundwater Recharge Models

3.1.1 Why Use the Model Mean Approach?

The inspiration behind the method comes from the European-funded eartH_2Observe project, which ran from 2014 to 2018 and successfully developed a global multi-model ensemble of all water cycle parameters from a multitude of hydrological and land surface models.[5] The philosophy behind that project was that there is no one model that is best and there never will be. Hence, taking a model mean will reduce model bias.

We have developed the same strategy yet simplified (we have used only three models and only looked at one variable; recharge). The reasons to use this strategy are that:

- we have utilised three of the currently most commonly used groundwater recharge models in New Zealand that were already national or able to be extended to the national scale without significant efforts
- as these models utilise different theoretical approaches, taking the model mean reduces model bias
- quantitative uncertainty can be calculated for the mean model, improving decision-making capabilities
- by looking at the differences between underlying models, we gain more knowledge on possible model improvements in underlying model approaches
- the methodology can be easily extended to encompass more models in the future.

3.1.2 Model Mean and Inter-Comparison

Three underlying models were used (NGRM, TopNet, IrriCalc; see Sections 2.1.1–2.1.3). TopNet and IrriCalc recharge were converted to the NGRM time step (monthly) and model mesh (1 x 1 km cells). Time conversion was performed by averaging TopNet and IrriCalc (daily) data to monthly.

For the TopNet polygons, centres of each catchment's polygon were collected and re-gridded onto the NGRM model mesh. All positive values of the TopNet net drainage were taken as an estimate of recharge.

The IrriCalc spatial raster was left intact; for each NGRM model cell the overlapping IrriCalc cell was used to calculate the Model Mean value.

The Model Mean, including standard deviation, of the three recharge models was calculated (mm/day) for each month over the full time period 2000–2015. Annual means were also calculated for an inter-comparison of the models.

[5] https://cordis.europa.eu/project/rcn/111322/reporting/en; www.earth2observe.eu/

3.2 Groundwater–Surface Water Exchange Estimates and Comparisons

3.2.1 Development of Groundwater Discharge Probability Classes

The NWT model was run for New Zealand, with the aim of estimating groundwater discharge to surface water. Normally, the model runs for approximately 36,525 daily time steps (100 years), at which time the model has converged well enough (Westerhoff et al 2018b). In this case, the model was set to store all data values of groundwater that discharges to surface for the last 50% of model run time (ie 18,263 time steps). Data of groundwater discharging to surface were compiled after the model run was completed, providing a gridded (250 x 250 m) output of average groundwater discharge to surface.

The original output of the NWT model has normalised values (between zero and one, see Figure 2.2) that represent a ratio of the total summed groundwater discharge for the NWT model run, that is, the sum of 18,263 model run time steps. That output was classified into ‘Groundwater discharge probability classes’: four classes that represent the probability of discharge according to the NWT model (None, Low, Medium and High, explained in Table 3.1).

Table 3.1 Definition of groundwater discharge probability classes.

Groundwater Discharge Class	Description
None	The NWT model never encountered groundwater discharge.
Low	A low probability of groundwater discharge; the NWT model has encountered discharge a few times (lower than the 25th percentile).
Medium	A medium probability of groundwater discharge; the NWT model has encountered discharge relatively often (in between 25th and 75th percentile).
High	A high probability of groundwater discharge; the model has encountered discharge very often (higher than 75th percentile).

3.2.2 Comparing the NWT Groundwater Discharge to NC-Predicted Gaining Reaches

Statistics were collected for how well NWT probabilities matched the NC-predicted gaining reaches.

As a pre-processing step, the polylines of reaches were converted to points along the polylines, with 100 m separation. Each point served as a potential sample but was only compared when a NWT raster cell overlapped the sample point. This leads to a total of 5,489,674 sample points.

A ‘pseudo-confusion matrix’ approach was developed to gather statistics on the match between NWT and NC predictions of gaining reaches. A confusion matrix compares how well observed and predicted values match.[6] However, in this case there is no ‘observed’ versus ‘predicted’ but instead ‘NWT model’ versus ‘NC model’. In addition, classes of the NWT classification (Section 3.2.1) are categorised somewhat differently to NC-predicted classes. Therefore, a ‘pseudo-confusion matrix’ was developed to compare NWT baseflow probability classes (High, Medium, Low, None) with NC Classes (gain, gain-loss, lose, uncertain).

[6] https://scikit-learn.org/stable/auto_examples/model_selection/plot_confusion_matrix.html

3.3 Groundwater Flow Estimation

The outputs of the NWT were coded such that it contained groundwater flow in x (west-east) and y (south-north) directions. The flow was estimated as follows:

1. The numerical gradients of the water table elevation in x and y directions were calculated. The numerical gradient of a function is a way to estimate the slope in multiple dimensions (in this case two: x and y). For a function of two variables, F(x,y), the gradient is defined as:

   $$\nabla F = \partial F \partial x\ \mathbf{i} + \partial F \partial y\ \mathbf{j}$$

   with $\partial F \partial x\ \mathbf{i}$ the partial derivative of F to x as the x-direction and $\partial F \partial y\ \mathbf{j}$ the partial derivative of F to y as the y-direction.

2. The slopes in x and y direction were multiplied by the transmissivity for each model cell (with a cell width of 250 m) to obtain a flow per cell-width in x- and y-direction: Q_X and Q_Y, respectively.
3. The flow amplitude was calculated as $Q = \sqrt{{Q_X}^2 + {Q_Y}^2}$.

Groundwater flow classes were based on all percentiles of amplitude as defined in Table 3.2.

Table 3.2 Definition of groundwater flow classes.

Groundwater Flow Class	Criteria
Low groundwater flow	Lower than 25th percentile
Moderate groundwater flow	In between 25th and 75th percentile
High groundwater flow	In between 75th and 90th percentile
Very high groundwater flow	Higher than 90th percentile

4.0 RESULTS

4.1 Model Mean of Three Groundwater Recharge Models

For the sake of consistency, the unit used for all recharge statistics is mm/day.

The Model Mean shows that rainfall recharge for 2000–2015 (Figure 4.1) varies spatially over the nation and is mostly influenced by rainfall, as seen by the high recharge in areas with high rainfall, for example, the West Coast and Taranaki. The spatial pattern of recharge from the Model Mean (Figure 4.1) is confirmed by all underlying models (NGRM, Figure 4.2; TopNet, Figure 4.3; IrriCalc, Figure 4.4). However, absolute values between models are different, with a clear trend of NGRM close to the Model Mean, TopNet values lower than the Model Mean and IrriCalc values being higher than the Model Mean. Reasons for these differences are explained by the difference in model assumptions and equations, which are discussed in Section 5.1. Differences between the underlying models fall within the standard deviation of the Model Mean (Figure 4.5 and Figure 4.6, left).

The standard deviation of recharge is high in the Model Mean as well as in its underlying models (Figure 4.6 and Figure 4.7). This high standard deviation is caused by differences in model assumptions; uncertainty of model input components (eg Westerhoff et al 2018a estimated a mean model uncertainty for the NGRM of approximately 20%) but is predominantly due to the large spatial and temporal variation of recharge in underlying models: recharge varies over the nation and between months (Figure 4.8) and seasons (Figure 4.9).

Yearly plots of recharge for the Model Mean and its underlying models (Figure 4.10) show the same trend as Figure 4.5, that is, that NGRM follows the Model Mean, IrriCalc is higher and TopNet is lower. Overall for New Zealand as an average, all models confirm that:

- within the 15-year time period, no long-term trend of decreasing or increasing recharge can be shown. It should be noted that this is an ‘all-of-nation’ average; it is very likely that individual regions have a trend over time
- 2004, 2006, 2008 and 2010 were relatively wet years; 2005 was a relatively dry year.

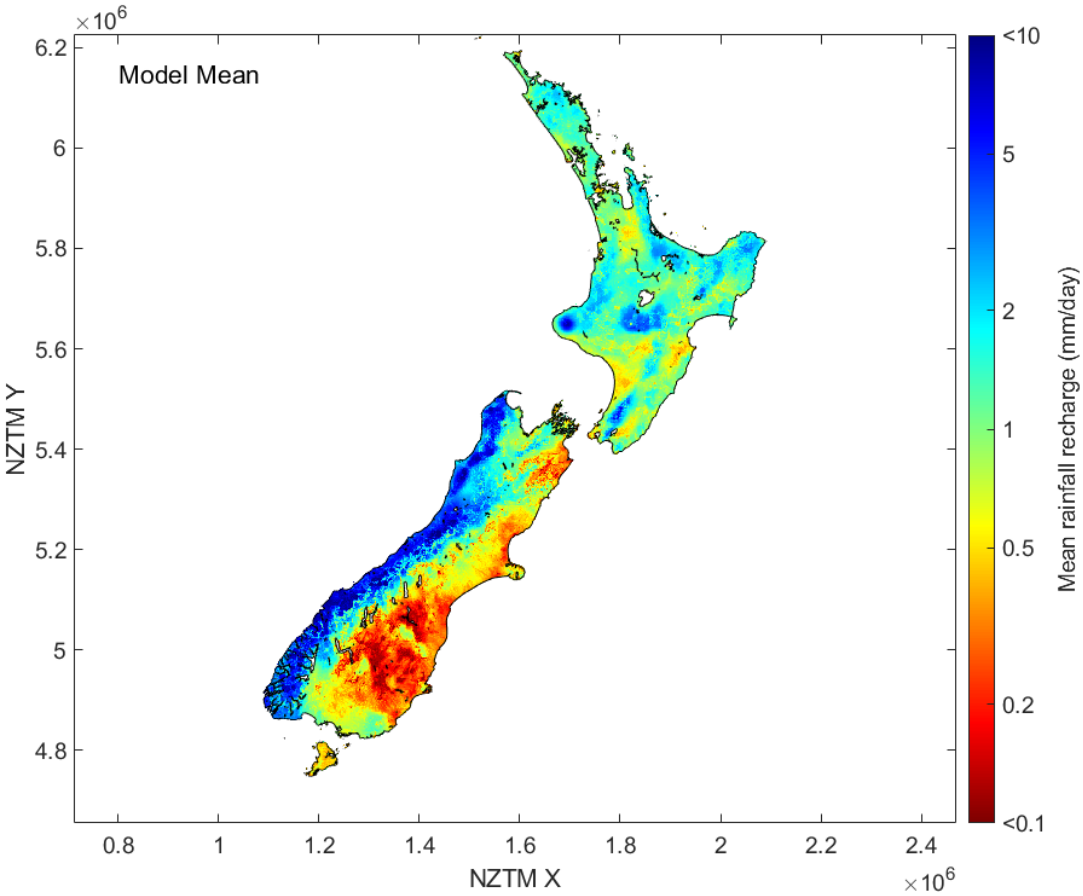

Figure 4.1 Mean 2000–2015 rainfall recharge estimated from the Model Mean in this study.

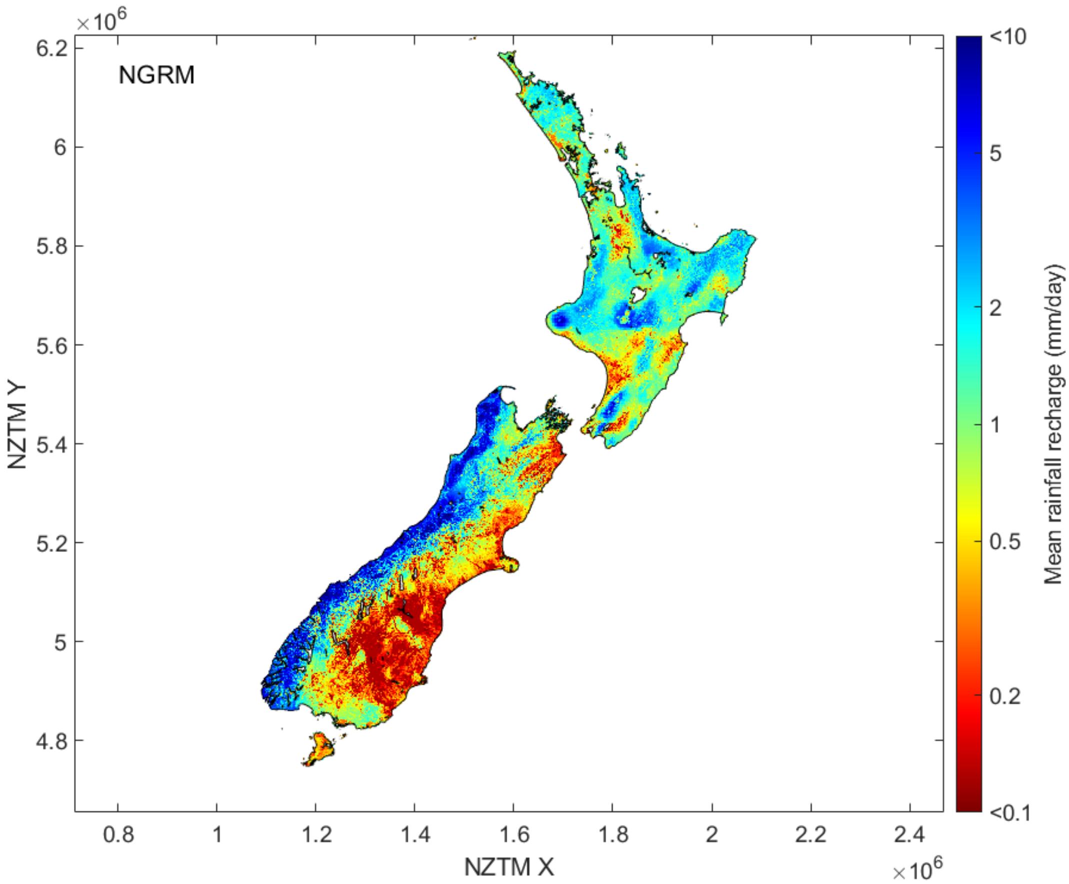

Figure 4.2 Mean 2000–2015 recharge according to the underlying NGRM estimates.

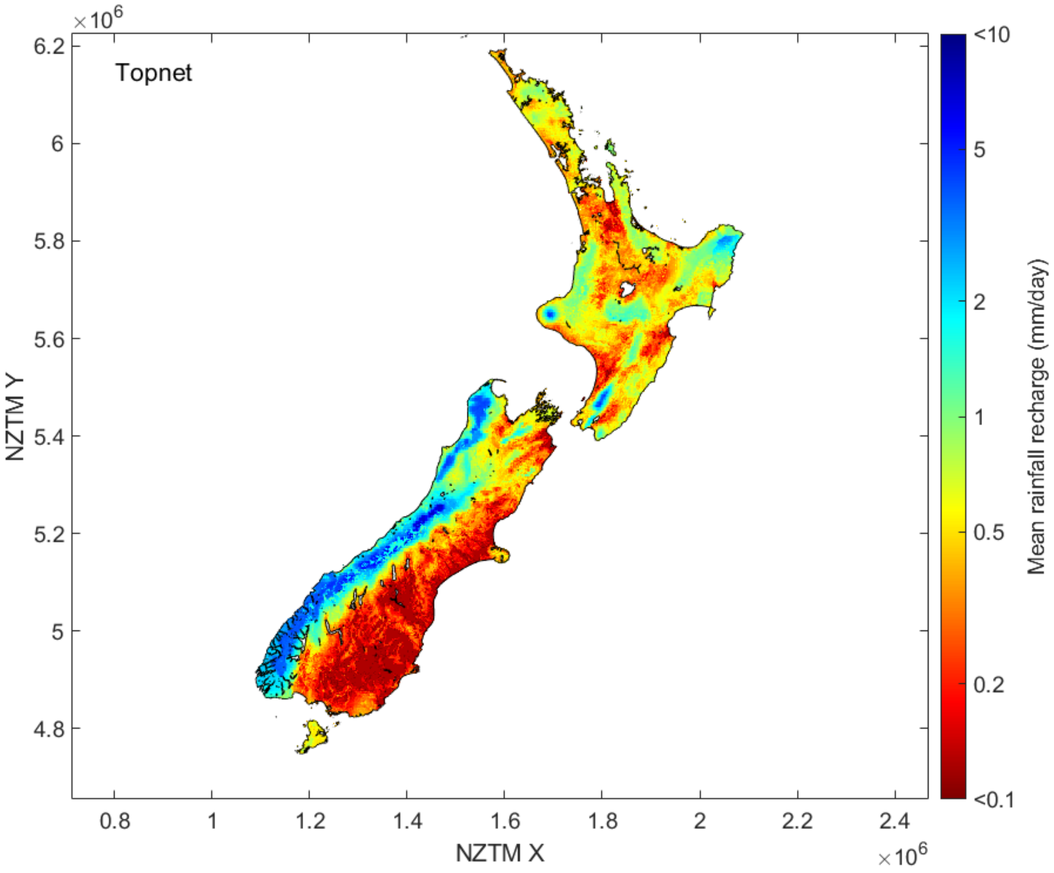

Figure 4.3 Mean 2000–2015 recharge according to the underlying TopNet estimates.

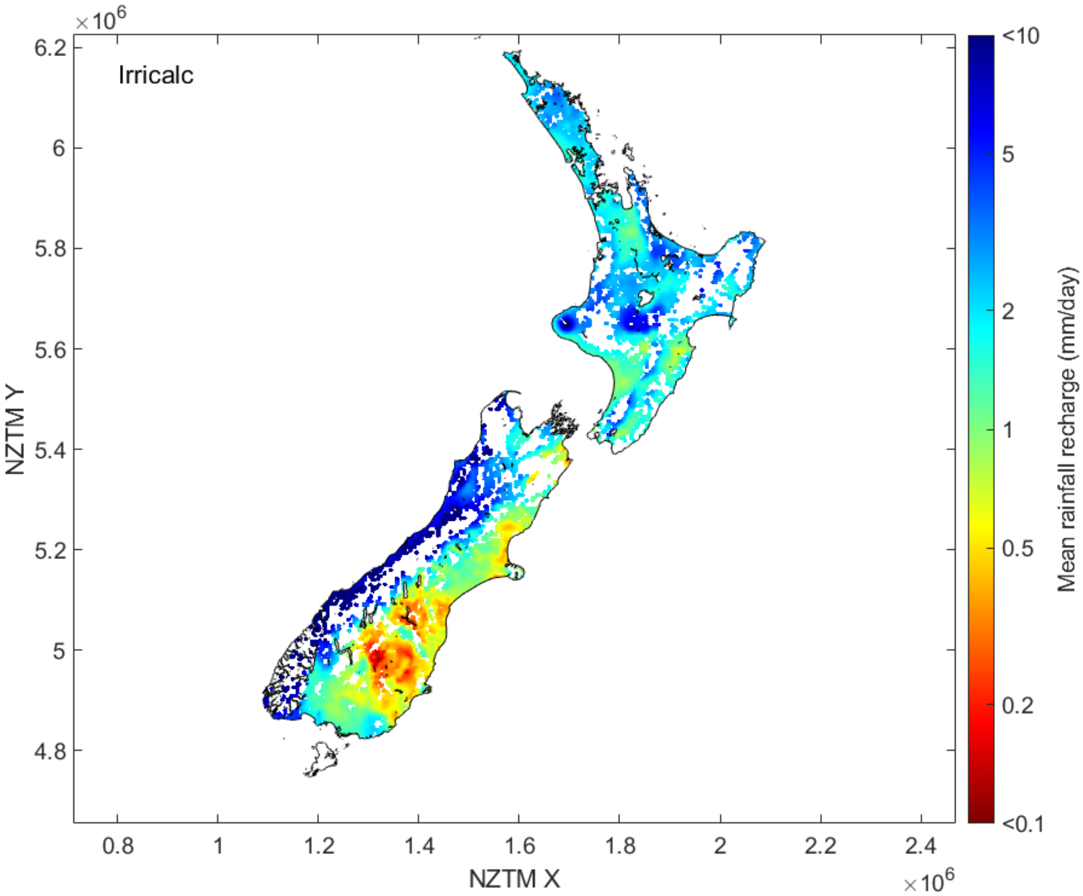

Figure 4.4 Mean 2000–2015 recharge according to the underlying IrriCalc estimates.

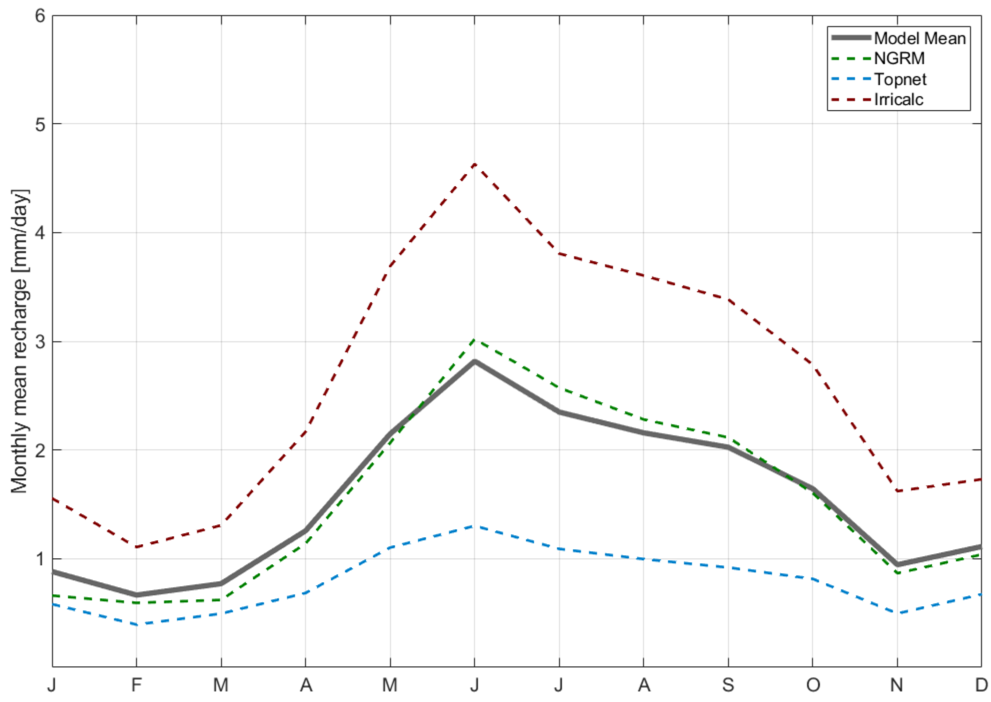

Figure 4.5 Monthly mean recharge (mm/day) for the Model Mean and its underlying models, NGRM, TopNet and IrriCalc. Values are the nationwide average.

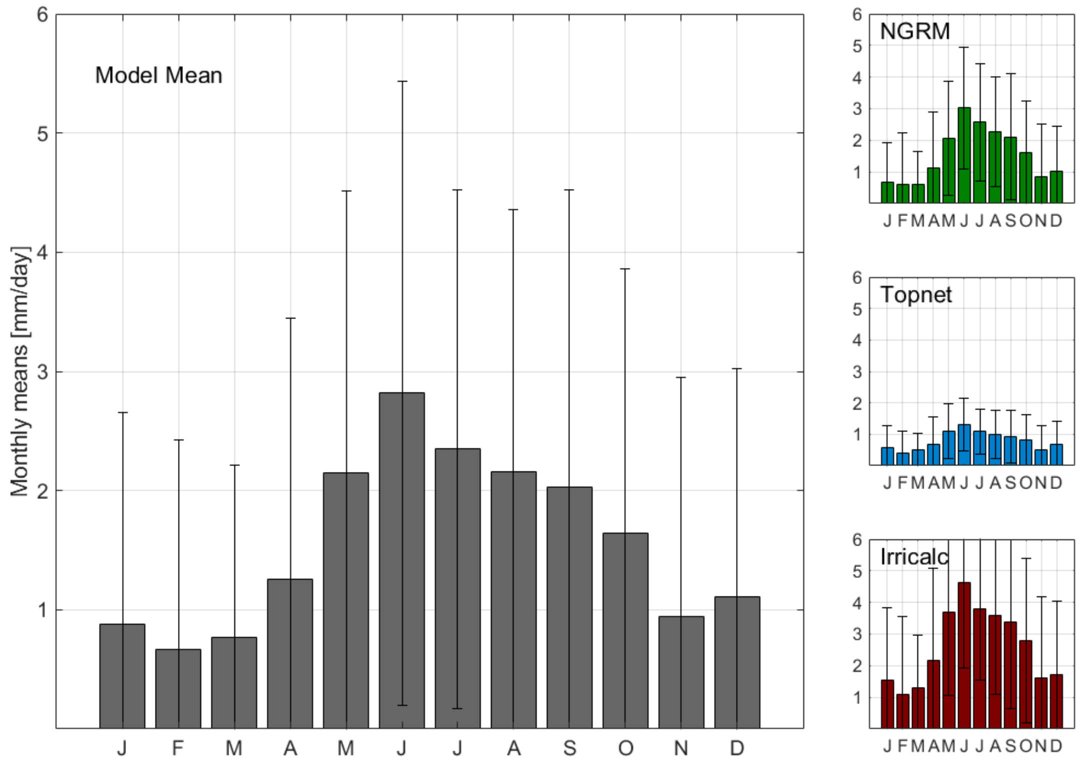

Figure 4.6 Model Mean monthly statistics (left), with the underlying NGRM, TopNet and IrriCalc statistics (right). Values are the nationwide average, with the error bars representing the standard deviation.

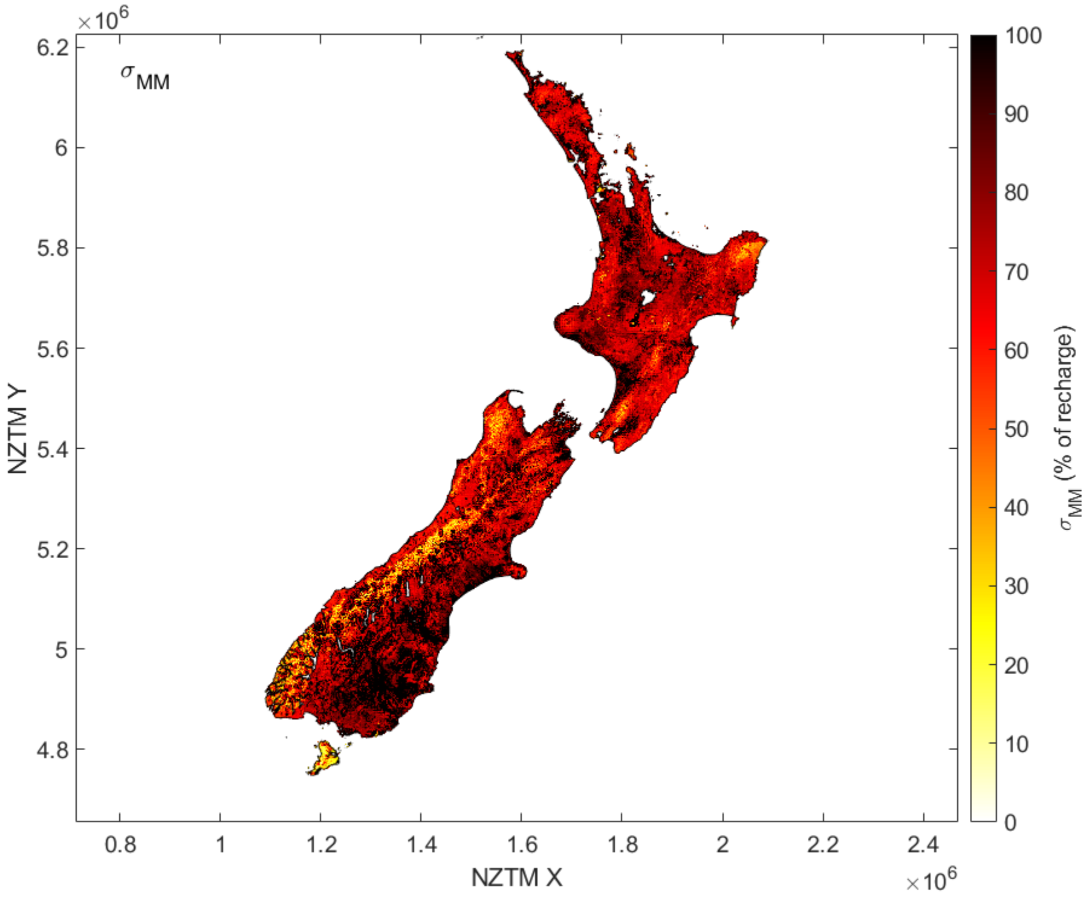

Figure 4.7 Standard deviation of the Model Mean (2000–2015), represented as a percentage of recharge. Standard deviations are high because of the temporally varying character of recharge over the year.

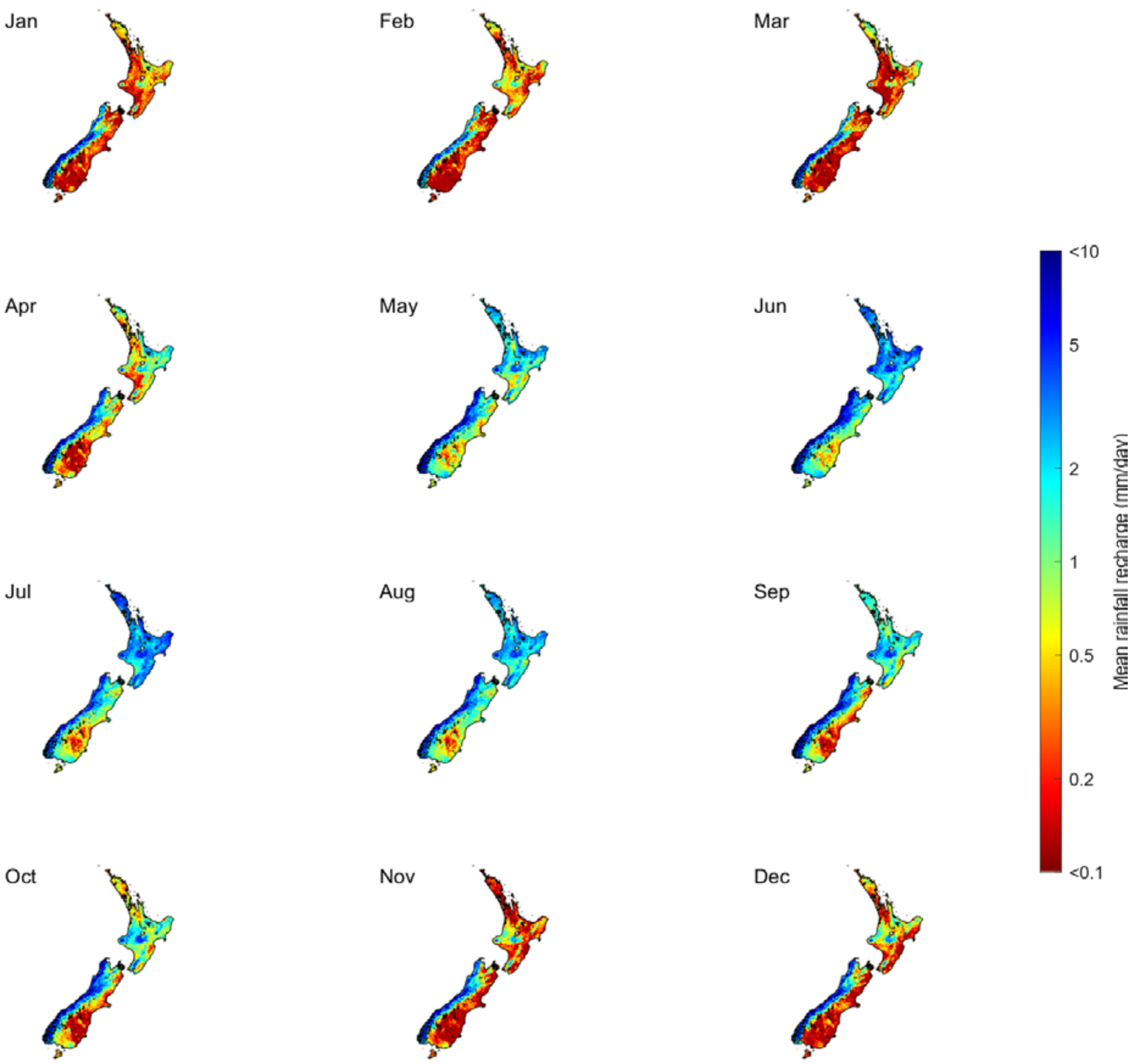

Figure 4.8 Monthly mean recharge of the Model Mean. Larger plots are detailed in Appendix 3.

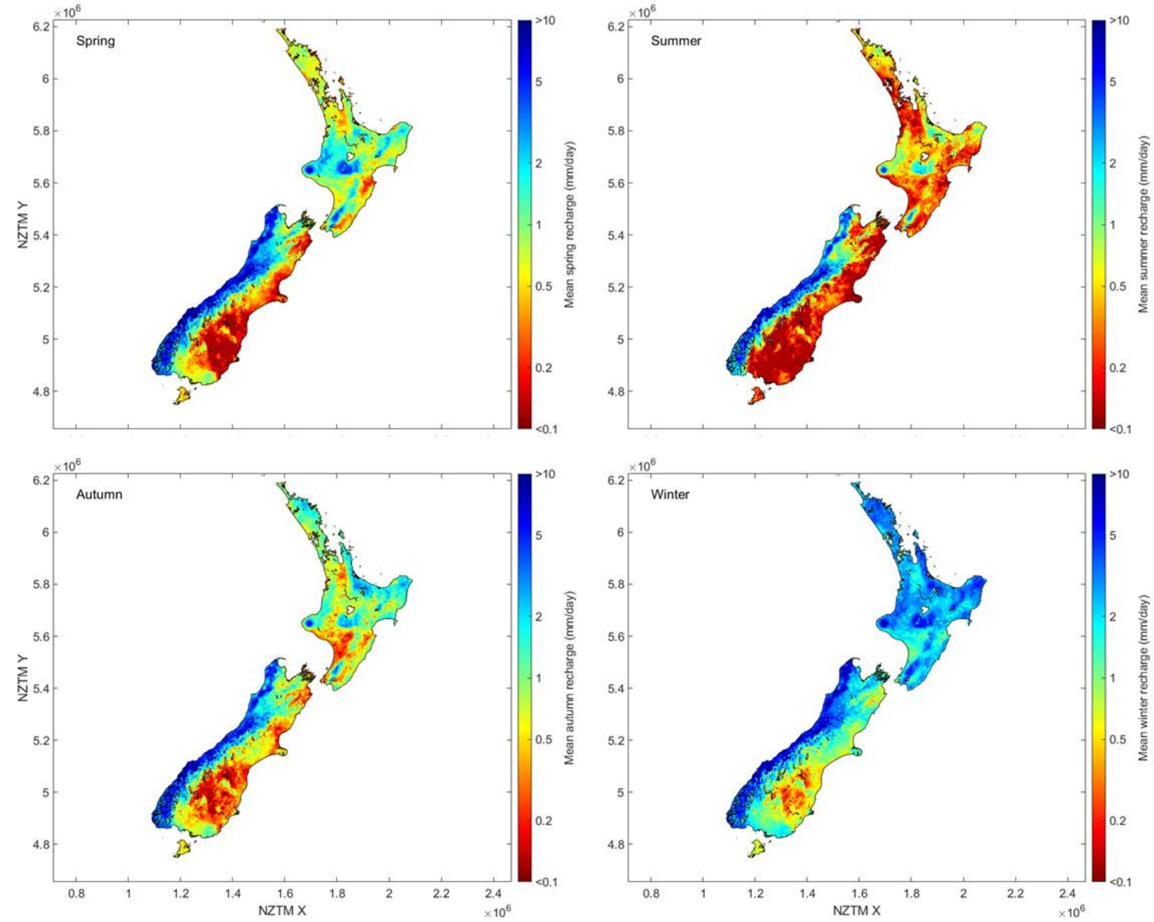

Figure 4.9 Seasonal mean recharge of the Model Mean (mm/day). Spring: September-October-November (SON), Summer: December-January-February (DJF), Autumn: March-April-May (MAM), Winter: June-July-August (JJA).

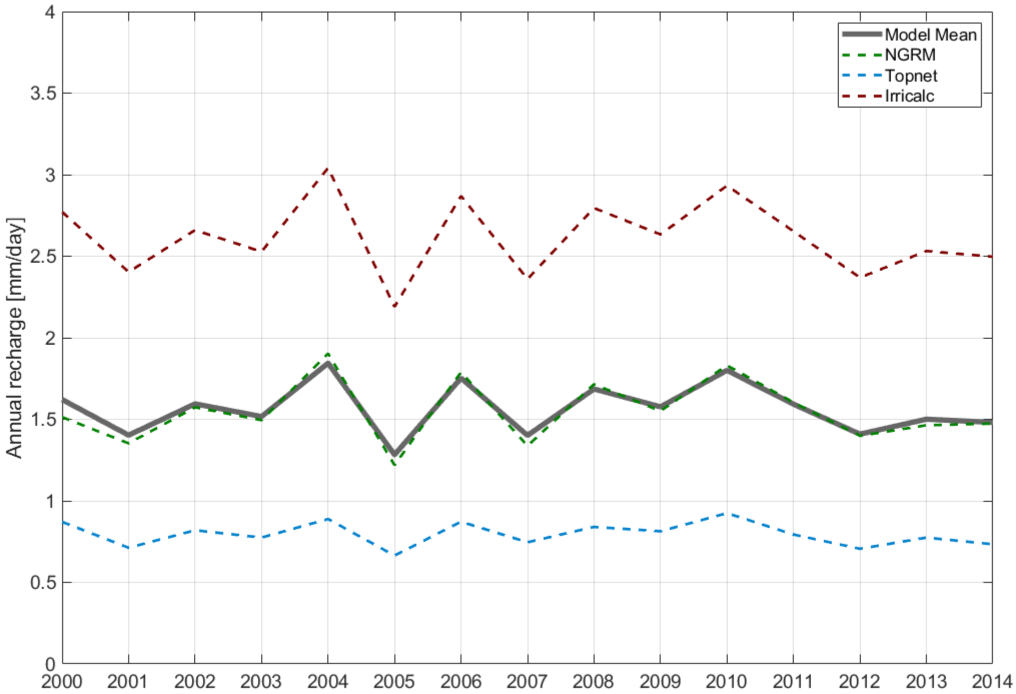

Figure 4.10 Yearly recharge (mm/day) from January 2000 to December 2014.

4.2 Groundwater–Surface Water Exchange

4.2.1 Groundwater Discharge Probability Classes from the NWT Model

The output data of groundwater discharge from the NWT model are nationwide and are shown as groundwater discharge probability classes (Figure 4.11). A relatively high number of reaches generate groundwater discharge in the model (either with low, medium or high probability) due to the water table being close to the surface and having sufficiently high hydraulic conductivity values. Blank cells have never recorded groundwater discharge to surface.

High probability of groundwater discharge often occurs from foothills to plains, for example, into the Taranaki, Canterbury, Hauraki, Wairau and Heretaunga Plains. This is as expected; water tables are often relatively close to the surface where topography changes from steep to flat. Groundwater discharge is often lower in areas where geology is less permeable, for example, impermeable rock, or clay layers that are often present near-shore in coastal plains.

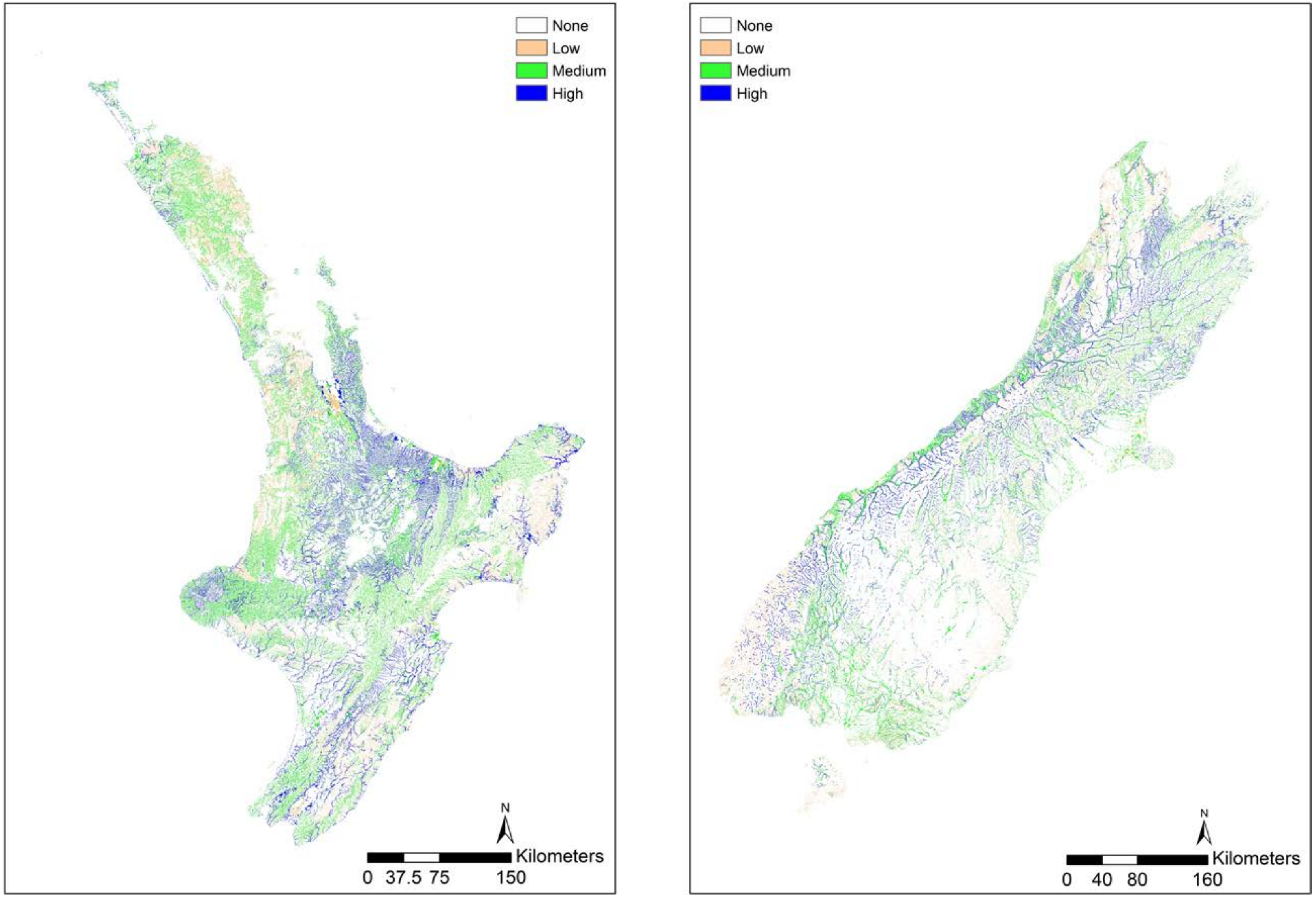

Figure 4.11 Groundwater discharge probability classes from the NWT model outputs.

4.2.2 Comparison of NWT Groundwater Discharge Probability Classes with NC Prediction

The comparison between NC predictions and NWT groundwater discharge probability classes is complex and does not show a clear match between the two data sets.

A visual comparison between national maps (NC, Figure 2.3; NWT, Figure 4.11) shows that NWT groundwater discharge occurs more often and more upstream than the NC predictions indicate. For example:

- NC predicts many streams as losing and uncertain in the foothills of the Canterbury, Hauraki, Heretaunga and Wairau Plains; the NWT largely models high probability of groundwater discharge in the foothills
- On the Canterbury Plains, NC predicts almost all streams as gaining; the NWT model does not discharge significant groundwater to surface in the Plains
- NC only predicts losing streams from the Mt Taranaki volcano flanks into the Ring Plains, where the NWT model models high probability of groundwater discharge
- In the Hauraki and Heretaunga Plains, NC predicts all streams to be gaining; NWT models groundwater discharge to be mostly coming from the foothills and upper plains and minimal to no discharge in the lower plains (ie close to the coast).

A more detailed zoom into the Wairau Plains (NC, Figure 4.12; NWT, Figure 4.13) show, in a similar fashion, that NC predicts all streams in the Plains as gaining, whereas the NWT model mainly shows groundwater discharging further upstream and only limited groundwater discharge in the Plains.

The above examples do not necessarily contradict each other. For example, a gaining reach is always sourced from groundwater discharging further upstream. However, our findings show that inter-model comparison is complex and needs further elaboration in the future. This is further discussed in Section 5.2.

Local studies show that gaining reaches are unlikely near the coast on the plains because Holocene clay layers tend to confine groundwater flow. Instead, most springs occur at the boundary of this confining layer, which is usually the boundary between coarser Pleistocene sediments in the upper plains and finer Holocene sediments in the lower plains. These types of confining near-coastal aquifer areas are common in coastal plains, for example, White et al (2016) show that, closer to the coast, the confining geology does not allow gaining streams in the Wairau Plain; Rakowski and Knowling (2018) show that no gaining reaches exist in the near-coastal confined aquifer areas of the Heretaunga Plains.

Local studies also show the presence of gaining reaches in or near the foothills of plains, for example, Wilding (2017) in the Heretaunga Plains and White et al (2016) in the Wairau Plains. The NC predictions indicate no gaining reaches in the foothills (ie all reaches are losing or uncertain); the NWT does indicate the presence of gaining reaches, but at many more locations than the aforementioned local studies.

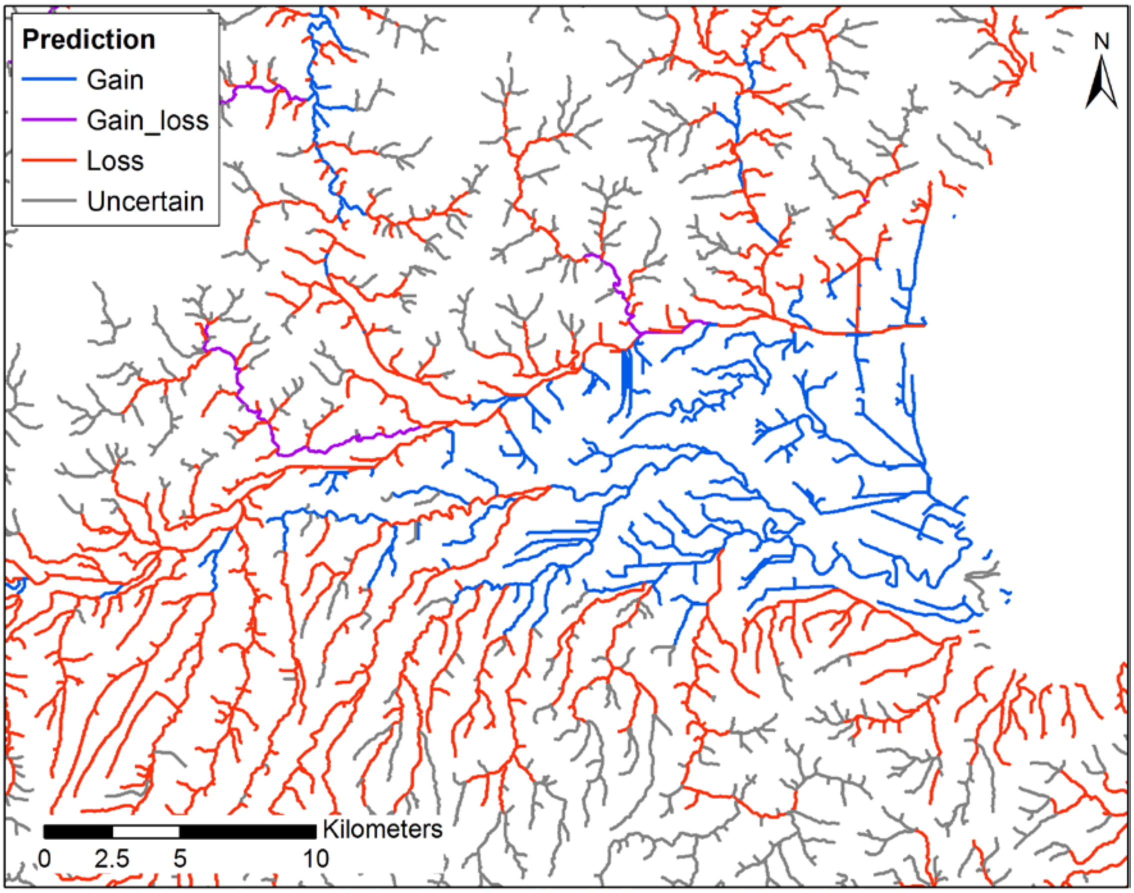

Figure 4.12 National Classification gaining and losing reach predictions. Zoom for the Wairau Plains.

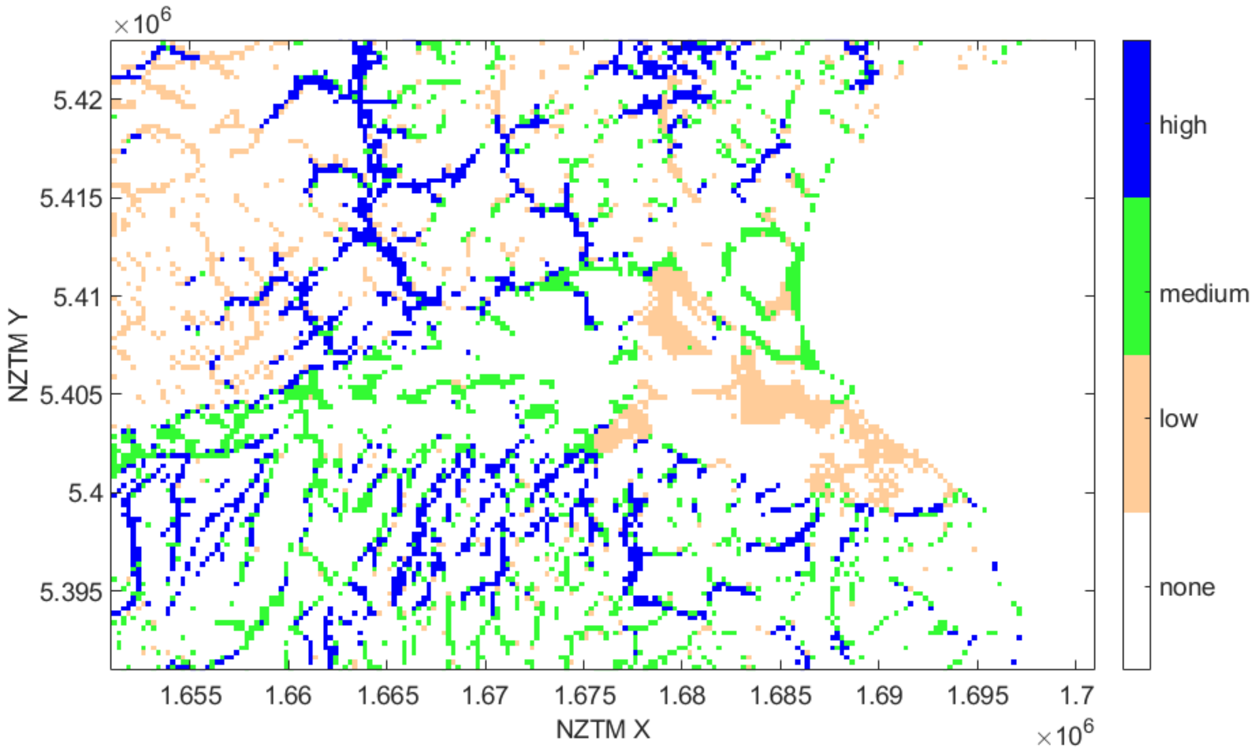

Figure 4.13 Groundwater discharge probability output of the NWT model. Zoom for the Wairau Plains.

The pseudo-confusion matrix analysis re-iterates the complexity of comparing the NC predictions and NWT groundwater discharge probability classes (Table 4.1). In 45% of all samples, the NWT model confirms (High, Medium or Low probability) groundwater discharge, where NC predicts 'Uncertain'. The NC 'Uncertain' class contains 84% of all samples. To better magnify model match, the following analyses are without incorporation of the 'Uncertain' class:

- Only in 13% of NC gaining samples does the NWT model confirm groundwater discharge (4% 'High', 7% 'Medium', 2% Low)
- In 25% of all samples identified as gaining by NC predictions, the NWT model does not predict any discharge ('None')
- In 39% of NC losing samples, the NWT model predicts groundwater discharge (17% 'High', 17% 'Medium', 5% 'Low')
- In 23% of all NC losing samples, the NWT does not predict groundwater discharge ('None').

The mis-match between NC predictions and NWT classes shows that not only are the two data sets distinctly different from each other, but also that the two approaches represent different outputs. NC predictions indicate losing and gaining reaches, while NWT outputs indicate groundwater discharge to surface and no losing reaches. Furthermore, NC is based on the inclusion of observations in a machine-learning training algorithm ('random forest'); NWT groundwater discharge is based on the outputs of a groundwater model. The differences between the two model approaches are further discussed in Section 5.2.

Table 4.1 Pseudo-confusion matrices showing the number of matches between NWT groundwater discharge classes and NC-predicted gaining-losing classes. Top: number of samples, Middle: percentage, Bottom: percentage without incorporation of the NC 'Uncertain' class.

	NC Gain	NC Gain-Loss	NC Loss	NC Uncertain
NWT HIGH	32217	1788	149613	686814
NWT MEDIUM	60544	1722	149428	1209026
NWT LOW	18818	179	40203	595952
NWT-NONE	211875	2150	194961	2134384

	NC Gain	NC Gain-Loss	NC Loss	NC Uncertain
NWT HIGH	0.6%	0.0%	2.7%	12.5%
NWT MEDIUM	1.1%	0.0%	2.7%	22.0%
NWT LOW	0.3%	0.0%	0.7%	10.9%
NWT-NONE	3.9%	0.0%	3.6%	38.9%

	NC Gain	NC Gain-Loss	NC Loss
NWT HIGH	3.7%	0.2%	17.3%
NWT MEDIUM	7.0%	0.2%	17.3%
NWT LOW	2.2%	0.0%	4.7%
NWT-NONE	24.5%	0.2%	22.6%

4.3 Groundwater Flow

Results point out areas where groundwater flow rates are low, moderate, high or very high (Figure 4.14). Intermediate outputs also show groundwater flow directions. For example, in the Canterbury Region (Figure 4.15) most water flowing from the foothills into the Canterbury Plains follows the terrain and flows from northwest to southeast. The flow amplitude absolute values are considered rough indications, given the simplifying assumptions of the NWT model (see discussion in Section 5.3); as such, the groundwater flow classes were created to encompass this uncertainty.

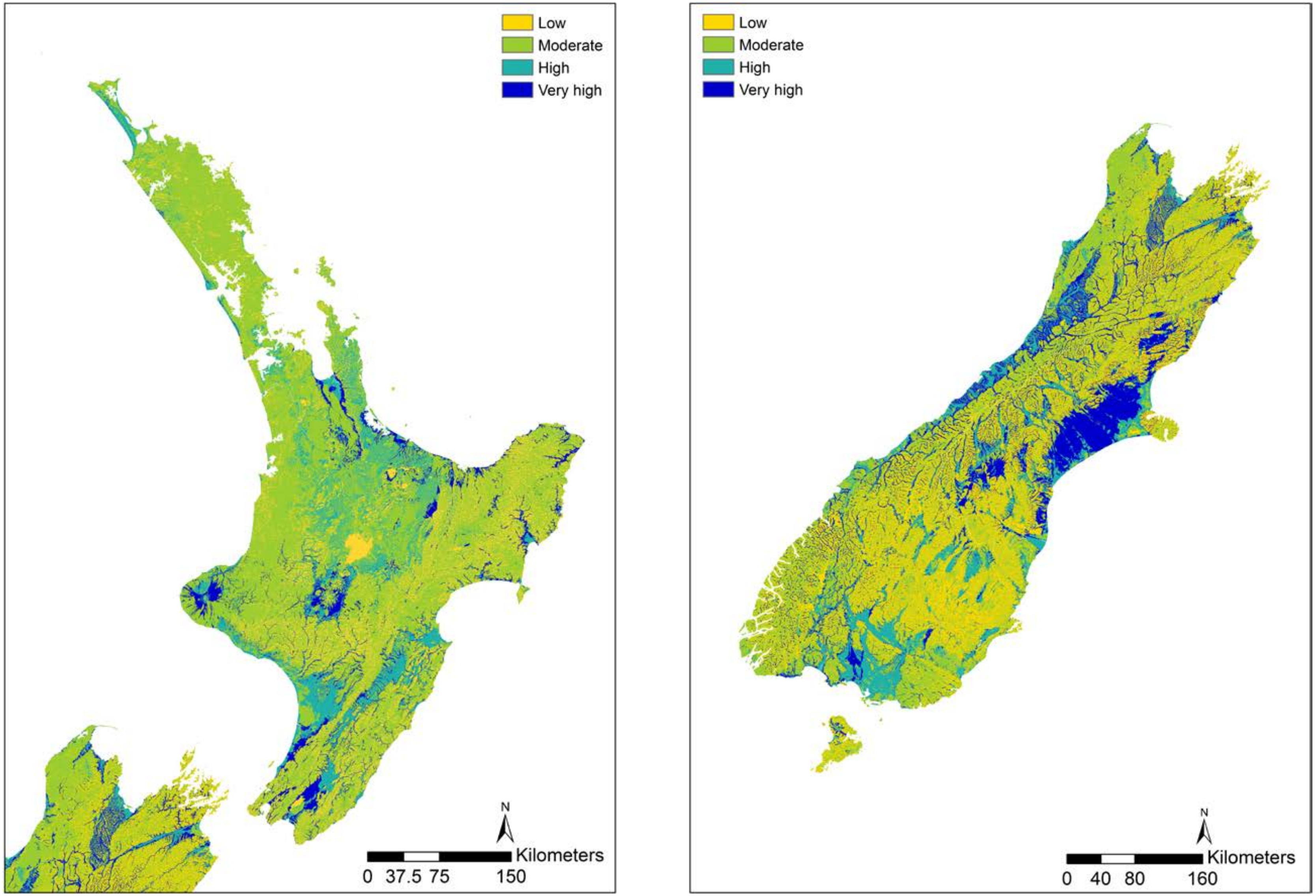

Figure 4.14 Groundwater flow classes throughout New Zealand.

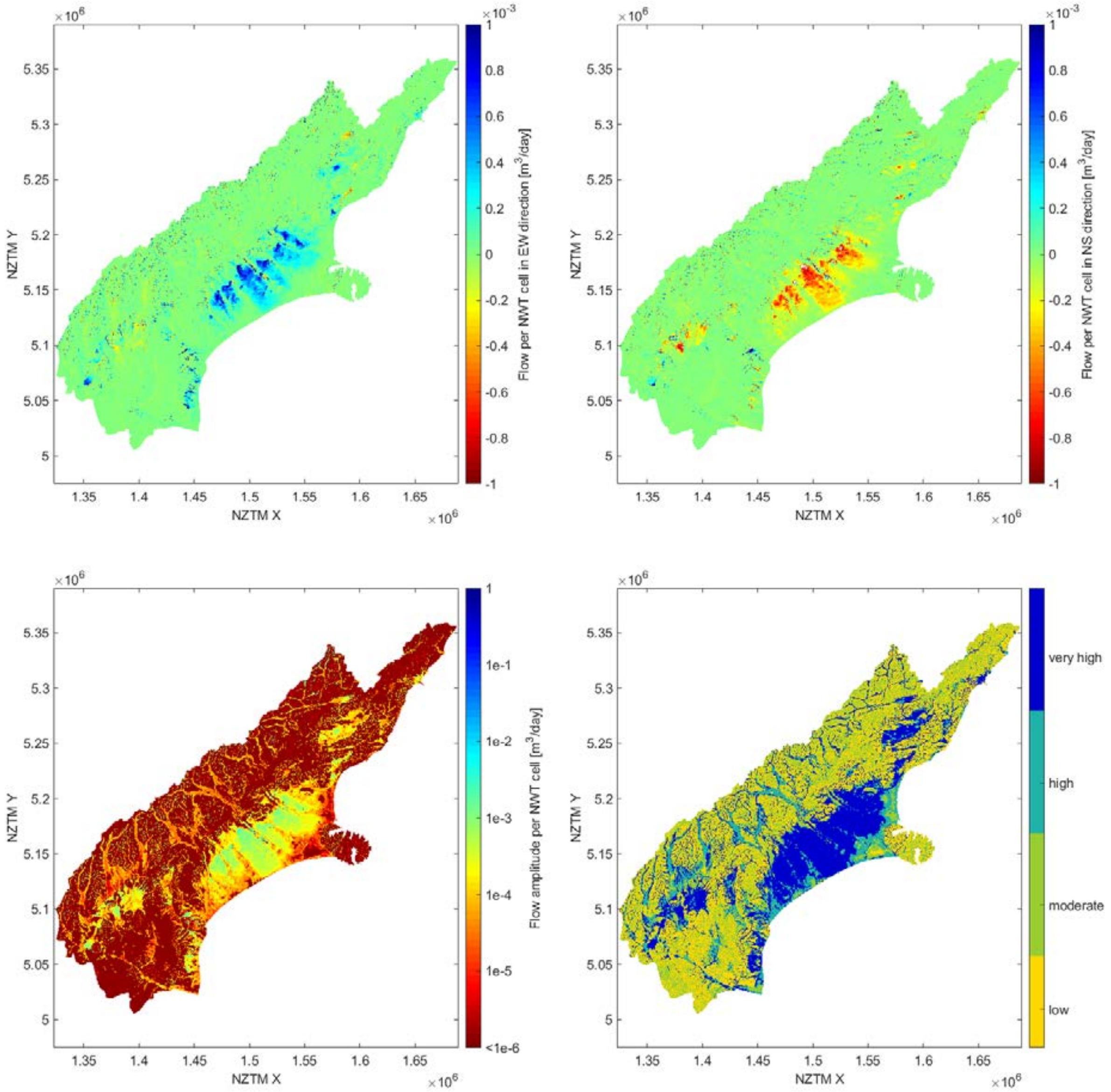

Figure 4.15 Groundwater flow results, example for Canterbury. Flow in east-west (east = +) direction (top left), flow in north-south (north = +) direction (top right), flow amplitude (bottom left) and flow class (bottom right).

4.4 Output Data Sets

The data sets provided to the Ministry along with this report are in GeoTIFF format with the following file names.

Groundwater recharge data sets:

- Groundwater Recharge Model Mean, mean: *NZGroundwaterRecharge_mean_20002015.tif*
- Groundwater Recharge Model Mean, mean uncertainty: *NZGroundwaterRecharge_mean_20002015_stdev.tif*
- Groundwater Recharge Model Mean, spring mean: *NZGroundwaterRecharge_meanspring_20002015.tif*

- Groundwater Recharge Model Mean, spring mean uncertainty: *NZGroundwaterRecharge_meanspring_20002015_stdev.tif*
- Groundwater Recharge Model Mean, summer mean: *NZGroundwaterRecharge_meansummer_20002015.tif*
- Groundwater Recharge Model Mean, summer mean uncertainty: *NZGroundwaterRecharge_meansummer_20002015_stdev.tif*
- Groundwater Recharge Model Mean, autumn mean: *NZGroundwaterRecharge_meanautumn_20002015.tif*
- Groundwater Recharge Model Mean, autumn mean uncertainty: *NZGroundwaterRecharge_meanautumn_20002015_stdev.tif*
- Groundwater Recharge Model Mean, winter mean: *NZGroundwaterRecharge_meanwinter_20002015.tif*
- Groundwater Recharge Model Mean, winter mean uncertainty: *NZGroundwaterRecharge_meanwinter_20002015_stdev.tif*

Groundwater discharge data sets:

- Groundwater–surface water exchange, groundwater discharge probability: *NZGroundwaterDischarge_ProbabilityClasses.tif*

Groundwater flow data sets:

- Groundwater flow, amplitude classes: *NZGroundwaterFlow_Amplitude_Classes.tif*

By request, the following data sets are also available:

- Monthly recharge of the Groundwater Recharge Model Mean as a NetCDF file that contains 24 layers: 12 of recharge and 12 of its standard deviation.
- Groundwater flow, mean in the east-west direction: *NZGroundwaterFlow_X_mean20002015.tif*
- Groundwater flow, mean in the north-south direction: *NZGroundwaterFlow_Y_mean20002015.tif*

5.0 DISCUSSION

5.1 Differences between Recharge Models Explained

Overall and across New Zealand, TopNet recharge is lowest, IrriCalc is highest and NGRM is closest to the Model Mean.

Differences between the models fall within the model uncertainty of each of the models. The definition of recharge in all three models is subtly different, but explain the differences found and provide insight into the different biases that each model has due to model input, assumptions and equations.

TopNet recharge is defined as the 'net drainage' per sub-catchment, which already assumes that recharge is corrected for groundwater discharge. Since this is a 'whole-of-catchment' estimation, any areas within the catchment that do have recharge (typically referred to as the saturated zone in TopNet) will be picked up by the model with a bias if groundwater discharge is also present. Hence, the TopNet recharge estimation will always be less than or equal to other estimates of recharge that do not include discharge in their calculation, that is, when the components are separated. To improve research on groundwater–surface water exchange, it is strongly advised that future net flux components of TopNet be delivered as two separate components, that is, recharge and groundwater discharge. This will facilitate a better future inter-model comparison. This non-compatibility issue could only be clarified over the course of recent GNS-NIWA collaborative studies, of which this study is an important one. Currently, this deficiency is being improved by NIWA. We expect that this study has set an example of the benefit of inter-Crown-research-institute collaborative studies and that future collaboration will help solve more intricacies in groundwater–surface water interaction studies.

IrriCalc recharge is an output of a daily soil-moisture balance. The model includes an irrigation component, with irrigation management rules that specify when, and how much, irrigation water is applied. Explicitly modelling irrigation events is more likely to lead to higher recharge than the other two models in areas where irrigation occurs. The recharge output from IrriCalc is the total water drained from the root zone; in some cases there will be a relatively short sub-surface flow path to a surface water body, and some of the recharge model output could be conceptualised as 'quickflow'. A separation of this component might allow a better model inter-comparison in the future.

At some areas the Model Mean shows circle-like features, an example shown in the southwest of the South Island in Figure 5.1. This is an artefact caused by model differences. As IrriCalc overestimates recharge and only calculates recharge for agricultural areas, the circle features are the agricultural areas used by IrriCalc.

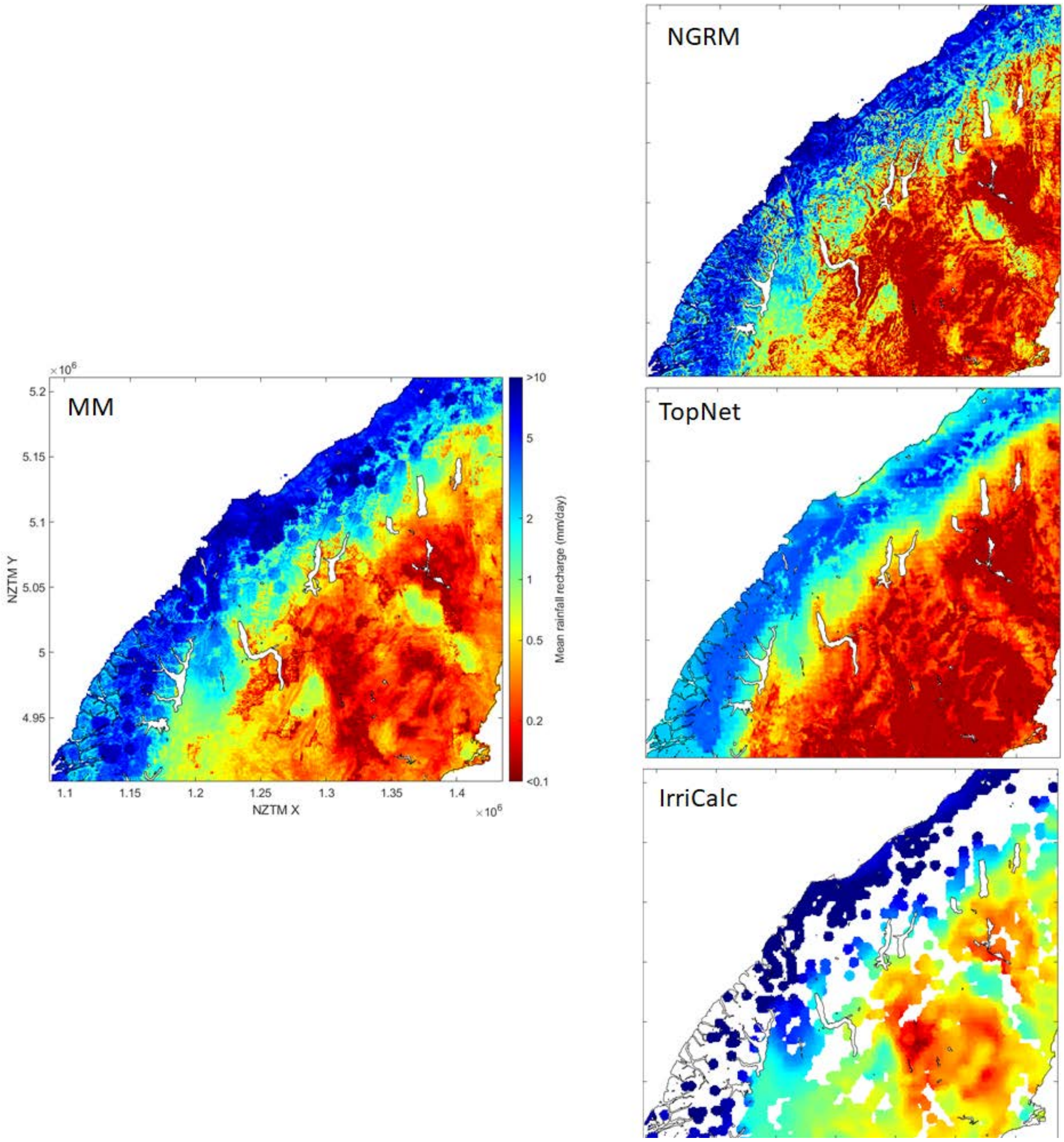

Figure 5.1 Mean recharge differences explained: zoom into the southwest of the South Island. Areas where IrriCalc calculates very high recharge remain visible in the Model Mean as circle-like features, mainly because IrriCalc only provides data in agricultural areas.

The three underlying models use different evaporation conceptualisation and sources of information that impact groundwater recharge. NGRM does not use AET data from an embedded model, such as IrriCalc and TopNet. Instead, it uses satellite-derived AET. If areas are irrigated, AET will be close to PET; any areas that are not irrigated will show a relative higher difference between AET and PET. Hence, NGRM uses satellite observations to look at the difference between AET and PET, while IrriCalc and TopNet use a model (but these model approaches are different from each other). Both approaches contain uncertainty. To reduce the bandwidth of the Model Mean at the high end, it is advised to compare AET and PET estimates between the three models; this comparison will likely explain these model differences.

It is currently unknown what the effect is of the three underlying recharge models using different model assumptions for surface run-off estimates. NGRM uses a national elevation, TopNet uses a global terrain model and IrriCalc uses slope classes. Further research is suggested to look at the implications of different terrain slope input data and model assumptions for surface run-off.

The recharge model comparison approach could be ideally expanded with more models to create a true multi-model ensemble. For example, Hong and White (2014) use two soil water balance models, SOILMOD-DRAIN and SMB-SMC, in the Canterbury Plains. Rawlinson et al (2015) compare NGRM outputs to a water balance model SWB in the Waipa catchment. However, these models are regional and are not (yet) available nationwide.

This study has generated a time series of yearly recharge and shows that, for a nationwide assessment within the 15-year study period, no clear long-term trend of decreasing or increasing recharge is visible. It should be noted that this is an 'all-of-nation' average; it is very likely that for different regions there can be a trend over time. Hence, a recommendation for further research is that individual region-specific compilations should be made for all regions of New Zealand.

5.2 Groundwater–Surface Water Exchange Estimates

The comparison between NC predictions of losing and gaining reaches and the groundwater discharge probability classes from NWT led to mixed results (Section 4.2). This is because the two outputs are distinctly different from each other, both in terms of data sets as well as in the modelling process. NWT groundwater discharge is based on groundwater model outputs; NC is based on the output of a machine-learning classification using surface water models and council observations. In addition, the two models have distinctly different classes as outputs. For example, the NWT model is not (yet) equipped to model losing streams and NC shows streams as gaining or not gaining (binary), whereas the NWT model derives the probability of groundwater discharge according to statistical compilation of flow occurring over many groundwater model run time steps.

Since it is not possible to perform a more appropriate inter-model comparison at this stage, it is recommended that other projects focus on the better inter-linking of groundwater-model derived groundwater–surface water exchange and surface-water-model-derived groundwater–surface water exchange. Both NIWA and GNS perform research in their Strategic Science Investment Funds (SSIF) programmes, for example, NIWA's New Zealand Water Model and GNS' Groundwater SSIF programme on this aspect. It is recommended that these programmes follow this recommendation.

Qualitative interpretation on the validity of NC predictions and NWT model outputs are possible when comparing with local studies. For example, Section 4.2 describes that NC predictions show gaining reaches in coastal plains all the way up to the coast and losing or uncertain reaches in the foothills or higher. The NWT model shows fewer gaining reaches near the coast; medium groundwater discharge probability in the upper plains and high probability of groundwater discharge in or close to the foothills. Local studies confirm that it is not likely to have gaining reaches close to the coast, as near-coastal Holocene (clay) layers near the surface confine the groundwater flow. Local studies also confirm groundwater discharge zones that are in or close to the foothills.

The NWT model incorporates the confining status of some aquifers by incorporation of the geological map: where the near-surface geology is relatively impermeable (it contains clay), the model is less likely to discharge water from groundwater to the surface. Also, the NWT model points out groundwater discharge in the foothills, but it indicates that many streams have gaining reaches; however, local studies indicate only a limited amount of reaches. More research is needed to indicate why the NWT overestimates the number of reaches compared with previous local research and observations. This could be caused by the model having a relatively shallow water table in plains, since it is not able to incorporate human-made draining patterns, that is, canals, tile drainage etc. Further, the NWT model could be run for a longer time before compiling groundwater discharge data. By doing this, it is more certain that water tables have converged and thus will likely not change per model iteration. Westerhoff et al (2018b) showed that there is relatively little gain in longer model running, but in regard to specific catchments there might still be improvements possible in such an approach.

The NC predictions are based on observations by regional councils and thus are potentially more reliable in areas with many observed data points. However, most of the training data was available from the South Island and not so much for the North Island. It is recommended that more findings of local studies are incorporated in the training algorithm (random forest classification) of the NC predictions. Furthermore, incorporation of confining layers in the classification algorithm is recommended.

The NWT model does not use a specific river bed hydraulic conductivity; instead, it used the hydraulic conductivity based on the New Zealand geological map. Inclusion of river bed hydraulic conductivity might be best in a coupled model environment and is a recommendation for further research. To better combine surface water and groundwater models, it might be better to perform coupled model runs. This research is currently taking place within NIWA's New Zealand Water Model project.

5.3 Groundwater Flow Estimates

As with any computer-based model of a complex natural system, the NWT model is incorrect but is an approximation of the natural system with the degree of incorrectness reflecting the model's level of sophistication and underpinning information. The NWT is further simplified, because it does not contain advanced calibration and modelling modules of more advanced groundwater models, such as MODFLOW, FEFLOW etc. This is one of the reasons that results were presented in groundwater flow classes instead of absolute values. However, the NWT model is the only model that is available nationwide. It was also specifically developed for that goal: to obtain a nationwide overview of groundwater levels that bridges the gap between the expensive advanced local models and the simple global-scale models.

To improve flow estimates it is recommended to include local data and model outputs into the nationwide estimates. We treat the NWT model suite used in this study as a framework: having a nationwide groundwater model, it is now possible to bring in more regional data in the form of in-situ measurements and/or more sophisticated local models. Using this framework, over time estimates of fluxes can be iteratively improved by bringing in regional or local data and models. GNS Science, with their SSIF funding, continues to improve the up- and downscaling of groundwater maps and models so scaling from national to local will be more seamless.

6.0 CONCLUSION AND RECOMMENDATIONS

An estimate of nationwide mean rainfall recharge (Model Mean) from 2000 to 2015 was developed by combining outputs of three existing models: TopNet, IrriCalc and NGRM. The Model Mean shows that recharge for 2000–2015 varies spatially over the nation, depending on climate and landscape conditions, which is also inherent in all underlying models. Inter-model comparison shows that, overall, TopNet recharge is lowest, IrriCalc is highest and NGRM is closest to the Model Mean. Differences between the models are within the uncertainty associated with each of the models. Model differences are mainly caused by the bias within each model caused by different model assumptions, mainly through subtly differing definitions of recharge and different model input variables.

A nationwide map of groundwater discharge probability was developed with a nationwide groundwater model (NWT). This shows that discharge often occurs from foothills to plains and less in areas where geology is less permeable, for example, impermeable rock, or near-surface clay layers that are often present near-shore in coastal plains. Comparison of NWT discharge outputs with another national approach (based on observations and machine-learned predictions) is complex because the two models produce different output variables and location of groundwater discharge. Initial insight from local studies indicate that the NWT model correctly identifies the reduced groundwater discharge in near-coastal clays and the existence of groundwater discharge close or in the foothills. However, it overestimates the number of streams with groundwater discharge when compared with local studies (whereas NC predictions, based on observations, do not).

The NWT model was also used to develop nationwide estimates of groundwater flow amplitude. Although a national model can only give a rough indication of groundwater flows, it supports existing understanding that flows are highest in areas that are very hydraulically conductive (eg gravels in plains) or are gravity-driven by a large and high upstream catchment (eg Taranaki) or both (eg the Canterbury Plains).

We have used existing nationwide modelling approaches to develop data on groundwater fluxes. We suggest that such a national approach can be used as a framework to include more regional and local data and we recommend such an approach in order to obtain seamless and consistent overviews of groundwater from the national to the local scale.

Inter-comparisons between models, both recharge and discharge, demonstrate that different models have different variables and definitions of fluxes (eg recharge/drainage, groundwater discharge and losing and gaining reaches). There is currently no robust coupled national model of surface water and groundwater in New Zealand. To further improve consistency of groundwater–surface water exchanges, we recommend continuing and extending inter-organisational model coupling approaches, such as the New Zealand Water Model.

For better inter-comparison of recharge, the net drainage component of TopNet should be delivered as two separate components, that is, recharge and groundwater discharge. Presenting both of these values would allow for evaluation of the simplified discrete parameters, for example, TopNet recharge vs. NGRM recharge and TopNet discharge vs. NGRM discharge. Comparison of inter-model evapotranspiration estimates are also recommended to increase insights in model differences.

Finally, this study showed long-term recharge trends at a nationwide scale; it is advised to have a more extensive study on long-term recharge trends that also looks at regional long-term trend analyses.

7.0 DISCLAIMER ON USE/LIMITATIONS

These data have been developed for the purpose of national-scale assessments. While all care and diligence has been used in processing, analysing and extracting data and information for this publication, the Ministry for the Environment, the Institute of Geological and Nuclear Sciences Ltd (GNS Science), Aqualinc Research Ltd (Aqualinc), and the National Institute of Water and Atmospheric Research (NIWA) give no warranty in relation to these data – including its accuracy, reliability and suitability – and accept no liability whatsoever in relation to any loss, damage or other costs relating to the use of any part of these data, or any compilations, derivative works or modifications of these data.

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APPENDICES

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APPENDIX 1 IRRICALC GENERAL MODEL DESCRIPTION

Irrigation water-use and drainage are 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 the irrigation water use component of the soil moisture balance 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 below. The result of applying the irrigation rule in conjunction 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.

Computer modelling of the soil moisture balance and the operation of irrigation systems 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.

A1.1 Summary of Key Assumptions

The key assumptions underlying Aqualinc's method for estimating irrigation water use and drainage 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 are used (discussed below)
- assumptions specific to the irrigation system model and irrigation management rules are used (discussed below).

A1.2 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 (AET).

$$S_{t_2} = S_{t_1} + R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - AET_{(t_2-t_1)} \qquad \text{Equation A1.1}$$

Where:

- S_{t_2} = Soil water content at time t_2
- S_{t_1} = Soil water content at time 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
- $AET_{(t_2-t_1)}$ = AET between time t_2 and t_1

And:

- $AET_{(t_2-t_1)}$ = $K_c \times f(S_{t_1}, a) \times ETref_{(t_2-t_1)}$
- K_c = Crop factor applicable over time t_1 to t_2
- $f(S_{t_1}, a)$ = Evapotranspiration reduction function (discussed below)
- $ETref$ = Evapotranspiration for a well-watered reference crop (discussed below)

The evapotranspiration reduction function is an empirical function that takes a value in the range zero to one, depending on the ratio of soil water content on day t_1 to the field capacity of the soil 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 (ET_{ref}) 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 can be input as time series measurements). 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.

A1.3 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 factors used in this project vary 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 (due to grazing or harvesting, for example). The crop factor time series for pasture has been derived from data from Canterbury Regional Council's lysimeter network. The crop factor time series for grapes has been developed from the results of research on sauvignon blanc vines in Marlborough.

A1.4 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 A1.1 shows the various combinations of irrigation system parameters that can be applied to replicate a wide range of irrigation systems and practices.

Table A1.1 Irrigation management options available in IrriCalc.

Application Depth	**When to Irrigate**			
	Never	**Every Return Period (in days)**	**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				✓

A1.4.1 Irrigation Applications

Irrigation applications are determined by the application of irrigation management rules or can be provided as an input time series of application depths (this latter option has not been used for this project).

The application depth 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 (discussed below), average application depth and uniformity is illustrated in Figure A1.1.

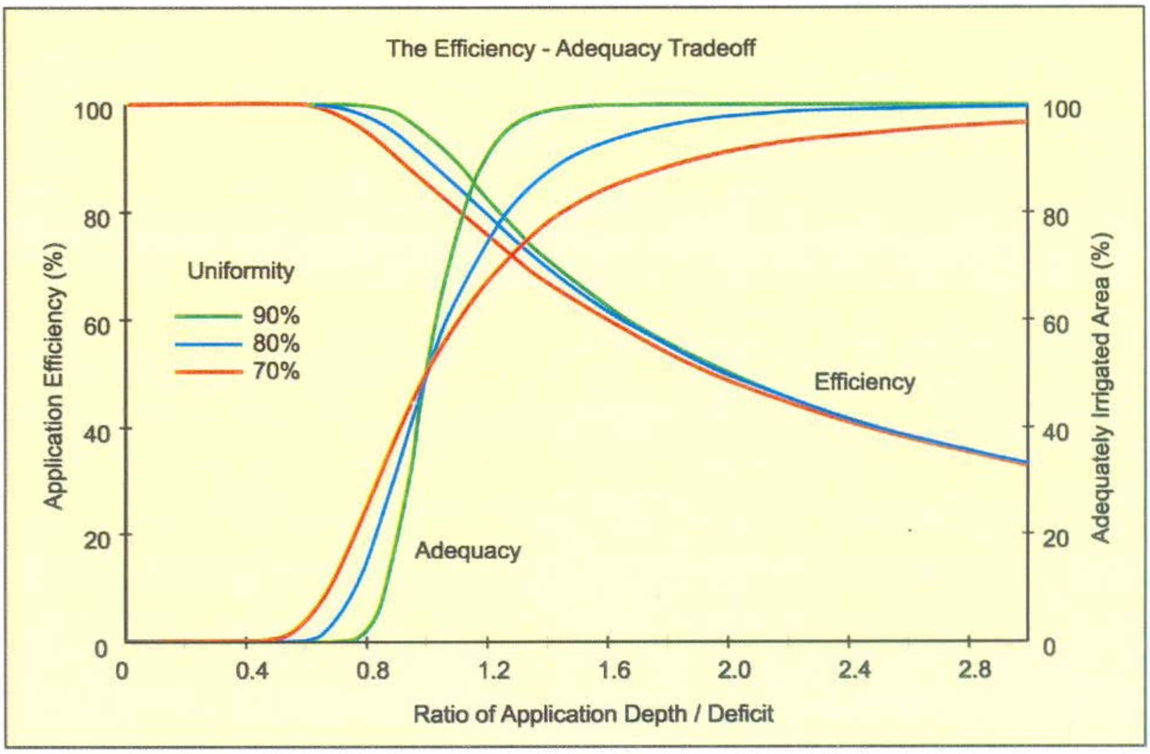

Figure A1.1 Relationship between application efficiency, application uniformity and application depth (Bright 1986).

For dryland (non-irrigated) areas the 'never irrigate' rule is used.

A1.4.2 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; it is a model output, not an input parameter.

A1.4.3 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:

Maximum Flow Rate =	(Application depth × 10,000) ÷ (Return period × 86,400) ℓ/s/ha
Where:	*Application depth* is in millimetres and *Return period* is in days

A1.4.4 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 a limited volume of water. The total volume of irrigation water used is reset to zero before the 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. This option has been used in this project to maintain consistency across all areas, as methods for setting water use limits vary across New Zealand and not all regions have implemented limits.

A1.5 Summary of Key Assumptions

- The soil is free-draining
- Crop canopy development is sufficiently consistent across years to enable the use of the same crop factor time series each year 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.

A1.6 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 from databases maintained by NIWA and Manaaki Whenua Landcare Research Ltd.

A1.6.1 Climate, Crop and Soils Data

- Daily time series for rainfall and potential evapotranspiration for the site of interest. These can be measured data, interpolation from measurements (eg NIWA’s Virtual Climate Station Network) or climate model outputs
- Crop factor time series (one representative year). For irrigated pasture, the crop factor time series is based on Van Housen (2015). Crop factors for grapes have been derived based on research on sauvignon blanc vines in Marlborough by Plant and Food Research. 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.

A1.6.2 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)
- 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 (if applicable)
- Beginning and end dates for the irrigation season.

A1.7 Model Calibration

A crop factor time series for irrigated pasture has been calibrated for use in Canterbury using data obtained from Canterbury Regional Council's (CRC) lysimeter network (Van Housen 2015). Figure A1.2 shows that the drainage modelled using this crop factor time series with IrriCalc matches closely with 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 across New Zealand are similar to the Methven site.

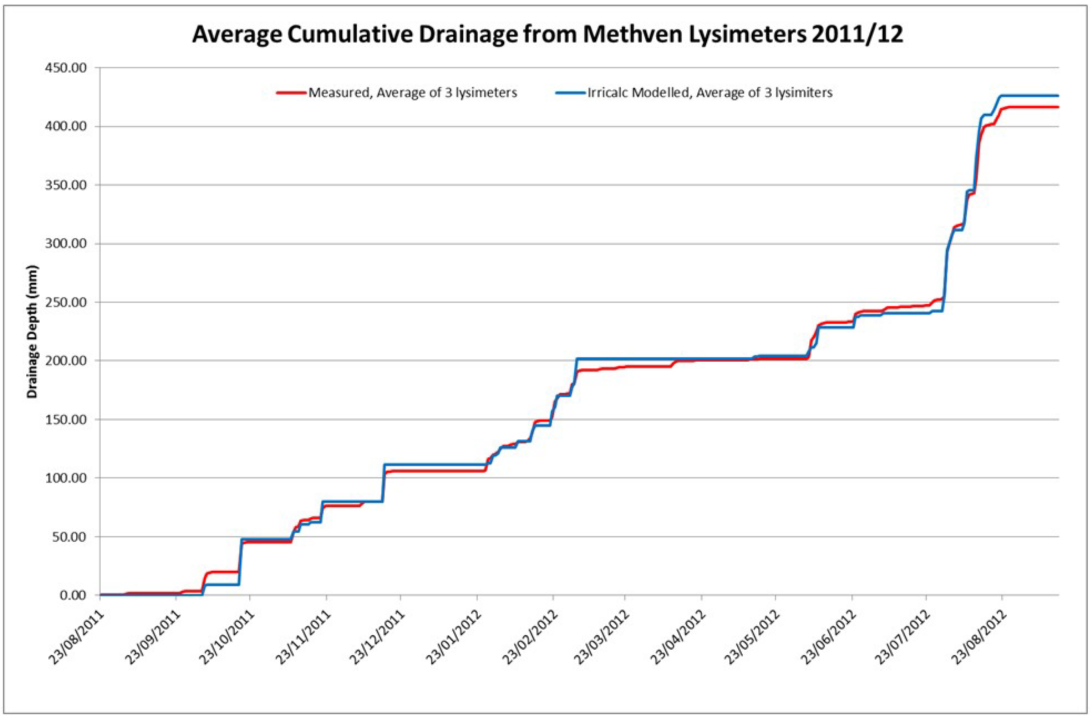

Figure A1.2 Comparison between measured and IrriCalc modelled drainage.

A1.8 References

Allen RG. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Rome (IT): Food and Agriculture Organization of the United Nations. 300 p. (FAO irrigation and drainage paper; 56).

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APPENDIX 2 IRRICALC DETAILED METHOD DESCRIPTION

A2.1 Introduction

Daily groundwater recharge was modelled for each Virtual Climate Station Network (VCSN) point in potentially irrigable areas, allowing for the soils, land use and irrigated area in a rectangular cell surrounding that point. Although the focus of the modelling was recharge rather than irrigation water use, it was important to also model irrigation as it influences the land-surface recharge in irrigated areas.

We have categorised land uses and irrigation systems broadly; it is not practical to represent all crops and irrigation types at a national scale.

A2.2 Methodology

Recharge was calculated using Aqualinc's soil moisture and irrigation simulation model, IrriCalc. The model was applied on a mesh basis in both irrigated and dryland (non-irrigated) areas. Model results for the dominant soil and land use combination for each mesh cell was assumed to represent recharge in that cell.

For dryland areas, IrriCalc was set to never irrigate, and therefore recharge resulted from rainfall alone. The total recharge in each mesh cell was calculated from the combination of irrigated (if applicable) and dryland model outputs, proportioned according to the mapped irrigated area in the cell.

The model inputs and assumptions used for this project are described below. A general description of the IrriCalc model, including key assumptions and data requirements, is included in Appendix 1.

A2.2.1 Climate Data Inputs

Daily rainfall and potential evapotranspiration data were supplied by NIWA from their VCSN. The time period covered by the data is January 1973–July 2018. Data were supplied in NetCDF format and extracted to csv. files (the format required for IrriCalc) for each relevant grid point using an R script.

A2.2.2 Model Mesh

A rectangular mesh was created, with a VCSN grid point at the centre of each mesh cell. The VCSN grid spacing is 0.05 degrees latitude and longitude, which is approximately 5 km, but varies from north to south. The area of the mesh cells therefore varies from 2,133 ha in the south of the South Island to 2,545 ha in the north of the North Island.

An example of the VCSN grid and the mesh, showing the lower North Island, is shown in Figure A2.1.

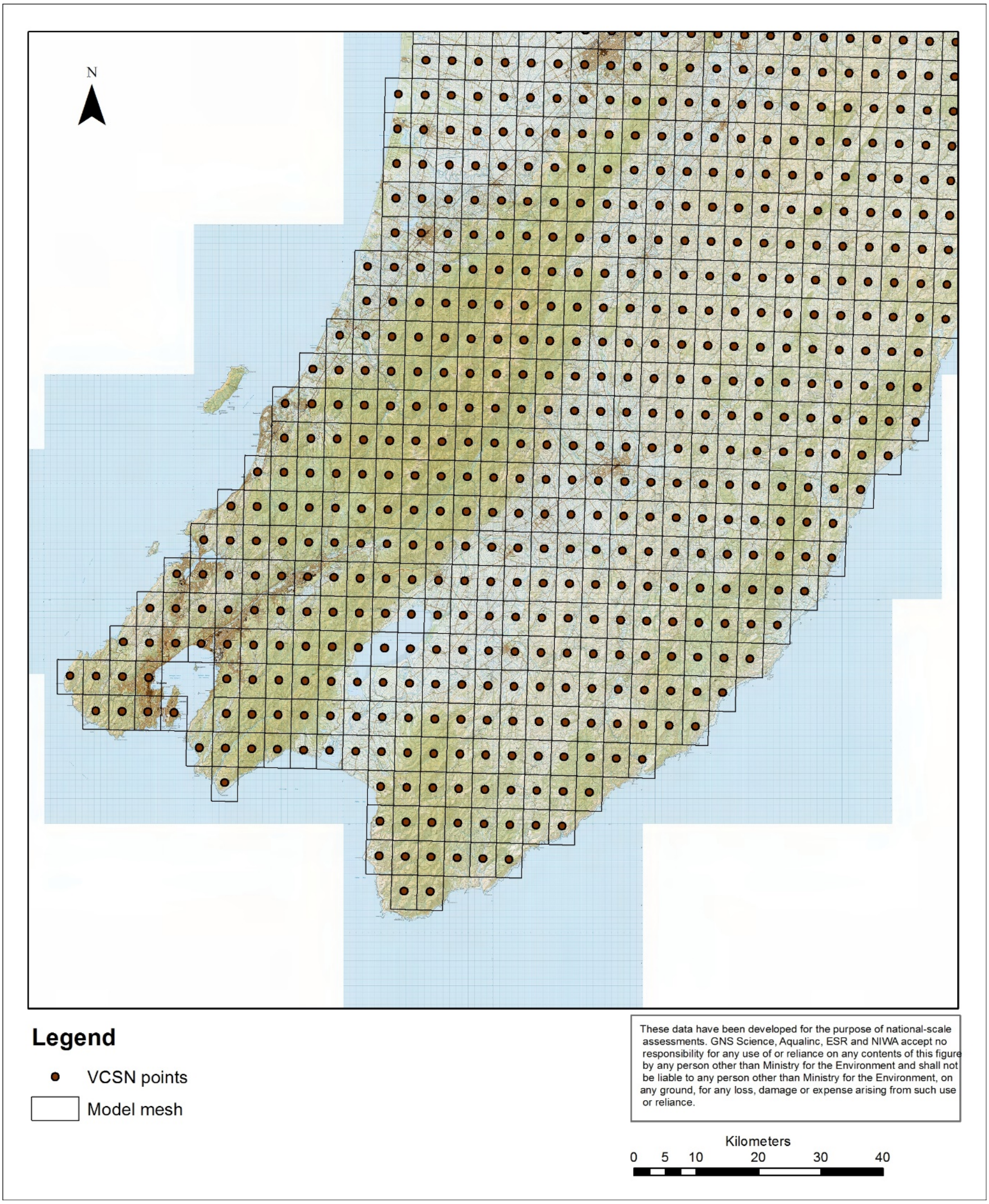

Figure A2.1 Example of VCSN grid points and model mesh, lower North Island.

A2.2.3 Potential Recharge Areas

Land slope was used as a proxy for areas where land-surface recharge to groundwater is likely to occur. Although aquifers were being mapped as part of the Groundwater Atlas project, the maps were not available at the time this work was completed.

These criteria used to identify recharge areas is similar to that used for identifying potentially irrigable land. Land slope data were obtained from the Land Resource Information System (LRIS).[7] All land with slopes up to 15° was identified. The categories less than this are:

- A = Flat to gently undulating 0–3°
- B = Undulating 4–7°
- C = Rolling 8–15°.

All areas with the primary code A and B were included, as well as all their secondary codes. Codes C, C+A and C+B were included, but any C code with a higher secondary code was excluded. These criteria are what are typically used for assessing potentially irrigable areas; we have assumed that they are also valid for assessing recharge areas.

If less than 10% of a cell's total area met the above criteria, the whole cell was excluded from the analysis.

Urban areas were excluded as IrriCalc is not relevant to impermeable surfaces.

Typically, high altitude and high rainfall areas would also be excluded if the analysis was solely for identifying irrigable areas. However, they have been included and modelled as dryland (non-irrigated) areas.

The cells in which IrriCalc was run are shown in Figure A2.2.

[7] https://lris.scinfo.org.nz/, Manaaki Whenua Landcare Research.

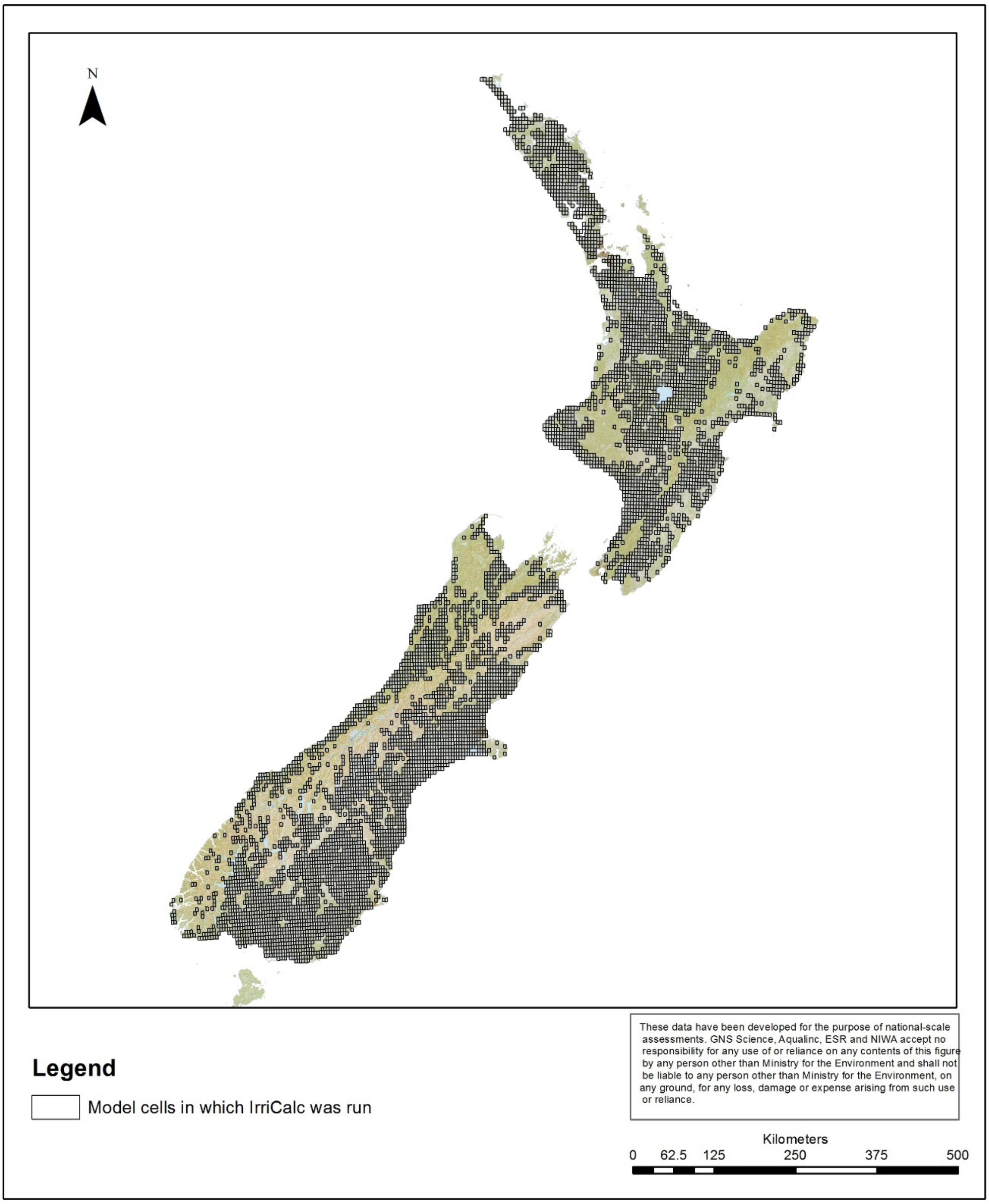

Figure A2.2 Potential recharge areas in which IrriCalc was run.

A2.2.4 Actual Irrigated Areas

Actual irrigated areas in each cell were calculated from the national irrigated area spatial data set. Although the irrigated area data set includes an irrigation system type attribute, the irrigation management rules represented in IrriCalc were assigned by land use (see below) rather than system type.

Soils were divided into profile available water (PAW) categories to model the various land use and soil combinations as follows:

- For 600 mm root depth (ie pasture and arable), PAW values less than 75 mm were modelled as 60 mm, values from 75–110 mm were modelled as 90 mm and everything else was modelled as 120 mm
- For 900 mm root depth (ie horticulture), PAW values less than 150 mm were modelled as 100 mm PAW; everything else was modelled as 200 mm PAW.

A2.2.5 Land Use

Land use was assessed from the Land Cover Database (LCDB) version 4.1[8].

For irrigated areas, land use was categorised as:

- Pasture
- Arable (cropping)
- Orchard
- Vineyard.

LCDB v4.1 does not distinguish between vineyards and orchards (although earlier versions did). It was assumed that areas mapped as ‘orchards, vineyard and other perennial crops’ in Canterbury, Otago, Marlborough and Wairarapa are vineyards and that elsewhere they are orchards.

Dryland areas were modelled as pasture.

A2.2.6 Soils Data

The soil’s PAW is an input to IrriCalc. Data from S-Map[9] was used where available; elsewhere, data from the Fundamental Soils Layer (FSL)[10] was used.

S-Map provides PAW values for 600 mm and 900 mm rooting depths. However, the FSL only provides a 900 mm value. The 900 mm PAW values from the FSL were converted to 600 mm for use in pasture and arable areas not covered by S-Map. For orchard and vineyard areas, the 900 mm values were used directly as these crops are deeper rooted.

A2.2.7 Irrigation Systems

It was assumed that water was always available for irrigation when required (ie supply is unrestricted). For most groundwater supplies this is the case. Surface water supplies are more often subject to supply restrictions based on river flows. However, we have assumed that (on average) the recharge from these areas will be closer to the fully irrigated case than the dryland case.

Irrigation rules were developed for each cell within which there was irrigated land. The rules were based on fully meeting irrigation demand at least 90% of the time and were intended to

[8] https://lris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/, Manaaki Whenua Landcare Research.

[9] https://smap.landcareresearch.co.nz/, Manaaki Whenua Landcare Research.

[10] https://soils.landcareresearch.co.nz/soil-data/fundamental-soil-layers/, Manaaki Whenua Landcare Research.

be broadly representative of the irrigation systems used for each land use (spray irrigation for pasture and arable crops and drip / micro-sprinkler for vineyards and orchards).

The IrriCalc model was run for both irrigated and dryland cases.

A2.3 Format of Results

Although historical climate data were used, the land use and irrigated areas were fixed at the present-day values, that is, the recharge estimates do not account for the history of land-use change and irrigation development.

For each modelled cell, daily time series of both irrigated and dryland drainage were modelled over the period 1973–2018. These raw outputs were then combined into a single time series of recharge for each cell, with irrigated and dryland values proportioned according to the proportion of mapped irrigated area in the cell. These time series represent the spatially-averaged recharge over the cell areas.

The following summary results were then calculated for each cell:

- Daily time series of spatially-averaged drainage (in m^3/ha) for each cell in which IrriCalc was run, from 2000–2015
- A table of annual statistics for each cell; mean, median and 10^{th}–90^{th} percentiles annual totals, based on the full 1973–2018 model run. Values are in millimetres
- An Esri shapefile of the annual statistics joined to the VCSN mesh.

The outputs were provided to GNS for comparison and presentation with outputs from other recharge estimation methods.

A2.4 Uncertainty and Limitations

As this is a national-scale study, the recharge estimates are not necessarily suitable for direct use in regional or catchment-scale models.

The accuracy of the mapped irrigated area is reduced in some areas, particularly where there is relatively low visual contrast between irrigated and non-irrigated land and where small parcels of land are being irrigated as a permitted activity (ie where there is no resource consent data to confirm that a property is irrigated).

Although the mapped irrigated area was categorised by irrigation system type, the irrigation regimes have been defined broadly for each land use.

LCDB 4 is the land cover for the 2012–2013 summer; some land-use change will have occurred since then. It also does not distinguish between vineyards and orchards. As discussed in Section A2.2.5, we have made assumptions about these land uses on a regional basis.

A2.5 Recommendations

The following are concepts for ongoing development of this work to improve its usefulness and accessibility:

- Set up IrriCalc to run automatically (eg monthly or seasonally) to update the recharge estimates. Ongoing access to the VCSN climate data is currently a barrier to doing this efficiently
- Refine recharge estimates by running a larger number of soil and land use combinations, rather than selecting the dominant combination in each cell. Smaller cell sizes could also be targeted to capture greater spatial variability in the soils and land-use data for improved applicability to catchment-scale assessments
- Host outputs on a database sever that can be accessed by practitioners and water managers.

APPENDIX 3 TOPNET MODEL DESCRIPTION

A3.1 TopNet

The catchment hydrological model used in this study is NIWA's TopNet model (Clark et al 2008), which is routinely used for surface water hydrological modelling applications in New Zealand. It is a spatially, semi-distributed, time-stepping model of water balance. It is driven by time series of precipitation and temperature, and additional weather elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time series of modelled river flow (without consideration of water abstraction, impoundments or discharges) throughout the modelled river network, as well as evapotranspiration (derived from weather/climate input information) but does not adjust river flows for effects of irrigation. TopNet has two major components, namely a basin module and a flow routing module. The structure of the basin model is presented in Figures A3.1 and A3.2.

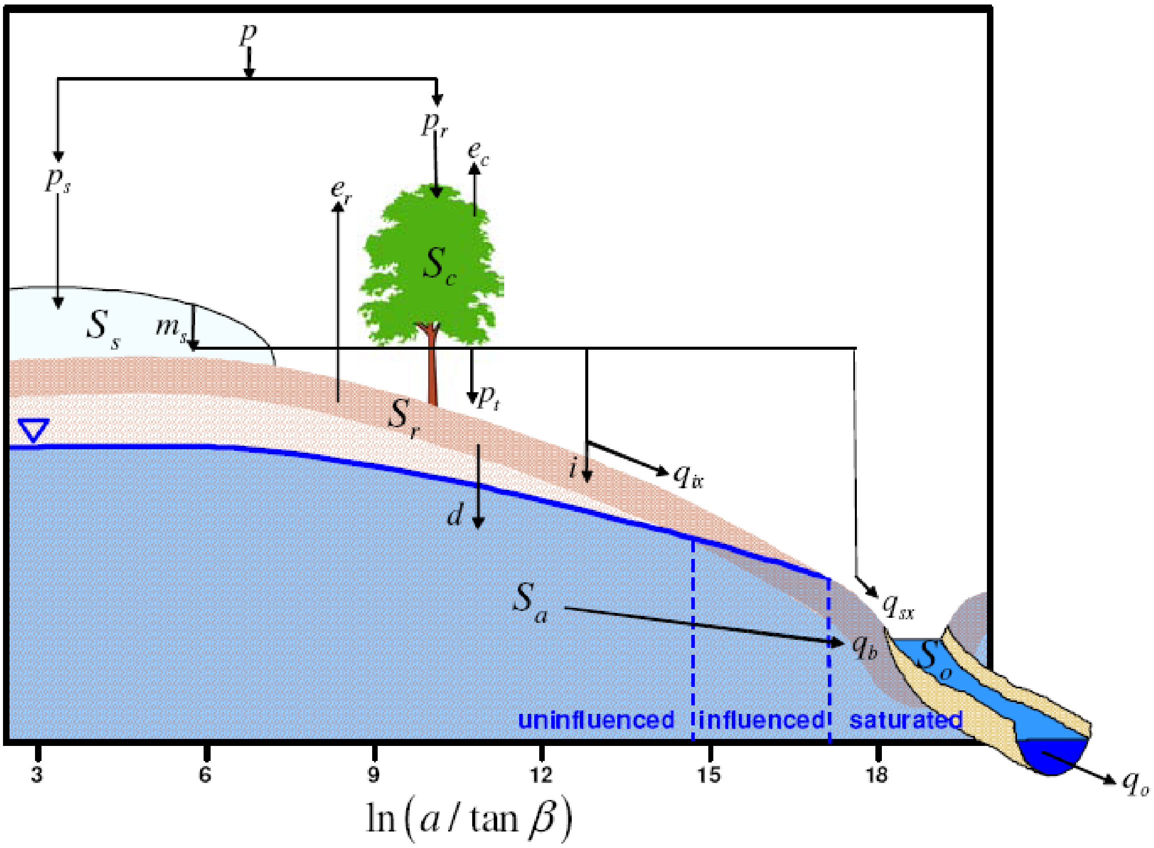

Figure A3.1 TopNet model structure within each sub-basin, showing modelled water fluxes and storages.

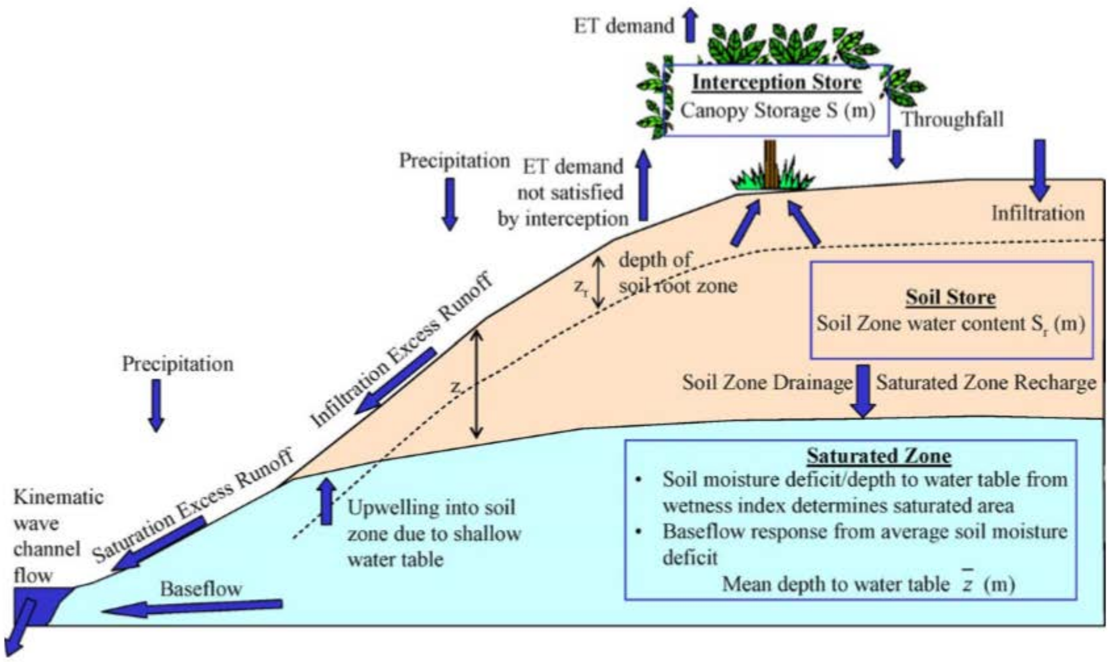

Figure A3.2 Schematic of the physical processes represented by the TopNet modelling system (Bandaragoda et al 2004).

The model combines TOPMODEL hydrological model concepts (Beven et al 1995) with a kinematic wave channel routing algorithm (Goring 1994) and a simple temperature based empirical snow model (Clark et al 2008). As a result, TopNet can be applied across a range of temporal and spatial scales over large watersheds using smaller sub-basins as model elements (Ibbitt and Woods 2002; Bandaragoda et al 2004). Considerable effort has been made during the development of TopNet to ensure that the model has a strong physical basis and that the dominant rainfall run-off dynamics are adequately represented in the model. TopNet model equations and information requirements are provided by Clark et al (2008) and McMillan et al (2013). The version of the model used in this project does not consider water transfers from river to river or water storage, nor does it model aquifer water balances.

A3.2 Spatial Information

For the development of the national version of TopNet used in this study, spatial information in TopNet was provided by national data sets as follows:

- Catchment topography based on a nationally available 30 m digital elevation model
- Physiographical data based on the Land Cover Database version 2 and Land Resource Inventory (Newsome et al 2000)
- Soil data based on the Fundamental Soil Layer information (Newsome et al 2000)
- Hydrological properties based on the River Environment Classification version 1 (REC2) (Snelder and Biggs 2002).

The method for deriving TopNet's parameters based on GIS data sources in New Zealand is given in Table 1 of Clark et al (2008). Due to the paucity of some spatial information at national and regional scales, some soil parameters are set uniformly across New Zealand.

TopNet is currently configured to use LCDB 3 (Newsome et al 2000), reflecting 2008 land cover, rather than the latest version, version 4, which corresponds to 2011. There will be differences in land use between the two, and these may have hydrological consequences, although they are likely to be small in comparison with other uncertainties. During the course of the simulations from 1972–2018, land use is kept constant.

A3.3 Climate Information

Climate information used in this project, that is, precipitation, temperature, relative humidity (rh), solar radiation (srad), mean sea-level pressure (mslp) and wind speed, is available through NIWA's Virtual Climate Station Network (VCSN) (Tait et al 2006). The VCSN network represents daily interpolated climate information over a regular 0.05 degrees latitude/longitude grid interpolated over nearly 500 climate stations across New Zealand with an ANUSPLIN spline since 1972. Note that a precipitation station will be included in the VCSN record only if the station is included in NIWA's climate database.

A3.4 National TopNet Assumptions

In this project, hydrological simulations are based on the REC2 network aggregated up to Strahler[11] catchment order three (approximate average catchment area of 7 km^2) used within previous national and regional scale assessments; residual coastal catchments of smaller stream orders that are not subsumed into larger catchments remain included. The simulation results comprise hourly time series of various hydrological variables for each computational sub-catchment. TopNet recharge calculations were provided to GNS as a NetCDF grid and csv. files, with concatenated monthly time step.

Because of TopNet assumptions, soil and land use characteristics within each computational sub-catchment are homogenised. Essentially, this means that the soil characteristics and physical properties of different land uses, such as pasture and forest, will be spatially averaged and the hydrological model outputs will be an approximation of conditions across land uses.

To carry out the simulations required for this study, TopNet was run continuously from 1971 to 2018, with the spin-up year 1971 excluded from the analysis. Climate inputs were stochastically disaggregated from daily to hourly time steps.

A3.5 Recharge Calculations

TopNet provides sub-catchment net drainage to the groundwater at each time step. It is an areal combination of the recharge from the uninfluenced zone (see Figure A3.1) and the influence and saturated upwelling into the soil zone (Figure A3.2). Formulation of the drainage can be found in Bandaragoda et al 2004 and Clark et al 2008.

[11] Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order one, second order streams develop at the confluence of two first order tributaries and stream order increases by one where two tributaries of the same order converge.

A3.6 References

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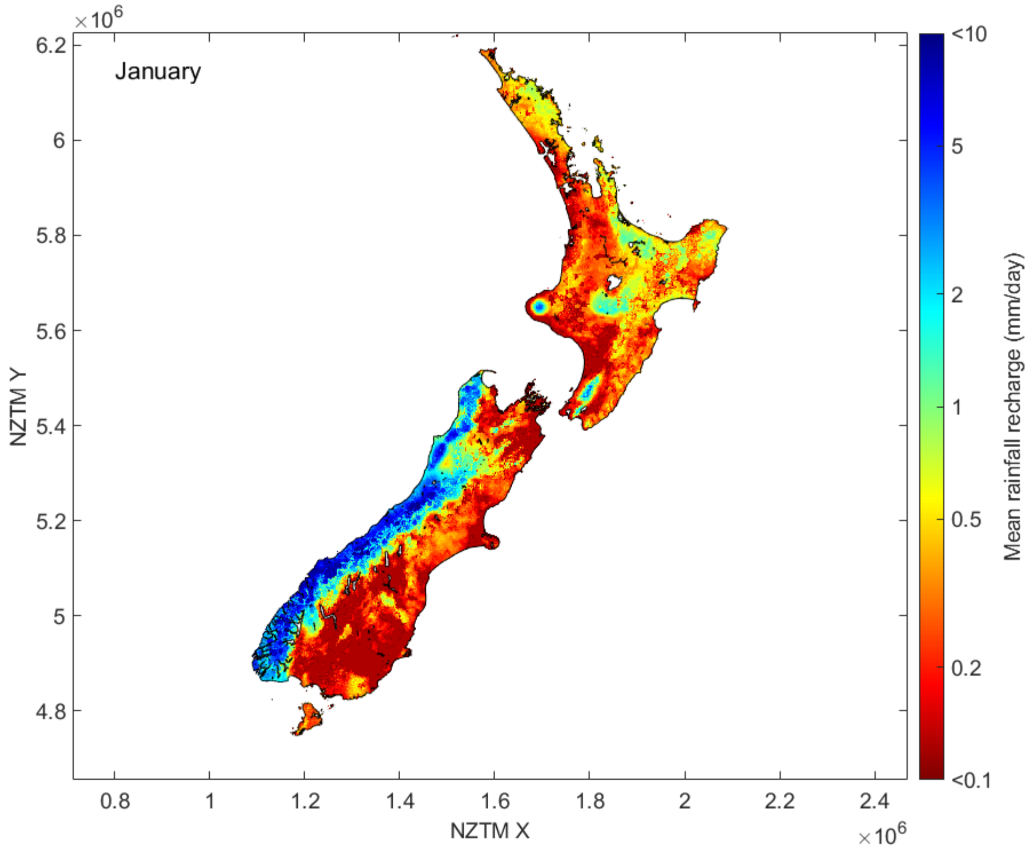
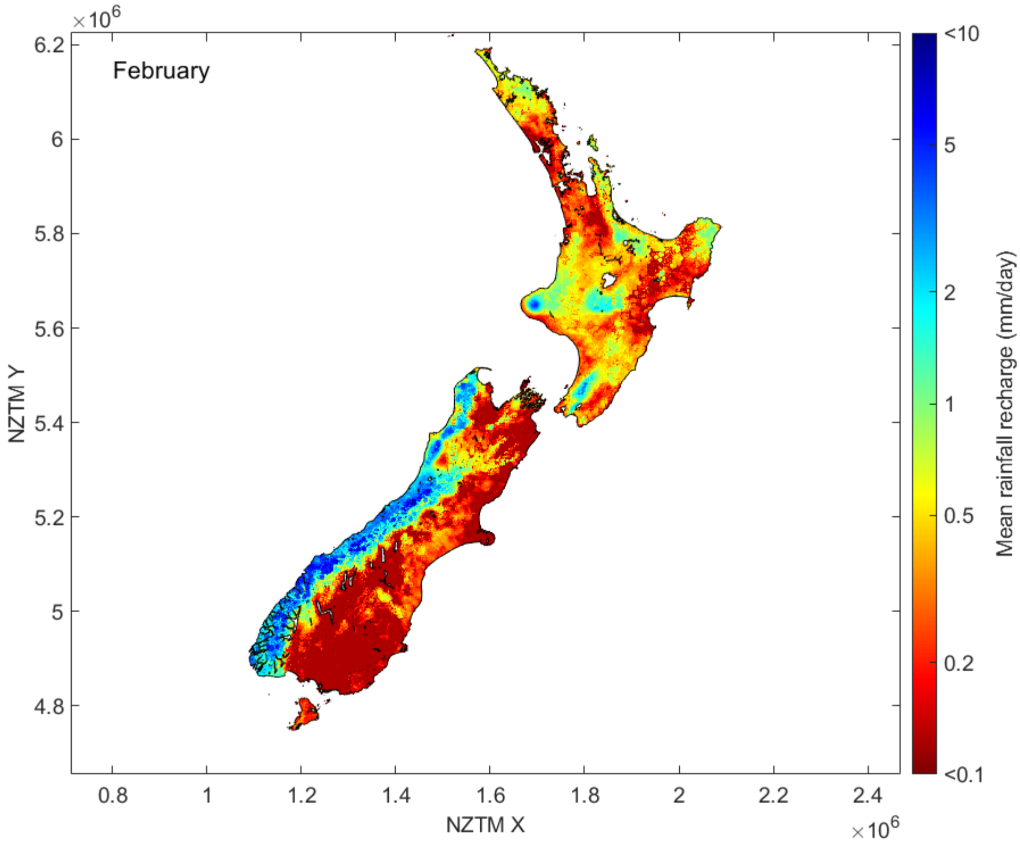
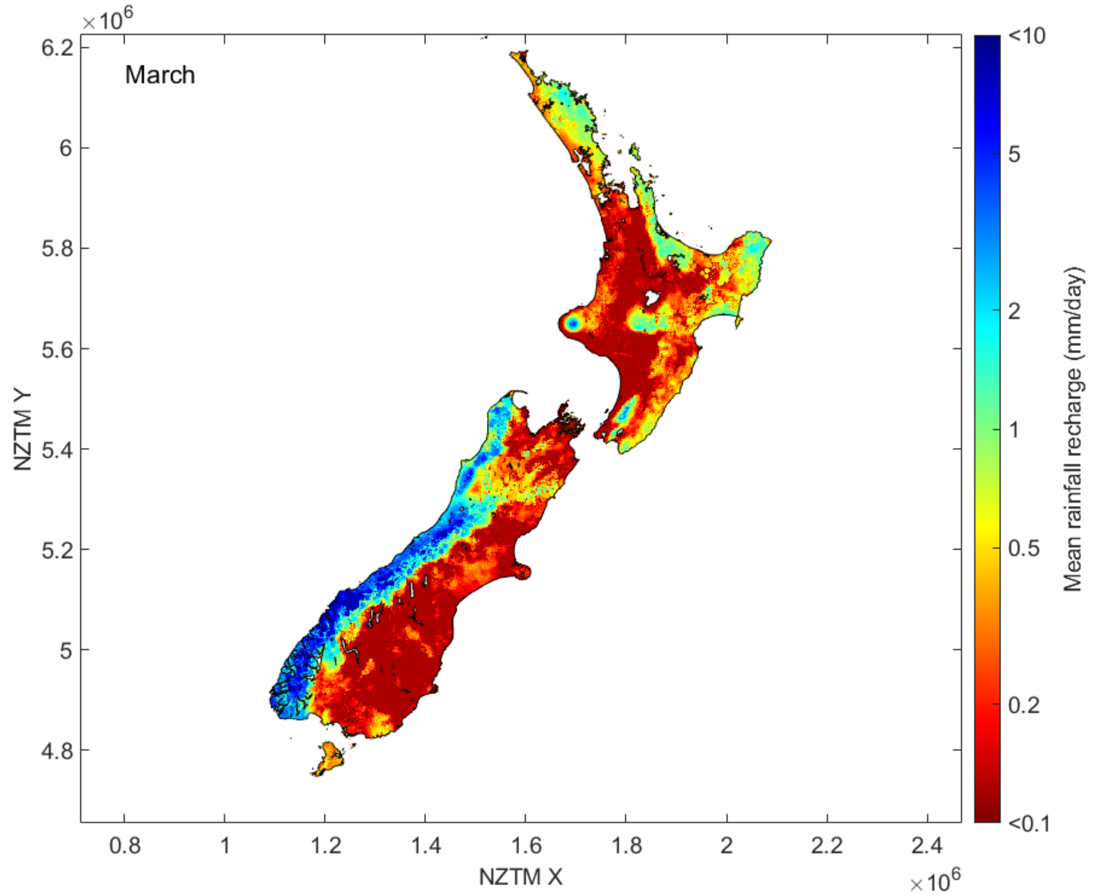
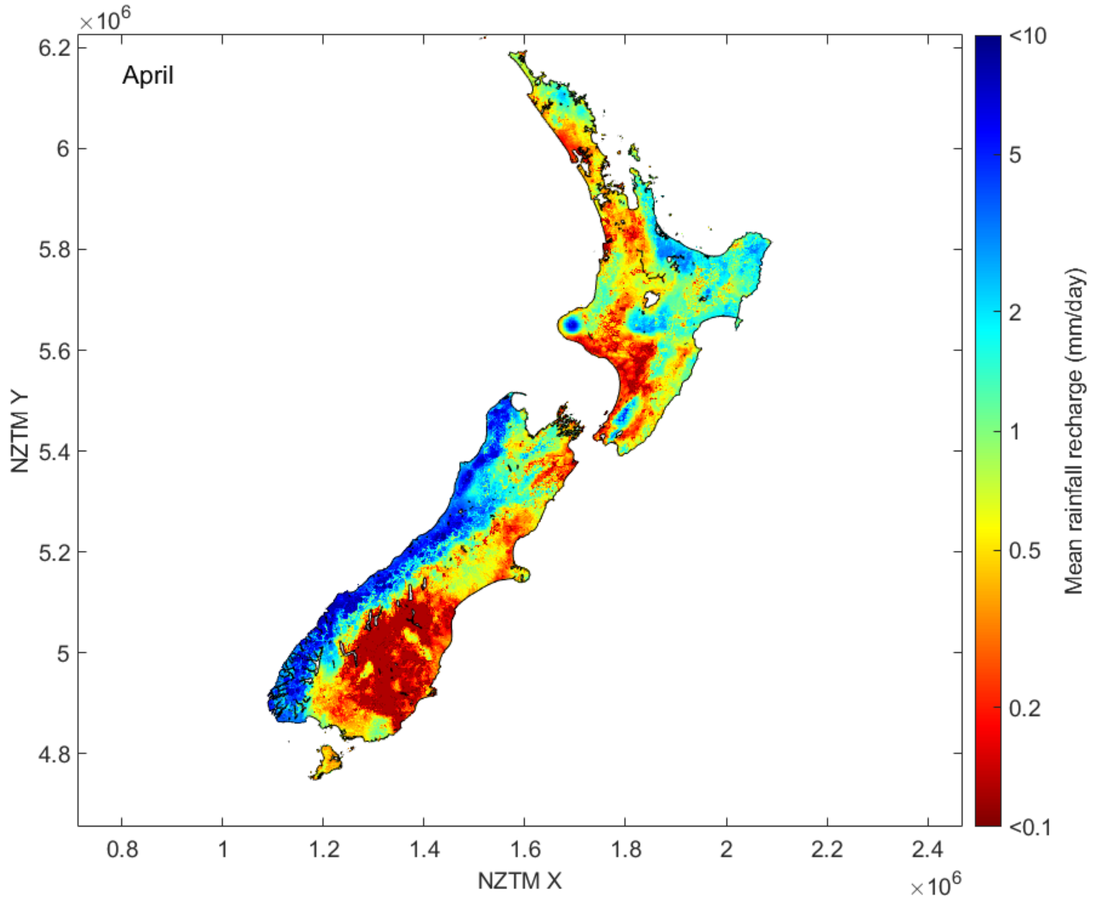
APPENDIX 4 MONTHLY PLOTS OF MODELLED MEAN RECHARGE

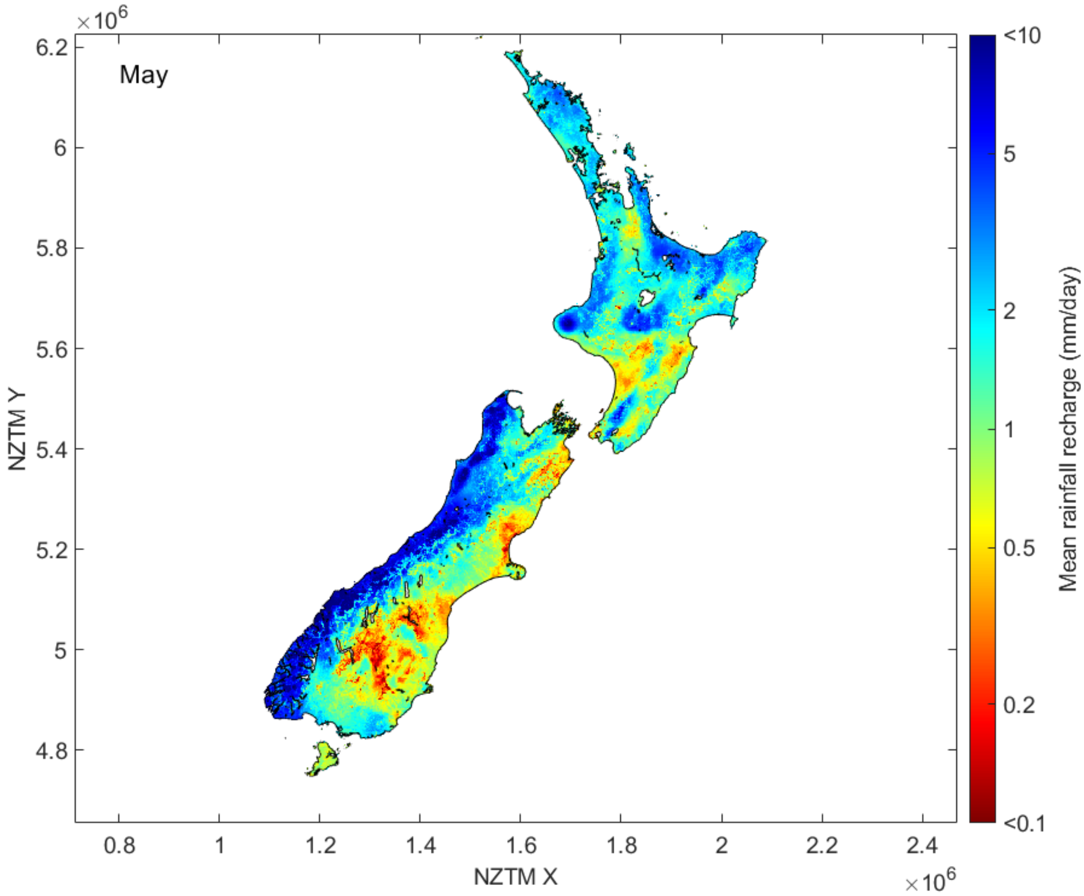
Twelve plots of mean monthly recharge, as described in Section 4.1.

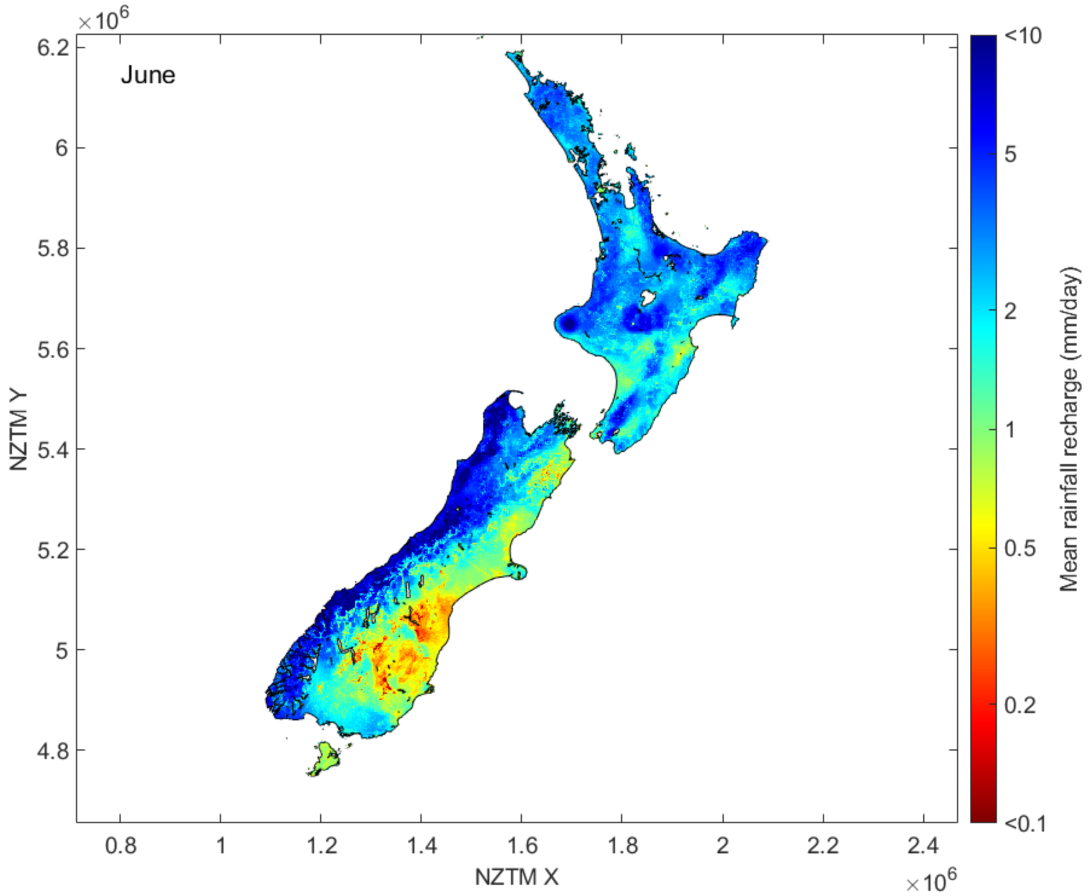


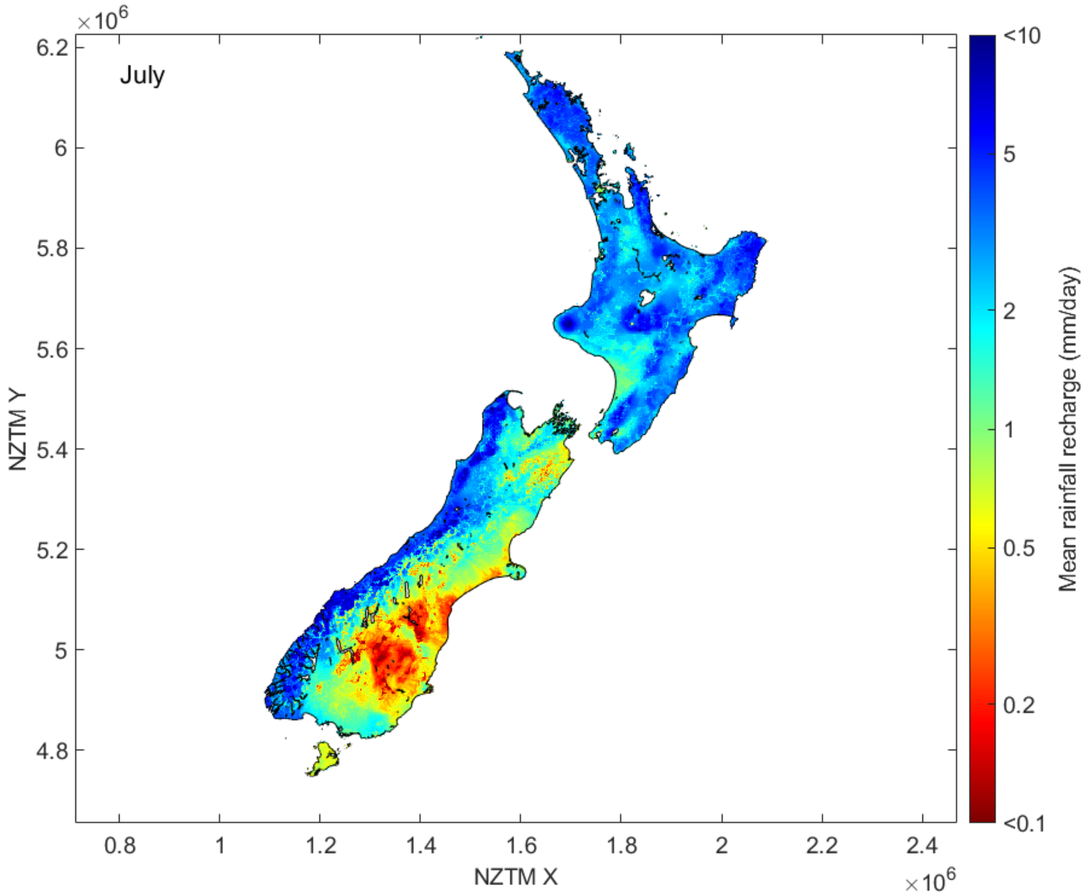


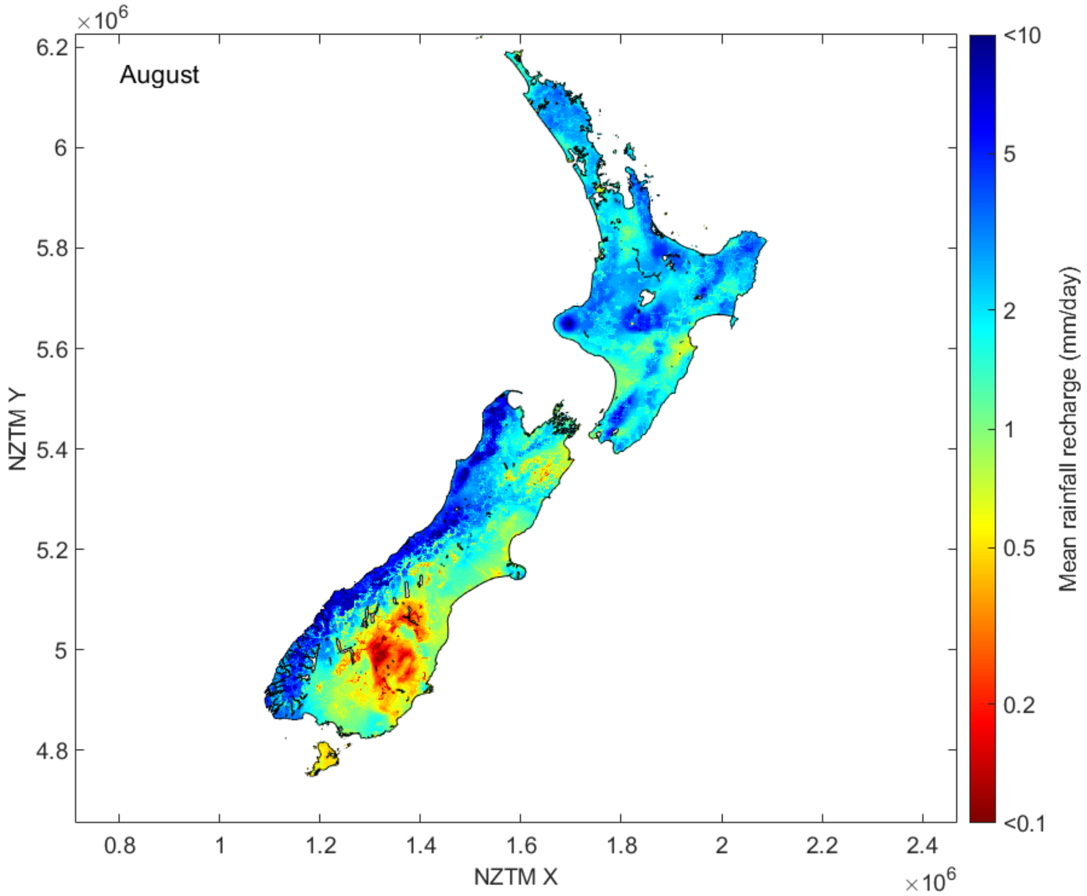

March
×10^6
6.2
6
5.8
5.6
5.4
5.2
5
4.8
NZTM Y
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
NZTM X
×10^6
<10
5
2
1
0.5
0.2
<0.1
Mean rainfall recharge (mm/day)

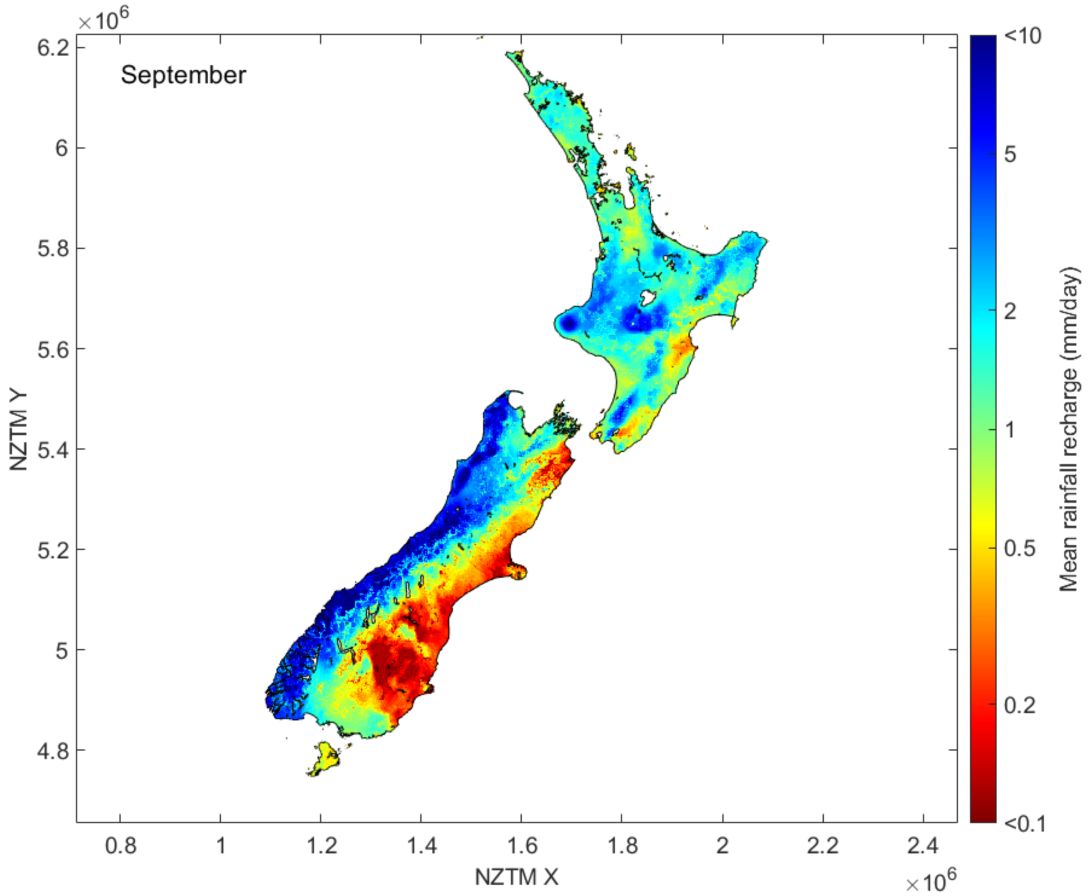

April
×10^6
6.2
6
5.8
5.6
5.4
5.2
5
4.8
NZTM Y
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
NZTM X
×10^6
<10
5
2
1
0.5
0.2
<0.1
Mean rainfall recharge (mm/day)

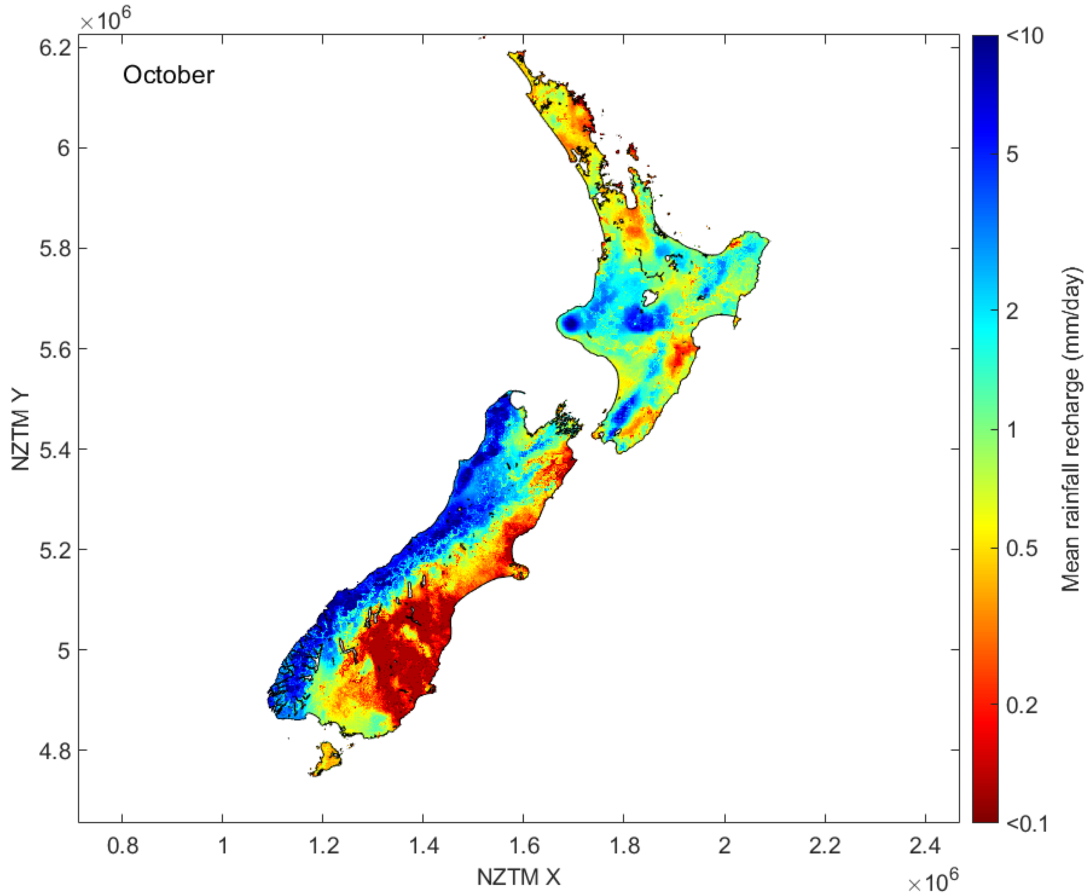

May
NZTM Y
NZTM X
Mean rainfall recharge (mm/day)
<10
5
2
1
0.5
0.2
<0.1

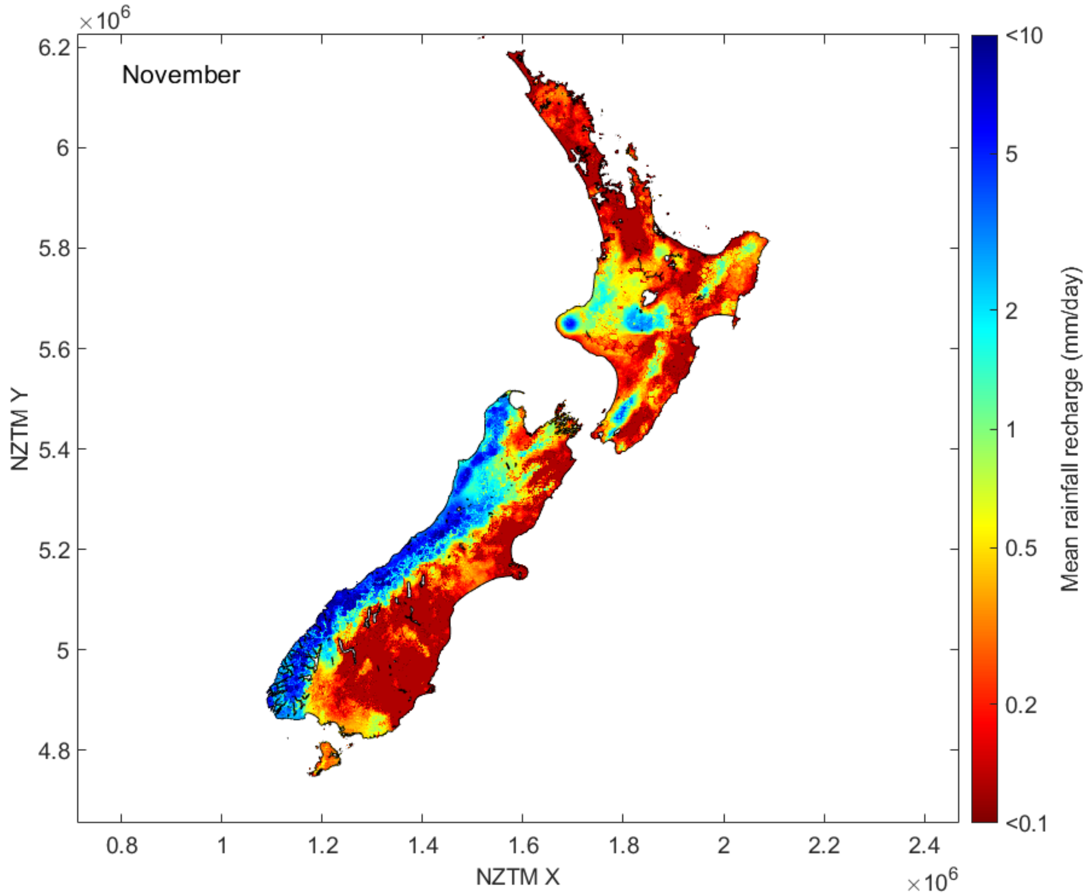

June
NZTM Y
NZTM X
Mean rainfall recharge (mm/day)
<10
5
2
1
0.5
0.2
<0.1

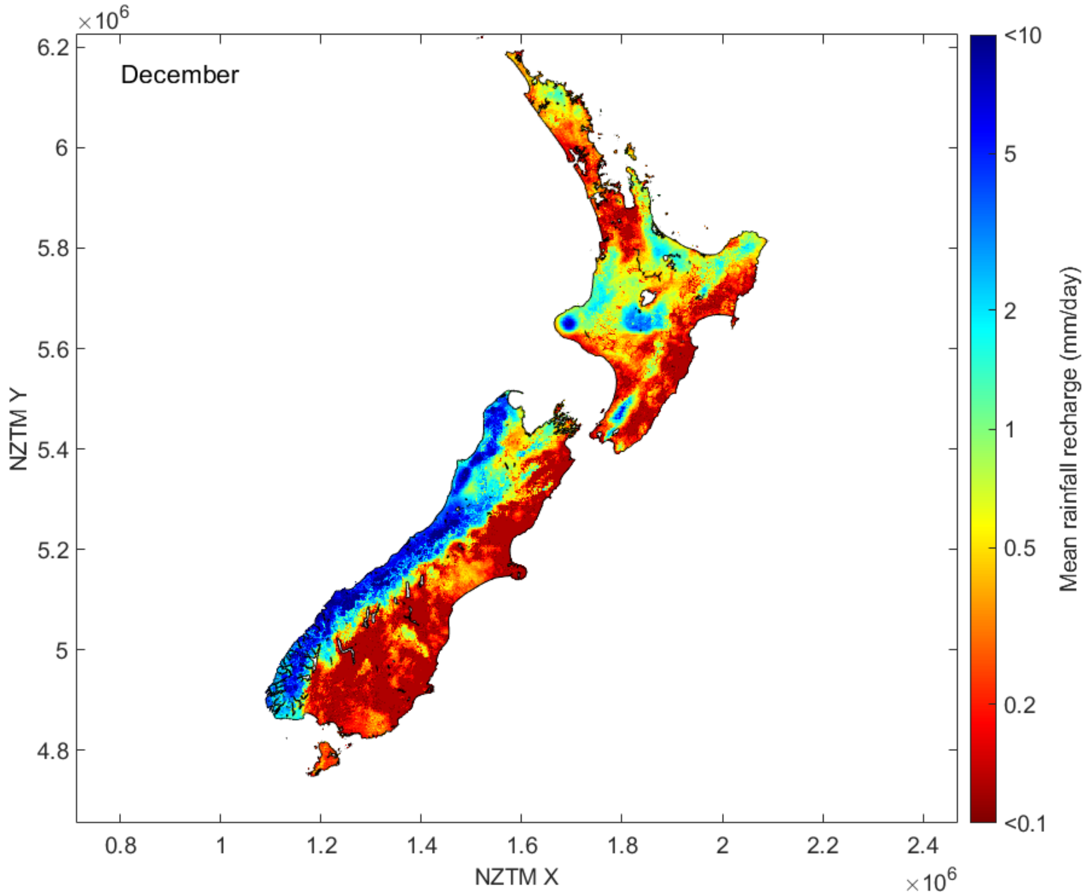

×10^6
6.2
6
5.8
5.6
5.4
5.2
5
4.8
NZTM Y
July
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
NZTM X
×10^6
<10
5
2
1
0.5
0.2
<0.1
Mean rainfall recharge (mm/day)


×10^6
6.2
6
5.8
5.6
5.4
5.2
5
4.8
NZTM Y
August
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
NZTM X
×10^6
<10
5
2
1
0.5
0.2
<0.1
Mean rainfall recharge (mm/day)


September
NZTM Y
NZTM X
Mean rainfall recharge (mm/day)
<10
5
2
1
0.5
0.2
<0.1


October
NZTM Y
NZTM X
Mean rainfall recharge (mm/day)
<10
5
2
1
0.5
0.2
<0.1


November
NZTM Y
NZTM X
$\times 10^6$
6.2
6
5.8
5.6
5.4
5.2
5
4.8
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
<10
5
2
1
0.5
0.2
<0.1
Mean rainfall recharge (mm/day)


December
NZTM Y
NZTM X
$\times 10^6$
6.2
6
5.8
5.6
5.4
5.2
5
4.8
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
<10
5
2
1
0.5
0.2
<0.1
Mean rainfall recharge (mm/day)

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