



Aupōuri Peninsula Rainfall-Recharge Modelling

RS Westerhoff

MW Taves

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CONTENTS

PURPOSE	iii
EXECUTIVE SUMMARY.....	iii
1.0 Introduction.....	1
1.1 Background	1
1.2 Objective	1
2.0 Data and Methodology.....	3
2.1 Input Data.....	3
2.1.1 Rainfall from the Virtual Climate Station Network.....	3
2.1.2 Radar Rainfall	3
2.1.3 Evapotranspiration from PML_v2 Algorithm	4
2.1.4 Evapotranspiration from MOD16 Algorithm	4
2.1.5 Evapotranspiration from ETMonitor Algorithm	4
2.2 Validation Data	5
2.2.1 Evapotranspiration Validation Points	5
2.2.2 Rainfall Validation Points.....	6
2.3 Comparisons between Different Rainfall and Evapotranspiration Datasets	6
2.4 Rainfall-Recharge Model	7
2.4.1 Definition of Rainfall Recharge.....	7
2.4.2 The National Groundwater Recharge Model v1.0	7
2.4.3 Changes Made in National Groundwater Recharge Model v2.0	8
2.4.4 Recharge Model Revisions Made in this Report.....	8
3.0 Results.....	10
3.1 Comparison of Rainfall Datasets	10
3.2 Comparison of Evapotranspiration Datasets	15
3.3 Rainfall-Recharge Models.....	20
4.0 Conclusions	23
5.0 Recommendations.....	24
6.0 Acknowledgements.....	25
7.0 References	25

FIGURES

Figure 1.1	Topographic map of the Aupōuri peninsula and Aqua Intel Aotearoa study area.	2
Figure 2.1	Comparison points for evapotranspiration models.....	5
Figure 2.2	Drivers of precipitation (i.e. rainfall) and evapotranspiration as used in the design of the multi-input recharge-model runs in this study.....	9
Figure 3.1	Comparison between Virtual Climate Station Network and radar mean rainfall for 2015–2023.	10
Figure 3.2	Annual compiled rainfall in the Aupōuri study area for Virtual Climate Station Network and rainfall radar	11
Figure 3.3	Annual rainfall averages at Aupōuri station.	12
Figure 3.4	Annual rainfall averages at Awanui station.	13

Figure 3.5	Annual rainfall averages at Waihopo at Kimberley Road station	14
Figure 3.6	Annual averages of the three satellite-derived evapotranspiration datasets for Aupōuri.	15
Figure 3.7	Spatial comparison of the three satellite-derived evapotranspiration datasets for the year 2019.	16
Figure 3.8	2001–2023 annual averages at the comparison point ‘North’ for the three satellite-derived evapotranspiration datasets.	17
Figure 3.9	200–2023 time-series at the comparison point ‘North’ for the three satellite-derived evapotranspiration datasets.	17
Figure 3.10	2001–2023 annual averages at the comparison point ‘Middle’ for the three satellite-derived evapotranspiration datasets.	18
Figure 3.11	2001–2023 time-series at the comparison point ‘Middle’ for the three satellite-derived evapotranspiration datasets.	18
Figure 3.12	2001–2023 annual averages at the comparison point ‘South’ for the three satellite-derived evapotranspiration datasets.	19
Figure 3.13	2001–2023 time series at the comparison point ‘South’ for the three satellite-derived evapotranspiration datasets.	19
Figure 3.14	Multi-model mean recharge (weighted) for the case-study area for the period 2001–2023.	21
Figure 3.15	Multi-model spread, as one standard deviation, for the period 2001–2023.	21
Figure 3.16	Line chart of recharge per model combination, including the weighted model mean.	22
Figure 3.17	Comparison of six instances of the rainfall-recharge models in the period 2015–2021.	22

TABLES

Table 2.1	Input datasets of rainfall and evapotranspiration as used in this study.	3
Table 2.2	Climate rainfall stations used for validation in this study.	6
Table 3.1	Kling-Gupta Efficiency goodness of fit scores between all used rainfall datasets in this study, based on monthly means of data between 2015 and 2021.	11
Table 3.2	Recharge compilations for multi-model mean and each model input combination.	20

APPENDICES

APPENDIX 1	Kling-Gupta Efficiency Score	29
APPENDIX 2	Satellite Maps of Case-Study Data	30

PURPOSE

This report describes the results from rainfall-recharge modelling in the Aupōuri Peninsula, Northland. Rainfall recharge is a critical input for groundwater modelling, which is taking place at and after the time of writing of this report, within the Aqua Intel Aotearoa (AIA) programme. Model results have been made available to Northland Regional Council and AIA. The model code can be made available to the client.

EXECUTIVE SUMMARY

The Aqua Intel Aotearoa programme collected airborne electromagnetic (AEM) data over the Aupōuri Peninsula in late 2022 to investigate groundwater characterisation. These AEM data will be used in the development of a numerical groundwater-flow model. The groundwater model will require a fit-for-purpose rainfall-recharge model in order to simulate net groundwater recharge to the system.

Rainfall recharge is a critical input for groundwater modelling. Northland Regional Council is seeking an updated rainfall-recharge model that considers the recent high-resolution datasets now available, the adequate representation of high-intensity event-driven rainfall recharge and the adequate representation of forestry cycles and wetland changes on rainfall recharge, as well as suitable climate-change simulations.

This study developed a rainfall-recharge model that best represents the dynamics of land-use change at appropriate resolution; at the best available accuracy; and with estimates of uncertainty that can be used in a numerical groundwater model and other future work, such as climate-change scenarios.

A rainfall-recharge model was applied to the study area of the Aupōuri Peninsula. The model uses existing and new sources of climate data at a daily time-step in the study area. In particular, the addition of new input datasets of rainfall to the model was tested, and three satellite datasets of evapotranspiration, which represent dynamic changes of land cover, were analysed and applied to the recharge model.

Comparisons of rainfall (radar rainfall and Virtual Climate Station Network [VCSN] rainfall) revealed that radar rainfall indicates a higher amount of rainfall than estimated by the previously used VCSN data. Radar rainfall has a better goodness of fit with climate-station data than VCSN data; however, this type of data is only available from 2014 onward and, due to inconsistencies in the data still needing to be fixed, is not yet considered operational.

Comparisons between three satellite evapotranspiration products (ETMonitor, MOD16 and PML_v2) indicated that all three products have their own characteristics. For example, ETMonitor data are particularly sensitive to changes in land cover, while MOD16 and PML_v2 appear more driven by the (atmospheric) climate.

A ‘multi-model approach’, i.e. running the model with all six combinations of rainfall and evapotranspiration data, was taken to calculate recharge for the period 2001–2023. This was based on the availability of multiple rainfall datasets and the fact that no single evapotranspiration product could be ruled out, i.e. these appear to each have their own strengths, and there is no ground observation available to further validate these evapotranspiration products.

The weighted multi-model mean for the period of January 2001 – December 2023 for the study area is 332 mm/yr. Uncertainty is larger than previously reported, which reflects the variation of the input data of rainfall and evapotranspiration. Recommendations are provided to further advance this rainfall-recharge model.

These rainfall-recharge data will be used in further numerical groundwater modelling of the study area.

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1.0 Introduction

1.1 Background

The Aqua Intel Aotearoa programme collected airborne electromagnetic (AEM) data over the Aupōuri Peninsula (the study area; Figure 1.1) in late 2022 to investigate groundwater characterisation. Aqua Intel Aotearoa has recently been in discussion with programme collaborators Northland Regional Council and the Te Hiku Project team on scoping the subsequent numerical groundwater modelling stage of work, which will utilise these data.

Although the Aqua Intel Aotearoa programme is funding the numerical groundwater-modelling task, the programme does not have funding to develop a new rainfall-recharge model. While a number of rainfall-recharge models have previously been developed in the Aupōuri Peninsula, these rainfall-recharge models do not consider the datasets that are now available.

We define rainfall recharge as the amount of rainfall that drains through the soil layer, making it available for groundwater recharge. This term is often also referred to as ‘land surface recharge’, ‘gross recharge’ or ‘potential recharge’ and usually represents the upper limit of recharge assuming no losses after infiltration.

Previous estimates for rainfall recharge in Northland, for parts of the Aupōuri Peninsula, have been developed by, for example, Northland Regional Council (1991), SKM (2007), Wilson and Shokri (2015) and WWA (2017). The National Groundwater Recharge Model (NGRM; Westerhoff et al. 2018) encompasses the study area at 1 x 1 km resolution and a monthly time-step.

As rainfall recharge is a critical input for groundwater modelling, Northland Regional Council is seeking an updated rainfall-recharge model that considers the recent high-resolution datasets now available, the adequate representation of high-intensity event-driven rainfall recharge, and the adequate representation of forestry cycles and wetland changes on rainfall recharge, as well as suitable climate-change simulations. More specifically:

- Multiple types of satellite data are now available that could potentially be used in rainfall-recharge models. The NGRM is the only recharge model in New Zealand that has used satellite data, i.e. of land cover and evapotranspiration. However, since its development, new and potentially better satellite data have been made available. These data represent the dynamic land-use changes that are of concern to Northland Regional Council, i.e. forestry cycles and wetland changes.
- High-intensity events of rainfall can be captured by rainfall radar, previously tested by Sutherland-Stacey et al. (2020) for Northland. These data have never been used in New Zealand recharge models.
- In order to capture the above processes, a model of rainfall recharge is needed that captures dynamic processes and runs at, at minimum, the daily time-step.
- It would be beneficial to establish the model code in such a way as to facilitate future climate-change simulations using the modelling approach.

1.2 Objective

The main objective of this study is to develop a model of rainfall recharge that is considered defensibly robust and fit-for-purpose for informing decision-making being undertaken using a numerical groundwater-flow model for the whole of the study area. ‘Fit-for-purpose’ is here defined as the rainfall-recharge model being able to:

- represent the dynamics of land-use change at appropriate resolution.
- estimate model outputs at the best available accuracy, driven by the quality of the available input data.

- generate an estimate of uncertainty of model outputs that can be utilised by a groundwater model.
- be used for other future work, for example, development of climate-change scenarios.

The implementation of new rainfall and evapotranspiration datasets for rainfall-recharge estimation is part of this objective. This implementation is accompanied by comparisons with previously used datasets.

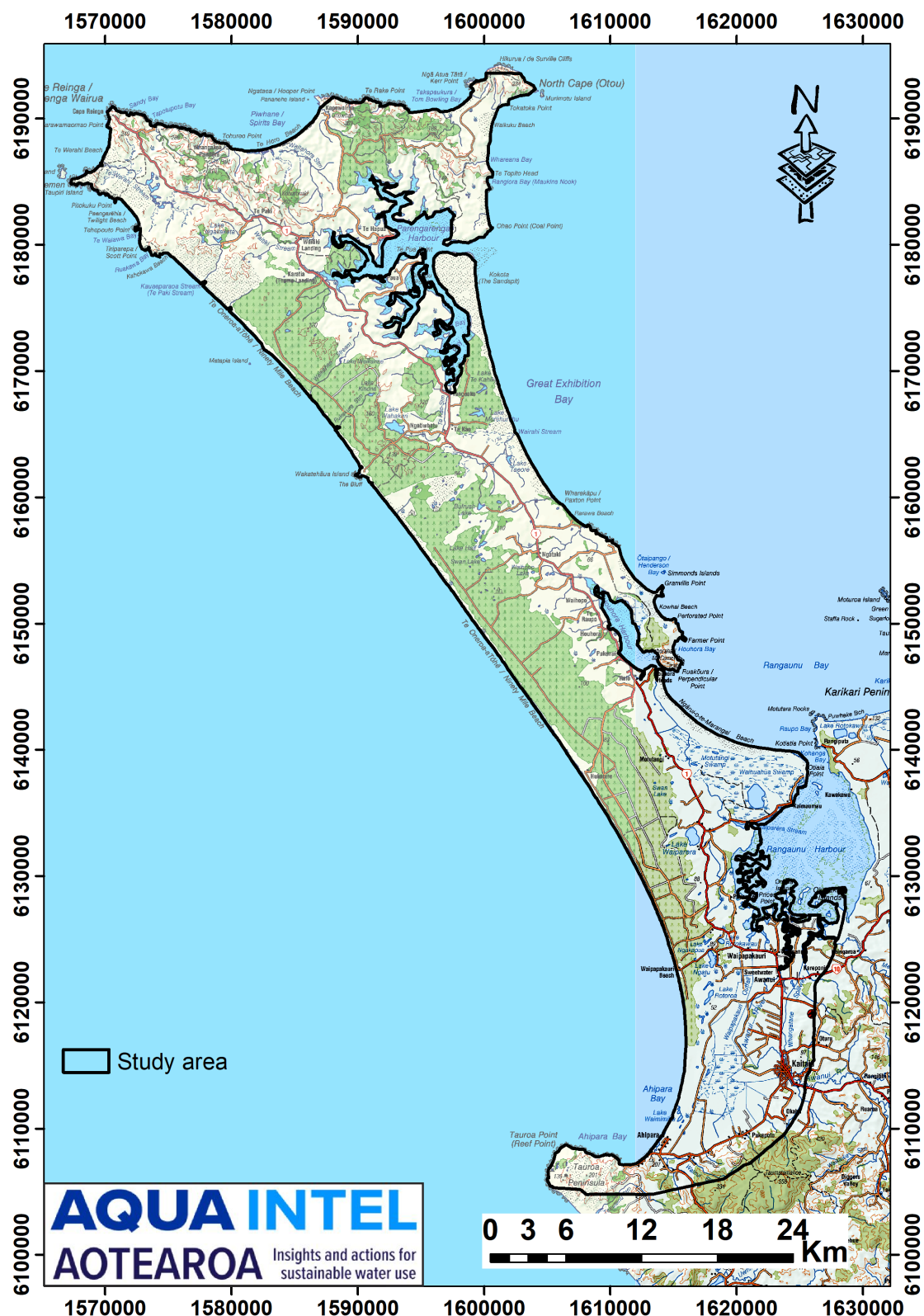


Figure 1.1 Topographic map of the Aupōuri peninsula and Aqua Intel Aotearoa study area.

2.0 Data and Methodology

2.1 Input Data

The input datasets used are described in Table 2.1, with further details provided in the sections below. Datasets utilised for rainfall-recharge modelling were from 1 January 2001, to strategically start rainfall-recharge modelling in a dry (austral summer) period, until 31 December 2023, as this matched datasets most conveniently on the full year.

Global evapotranspiration estimates are provided as a measure of comparison between the different evapotranspiration datasets in Sections 2.1.3–2.1.5.

Table 2.1 Input datasets of rainfall and evapotranspiration as used in this study.

Name	Type	Spatial Resolution (Approximate Cell Size)	Temporal Resolution	Start Date	End Date
PML_v2	Evapotranspiration	500 m	8-daily	2000-02-26 ¹	2023-12-27
MOD16	Evapotranspiration	500 m	8-daily	2001-01-09 ¹	2023-12-27
ETMonitor	Evapotranspiration	1 km	Daily	2000-06-01 ¹	2021-12-31
VCSN	Rainfall	5 km	Daily	1960-01-01 ¹	2024-06-31
Radar	Rainfall	500 m	10-minute	2014-07-01 ²	2024-12-31

¹ Data starting from 1 January 2001 were used to strategically start recharge modelling in a dry (austral summer) period.

² Recharge models using radar data were started on 1 January 2015 to strategically start recharge modelling in a dry (austral summer) period.

2.1.1 Rainfall from the Virtual Climate Station Network

Daily precipitation data from January 1960 to June 2024 are available for New Zealand in a regular grid (0.05° of latitude and longitude, or approximately 5 km) from the Earth Sciences New Zealand (NIWA Business Unit) Virtual Climate Station Network (VCSN). The VCSN is the result of a sophisticated interpolation, i.e. with a thin-plate smoothing spline method (Tait et al. 2006), between ground-based NIWA Business Unit climate stations.

An updated dataset of the VCSN for Northland was developed, in which the publicly available nationwide operational VCSN data were post-processed ('augmented') such that observations from council rain stations were used alongside the spline interpolation.

These data were used in this study and are called 'VCSN' onward. The data were obtained through a data licence agreement between Northland Regional Council and the NIWA Business Unit.

In the case of Northland, we can safely assume that no snow is present and that VCSN precipitation equals rainfall. For this study, VCSN rainfall data in the period January 2000 – December 2023 were used.

2.1.2 Radar Rainfall

Ground-based rainfall-radar data from 2014 to the present day are available for New Zealand with a 10-minute time-step at a regular grid with spatial resolution of 500 m. The process of data provision comprises a data merger of the radar signal with available ground-based climate stations (Sutherland-Stacey et al. 2020).

Rainfall-radar data were obtained through Northland Regional Council. Weather Radar New Zealand processed all available radar data from July 2014 to December 2024 (Sutherland-Stacey 2025). We provided testing and error reports for the first datasets, upon which data were updated and provided again. Some errors were still spotted for the years 2022 and 2023, which could not be fixed within the timeframe of this study. This was discussed with Northland Regional Council, upon which it was decided to not include rainfall-radar data from those years for further analyses.

2.1.3 Evapotranspiration from PML_v2 Algorithm

Penman-Monteith-Leuning Evapotranspiration V2 (PML_V2) is a global satellite-derived product that includes evapotranspiration at 500 m and 8-day resolution. The model equations include the use of satellite (MODIS) data of leaf area index, albedo and emissivity, together with meteorological forcing of a global land-surface model. The model is calibrated against 95 widely-distributed flux towers for 10 plant functional types. At the global scale, the PML-V2 products are noticeably better than most evapotranspiration products that have a similar spatial resolution, including those of MOD16 (Zhang et al. 2019). Global evapotranspiration by Zhang et al. (2019) was calculated as approximately 490 mm/yr.¹

PML_v2 data were downloaded from the Google Earth Engine data catalogue² for the period 26 February 2000 – 27 December 2023, i.e. the entire available archive.

2.1.4 Evapotranspiration from MOD16 Algorithm

The MOD16 algorithm uses the Penman-Monteith approach to calculate evapotranspiration using satellite data from the United States National Aeronautics and Space Administration (NASA)'s MODerate-resolution Imaging Spectroradiometer (MODIS) sensor. The satellite-derived parameters embedded in the MOD16 dataset are land cover, albedo, leaf area index, fraction of absorbed photosynthetically active radiation (FPAR), and enhanced vegetation index. Temperature, radiation, air humidity and pressure data are derived from the daily global meteorological re-analysis dataset from NASA's Global Modeling and Assimilation Office. The MOD16 model has been validated at 46 eddy flux towers, most of these in the United States. Global evapotranspiration was estimated as approximately 570 mm/yr (Mu et al. 2011).

2.1.5 Evapotranspiration from ETMonitor Algorithm

ETMonitor evapotranspiration (Zheng et al. 2022) was developed with the aim to target for a global product of evapotranspiration with higher temporal resolution. The downscaling of data to daily 1 km data is done using a variety of satellite remote-sensing data products and machine-learning algorithms (i.e. of albedo, leaf area index, field cover, land cover, snow cover, water cover, surface soil moisture, precipitation and canopy height [Zheng et al. (2022), their Table 2]). MOD16 and PML_v2 data were, amongst others, used for cross-comparison. Globally, ETMonitor performs similar or better in many cases (Zheng et al. 2022). ETMonitor evapotranspiration performs better than others in irrigated cropland and mountain regions (Zheng et al. 2022). Global annual evapotranspiration by ETMonitor was estimated as very similar to those of PML_v2, i.e. 496 ± 10 mm/yr.

Daily data were kindly provided by personally contacting the authors (Jia 2025; Zheng 2025). Daily data for the study area showed unusual extremes of >10 mm/day, especially over forested area. The majority of these data peaks were therefore filtered out by an 8-day median filter before use in this study.

1 Zhang et al. (2019) estimate global evapotranspiration for 2003–2017 as $72,800 \text{ km}^3 \text{ yr}^{-1}$, which amounts up to 491 mm yr^{-1} if total land on earth (excluding water bodies and permanent ice) is estimated as 148 million km^2 . This land-mass volume assumption was also used to convert volumes of Zheng et al. (2022) ($73,570 \pm 1390$) to millimetres per year.

2 https://developers.google.com/earth-engine/datasets/catalog/CAS_IGSNRR_PML_V2_v018

2.2 Validation Data

2.2.1 Evapotranspiration Validation Points

Ideally, validation takes place at *in situ* observations of evapotranspiration. However, these data were not available for this study at this point in time (see Section 5). Therefore, virtual locations were utilised for comparison of the satellite-derived evapotranspiration products.

To enable these comparisons, for the period 2014–2024, satellite images were developed based on a combination of available optical RGB (i.e. the combined bands of Red, Green and Blue) satellite data. Data of the archives of Landsat 8 and Sentinel-2 were compiled to annual images in the Google Earth Engine (Gorelick et al. 2017). The advantage of using these maps is that land cover, and its changes over time, can be identified. For example, areas of harvested pine forest in the Aupōuri Forest in 2019 are easily discernible (Figure 2.1). All RGB maps are available in Appendix 2.

Three virtual locations were identified as suitable for comparison of the satellite-derived evapotranspiration products (Figure 2.1).

- The first point, called ‘North’, has been tree-covered (pine plantation) for the period of 2001–2023, assuming negligible changes of land cover.
- The second point, called ‘Middle’, has been covered by trees for the period of (approximately) 2001–2014, after which forest harvesting took place (for example, see Figure 2.1, showing the satellite image for 2019 average conditions). The area is currently re-growing.
- The third point, called ‘South’, has been mostly covered by grass for the period of 2001–2023, assuming negligible changes of land cover.

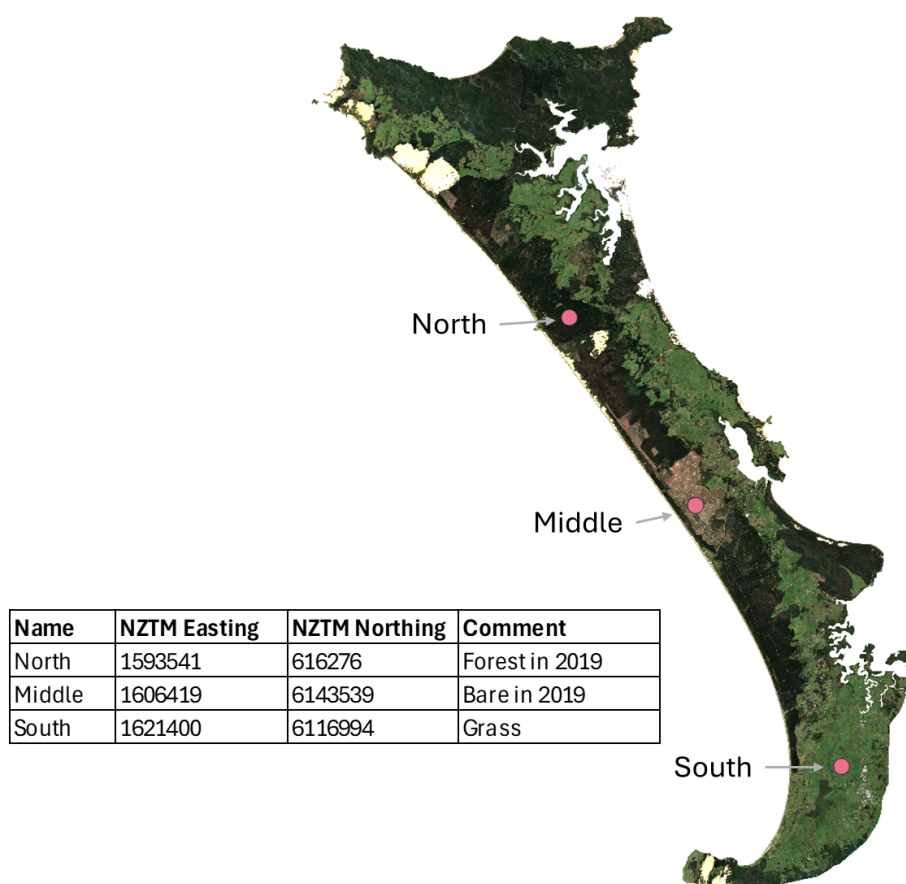


Figure 2.1 Comparison points for evapotranspiration models. The background map is the satellite (RGB colour) image for average conditions over 2019.

2.2.2 Rainfall Validation Points

Through a data request to Northland Regional Council, daily rainfall data for three council stations were received for the period 2015–2023 (Table 2.2). These data were used to validate VCSN and radar-rainfall data.

Table 2.2 Climate rainfall stations used for validation in this study.

Station Name	Easting (NZTM)	Northing (NZTM)
Aupouri Forest at Forest HQ	1618008	6125582
Awanui at Weissing	1623322	6119400
Waihopo at Kimberley Road	1604209	6153205

2.3 Comparisons between Different Rainfall and Evapotranspiration Datasets

To assess differences and similarities, the two different rainfall and three different evapotranspiration datasets were compared to each other in the following ways:

- Bar charts of annual average VCSN and radar rainfall were compared for the Aupōuri case-study area.
- Bar charts of annual averages of the three satellite-derived evapotranspiration products (PML_v2, MOD16 and ETMonitor) were compared for the Aupōuri case-study area.
- Rasters of annual means were compared to identify any spatial variations in rainfall and evapotranspiration.
- At the locations of climate stations (Section 2.2.2), annual VCSN and radar rainfall were compared to climate-station rainfall (see Section 2.3.1).
- At the three virtual locations (Section 2.2.1), evapotranspiration data were compared for differences and similarities.

Time-series of rainfall were compared to each other by using the Kling-Gupta Efficiency (KGE) score (Gupta et al. 2009). This statistical score is a goodness-of-fit measure that considers not just the correlation (which traditional metrics often emphasise) but also whether the model reproduces the correct volume (bias) and dynamics (variability) of the observed data.

Where observed data were present, KGE scores between observed data and simulated time-series were calculated. In addition, KGE scores between the different simulation time-series were also calculated.

A full explanation of the KGE score is found in Appendix A1.1. In short, KGE values range from $-\infty$ to 1, where, in the case of observed data compared to a simulation:

- **KGE = 1** states a perfect match between observed and simulated.
- **KGE = 0** states that the simulation is no better than using the mean of observations.
- **KGE < 0** states that the simulated data has a poor fit with the observation.

Time-series of evapotranspiration can also be compared in a similar fashion; however, there were no ground-observed actual evapotranspiration data available at the time of this study.

Data were compiled to monthly before the KGE estimation. This was mainly because using daily data came with a significantly lower KGE score for both VCSN and radar rainfall than monthly. See Section 5 for more detail.

2.4 Rainfall-Recharge Model

2.4.1 Definition of Rainfall Recharge

Rainfall recharge is defined here as the amount of rainfall that drains through the soil layer. The soil layer is often referred to as the first approximate 1 m of the surface but depends on the soil type and rooting depth (Newsome et al. 2008).

Rainfall recharge is also referred to as ‘land surface recharge’, ‘gross recharge’ or ‘potential recharge’. This is mainly because rainfall recharge is not necessarily equal to the actual amount of water reaching the aquifer. For example, in the case of a shallow water table, a groundwater model will reject rainfall recharge if it causes the water table to rise above surface; or, in areas with a deep-water table water, the infiltrated water may still remain in a thick ‘unsaturated’ zone without reaching the water table. To estimate net volume of recharge entering an aquifer from rainfall recharge, a numerical groundwater model is typically used.

2.4.2 The National Groundwater Recharge Model v1.0

The NGRM (v1.0) was developed and described by Westerhoff et al. (2018). The aim of the model was to demonstrate the utility of satellite data in its use for a consistent rainfall-recharge estimate across all regions of New Zealand.

The NGRM v1.0 was developed in the MATLAB programming language. It had a 1 × 1 km model grid that covered most of New Zealand. The model formulation used monthly time-steps and a cell-by-cell soil-water-balance approach to estimate rainfall recharge:

$$R_i = [P_i f_{slope} - ET_i - S_{i-1}] f_{soil} f_{geol}; R_i > 0 \quad \text{Equation 2.1}$$

where:

- i Indicates the time-step.
- P_i is the precipitation (in millimetres, after correction for interception and snow).
- f_{slope} is a correction factor for rainfall runoff due to slope [0 to 1].
- ET_i is actual evapotranspiration (in millimetres).
- S is soil storage (millimetres). Soil storage is a time-variant grid, with values ranging from zero to a maximum, which was obtained from nationwide rasters of profile of available water, a soil property dependent on assumptions of rooting depth of the local vegetation and the difference between the field capacity and wilting point. More details can be found in Westerhoff et al. (2018).
- f_{soil} is a correction factor for the soil permeability [0 to 1], an empirically derived factor resembling the impedance in recharge due to a restricted infiltration capacity based on the soil-type classes (Döll and Fiedler 2008).
- f_{geol} is a correction factor for the geology [0 to 1], a time-variate correction factor (between 0 and 1) that is defined as the ratio between the possible recharge at time-step i and the hydraulic conductivity as defined by Tschirter et al. (2017).

The NGRM v1.0 has been used by Mourot et al. (2022) to assess the effect of climate change on New Zealand’s aquifers.

The NGRM v1.0 model equations have revealed some important desired adjustments in recent years. Some of these are:

- The monthly time-step is likely not capturing processes of extreme weather. Heavier downpours of rain will likely cause (less permeable) soils to reach saturation within hours or days.
- Ideally, soil-water-balance models are used to also develop estimates of run-off or to be used in conjunction with models that do. Run-off is ideally also captured at (sub-)daily time-steps; hence, a recharge model is also ideally capturing at such temporal scales.
- The MATLAB programming language is a proprietary programming language. The desire is for a model in an open-source environment.

2.4.3 Changes Made in National Groundwater Recharge Model v2.0

Prior to the start of the project and funded internally by GNS Science Business Unit' strategic science investment funding, the NGRM v2.0 was developed in the Python open-source programming language. The intention of the shift to Python was to facilitate better collaboration between model developers in the field of hydrogeology.

The model code exports model results in a standardised format, i.e. NetCDF files with dimensions 'x', 'y' and 'time', which can then be easily used by other models.

Westerhoff et al. (2018) used VCSN rainfall and MOD16 satellite-derived evapotranspiration for the period from 2000 to 2015 as input for the NGRM. More recently, other data of climate have been made available, such as the rainfall and evapotranspiration datasets described in Section 2.1. The model code has been adjusted to incorporate a variety of input datasets.

The NGRM v2.0 has the option of 'turning off' the geology layer calculation step, i.e. setting f_{geol} to 1 everywhere.

2.4.4 Recharge Model Revisions Made in this Report

Within this study, the use of one alternative rainfall dataset (radar rainfall) and two alternative satellite-derived evapotranspiration datasets (PML_v2 and ETMonitor) were implemented as input datasets to NGRM v2.0.

The NGRM was run as 'multi-input', i.e. the model was run with all combinations of rainfall and evapotranspiration (Figure 2.2) and the outputs of the model means used as the result, with the model spread as a measure of uncertainty.

The NGRM was run at a daily time-step, with 250 m cell resolution. In this way, the model will better reflect short-term, i.e. daily, events, such as peak rainfall events.

In the calculation of the model mean and model spread, the models were weighted. This weighting scheme was simple, given that no ground-observed data were available for actual validation. The weighting scheme put half as much weight on the models using ETMonitor data compared to the other model combinations. This was decided after discussion of initial results with Northland Regional Council (1 May 2025), as peaks in the ETMonitor data had to be filtered out before model input. See Section 3.2 and Section 5 for more elaboration.

For this study, f_{geol} was turned off, i.e. set to 1 everywhere.

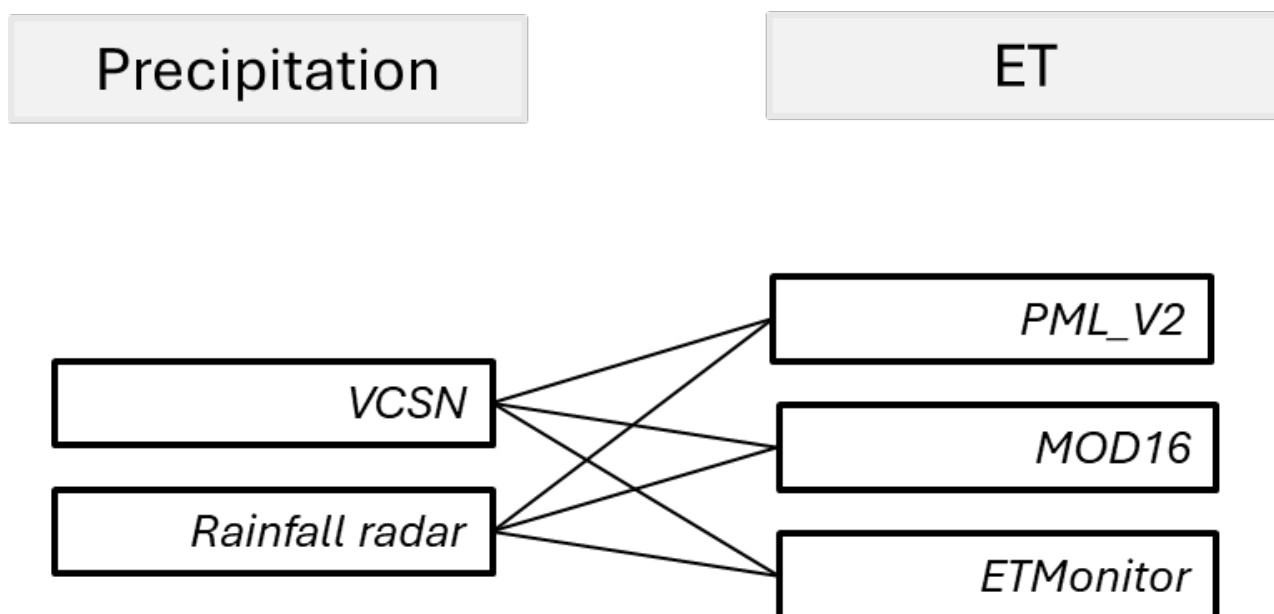


Figure 2.2 Drivers of precipitation (i.e. rainfall) and evapotranspiration as used in the design of the multi-input recharge-model runs in this study.

3.0 Results

3.1 Comparison of Rainfall Datasets

The approximate 5-km-resolution cells of VCSN cells are on a coarser grid than the 500-m-resolution rainfall radar (Figure 3.1). Hence, spatial patterns in rainfall are much more visible on the radar rainfall, for example, the orographic effect of rainfall in the peninsula (Figure 3.1, right).

Between 2015 and 2023, and averaged for the entire peninsula, the temporal annual pattern of both rainfall datasets is similar (Figure 3.2). At the locations of climate stations, in almost all years, both VCSN and radar show lower rainfall than the climate stations; VCSN is often lower than radar.

Both VCSN and rainfall radar have a good fit (i.e. KGE score) between simulated and observed data at the locations of council climate stations (Figures 3.3–3.5; Table 3.1). This is not surprising; the rainfall-radar dataset is a direct merge between the radar signal and these climate stations (Sutherland-Stacey et al. 2020), and the VCSN data were post-processed so that council stations were augmented to the VCSN interpolation algorithm. Of the two rainfall datasets, rainfall radar overall has the highest KGE score.

Figures 3.3–3.5 show that, in almost all cases, VCSN rainfall provides lower values than the climate stations; it also shows that rainfall radar provides values closer to the observed climate-station data. We surmise that using the VCSN and rainfall radar provides an envelope of uncertainty that should ensure that the true value is encapsulated.

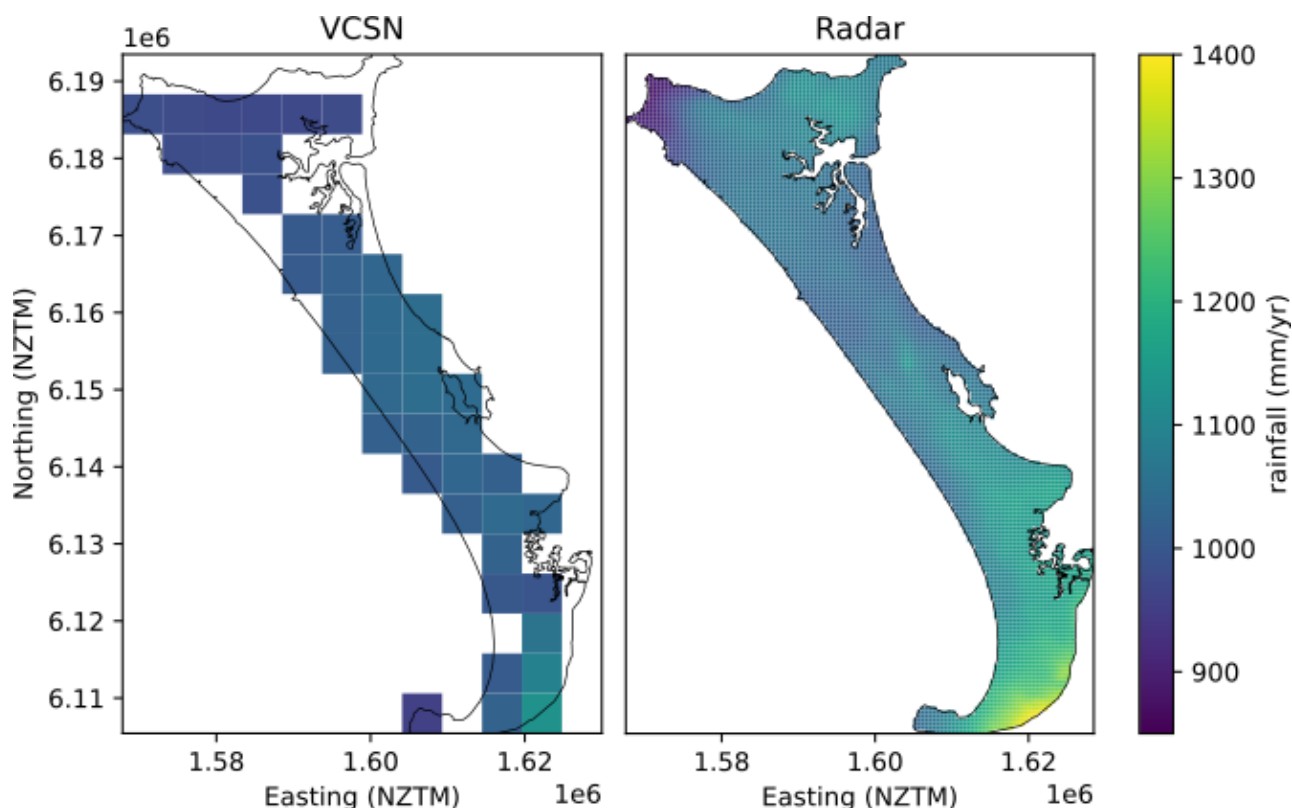


Figure 3.1 Comparison between Virtual Climate Station Network (VCSN) (left) and radar (right) mean rainfall for 2015–2021.

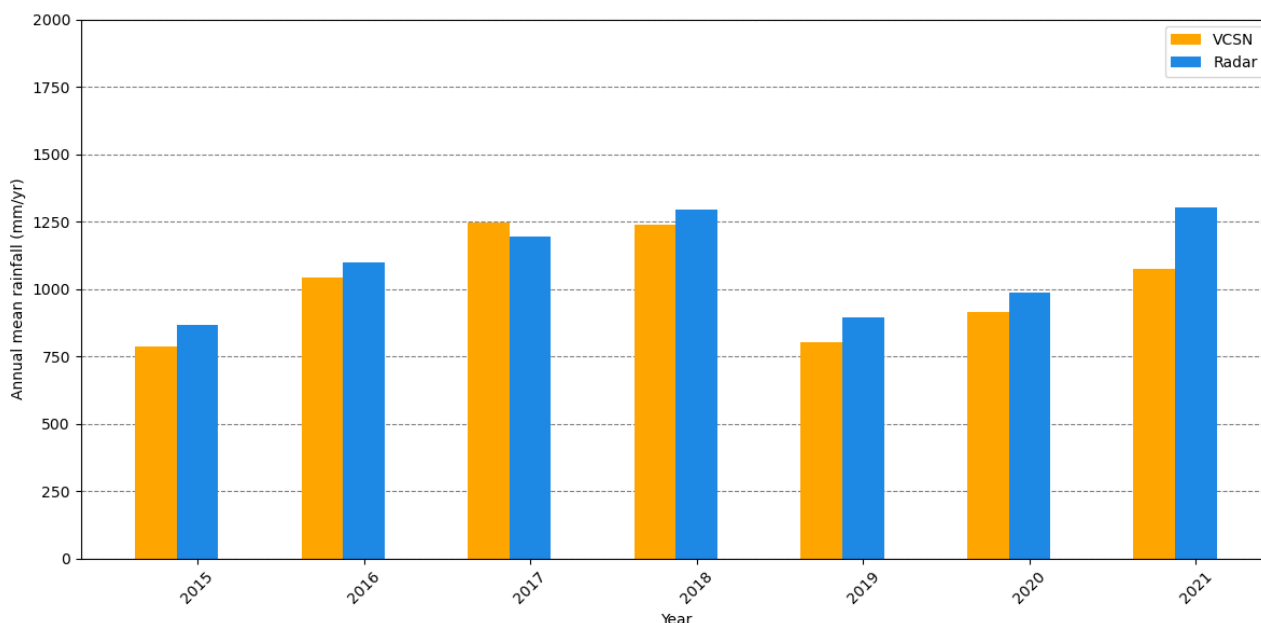


Figure 3.2 Annual compiled rainfall in the Aupōuri study area for Virtual Climate Station Network (VCSN) (orange) and rainfall radar (blue) in between 2015 and 2021.

Table 3.1 Kling-Gupta Efficiency (KGE) goodness of fit scores between all used rainfall datasets in this study, based on monthly means of data between 2015 and 2021.

Station Name	Aupouri at Forest HQ	Awanui at Weissing	Waihopo at Kimberley Road
KGE score station versus VCSN	0.764	0.760	0.812
Pearson correlation (r)	0.897	0.913	0.951
Variability (alpha)	0.848	0.834	0.838
Bias (beta)	0.851	0.850	0.919
KGE score station versus radar	0.835	0.838	0.962
Pearson correlation (r)	0.905	0.894	0.969
Variability (alpha)	0.885	0.881	0.990
Bias (beta)	0.929	0.970	0.1.019
KGE score VCSN versus radar	0.881	0.839	0.788
Pearson correlation (r)	0.939	0.947	0.978
Variability (alpha)	1.044	0.1056	1.181
Bias (beta)	1.092	1.141	1.109

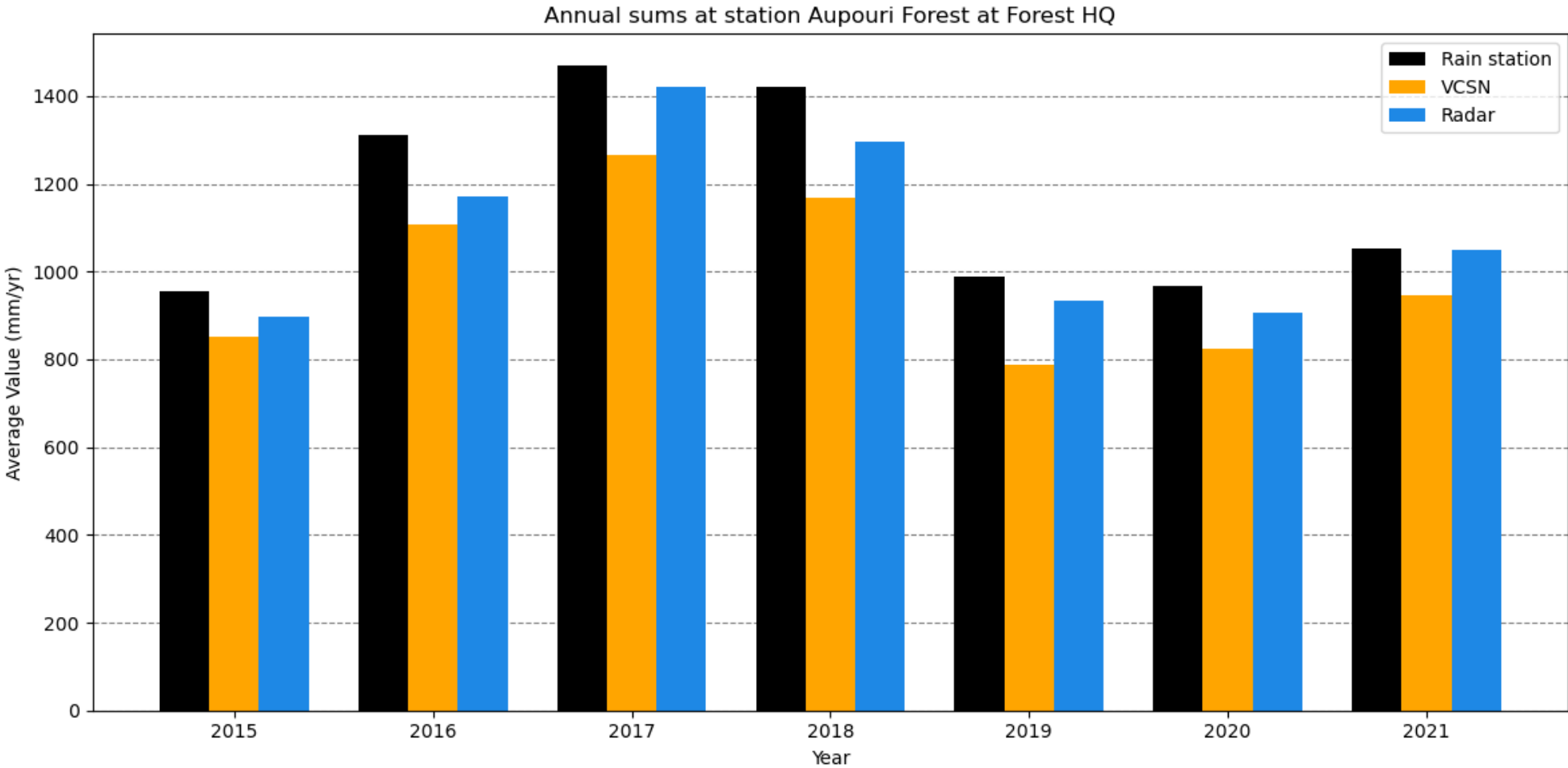


Figure 3.3 Annual rainfall sums at Aupōuri station.

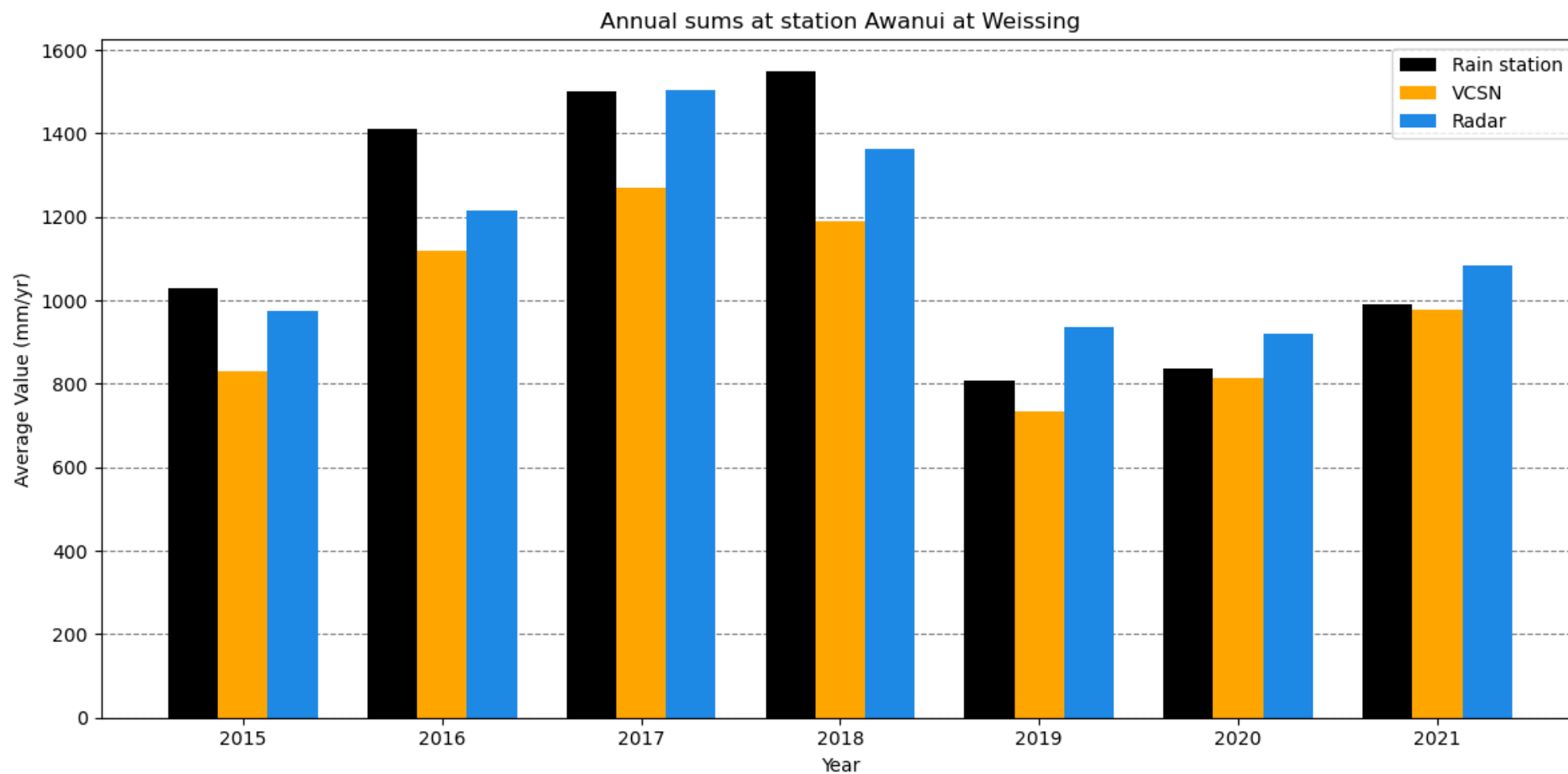


Figure 3.4 Annual rainfall sums at Awanui at Weissing station.

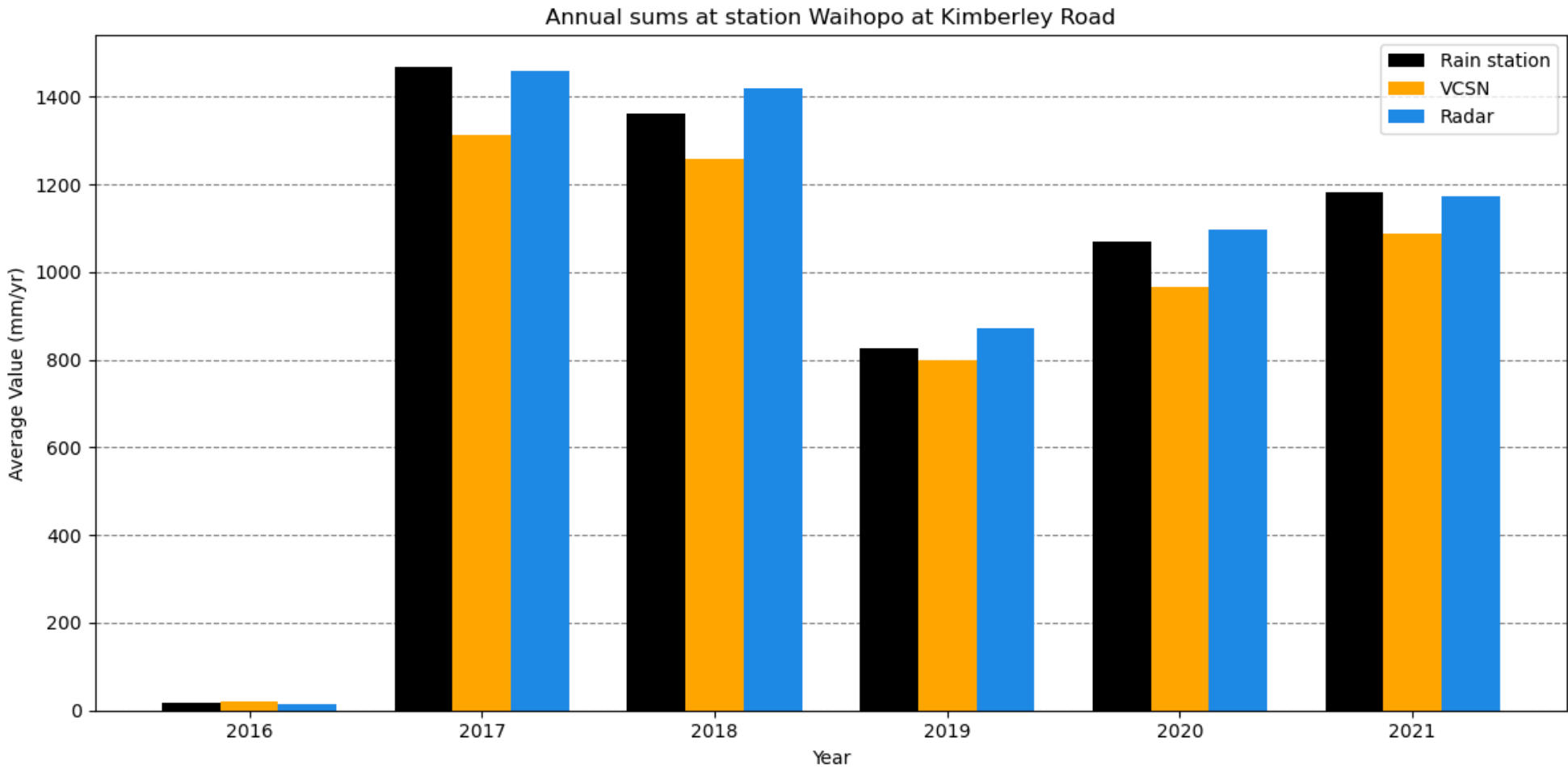


Figure 3.5 Annual rainfall sums at Waihopo at Kimberley Road station. Station data start at 1 December 2016.

3.2 Comparison of Evapotranspiration Datasets

Evapotranspiration volumes and characteristics differ significantly across evapotranspiration datasets. Annual means of the case-study area (Figure 3.6) show that MOD16 often has the highest evapotranspiration estimate that and ETMonitor often has the lowest.

A spatial comparison between the three datasets (Figure 3.7) shows that all satellite-derived evapotranspiration products represent changes in land cover well. Satellite-derived evapotranspiration will therefore better capture the dynamic and spatial changes in land cover than static estimates of land cover through traditional estimates, such as those from the often-used Land Cover Database³. Distinct spatial differences between the datasets are, among others, that:

- Evapotranspiration estimates from MOD16 are significantly higher for tree-covered areas compared to the other datasets.
- Evapotranspiration estimates from ETMonitor are specifically more sensitive to forest cover than climate (see below). These are significantly lower for tree-harvested areas (Figures 3.8–3.11) compared to the other datasets, while in grass areas these are similar (Figures 3.12 and 3.13). Despite usage of the median filter (Section 2.1.5), some peaks are still visible over forested area (e.g. Figure 3.9).

Annual bar charts (Figures 3.8, 3.10 and 3.12) and time-series (Figures 3.9, 3.11 and 3.13) at three points of comparison ('North', 'Middle', 'South'; see Figure 2.1 for locations) highlight the vastly different characteristics of ETMonitor data when compared to PML_v2 and MOD16: ETMonitor shows more peaks of high and low evapotranspiration, while PML_v2 and MOD16 show more smooth seasonal behaviour. In addition, ETMonitor appears more sensitive to land-use change, for example, the harvest of forest from 2015 at the 'Middle' point (Figure 3.11). Finally, ETMonitor shows less seasonal climate-driven fluctuations, re-iterating that it seems to be mostly driven by land cover (Figures 3.9, 3.11 and 3.13).

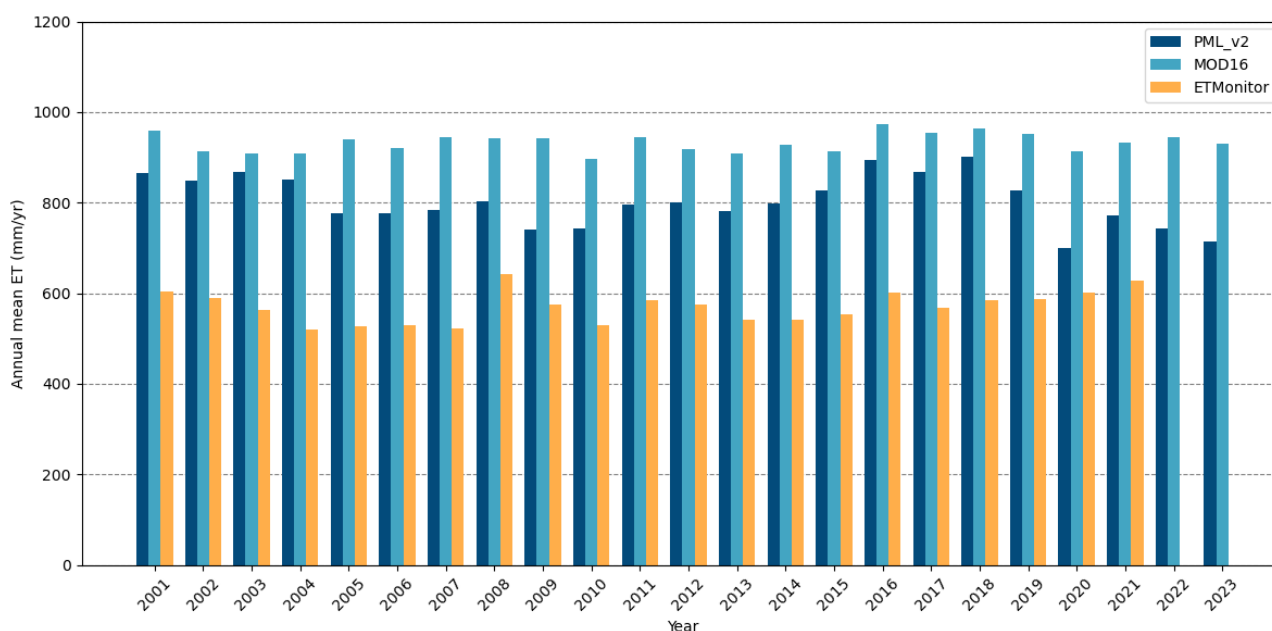


Figure 3.6 Annual averages of the three satellite-derived evapotranspiration datasets for Aupōuri.

³ <https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/>

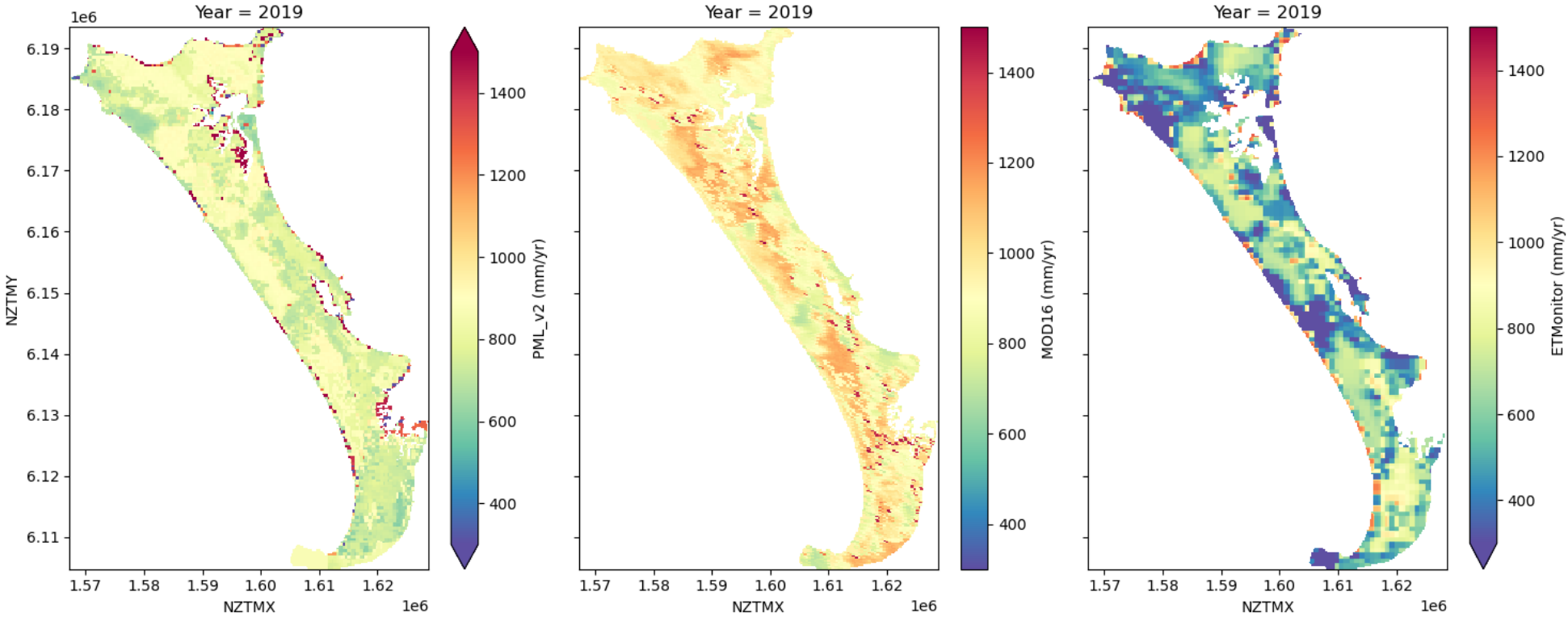


Figure 3.7 Spatial comparison of the three satellite-derived evapotranspiration datasets for the year 2019. (Left) PML_V2; (middle) MOD16; (right) ETMonitor.

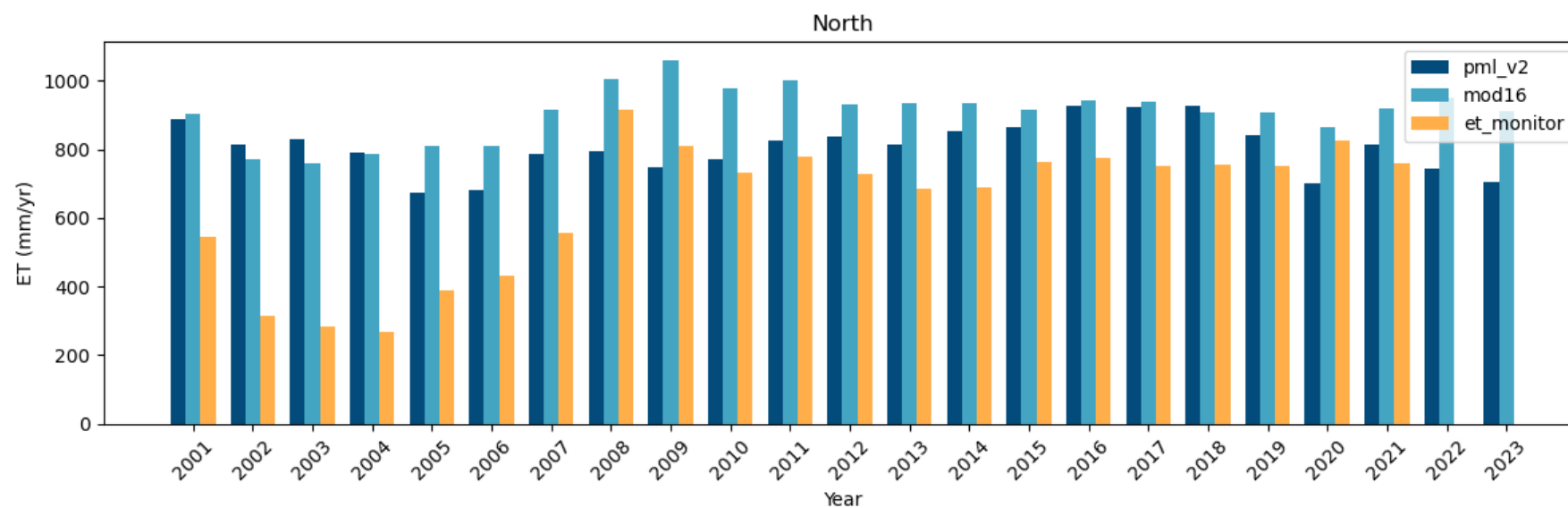


Figure 3.8 2001–2023 annual averages at the comparison point 'North' (Figure 2.1) for the three satellite-derived evapotranspiration datasets.

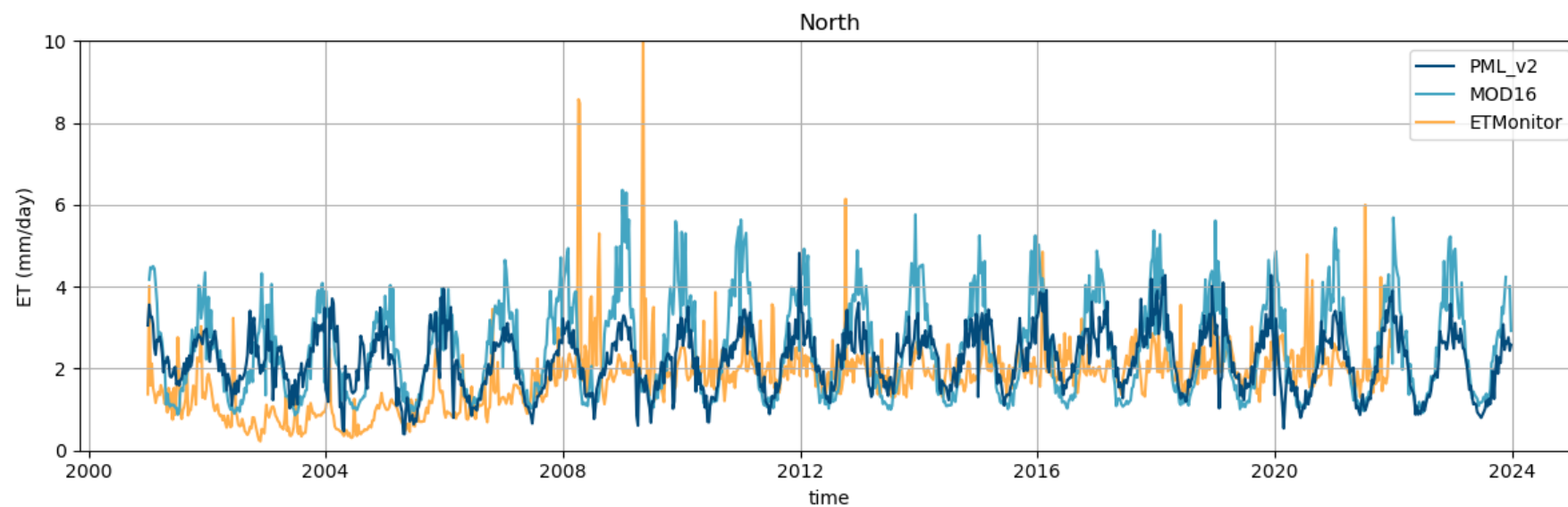


Figure 3.9 200–2023 time-series at the comparison point 'North' (Figure 2.1) for the three satellite-derived evapotranspiration datasets.

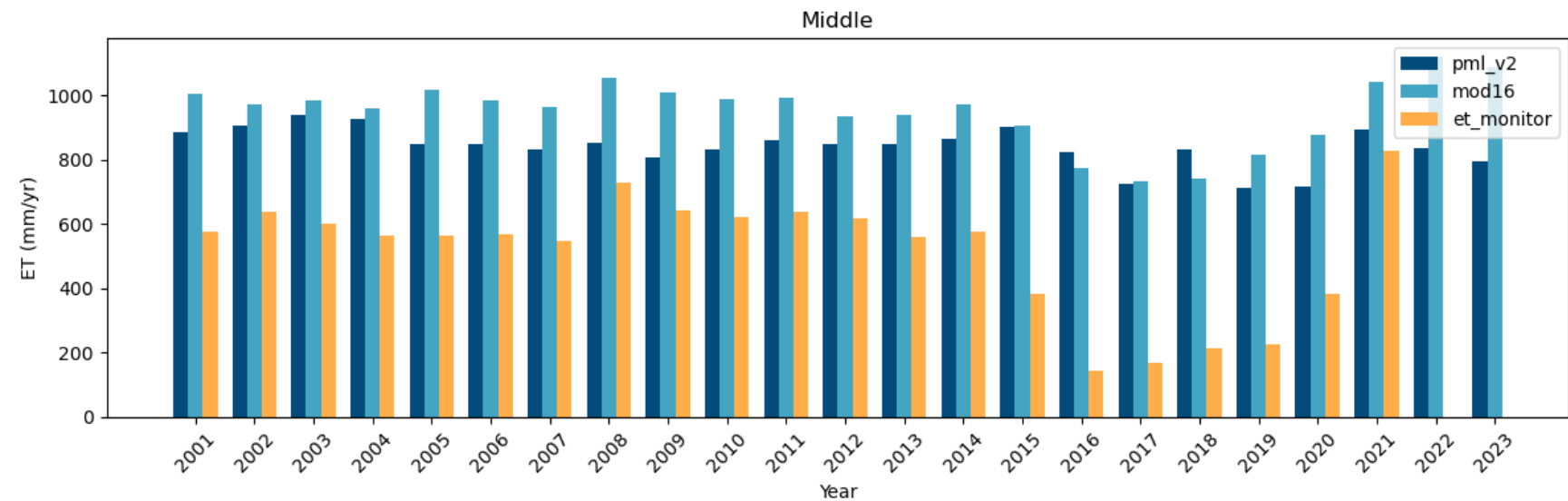


Figure 3.10 2001–2023 annual averages at the comparison point ‘Middle’ (Figure 2.1) for the three satellite-derived evapotranspiration datasets.

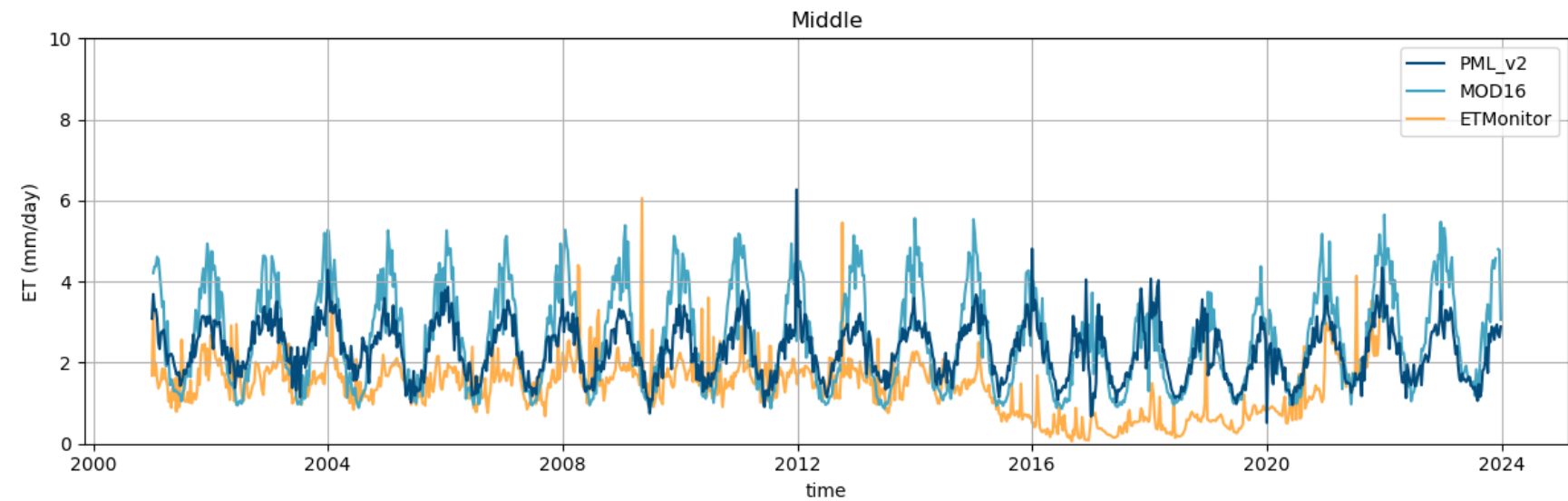


Figure 3.11 2001–2023 time-series at the comparison point ‘Middle’ (Figure 2.1) for the three satellite-derived evapotranspiration datasets.

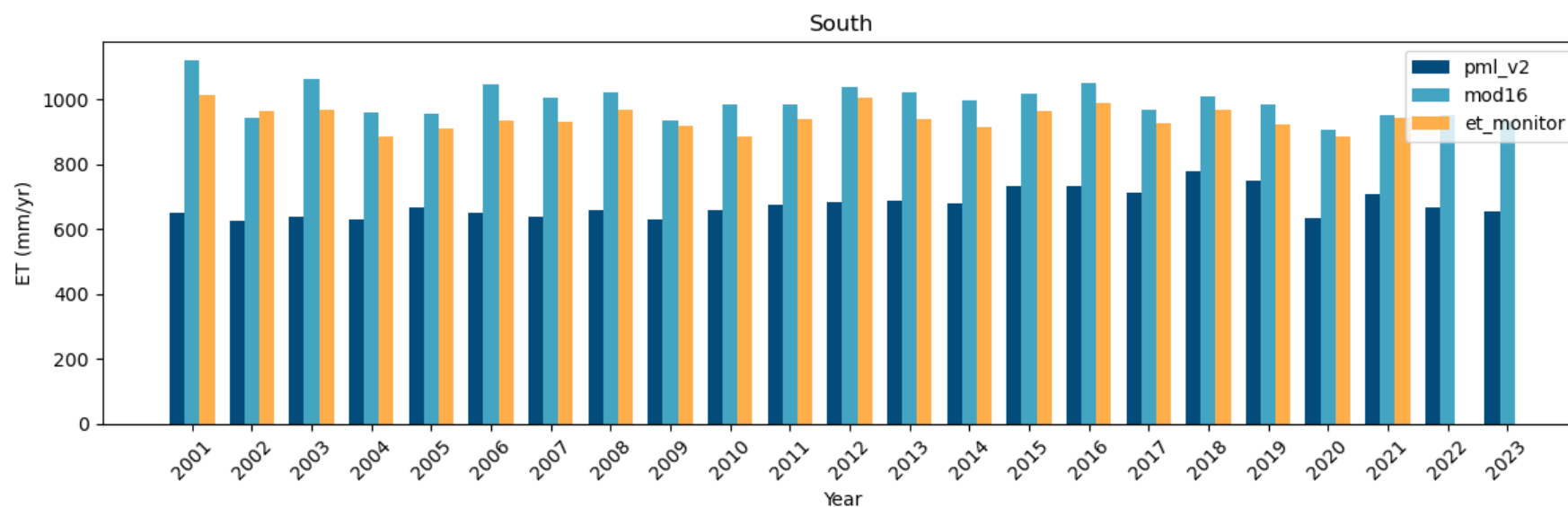


Figure 3.12 2001–2023 annual averages at the comparison point 'South' (Figure 2.1) for the three satellite-derived evapotranspiration datasets.

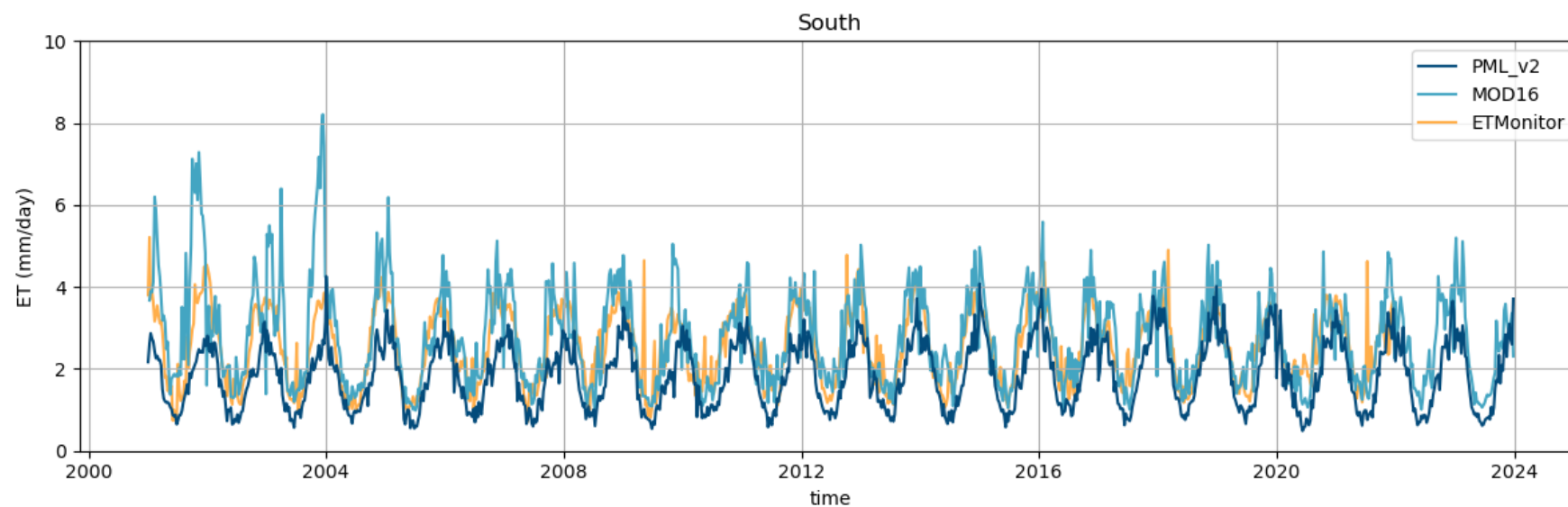


Figure 3.13 2001–2023 time series at the comparison point 'South' (Figure 2.1) for the three satellite-derived evapotranspiration datasets.

3.3 Rainfall-Recharge Models

The weighted multi-model mean rainfall recharge for the period is available for the period January 2001 – December 2023. The 2001–2023 multi-model mean recharge (Figure 3.14) for the study area is 332 mm/yr. Recharge outputs for the different model combinations (Table 3.2) show significant variations depending on the chosen input and modelling period. Key observations are described below.

The spread in recharge for the years 2022 and 2023 is significantly higher than for other years. This is mostly caused by the disagreement of rainfall products, i.e. VCSN and rainfall-radar observations (see also Figure 3.2).

Recharge is higher for the model combinations with ETMonitor. This logically follows from these evapotranspiration data predicting lower evapotranspiration over forested areas (Section 3.2).

Uncertainty (Table 3.2; Figure 3.15) is larger than previously reported for earlier versions of the NGRM. For example, Westerhoff et al. (2018), for their 2000–2014 nationwide results, estimated average model uncertainty to be 17%. This study estimates uncertainties for the similar period, 2001–2014, to be 47%. This increase in uncertainty is caused by the different model inputs utilised in this study. This study therefore shows that differences between input data can be substantially larger than the assumed uncertainty of input parameters by Westerhoff et al. (2018).

All model results have been made available to Northland Regional Council and Aqua Intel Aotearoa as NetCDF4/HDF5 files, which are the most modern and widely supported NetCDF format files. The model code (Python, Jupyter Notebook) can be made available upon request.

Table 3.2 Recharge compilations for multi-model mean and each model input combination.

Model Input			Recharge for Case-Study Area (mm/yr)			
Rainfall	Evapotranspiration	Weight	2001–2021	2001–2014	2015–2021	2001–2023
Multi-model mean unweighted			335	348	309	349
Multi-model mean weighted			317	329	292	332
Uncertainty: Multi-model mean spread as $1\sigma^*$			185 (55%)	165 (47%)	219 (71%)	179 (51%)
VCSN	PML_v2	1	285	308	239	308
VCSN	MOD16	1	270	291	227	285
VCSN	ETMonitor	0.5	428	456	371	N/A***
Radar	PML_v2	1	N/A**	No data	308	
Radar	MOD16	1			289	
Radar	ETMonitor	0.5			444	

* The model spread was calculated as standard deviation of the unweighted mean, where daily model output data were resampled to monthly first.

** Only data for the period 2015–2021 were available.

*** Only data until 2021 were available.

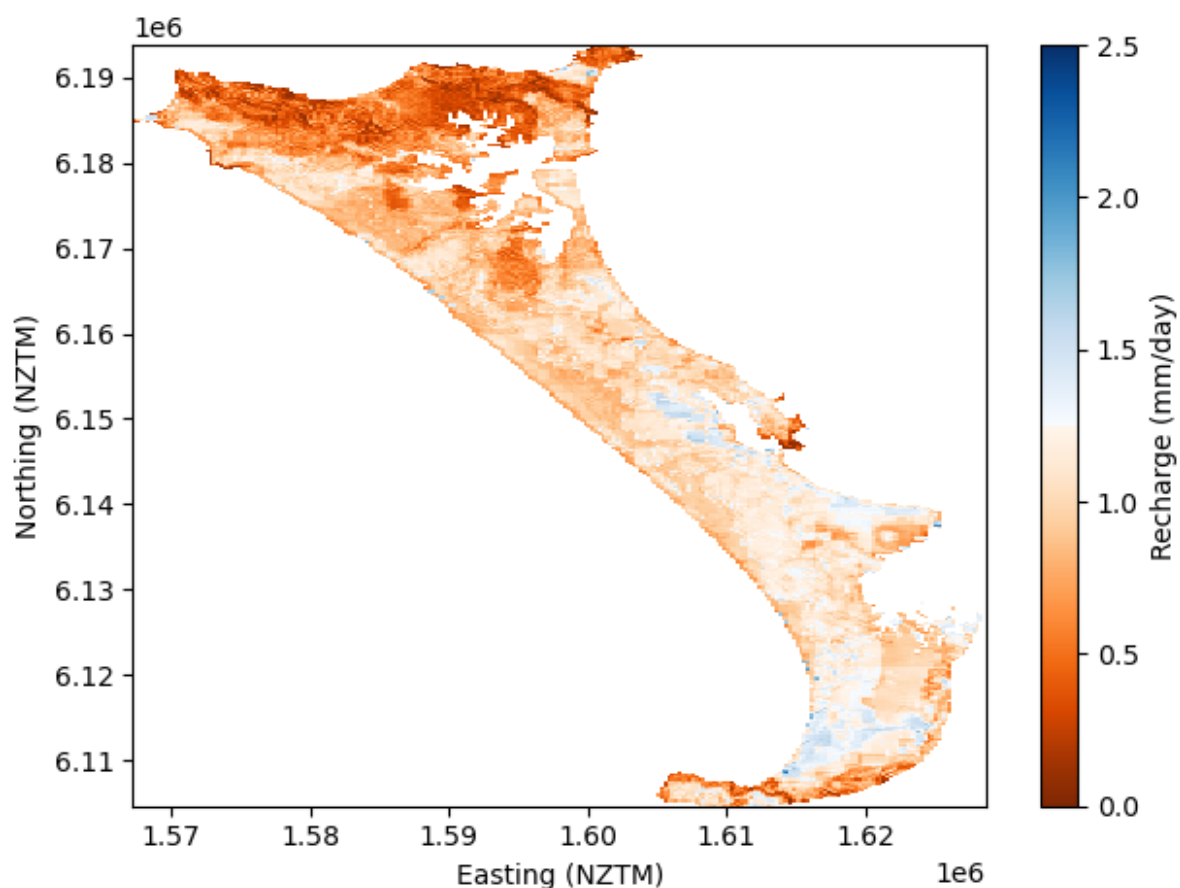


Figure 3.14 Multi-model mean recharge (weighted) for the case-study area for the period 2001–2023.

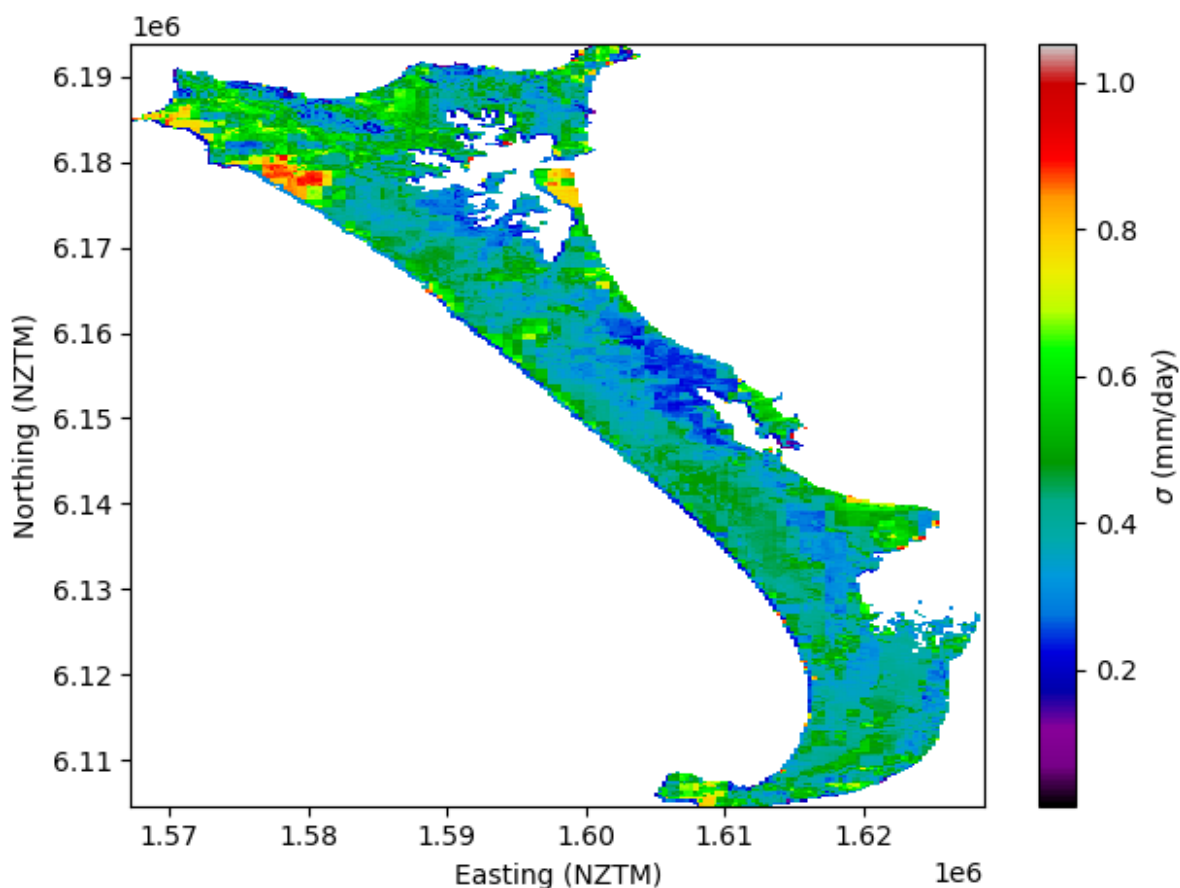


Figure 3.15 Multi-model spread, as one standard deviation (1σ), for the period 2001–2023.

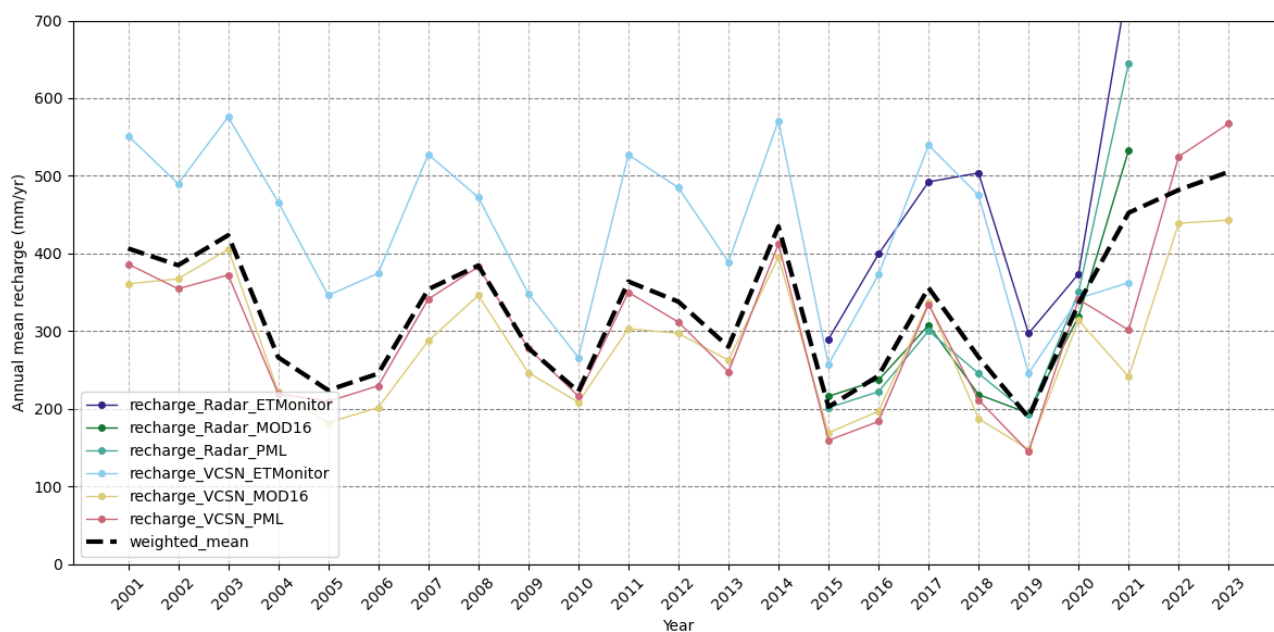


Figure 3.16 Line chart of recharge per model combination, including the weighted model mean.

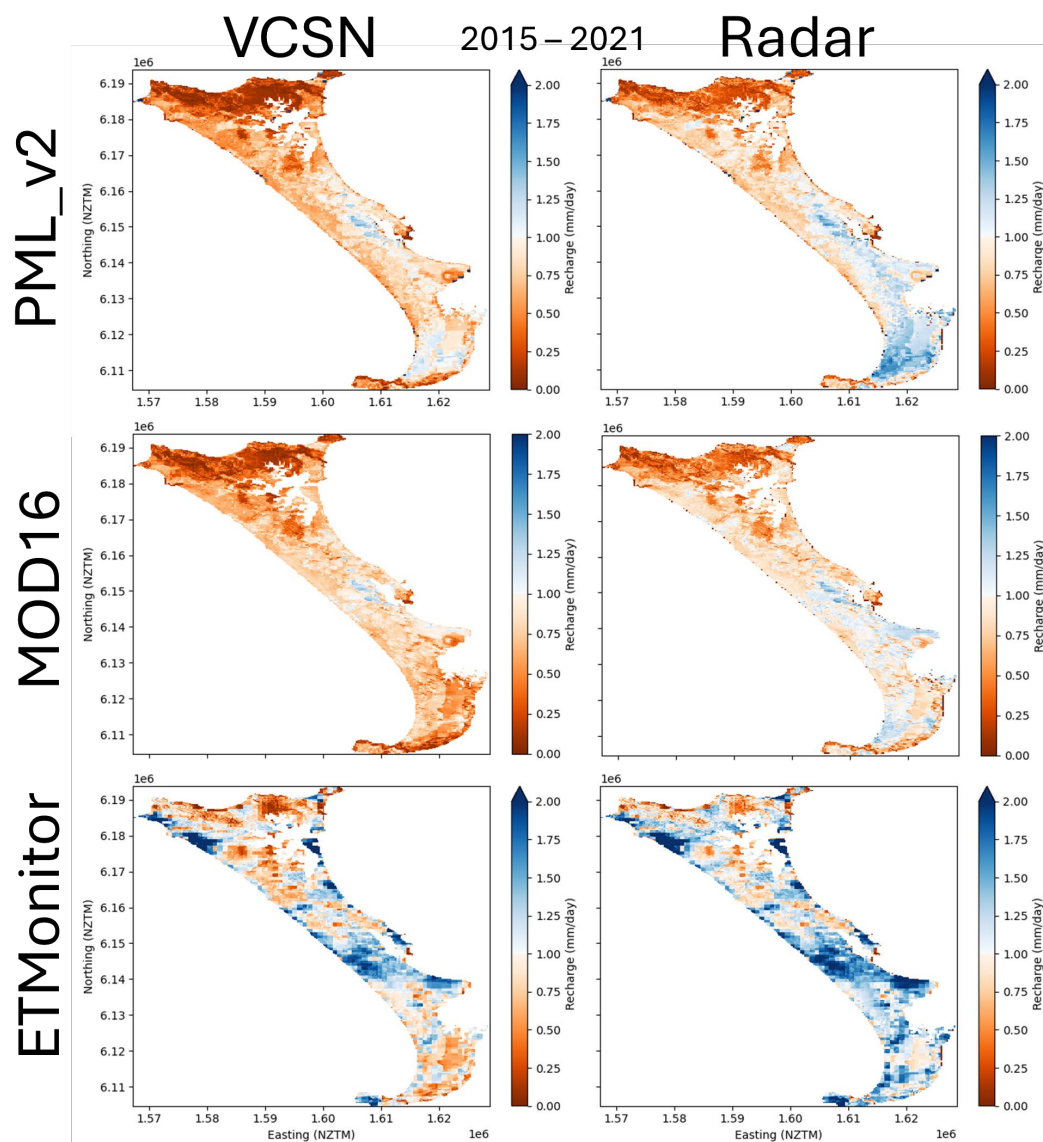


Figure 3.17 Comparison of six instances of the rainfall-recharge models in the period 2015–2021.

4.0 Conclusions

This study developed a rainfall-recharge model of the Aupōuri Peninsula to address concerns of Northland Regional Council that previously developed rainfall-recharge models did not appropriately address the availability of more recent high-resolution datasets, the adequate representation of high-intensity event-driven rainfall recharge or the adequate representation of forestry cycles and wetland changes on rainfall recharge, nor suitable climate-change simulations.

At a daily time-step, at 250 m model cell resolution, and with the inclusion of novel satellite datasets, this rainfall-recharge model of the Aupōuri Peninsula represents the dynamics of land-use change at appropriate resolution, at the best available accuracy and with estimates of uncertainty suitable for use within a numerical groundwater-flow model and for future work on climate change. This recharge model better represents the effect of short-term high-rainfall events, as it runs at the daily time-step, instead of monthly time-step, of the older version of the model (NGRMv1.0).

Comparisons of rainfall indicated that radar-derived rainfall provides a similar (high) goodness-of-fit to council-station data compared to VCSN data. Radar rainfall also has a higher spatial and temporal resolution compared to VCSN data. However, radar-rainfall data are only available from 2015 onward and still have unexplained lower rainfall (in the period 2022–2023) that need fixing; therefore, these data are not yet considered operational.

Comparisons between three satellite-derived evapotranspiration products indicated that each product has their own characteristics. For example, ETMonitor data are particularly sensitive to changes in land cover, while MOD16 and PML_v2 appear more driven by the (atmospheric) climate. There are no ground-observation data available to further validate these evapotranspiration products.

A multi-model approach to calculate recharge for the period 2001–2023 was taken. This was based on the availability of rainfall data and the fact that no single evapotranspiration product can be ruled out, i.e. these all appear equally likely. The outputs of the multi-model mean are a weighted multi-model mean, an estimate of uncertainty by the width of the model spread and all individual model outputs.

The weighted multi-model mean, used with all six combinations of rainfall and evapotranspiration, for the period of January 2001 – December 2023 for the study area is 332 mm/yr. Uncertainty is larger than previously reported, which reflects the variation of the input data of rainfall and evapotranspiration.

These rainfall-recharge data will be used in further numerical groundwater-flow modelling of the study area.

5.0 Recommendations

This study developed a rainfall-recharge model that best represents the dynamics of land-use change at appropriate resolution, the best available accuracy and with estimates of uncertainty that can be used in a groundwater model and other future work. In having done so, it also comes with recommendations for further research. These are described below.

Three virtual locations were identified as suitable for comparison of the satellite-derived evapotranspiration products. Ideally, validation takes place at *in situ* observations of evapotranspiration. However, these data were not available to this study at this time. Ground-observed data from a research programme 'Forest Flows', led by Scion (now part of the Bioeconomy Science Institute), exists for the approximate period 2021–2023, but agreed access to this data could not be arranged within the timeframe of this research. We recommend a follow-up study where Forest Flows data are analysed for their feasibility to act as validation data and, if so, a subsequent validation study.

The sophistication of the weighted-model scheme for recharge was simplified. The use of actual validation data would make for a more defensible weighting scheme. However, no ground-observed recharge was available in this study. We recommend that future studies explore the use of validation data, if available then, in a more advanced weighting scheme. For example, the above 'Forest Flows' data, or the collection of new data, such as from the installation of lysimeters, might provide valuable validation data.

Rainfall data of VCSN, rainfall-radar and climate stations were compiled to monthly before the KGE goodness-of-fit estimation. This was mainly because using daily data came with a significantly lower KGE score (in between 0.1 and 0.2) for both VCSN and radar rainfall, yet both simulations (VCSN and radar rainfall) compared well with one another (KGE score ~0.7). Reasons for this discrepancy, for example, difference in timing of data collection, are yet unresolved, and we recommend investigating this as a future research topic.

We recommend the use of rainfall radar as an alternative input to VCSN data once these data have been operationalised. We found that radar rainfall has a higher goodness-of-fit with the weather stations in the study area. Rainfall radar might potentially be able to characterise rainfall with superior spatio-temporal detail compared to current VCSN data. However, rainfall-radar data are not yet operational: we found small errors in the data, and up-to-date data provision has not yet been operationalised. For example, some errors were spotted for the years 2022 and 2023, which will need to be investigated by the provider. It was decided to not include these years of radar-rainfall data in the recharge analyses.

With the results of this study, rainfall recharge is modelled at the daily time-step. It is therefore better able to represent the effect of short-term high-rainfall events. Given that some extreme rainfall events in Northland took place in the years 2022 and 2023, we recommend that, if corrected rainfall-radar data were to be provided in the near future, rainfall radar be used to analyse more in depth as to how to use these data in a better estimate of rainfall recharge during extreme events.

If climate-change analyses were to take place in the study area in the near future, it is relatively straightforward to implement climate-change scenarios and re-run the developed recharge models of this study. Using the developed coding infrastructure is therefore recommended for future climate-change analyses.

6.0 Acknowledgements

The authors thank the two reviewers for improvements made to the report. The input and enthusiasm from Susie Osbaldiston and Hagen Robertson, Northland Regional Council, has been hugely appreciated in developing successful project results.

The authors would also like to thank Christian Zammit (Earth Sciences New Zealand, NIWA Business Unit) for provision of the updated – augmented – VCSN data for Northland and Luke Sutherland-Stacey (Weather Radar) for the fruitful discussion on the rainfall-radar data and improvements needed.

In developing the rationale for the multi-model mean estimates, we have benefited from useful discussions with Mathijs van den Adel (Wageningen University, currently working at Resilience BV, Netherlands) who, in 2022, successfully completed an MSc thesis internship at GNS Science.

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APPENDICES

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APPENDIX 1 Kling-Gupta Efficiency Score

The explanation of Kling-Gupta Efficiency (KGE) components was informed by information provided by Anthropic's Claude AI assistant (accessed 17 April 2025).

KGE (Gupta et al. 2009) is a goodness-of-fit measure that provides a balanced assessment considering not only correlation (which traditional metrics often emphasise) but also whether a model reproduces the correct volume (bias) and dynamics (variability) of observed data.

1. **Pearson correlation coefficient (r):** The linear relationship between observed and simulated values. A perfect value of $r = 1$ and ranges from -1 to 1. Higher values indicate better timing alignment between observed and simulated data.
2. **Variability component (alpha):** The ratio of standard deviation (stdev) of simulated to observed values, i.e. $\text{stdev}(\text{simulated}) / \text{stdev}(\text{observed})$. A perfect value of $\alpha = 1$ and ranges from 0 to ∞ . Alpha can be interpreted as:
 - **alpha = 1:** The model correctly reproduces the variability of observations.
 - **alpha < 1:** The model under-estimates variability (simulated values have less spread).
 - **alpha > 1:** The model over-estimates variability (simulated values have more spread).
3. **Bias component (beta):** The ratio of means of simulated to observed values, i.e. $\text{mean}(\text{simulated}) / \text{mean}(\text{observed})$. A perfect value of $\beta = 1$ and ranges from 0 to ∞ . Beta can be interpreted as:
 - **beta = 1:** The model correctly reproduces the mean of observations.
 - **beta < 1:** The model under-estimates the mean (systematic negative bias).
 - **beta > 1:** The model over-estimates the mean (systematic positive bias).

The KGE combines these components into a single metric:

$$KGE = 1 - \sqrt{[(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2]}$$

KGE values range from $-\infty$ to 1, where:

- **KGE = 1:** Perfect match between observed and simulated.
- **KGE = 0:** Simulations are no better than using the mean of observations.
- **KGE < 0:** Poor performance.

APPENDIX 2 Satellite Maps of Case-Study Data





2015



2016





2018







2021





2023





earthsciences.nz