Rangitāiki Tarawera Whakatāne Transient Groundwater Model

IZ125900-A.CS.EV.160-NW-RPT-0001 | 2

15 November 2021

Bay of Plenty Regional Council

Rangitāiki Tarawera Whakatāne Transient Groundwater Model

Project No: IZ125900
Document Title: Rangitaiki Tarawera Whakatane Transient Groundwater Model
Document No.: IZ125900-A.CS.EV.160-NW-RPT-0001
Revision: 2

Date: 15 November 2021
Client Name: Bay of Plenty Regional Council

Project Manager: Pride Mangeya
Author: Mauricio Taulis and Brian Barnett
File Name: IZ125900-A.CS.EV.160-NW-RPT-0001_REV2

Jacobs New Zealand Limited

Carlaw Park
12-16 Nicholls Lane, Parnell
Auckland 1010
PO Box 9806, Newmarket
Auckland 1149
New Zealand
T +64 9 928 5500
F +64 9 928 5501
www.jacobs.com

Document history and status

Revision	Date	Description	Author	Checked	Reviewed	Approved
0	30/04/2021	Draft calibration report	MT, RW		BB	
1	10/05/2021	Reviewed calibration report	MT, RW		BB	GH
2	15/11/2021	Amended Report reporting addressing reviewer comments	MT, BB	PM	PM	PM

Contents

Executive Summary

Introduction

Jacobs New Zealand Limited (Jacobs) was engaged by Bay of Plenty Regional Council (BoPRC) to update the existing Steady State model of the Rangitāiki Tarawera Whakatāne Water Management Area (RTW Model), to convert it to transient state, and to develop two additional (transient) model predictions (MP6 and MP7). The aim is for these predictions to inform the groundwater allocation process for groundwater management zones within the existing model area. These additional model predictions will help estimate the maximum groundwater available for allocation for each management zone, without triggering environmental impact criteria (aimed at limiting the amount of stream baseflow reduction and potential seawater intrusion).

Transient model conversion

The transient RTW model has the same spatial domain, numerical grid and layer structure as the existing Steady State model. In addition, although this model is set up in transient mode, it includes the same Steady State boundary conditions for rivers, drains, constant head boundaries (CHB), and general head boundaries (GHB) as those used in the original Steady State model. The only transient features included in the RTW transient model are the spatially distributed recharge and groundwater pumping from extraction wells.

The RTW numerical groundwater model was developed using the three-dimensional (3D) finite difference MODFLOW simulation code. The model framework was constructed with Hydrostratigraphic Unit (HSU) vertical discretization and the simulation was executed using the MODFLOW-USG solver (USGS, 2019). A total of six HSUs (HSU1 to HSU6) have been set up in the model to represent aquifer units.

The transient calibration period, determined by the available observed data, is from 1 December1984 to 1 December 2016, employing a total of 256 stress periods (32 years).

The recharge rates used in the RTW transient model were based on lysimeter data previously analysed during Steady State model construction (Jacobs, 2019). Following discussions with BoPRC, it was agreed to define recharge in two model zones based on ground elevation and with rates obtained from two lysimeters, one considered typical of the coastal plain and alluvial valleys and the other typical of elevated inland areas. The maximum ET rate was estimated by the average annual evaporation rate over the whole model domain (0.002 m/day). This evapotranspiration value was applied for each of the stress periods with an extinction depth of 2 m (consequence of calibration).

Pumping information was not available for years prior to 2011. Meter readings for the years between 2011 and 2017 were used to estimate the historical take volume for years prior to 2011 and for those wells without metered readings.

Transient calibration

Calibration has been undertaken to select a combination of parameters and boundary conditions that are suitable for use in predictive models. The transient calibration was performed manually to match calculated groundwater heads and river baseflows with historic observations over a period of about 32 years. As the original Steady State RTW Model has been well calibrated against the average groundwater level (1.9% RMSE), the transient calibration mainly focused on matching the temporal variations of groundwater head with water level observations.

Calibration was achieved by adjusting river conductance, hydraulic conductivity and storage parameters (specific yield and specific storage). A value of 4.0E+04 m^2/d for river conductance was selected during calibration. For

hydraulic conductivity, calibration values vary from 0.5 m/day to 600 m/day. Both Hydrostratigraphic Units HSU1 and HSU6 exhibit the lowest values whereas HSU2 features the highest values. Sedimentary units (HSU1 and HSU4) consist of fine sediments which would explain the relatively low hydraulic conductivity values whereas the Basement unit (HSU6) consists of greywacke and other low-porosity pre-Quaternary lithologies. In general, volcanic units (HSU2, HSU3, and HSU5) have hydraulic conductivities ranging from 10 to 600 m/day.

Transient calibration of the Rangitāiki Tarawera Whakatāne model (RTW Model) has produced statistics and residuals that are very similar to the Steady State model (RMSE 1.7% Transient vs 1.9% Steady State). In general, transient hydrographs and seasonal trends for both heads and baseflow show that the calibration is successful at matching observed historic values. It is noted however that the model does not replicate the observed seasonal fluctuations in head observed in some wells – however for a model of this size and given the objectives of assessing sustainability of groundwater extraction, such fluctuations are of little importance. The model exhibits most attributes of a Class 2 Confidence Level Classification under the Australian Groundwater Modelling Guidelines (Barnett et al, 2012).

Model Predictions

Two model predictions have been assessed (MP6 and MP7), to characterise aquifer response to groundwater extraction (over a period of 18 years) at the currently consented use (MP6), and to estimate extraction in excess of the currently consented rates (MP7).

<u>Model Prediction 6 (MP6)</u>

MP6 considers wells pumping at their maximum consented rate (Qmax) and assesses baseflow reduction and coastal heads against Environmental Triggers. This prediction assesses the spatial distribution of drawdown and provides an estimate of groundwater allocation for groundwater management zones (default HSU zones). Baseflow reduction estimates were obtained by comparing the modelled baseflow for MP6 with that of the null scenario – the same model with no groundwater extraction. In general, for river reaches receiving baseflow contribution (reaches 2, 4-8) baseflow reduction ranges from 0.01% to 1.2% when the model includes pumping at the maximum consented rate. Predicted coastal heads, apart from a couple of exceptions at specific moments in time, were higher than -0.5 m Moturiki for all observation wells in layers 1 and 2. In addition, MP6 has identified five areas of interest (zones A-E) where drawdown could potentially impact users within the Rangitāiki Plains.

A mass balance analysis using the MODFLOW's USG Zone Budget tool was carried out for the 6 HSU zones included in the model. Recharge is the highest in HSU6 (1,036 Mm^3/year), HSU2 (892 Mm^3/year), and HSU3 (665 Mm^3/year) which is not surprising as these zones correspond to major units present at the surface over extensive areas within the model domain. Well extraction is the highest in HSU 1 (26 Mm^3/year) and HSU 2 (8 Mm^3/year). HSU 1 corresponds to superficial Holocene deposits present in the Rangitāiki Plains, Taneatua, Waiohau, and Galatea basins. In addition, the mass balance shows losses to coastal discharge (constant heads) mainly occurring in HSU 5 (356 Mm^3/year) and HSU 2 (271Mm^3/year). Total coastal discharge from all zones is about 709 Mm^3/year.

<u>Model Prediction 7 (MP7)</u>

MP7 involved multiple model runs with increasing groundwater production above the maximum rate of consented extraction for all pumping wells, until baseline Environmental Triggers are breached. Baseflow reduction does not increase significantly at 1.5 times Qmax (1.5Qmax) but for subsequent increments (2Qmax and 4Qmax) baseflow reduction tends to nearly double each time. In addition, coastal heads tend to decrease as pumping increases with only few coastal observation wells having heads lower than -0.5 m Moturiki at 1.5Qmax. At pumping increments higher than 1.5Qmax coastal heads tend to decrease significantly. Therefore, 1.5Qmax has been identified as the maximum rate of groundwater extraction that will not trigger the prescribed environmental limits. In terms of drawdown, it is noted that the area of the 0.5 m drawdown contour previously identified with MP6 (A-E) has expanded by approximately 200 m with MP7.

MP7 has resulted in an estimate of additional groundwater allocation for the 6 HSUs, with wells pumping at 1.5Qmax. The increase in allocation in the HSU's with the greatest current allocations is about 12 Mm^3/year in HSU1 (Superficial Holocene Deposits in the Rangitāiki Plains and Galatea basins) and about 4 Mm^3/year in HSU2 (Upper Volcanics) in which extraction wells are located to the south of the Rangitāiki Plains and in deeper sections of the Rangitāiki Plains and Galatea basins. The remaining HSUs hold either no additional allocation or an additional extraction less than 0.4 Mm^3/year.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to assemble and calibrate a transient groundwater flow model of the Rangitāiki Tarawera Whakatāne Water Management Area(s), and to carry out two model scenarios (MP6 and MP7), in accordance with the scope of services set out in the contract between Jacobs and the Bay of Plenty Regional Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate, or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from information sourced from the Client and available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations, and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures, and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context.

1. Introduction

Jacobs New Zealand Limited (Jacobs) recently developed a regional Steady State groundwater flow model of the Rangitāiki Tarawera Whakatāne Water Management Area (RTW Model) for Bay of Plenty Regional Council (BoPRC) and used it to predict potential long-term impacts of groundwater take scenarios on groundwater levels and baseflow to rivers in the area. A total of 5 model predictions were reported using the model (Jacobs, 2019).

Since the writing of the Steady State report, BoPRC has requested updating the existing Steady State model by implementing a transient calibration with additional (transient) model predictions.

This report outlines specific details of model design, construction, and calibration associated with the transient RTW transient model. These details refer to specific differences between the Transient and the Steady State model as well as new transient model definitions and assumptions (presented in sections 3.2 - 3.7 below).

2. Objectives

The modelling objectives are:

- To improve confidence in model predictions by undertaking a transient calibration that illustrates the model's ability to replicate historic groundwater head and baseflow responses.
- To undertake predictive analysis to inform the groundwater allocation process.
- To estimate the maximum groundwater available for allocation, for each management zone in the model domain, that can be sustained without triggering environmental impact criteria aimed at preventing unacceptable baseflow reduction and potential seawater intrusion.

3. Transient model design and construction

Converting the existing Steady State RTW Model to transient has involved defining transient stresses (annual pumping rates and recharge) and calibrating the model according to transient observations (groundwater level and stream flow). It is noted that transient data within the Rangitāiki Tarawera Whakatāne is scarce, which hinders the calibration process. It is expected that BoPRC will re-calibrate this model in the future, once sufficient transient data are collected.

3.1 Steady state to transient conversion

The construction and calibration of the previous Steady State RTW Model is documented in Jacobs (2019). Model conceptualisation, including a detailed study of groundwater levels, hydraulic properties, recharge, groundwater use, and surface hydrology is presented in the 2019 report.

The RTW transient model has the same layer structure, numerical grid, and layer type as the original Steady State model. Although this model is set up in transient mode, it includes the same Steady State boundary conditions for rivers, drains, constant head boundaries (CHB), and general head boundaries (GHB) as the original Steady State model. The transient stresses in the RTW transient model are rainfall recharge and pumping from extraction wells.

3.2 Model code

The RTW numerical groundwater model was developed using the three-dimensional (3D) finite difference MODFLOW simulation code. The model framework was constructed with Hydrostratigraphic Unit (HSU) vertical discretization and the simulation was executed using the MODFLOW-USG solver (USGS, 2019). MODFLOW was developed by the United States Geological Survey (USGS) and is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. Groundwater Vistas (version 7.24 build 260), a software package developed by Environmental Simulations Inc., was used as a graphical user interface for pre- and post-processing of model inputs and outputs.

3.3 Model stratigraphy

The model consists of 10 layers which are used to host the Hydrostratigraphic Units (HSUs) present within the RTW model area. To work within an HSU vertical discretization approach, layers were assigned a fixed thickness whereas the last layer, layer 10, was defined as having variable thickness. The top of layer 1 follows the topographic surface so the tops of layers 2-8 are offset by 50 m each (e.g. each of these layers is 50 m thick). Layer 9 has a thickness of 200 m but, as the bottom of the model (bottom of layer 10) has a fixed elevation (-1,500 mRL), Layer 10 has a variable thickness (from 950 to 1,487 m). The actual HSUs (e.g. hydraulic properties) were assigned to this layer framework using the actual depths of hydrogeologic units in the GNS (2014) geological model. In other words, these HSUs were defined based on grouping similar units identified in the GNS (2014) geological model and the known aquifer parameters of the geological units. These HSUs were defined in the Steady State report (Jacobs, 2019) and are shown in **Figure 1** and **Table 1**.

While the representation of thin hydrogeological units within a 50 m thick model layer may be problematic, thickness weighted averaging of hydrogeological parameters can be applied to account for the presence of multiple overlapping units in a single model layer if necessary. The relatively coarse, near surface model layer structure is not expected to adversely impact the model's ability to simulate groundwater interactions with surface water bodies including rivers and streams. The layer thickness is still small compared to the horizontal grid cell dimensions (200 m by 200 m) and the assumption that head responses from surface water bodies propagate to depths of up to 50 m is not unreasonable.

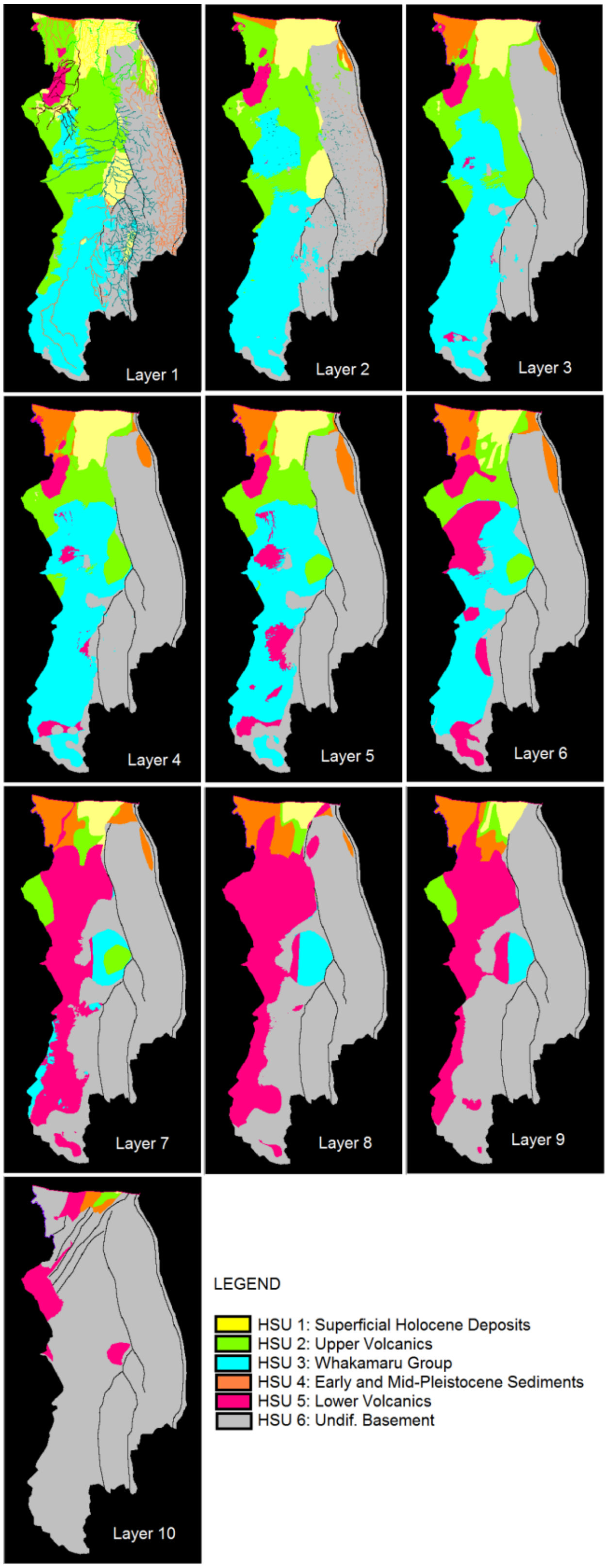


Figure 1. HSU zones present in model layers

Table 1. MODFLOW HSU units used in the RTW numerical model

HSU	HSU Name	Geological unit	Geological description
1	Superficial Holocene deposits	Superficial non-marine deposits, Q1 marine sediments, Q2-Q4 non-marine sediments, Q5 marine sediments, Q6-Q8 non-marine sediments, Tauranga Group Alluvium	Shallow deposits of variable lithologies, beach ridge deposits, shells in pumiceous marine sands, silts and sands with some gravels, terrestrial sediments, volcanoclastic silts and sands with some gravels in places (Tauranga Group Alluvium)
2	Upper volcanics	OMER, Q1-Q4 undifferentiated pyroclastics, Kaingaroa Formation, Matahina Formation, Youngest Okataina Rhyolites	Various types of ignimbrite deposits resulting from the Earthquake Flat Formation eruption, the Rotoiti Formation eruption, the Taupo Caldera eruption, and the Reporoa Caldera eruption.
3	Whakamaru Group	Whakamaru Group, Taupo Group in Upper Rangitāiki	Voluminous welded ignimbrite deposits found in valleys and grabens of older volcanic units. The Whakamaru Ignimbrite is commonly rose-coloured, soft and contains up to 10% of pumice clasts (GNS, 2010/113)
4	Early and Mid-Pleistocene sediments	Early/Mid-Pleistocene sands/gravels, Mid-Pleistocene mudstones, Tauranga Group (sand and gravel)	These units include volcanic debris reworked by fluvial processes (sand and gravel). Although this unit is expected to be permeable, mudstones may control this permeability in places.
5	Lower volcanics	Oldest Okataina Rhyolites, Old undifferentiated volcanics, Aongatete Formation, Other Volcanics	Oldest rhyolites pre-dating the Matahina Ignimbrite. Outcrops are located outside of the Matahina and Rotoiti calderas, but downfaulting or erosion are likely to have buried or removed these deposits within the caldera boundaries. Groundwater flow in all of the rhyolites is fracture dominated. However, permeability may vary as flow is affected by the size and amount of fractures and the linkage between them. The Aongatete Formation consists of Andesitic lava flows with subordinate dacitic unwelded ignimbrite.
6	Undifferentiated Basement		Greywacke basement and other pre- Quaternary lithologies

3.4 Stress period setup

Eight stress periods per year (refer to **Table 2**) were defined for the transient calibration period based on seasonal rainfall variability and the frequency of groundwater takes during the year (**Figure A.1, Appendix A**). During each stress period all time dependent stresses (i.e. recharge and groundwater extraction) are assumed to be constant.

Table 2. Transient calibration stress period set up

Season	Months	Stress Period	Stress Period Duration (Days)
Summer	December	1	31
	January	2	59
	February		
Autumn	March	3	31
	April	4	30
	May	5	31
Winter	June	6	92
	July		
	August		
Spring	September	7	30
	October	8	61
	November		

The transient calibration period, determined by the available observed data, is from 1 December1984 and1 December 2016, employing a total of 256 stress periods (32 years).

3.5 Recharge

The recharge rates included in the RTW transient model are based on lysimeter data previously analysed during Steady State model construction (Jacobs, 2019). There are two lysimeters within the model area: 1) Hogg Rd lysimeter located south of the Rangitāiki Plains and assumed to provide quantitative recharge data for superficial Holocene deposits, and 2) Kokomoka Rd lysimeter located in the Upper Rangitāiki area providing recharge estimates for the Whakamaru Group and Undifferentiated Basement deposits. Following discussions with BoPRC, it was agreed to distribute recharge rates obtained from these lysimeters throughout two zones (**Figure 2**):

- Zone 1: This is a zone delimited by the 200 m Moturiki topographic contour line and represents basins and coastal areas where superficial Holocene deposits are present.
- Zone 2: This zone represents elevations higher than 200 m Moturiki and represents recharge in the Upper Volcanics, Whakamaru Group, and Undiff. Basement units.

In summary, average recharge rates from lysimeter data were expressed as a percentage of measured rainfall, and these percentages were used to estimate recharge rates across the entire recharge Zone on a monthly and seasonal basis as per **Table 3** within the model area. Thus, the measured monthly rainfall was multiplied by the lysimeter estimated recharge percentages for each zone, and this resulted in transient, spatially varying recharge datasets for the calibration period.

Groundwater recharge rates are likely to be influenced by the surface soils and outcropping geology, land use (including irrigation and frost protection) and elevation. Further refinement of the model should consider how the spatial variability of these features can be incorporated in the distribution of recharge across the model domain.

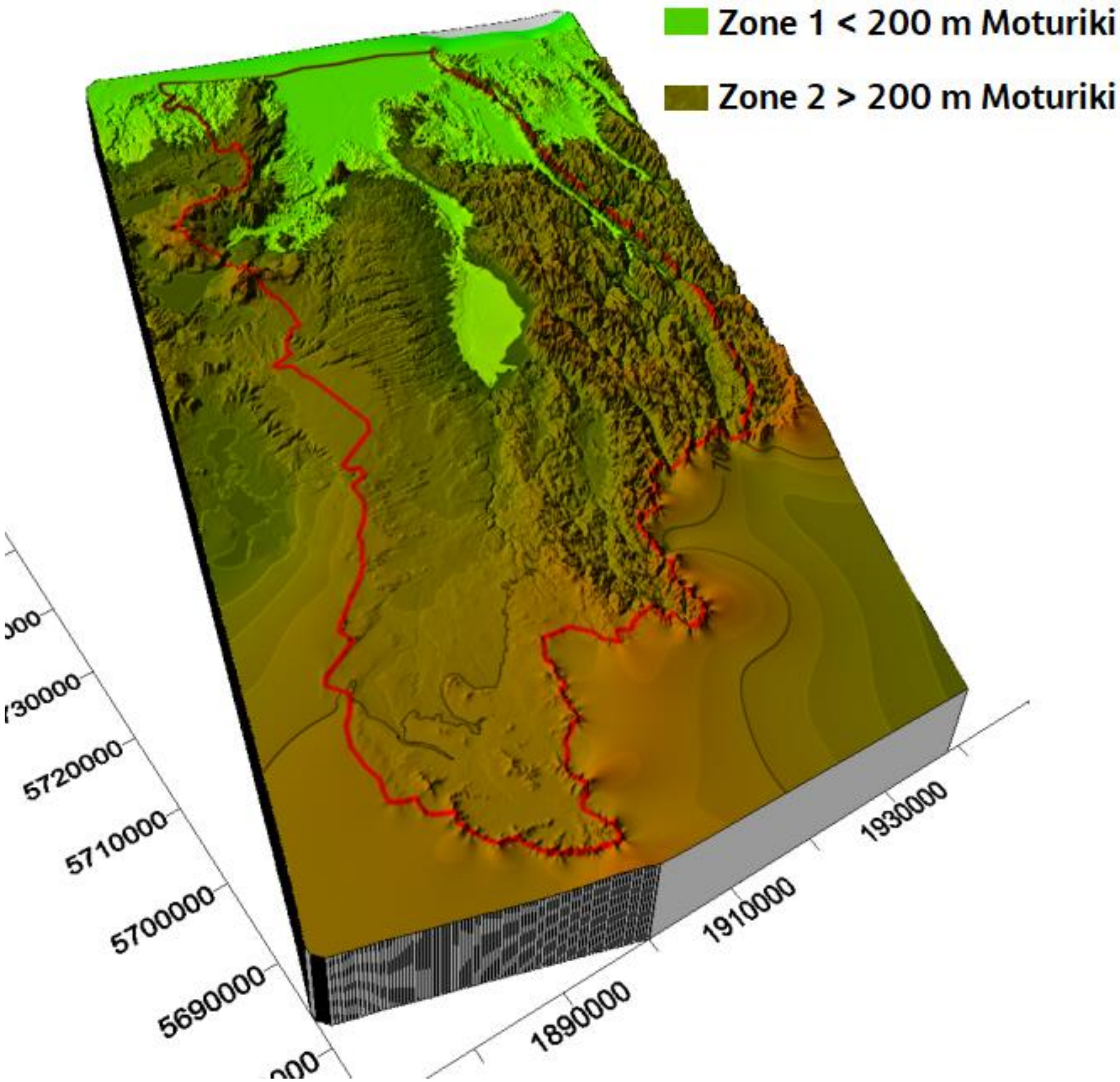


Figure 2. Recharge zones within the RTW model domain

Table 3. Recharge as % of precipitation for all months and seasons, within the RTW model domain

Season	Period	Zone 1 (elevation < 200 m Moturiki)	Zone 2 (elevation > 200 m Moturiki)
Summer	December	16%	6%
	January	8%	13%
	February	54%	5%
	Seasonal	**30%**	**8%**
Autumn	March	61%	2%
	April	88%	0.4%
	May	32%	47%
	Seasonal	**71%**	**20%**
Winter	June	80%	79%
	July	77%	72%
	August	62%	77%
	Seasonal	**77%**	**76%**
Spring	September	64%	69%
	October	46%	41%
	November	14%	34%
	Seasonal	**45%**	**48%**

3.6 Evapotranspiration

The MODFLOW evapotranspiration package (EVT) assumes a linear relationship between groundwater contribution to evapotranspiration (ET) and the depth of the water table. This package represents losses from shallow groundwater to evaporation and plant transpiration. The ET rate is at its maximum value if the water table is at or above the ground surface and, as the water table drops below the ground surface, the ET rate simulated by the model linearly decreases until the water table falls to the extinction depth (i.e. the depth of water table at which ET is no longer possible) is reached.

Evapotranspiration from groundwater is thought to occur at low elevations because groundwater is near the surface and vegetation (including trees, native vegetation and grasses) can access the shallow water table. In the RTW model, evaporation processes represented with the EVT package provides a natural control on groundwater levels. Evapotranspiration is included to act as a constrain on groundwater level elevations, because the groundwater domain is covered by vegetation.

ET inputs to MODFLOW are the maximum ET rate and the extinction depth. The maximum ET rate was estimated by the average annual evaporation rate over the whole model domain (0.002 m/day). This evapotranspiration value was applied for each of the stress periods with an extinction depth of 2 m (consequence of calibration).

3.7 Groundwater takes

The location and consented rates of groundwater takes has been previously discussed in the Steady State calibration report (Jacobs, 2019) where it is noted that extraction volumes exceeded the consented volumes in only three active consents.

Pumping information was not available for years prior to 2011. Meter readings for the years between 2011 and 2017 were used to estimate the historical take volume for years prior to 2011 and for those wells without metered readings.

A summary of the actual pumping schedule (from 1985 to 2016) is presented in **Table 4**, **Figure 3**, **Figure 4**, and **Figure 5**. The estimated annual groundwater production for frost protection (1985 -2016) was 1.7 Mm^3/year (**Table 4**). The majority of groundwater extraction for frost protection occurs in the Rangitāiki Plains. **Figure 3** shows the location of the most significant frost protection extraction, which tends to occur in the southern section of the Rangitāiki Plains where the superficial Holocene deposits tend to thin out.

Table 4 also shows that the estimated average annual groundwater extraction for irrigation (1985 – 2016) was 8.3 Mm^3/year. The majority of groundwater extraction for irrigation occurs in the Rangitāiki Plains but some extraction also occurs in the Galatea Basin. **Figure 4** shows the location of the most significant irrigation extraction wells in the Rangitāiki Plains. The highest extraction occurs in the south west of the Rangitāiki Plains with well 4964 extracting an average of 1.2 Mm^3/year. Near the coast, wells 4872 and 3371 extract an average of 0.37 and 0.34 Mm^3/year respectively. About 6.5 km south of these coastal wells, well 11192 extracts about 0.44 Mm^3/year.

Table 4 also shows that the estimated average annual groundwater extraction for irrigation (1985 – 2016) was 7.6 Mm^3/year. The highest annual extraction is about 2.5 Mm^3/year for well 4724. The remaining wells (36) extract an average of about 0.1 Mm^3/year (representing a total extraction of 5.1 Mm^3/year).

The model does not include non-consented takes associated with stock-and-domestic groundwater use. These takes are expected to be negligible when compared to the groundwater extractions that support irrigation and frost protection discussed above.

3.8 Boundary conditions

The steady state model boundary conditions are described in detail in Jacobs, 2019 and simulate:

- groundwater exchange with formations surrounding the model,
- groundwater flow to and from the ocean, and
- groundwater interaction with rivers and creeks.

Steady state boundary conditions have been carried forward as time constant boundary conditions into the transient model. Boundary conditions assume groundwater heads at mean sea level throughout the full thickness of the model at the shoreline. This assumption is not necessarily correct as deep aquifer units are expected to discharge some distance offshore and hence groundwater heads at the shoreline are expected to be above marginally above sea level. The current model will provide slightly conservative estimates in predictive analysis in that predicted heads in deep aquifers near the coast are likely to be marginally lower than if the model included boundary conditions that are more aligned with the conceptual understanding of where the deeper aquifers intersect the sea floor.

Table 4. Estimated actual pumping (Mm^3/year) for the years between 1985 and 2016 (32 stress periods). The pumping has been allocated to wells completed in corresponding model layers.

Take category	Model layer	Mm3/year
Frost	1	0.3
	2	0.5
	3	0.3
	4	0.4
	5	0.0
	7	0.1
	9	0.0
Frost total		**1.7**
Irrigation	1	2.2
	2	2.7
	3	1.5
	4	0.9
	5	0.6
	7	0.2
	9	0.3
Irrigation total		**8.3**
Municipal/other	1	2.8
	2	3.0
	4	1.3
	6	0.2
	7	0.3
	10	0.0
Municipal/other total		**7.6**
Grand Total		**17.6**

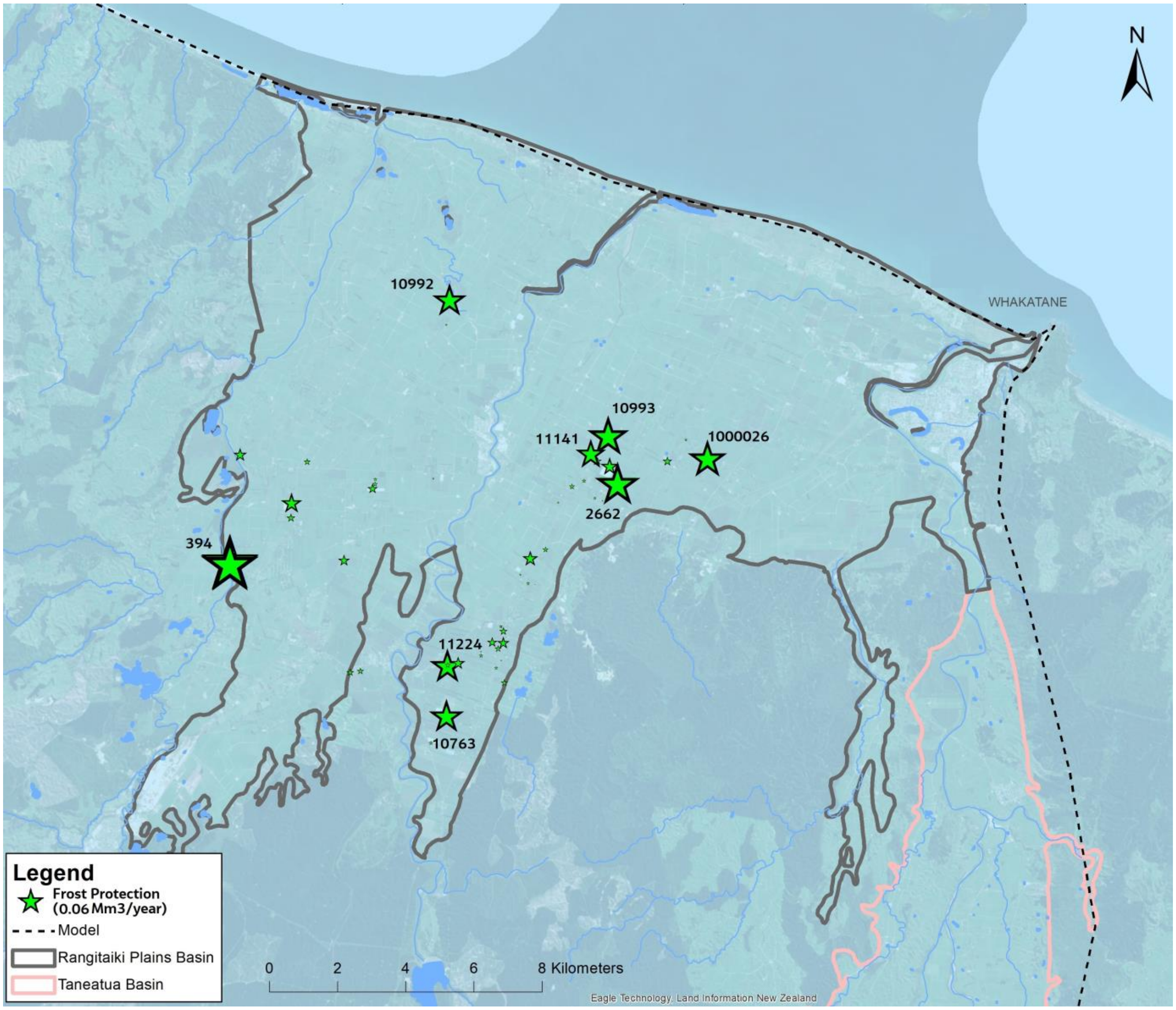


Figure 3. Frost protection wells in the Rangitāiki Plains. The symbol size is proportional to their annual groundwater extraction in Mm^3/year.

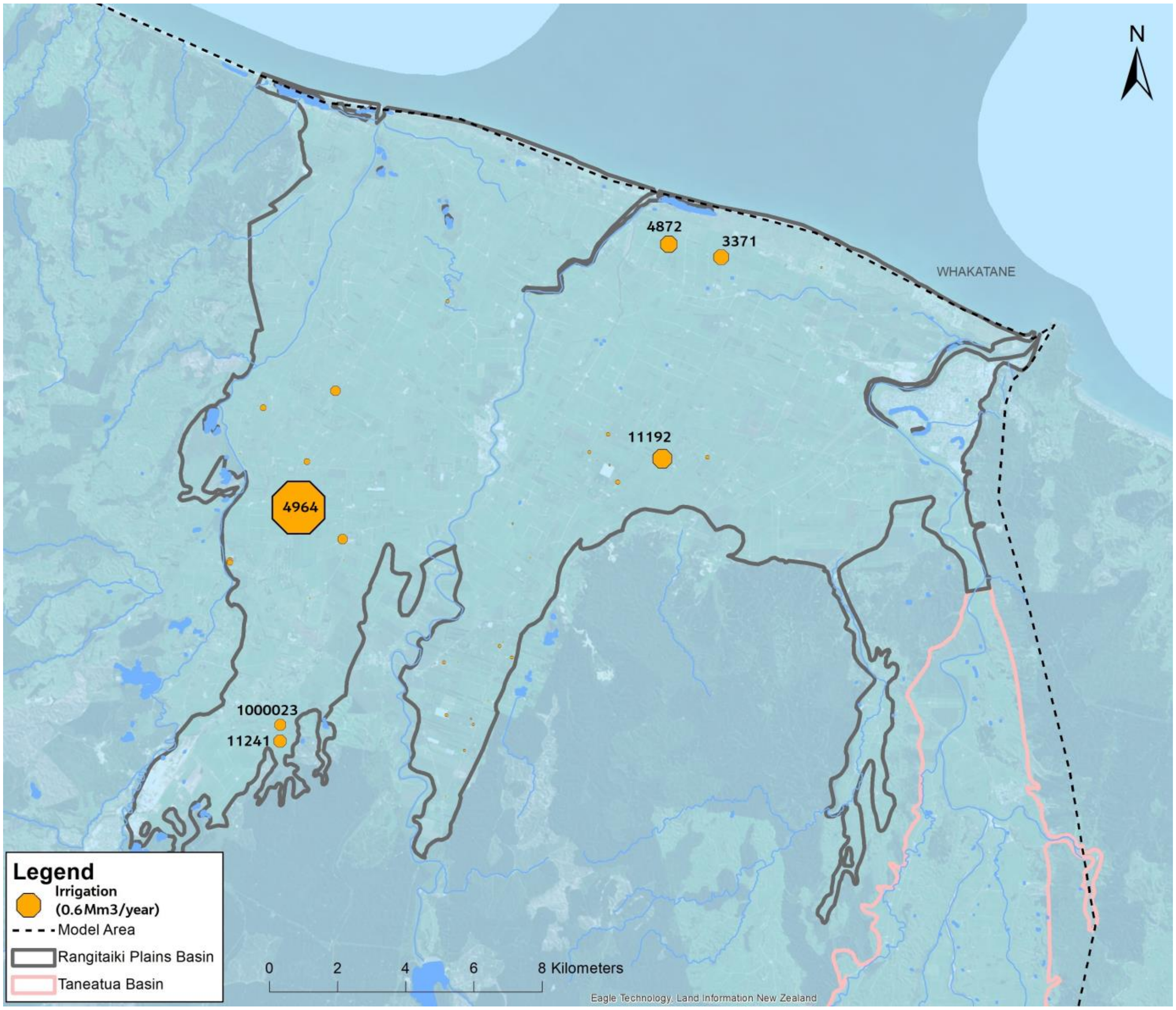


Figure 4. Irrigation wells in the Rangitāiki Plains. The symbol size is proportional to their annual groundwater extraction in Mm^3/year.

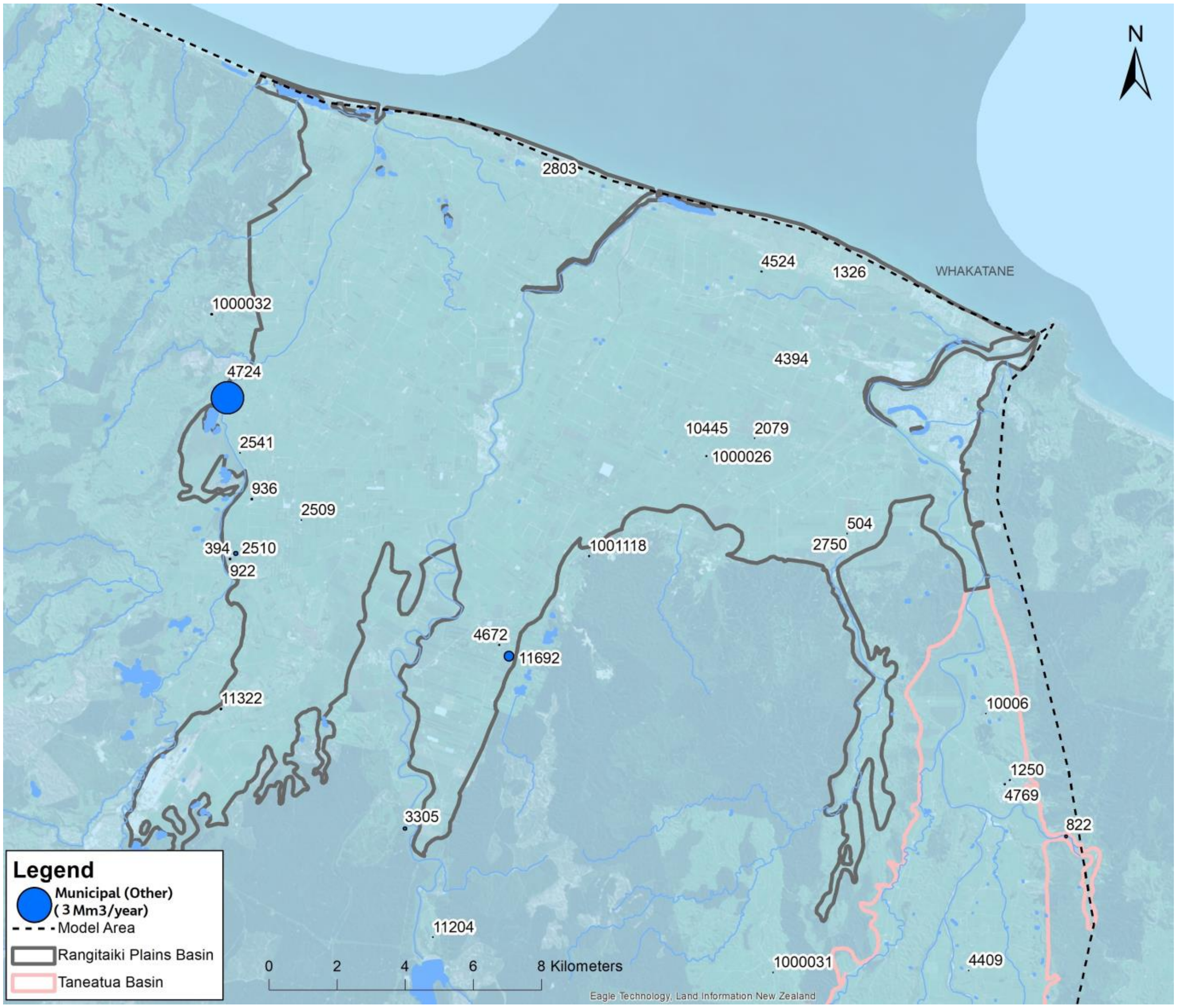


Figure 5. Municipal/Other extraction wells in the Rangitāiki Plains. The symbol size is proportional to their annual groundwater extraction in Mm^3/year.

4. Transient Calibration

4.1 Procedure

Calibration has been undertaken to select a combination of parameters and boundary conditions that are suitable for use in predictive models. The method involves modelling historic conditions with iterative refinement of model parameters to optimise the match between model-predicted and observed groundwater behaviour. The transient calibration was performed manually to match modelled hydrographs for heads and river baseflows with historic observations. Location of observation wells and river gauging stations are shown in **Figure 6**.

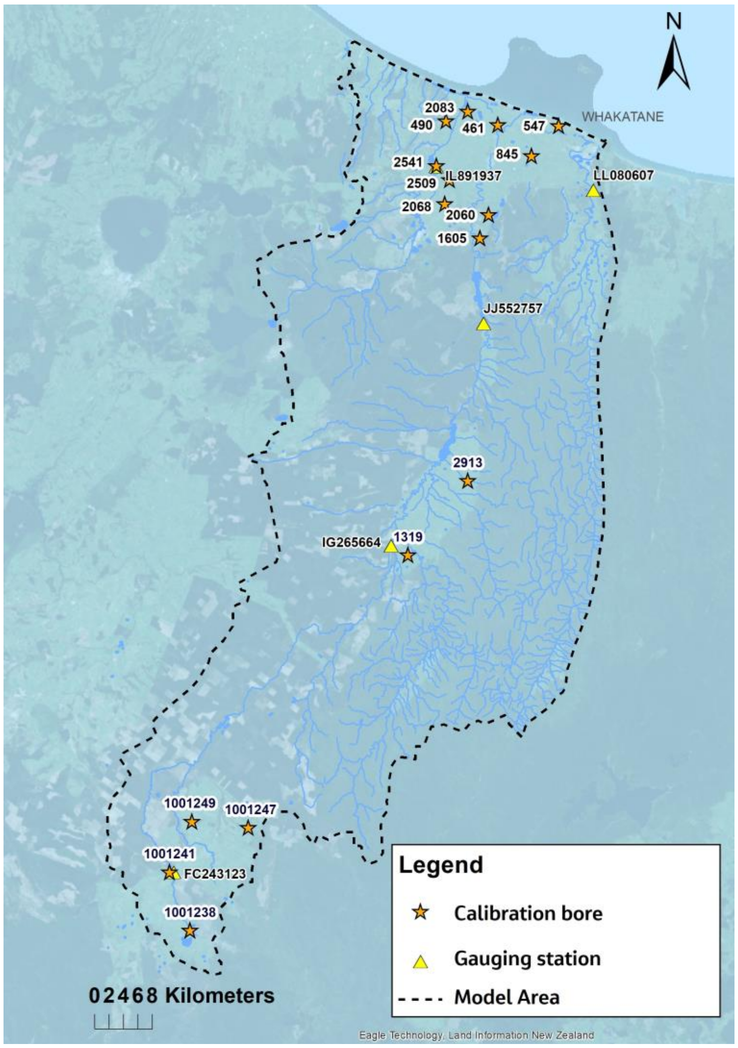


Figure 6. Location of observation wells and river gauging stations in the RTW model

4.1.1 Hydrograph calibration

As the original Steady State RTW Model has been well calibrated against the average groundwater level (1.9% RMSE), the hydrograph calibration mainly focused on matching the seasonal variations of groundwater head with water level observations. To achieve this, the parameters listed in **Table 5** were adjusted using a trial and error approach:

- Specific Storage was defined as 5e-6 which reflects the compressibility of water in the aquifer, and this is the principal contributor to the confined storage.
- Evapotranspiration Rate and Extinction Depth were reduced from 2.25e-3 m/d and 4m to 2.00e-3 m/d and 2m respectively, to reduce the magnitude of seasonal variations of modelled head. These parameters remained constant over the modelled period.
- Transient recharge data was calculated based on historical rainfall records. Assuming the Steady State recharge is equivalent to average rainfall, multipliers were applied to recharge rate at different stress periods. Spatial variation of recharge data in the calibrated Steady State model was maintained in creating transient recharge dataset.

Table 5. Adjusted parameters in hydrograph calibration

Parameters	Before calibration	After calibration
Specific Storage*	0.01	5e-6
Specific Yield	0.01	0.2
Evapotranspiration Rate	2.25e-3 m/d	2.00e-3 m/d
Evapotranspiration Extinction depth	4 m	2 m
Note: * Specific storage does not influence the steady state solution.		

Stage and conductance in river and drain cells were adjusted to obtain a better match between observed and calculated groundwater heads.

4.1.2 River baseflow calibration

Before calibration, the computed river fluxes were generally below the baseflow targets. Therefore, a few parameters had to be adjusted to increase computed river fluxes to improve the match with baseflow targets (**Table 6**). River conductance was increased 4 to 57 times to 400,000 m^2/d for reach 6 and 40,000 m^2/d for all the other reaches, which is equivalent to a river bed hydraulic conductivity of 10 m/d for reach 6 and 1 m/d for all the other reaches. In addition, heads in river reach 6 and drain cells were dropped by 1 m to increase the computed river flux in the Rangitāiki Plains.

Table 6. Adjusted parameters in river base flow calibration

Parameters	Before calibration	After calibration
River conductance (reach 1)	2.00E+03 m2/d	4.00E+04 m2/d
River conductance (reach 2)	3.00E+03 m^2/d	4.00E+04 m^2/d
River conductance (reach 3)	1.00E+03 m^2/d	4.00E+04 m^2/d
River conductance (reach 4)	7.00E+02 m^2/d	4.00E+04 m^2/d
River conductance (reach 5)	1.00E+04 m^2/d	4.00E+04 m^2/d
River conductance (reach 6)	1.00E+04 m^2/d	4.00E+05 m^2/d
River conductance (reach 7)	1.00E+03 m^2/d	4.00E+04 m^2/d
River conductance (reach 8)	1.00E+04 m^2/d	4.00E+04 m^2/d
River conductance (reach 9)	1.00E+04 m^2/d	4.00E+04 m^2/d
River head (reach 6)	Steady state stage	Steady state stage -1 m
Drain head	Steady state invert	Steady state invert -1 m

4.2 Calibration results

4.2.1 Hydrograph calibration

The modelled and observed heads for the whole model domain are presented in the following figures:

- **Figure 7** (Calculated vs Observed Average Heads),
- **Figure 8** (map showing average residuals or differences between calculated and observed heads)
- **Figure 9** (water level hydrographs Rangitāiki Plains), and
- **Figure 10** (water level hydrographs Galatea and Upper Rangitāiki basins).

For most observation wells, the modelled hydrographs match with the observation reasonably well in terms of both average values (**Figure 7**) and seasonal variation range (**Figure 9** and **Figure 10)**. It is noted that the model does not replicate the observed seasonal fluctuations in head which is observed in some wells, such as well 461 and 2913, however for a model of this size and given the objectives of assessing sustainability of groundwater extraction on a regional scale, such fluctuations are of little importance. The calculated Root Mean Square Error (RMSE) is 1.7% is well within commonly used benchmarks of 5% 10% (Barnett et al, 2012). Calibration residuals and the model's replication of observed hydrographs suggest a reasonably good level of calibration to heads on the coastal plain and particularly near the shoreline where sustainability drawdown criteria are assessed in the predictive analysis.

The map of average residuals (**Figure 8**) shows that calibration residuals tend to be low in lower Rangitāiki Plains and in the Galatea Basin. There are two wells with higher average transient calibration residuals in the Rangitāiki Plains: well 2541 (average residual = -14.8 m) and 2509 (average residual = -10.1 m). These wells are located to the south west of the Rangitāiki Plains in an area where the Superfical Holocene Deposits units tends to thin out.

In the Upper Rangitāiki area, wells 1001249 has an average transient residual of -20.3m and well 1001247 presents an average residual of -54.4m. The two remaining wells in this area have residuals ranging from -4.0 m to 2.5 m.

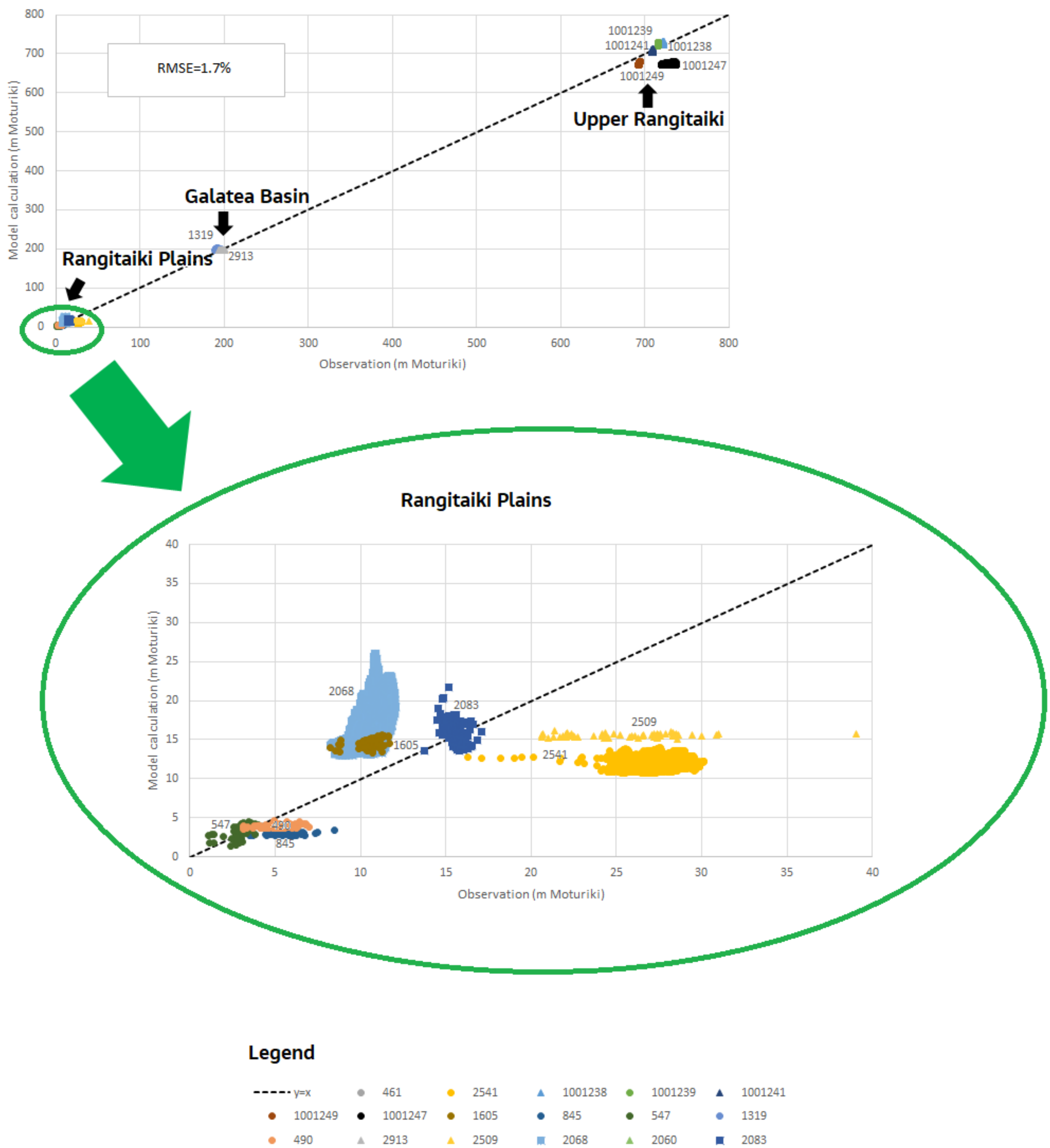


Figure 7. Modelled groundwater level plotted against observed groundwater level (Rangitāiki Plains, Galatea, and Upper Rangitāiki). The figure includes a zoomed inset of the Rangitāiki Plains area.

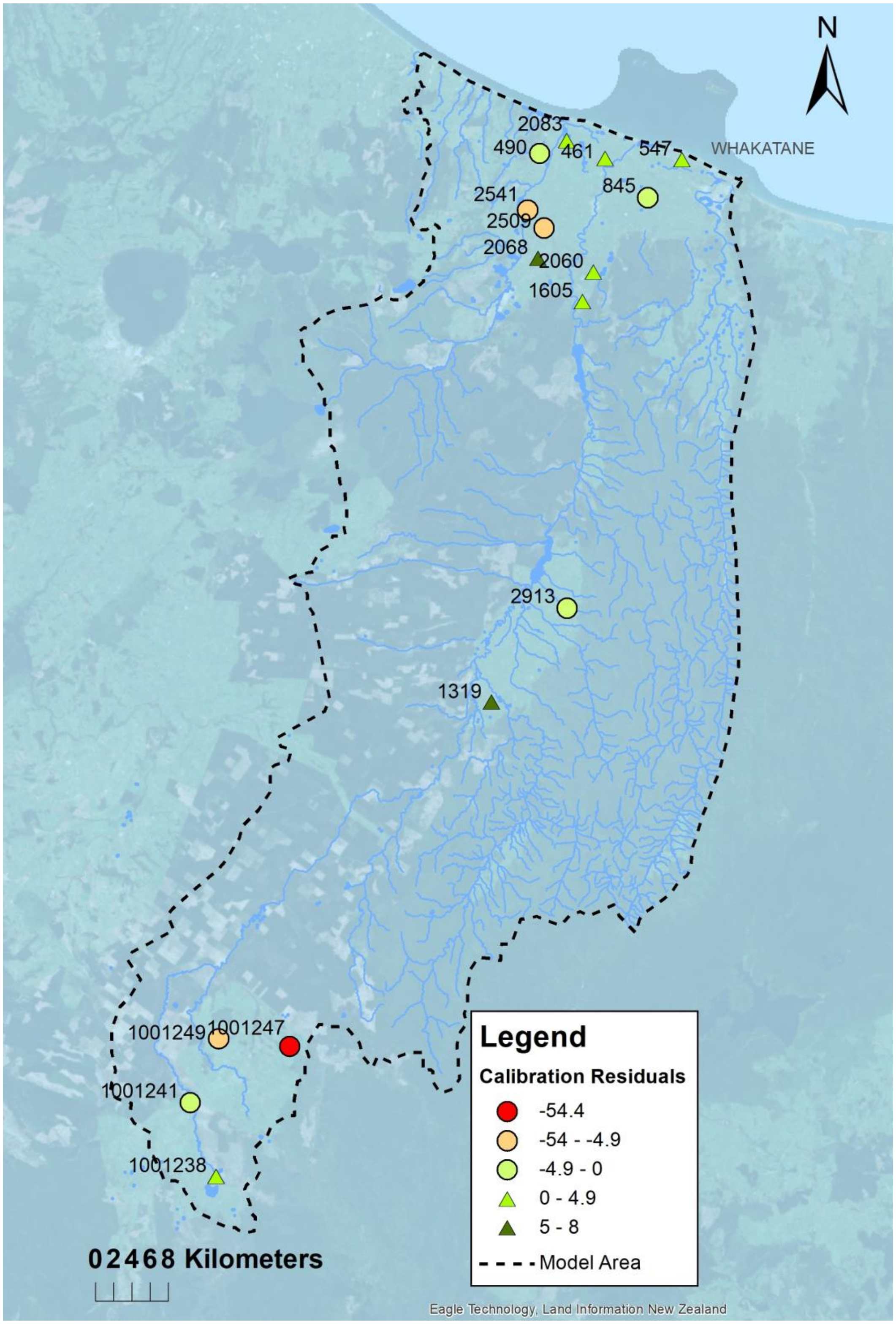


Figure 8. Calibration residual map for Transient calibration (average residuals as Calculated heads minus Observed heads).

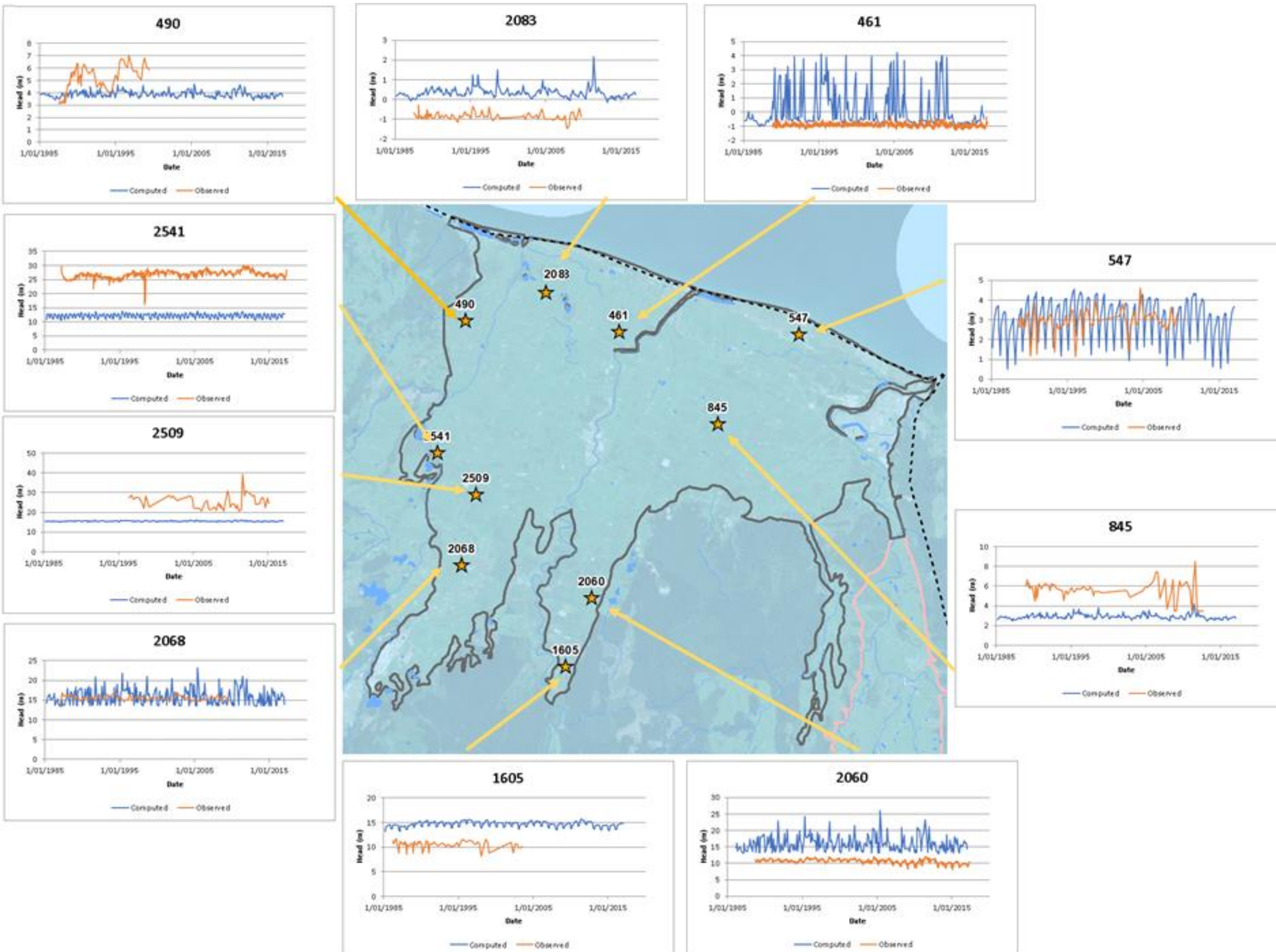


Figure 9. Hydrographs for calibration wells in the Rangitāiki Plains

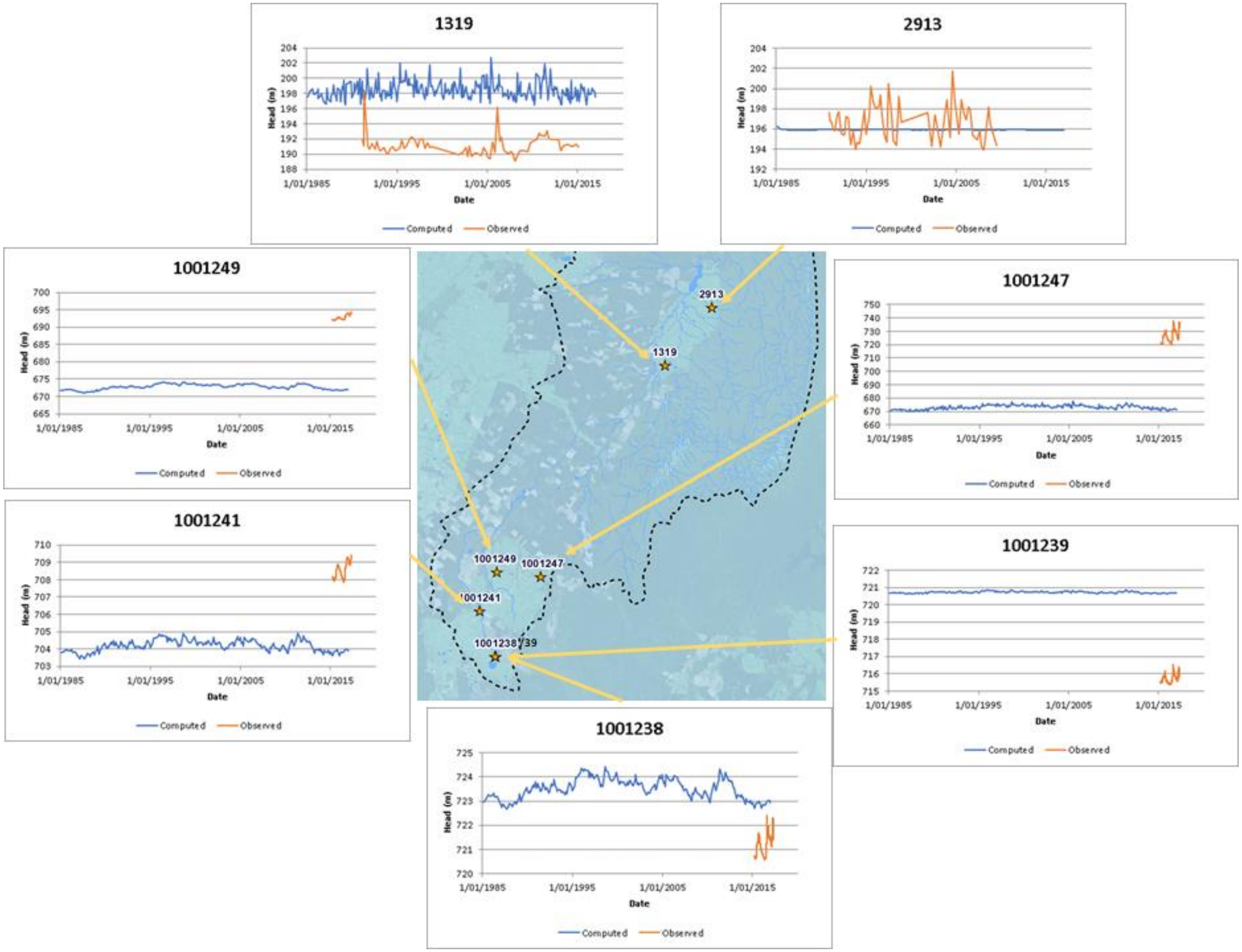


Figure 10. Hydrographs for calibration wells in the Galatea and Upper Rangitāiki basins

4.2.2 River baseflow calibration

The modelled and targeted river baseflow estimates are presented in **Figure 11** (baseflow hydrographs at five stations are shown) for comparison purposes. Calibration involved the comparison between the estimated baseflow at each of the gauging stations with the accumulation of groundwater fluxes to and from river boundary conditions upstream of the gauge. The modelled baseflows are around the lower end of the estimated historic river baseflows, and the estimated historic river baseflows vary over a larger range than the modelled baseflow. Targeted river baseflow values were estimated from gauging station river flux measurements, based on inherently uncertain baseflow separation assumptions. Considering the relatively slow speed of groundwater movement, it is unlikely that groundwater fluxes vary by an order of magnitude over a period of a few days as estimated baseflows indicate. The river cell conductance terms assigned to each river reach were refined during calibration to improve the match between the modelled baseflows and the lower end of the estimated river baseflow. Data required to provide alternative estimates of river losses and gains from multiple gauges on the same river reach were not available for conceptualisation or calibration purposes.

Calibration statistics for the match between modelled and measured baseflow have not been prepared because baseflow is not measured – it is calculated from measured river flow and the accuracy of the baseflow calculation can have a significant impact on the calibration statistics. As a result, baseflow calibration statistics are not just indicative of whether the model replicates observed response, but also influenced by the accuracy of the baseflow calculation.

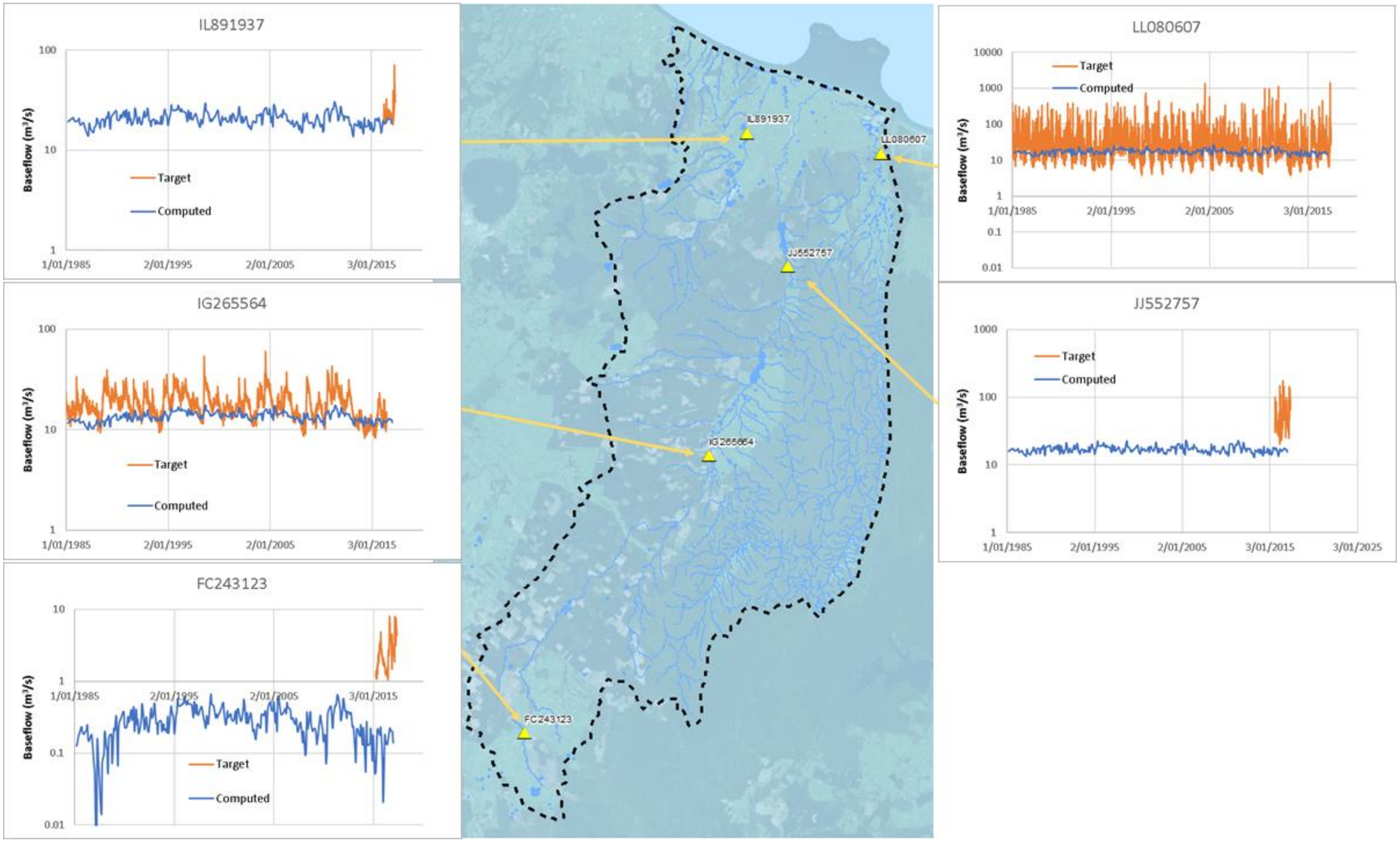


Figure 11. Computed river flux and target river flux comparison

4.2.3 Calibration Water Balance

The water balance from the calibrated groundwater model is presented in **Figure 12** and the average net flux is presented in **Figure 13**.

Figure 12 shows that river fluxes in and out of the groundwater system are significantly higher than other water balance components. River flux entering the groundwater system appears to be correlated with recharge throughout the simulation period. **Figure 12** includes the net river out flux rather than the individual river out and in components. Plotting of the river in and river out components separately produces inflated fluxes associated with simulated groundwater movement between neighbouring river cells that have different heads assigned to them. This is a modelling artefact in which the flow of groundwater that occurs along the course of the river and immediately below the river bed appears equally in both the river out and in components. Plotting the net river flux provides a better understanding of the quantum of river interaction with groundwater.

The net flux (**Figure 13**) was calculated by adding the average inflows (+) and outflows (-) between 1985 and 2016, and this resulted in a mass balance error of 0.03%. The average annual flow through the RTW model is about 21,671 M m^3/year. The main flux component into the model is recharge from rainfall (3,170 M m^3/year) and the main flux component out of the model is through rivers (2,177 M m^3/year) and discharge to the sea (modelled using Constant Head boundaries and having an average of 711 M m^3/year), followed by evapotranspiration (ET, 349 M m^3/year). In addition, inter basin flow (e.g. General Head Boundary condition on the shared border with Kaituna) is about 111 Mm^3/year. Groundwater abstraction, on average, accounts for about 0.08 % of the total fluxes out of model (18 M m^3/year). Average storage is about 64 M m^3/year (in) but it is noted that actual annual net flux storage varies significantly over the years (Min =-495M m^3/year, Max = 687M m^3/year and standard deviation =88 M m^3/year). These fluxes are consistent with the conceptual understanding of the system as outlined in the Steady State calibration report (Jacobs, 2019).

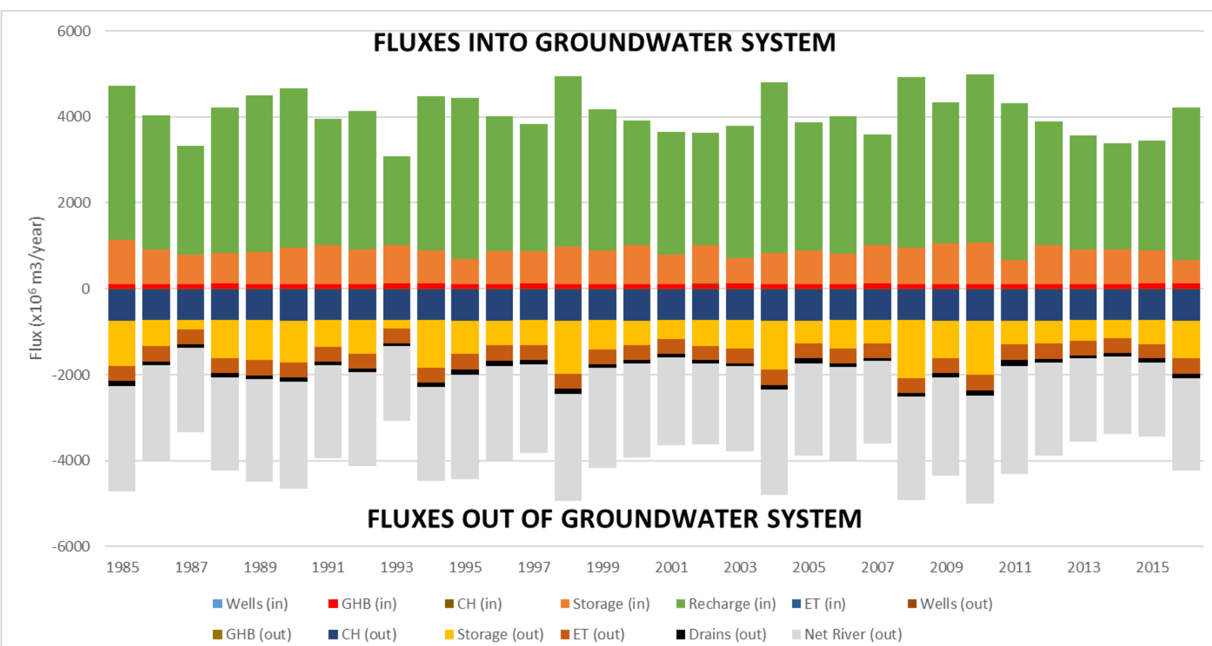


Figure 12. Model mass balance. Fluxes are presented as x10^6 m^3/year on the plot (CH = Constant Head, GHB = General Head Boundary, ET = Evapotranspiration).

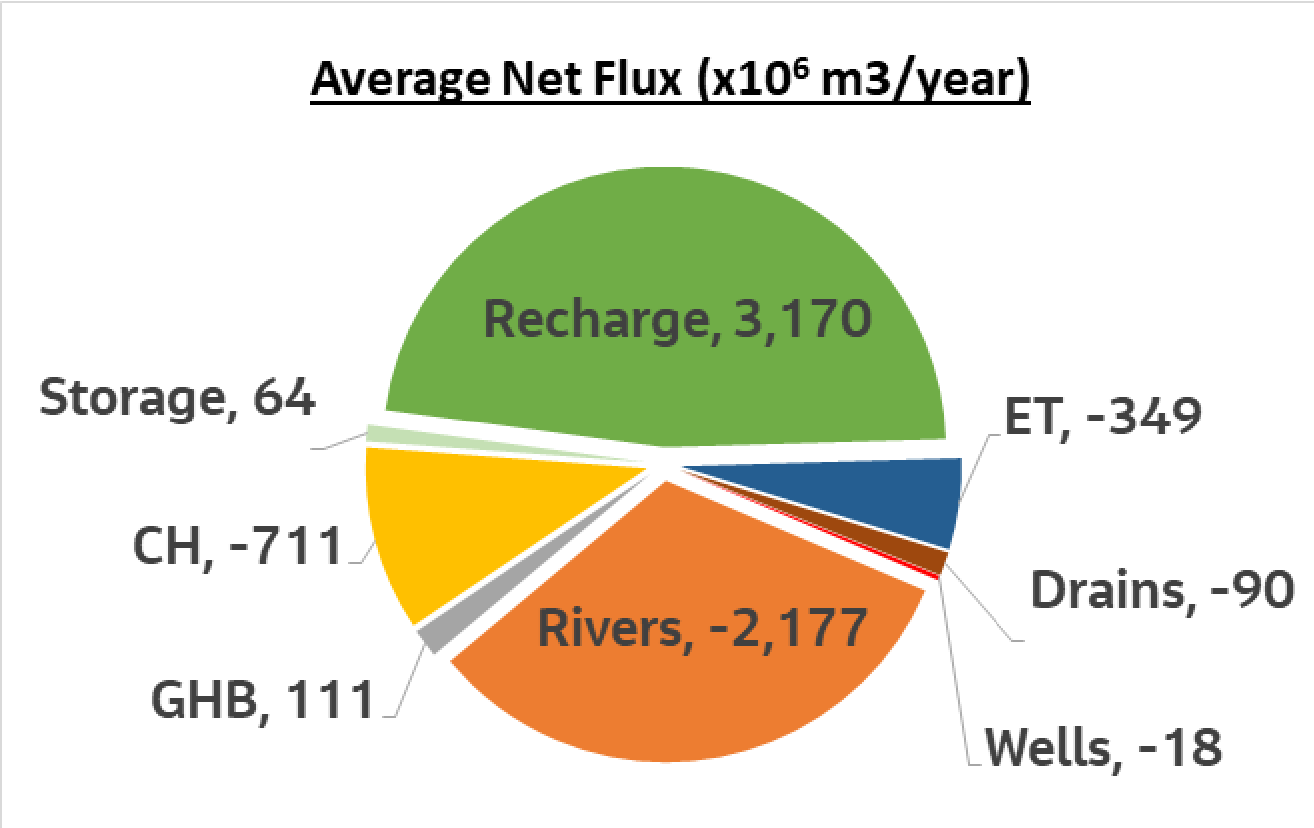


Figure 13. Net average flux for 1985 - 2016 (CH = Constant Head, GHB = General Head Boundary, ET = Evapotranspiration).

4.2.4 Model parameters obtained from calibration

Calibration to transient data sets was achieved with assumptions of parsimony and seeking the best fit to observations by varying hydraulic parameters for the six model HSUs (please refer to section 3.3). Transient calibration was carried out by adjusting hydraulic conductivity values as well as specific storage (Ss) and specific yield (Sy). In addition, river conductance values (see Section 4.1.2) were adjusted and a value of 4.00E+04 m^2/d was selected during calibration.

Table 7 presents the hydraulic conductivity values resulting from the calibration process. Horizontal hydraulic conductivity values vary from 0.5 m/day to up to 600 m/day. Both HSU1 and HSU6 exhibit the lowest values whereas HSU2 exhibits the highest values. Sedimentary units (HSU1 and HSU4) consist of fine sediments which would explain the low hydraulic conductivity values whereas the Basement unit (HSU6) consists of greywacke and other low-porosity pre-Quaternary lithologies. In general, volcanic units (HSU2, HSU3, and HSU5) have hydraulic conductivities ranging from 10 to 600 m/day. These high values are explained by the high porosity of ignimbrite and pumiceous materials present in these formations. In addition, anisotropy for most of these units is 10:1 (Kh:Kz) except for the Whakamaru Group (HSU3) which has an anisotropic ratio of 200:1 (Kh:Kz).

Transient calibration established that the best results were obtained by adopting the hydraulic conductivity values in **Table 7**, with Ss values of 5.0E-06 m^{-1} for all model layers. In addition, it was established that it was not necessary to modify recharge values to produce a good calibration (recharge multiplier = 1).

Table 7. Hydraulic conductivity values (m/day) for HSU zones throughout the model domain (Kh = horizontal hydraulic conductivity, Kv = vertical hydraulic conductivity).

HSU zone	Kh (m/day)	Kv (m/day)
HSU1 (Superficial Holocene Deposits)	0.5	0.05
HSU2 (Upper Volcanics)	600	60
HSU3 (Whakamaru Group)	10	0.05
HSU4 (Early and Mid-Pleistocene Sediments)	0.8	0.08
HSU5 (Lower Volcanics)	70	7
HSU6 (Undif. Basement)	0.5	0.05

5. Model Predictions

A series of five model predictions (MP1 – MP5) were previously carried out with the Steady State Model (Jacobs, 2019). These predictions were designed to simulate changes in the groundwater system in Steady State mode under various conditions. It is noted that the previously reported Steady State model is no longer consistent with the transient calibration and transient predictions.

This report presents two additional model predictions (MP6 and MP7), using the calibrated transient model, to assess maximum groundwater extraction and allocation without breaching environmental triggers.

5.1 Model predictions definition

This chapter presents two additional model predictions (MP6-MP7) developed following the calibration of the Transient Model. These two model predictions aim to characterise aquifer response to different levels of groundwater extraction (i.e. maximum consented extraction and pumping in excess of the maximum consented extraction). These two additional model predictions have been prepared for a predictive time frame of 18 years (145 stress periods). They are defined as follows:

- Model Prediction 6 (MP6). This scenario considers wells pumping at their maximum consented rate (Qmax) and assesses baseflow reduction and coastal heads against Environmental Trigger levels designed to minimise adverse environmental outcomes. The spatial distribution of drawdown has been assessed and provides an estimate of the impacts of the current allocation for individual groundwater management zones (default HSU zones).
- Model Prediction 7 (MP7). This model prediction focuses on increasing water production by progressively increasing Qmax (e.g. 1.5Qmax, 2Qmax, and 4Qmax) for all pumping wells, until baseline Environmental Triggers are breached. This results in an increased allocation estimate.

5.2 Model Prediction 6

5.2.1 Methodology

This model prediction was set up by having wells pumping at their maximum consented rate (Qmax) and having an additional run with no pumping to enable the calculation of drawdown. In addition, virtual observation wells were incorporated in the model in order to monitor heads by the coast. MP6 reports baseline Baseflow Reduction (%) values from stream and river reaches (no pumping vs Qmax). Also, heads at the coast (i.e. at new virtual observation wells at about 1 km from the coast) were used to inform the definition of baseline and environmental trigger levels to help prevent potential seawater intrusion. Environmental Triggers used in subsequent model predictions (e.g. MP7) were defined relative to modelled estimates of baseflow and heads with extraction set at current level of consent. **Figure 14** shows the wells (both pumping and observation wells), as well as the stream and river reaches for MP6.

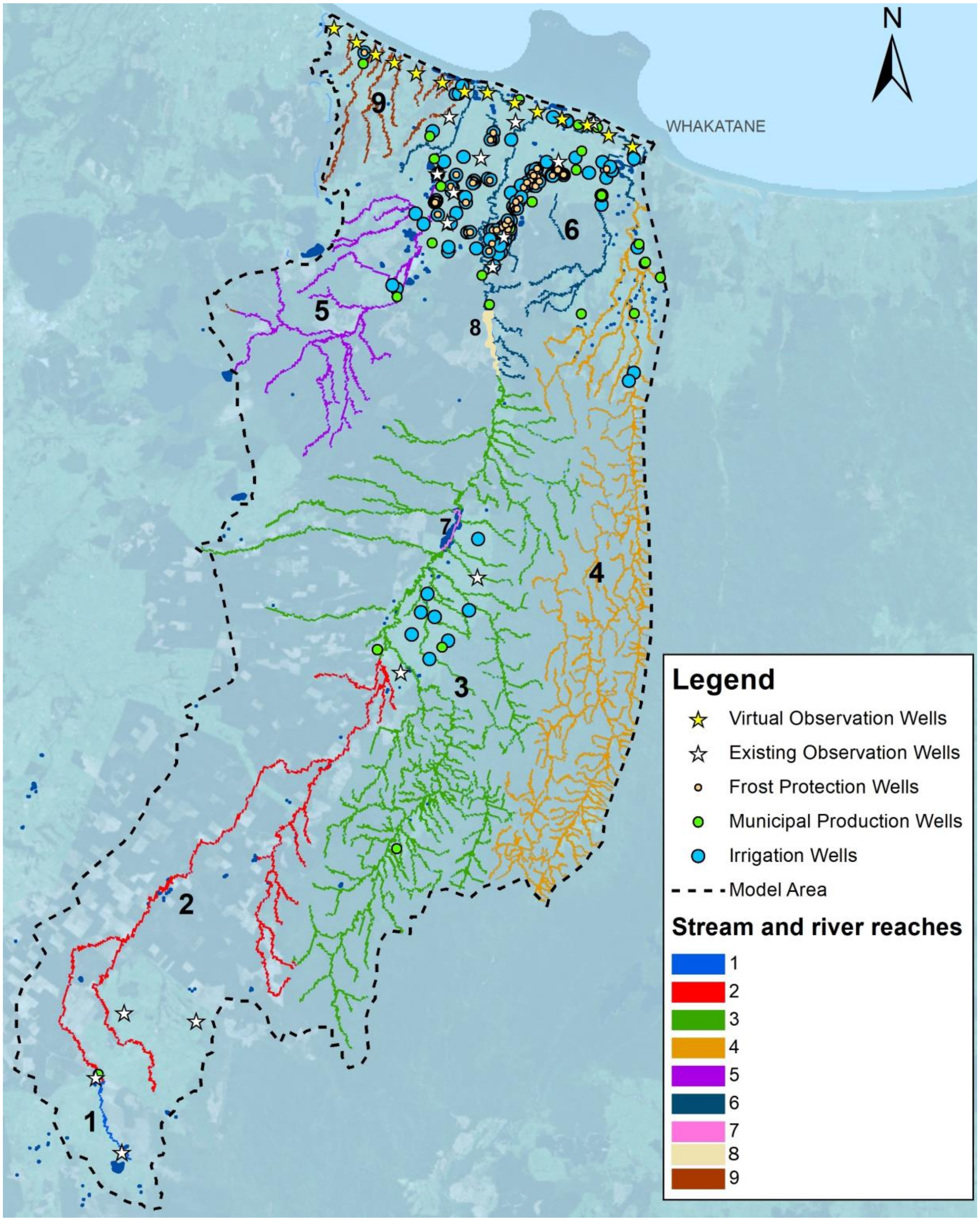


Figure 14. Pumping and observation wells within the model area. This figure also shows the stream and river reaches included in the model domain. Reaches 1 to 6 represent main rivers (Tarawera, Rangitāiki, and Whakatāne rivers) and associated streams. Reach 7 corresponds to the Aniwaniwa Lake and Reach 8 corresponds to the Matahina Lake at the Rangitāiki River.

This model prediction is used to assess the baseflow reduction criteria by establishing a baseline with existing wells pumping at Qmax. The following Environmental Triggers (sustainability criteria) have been prescribed by BoPRC:

- Minimal (less than 1%) baseflow reduction at stream and river reaches within the model domain (Figure 14); and
- Heads near the coast remaining above -0.5 m Moturiki for the shallow aquifer system

Model Prediction 6 also assesses the spatial distribution of drawdown when Qmax is considered and defines restricted zones based on the maximum drawdown delimited by a 0.5m drawdown contour.

Finally, this scenario provides a summation of the total current groundwater allocation from all HSU based zones. The groundwater zones for this water balance assessment are the 6 HSUs defined during the model construction stages (Jacobs, 2019). **Figure 1** shows the tops of these HSUs within the model domain for Layers 1 – 10. This figure shows that HSU 1 (Superficial Holocene Sediments) tends to be present for the most part in the Rangitāiki Plains and in the Galatea Basin (Layers 1-2). However, at depths greater than 100 m (e.g. Layers 3 -10), the Superficial Holocene Sediments become less prevalent. Similarly, the Whakamaru Group (HSU 3) and the Upper Volcanics Group (HSU 2) are present mostly in Layers 1 – 6. At depths greater than 300 m (Layers 7 -10), HSUs 2 and 3 tend to disappear. This figure also shows that at depths greater than 300 m the Lower Volcanics Unit (HSU 5) tends to be present along with the Basement Rocks (HSU 6).

5.2.2 MP6 Results

Impacts on rivers

Average groundwater-surface water interaction fluxes throughout the stream and river reaches is presented in **Table 8** for the two conditions being modelled: no pumping (Q=0) and wells pumping at their maximum consented rate (Q= Qmax). **Figure 15- Figure 17** show the modelled exchange fluxes for each of the reaches (reaches 1 -9) for the 18 years being modelled. Most river reaches are characterised as gaining streams (baseflow on average exceeds river seepage to groundwater), except for reaches 1, 3, and 9. Reach 1 is a short section (~10 Km) of the Upper Rangitāiki River and is predicted to be predominantly loosing (on average, river seepage to groundwater exceeds baseflow from groundwater discharge) at this location as shown by its predicted baseflow graph (**Figure 15**) which shows seasonal baseflow fluctuations ranging from -245 L/s to 620 L/s.

Reach 3 mostly represents streams located in the Ikawhenua Range to the east of Galatea, and streams in the range to the west of Galatea. Reach 3 is predicted to be predominantly losing (on average, -42,315 L/s at Qmax in **Table 8**) with predicted exchange fluxes varying from -50,847 L/s to -23,622 L/s as shown in **Figure 16**. This behaviour is not consistent with the conceptual model of the upstream river reaches where it is expected that the rivers and creeks drain steep alluvial valleys and interaction with groundwater would be dominated by groundwater discharge rather than recharge. The groundwater interaction with the rivers and creeks in this region may have been disturbed by groundwater extraction that causes additional losses from the rivers.

Reach 9 is a groundwater recharge source for the Rangitāiki Plains and this is evidenced by negative modelled river exchange fluxes (on average, -22,635 L/s at Qmax, **Table 8**) that range from -25,489 L/s to -12,054 L/s (**Figure 17**). This reach is on the coastal plain and coastal drainage systems and nearby groundwater extractions are likely to be contributing to the modelled losses from the river.

Reaches 2 and 4 – 8 have modelled river baseflow fluxes for every season over the 18-year period. This is consistent with river reaches receiving varying groundwater discharge fluxes as baseflow contribution. Average baseflow contribution for these reaches ranges from 9,948 L/s to 41,296 L/s with seasonal fluctuations presented in Figure 16 and Figure 17.

Table 8 shows the baseflow reduction and river seepage increase percentages caused by pumping at Qmax. These changes have been calculated by comparing the modelled exchange fluxes for the case in which wells are pumping against the case in which wells are not pumping. For rivers receiving baseflow contribution (Reaches 2 and 4-8) baseflow reduction ranges from 0.01% to 1.2%. Reaches 2, 4, 7 and 8 experience low baseflow reduction (<0.3%) while reach 6 experienced a 0.7% reduction and reach 5 a 1.2% reduction. Reach 5 represents the upper Tarawera River which is actually discharging into Reach 6 (lower Tarawera, Rangitāiki, and Whakatāne rivers). Most pumping wells are located within the Rangitāiki Plains so, when pumping takes place at Qmax, baseflow reduction for Reach 6 increases.

Table 8. Average baseflow for nil-pumping vs pumping at maximum consented rate (Qmax). Positive (+) values represent Gaining Streams, whereas negative (-) values represent losing streams.

Reaches	Baseflow with Q = 0 (L/s)	Baseflow with Q = Qmax (L/s)	Baseflow Reduction (%)
1	40.70	40.69	0.02
2	9,950	9,948	0.01
3	-42,181	-42,315	-0.3
4	15,759	15,716	0.3
5	24,801	24,507	1.2
6	30,059	29,854	0.7

7	11,188	11,175	0.1
8	41,321	41,296	0.1
9	-22,615	-22,635	-0.1

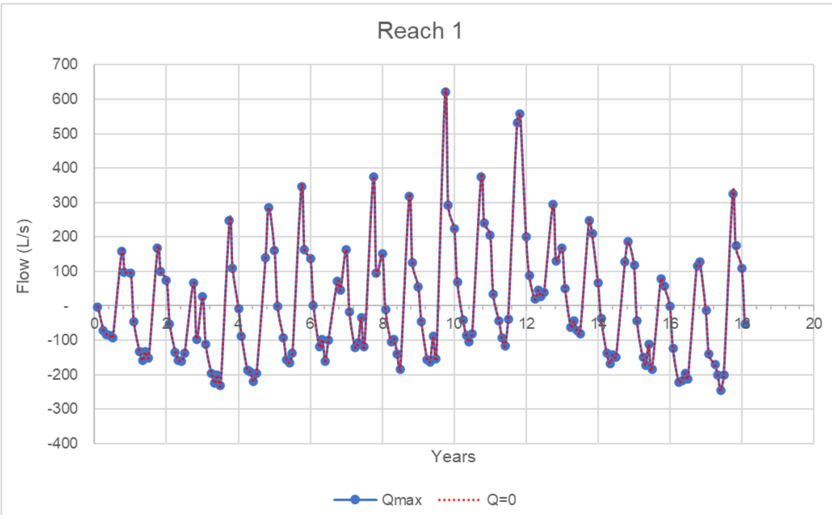


Figure 15. Baseflow for no pumping (Q=0) and pumping at the maximum consented rate (Q=Qmax) for reaches 1.

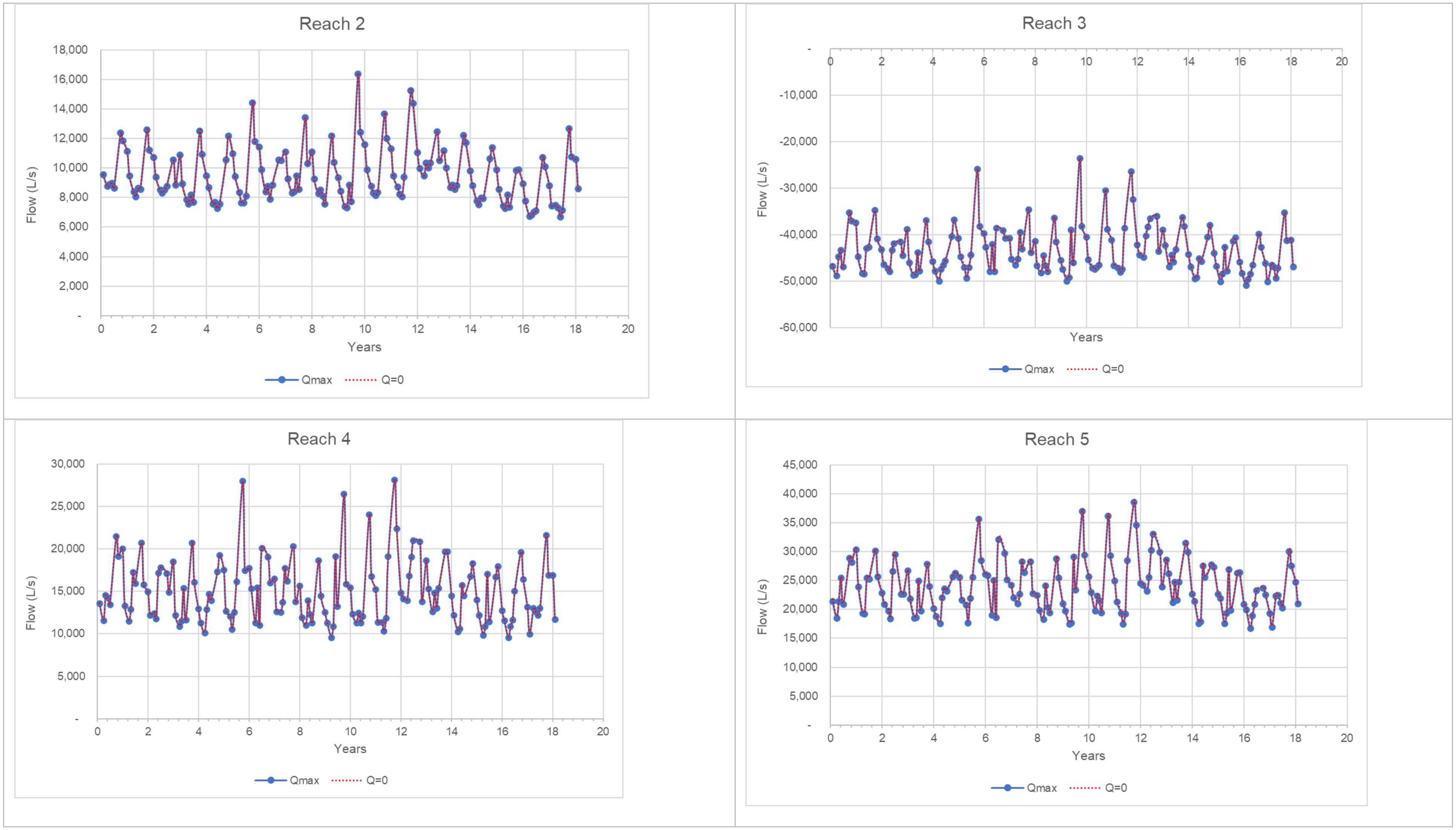


Figure 16. Baseflow for no pumping (Q=0) and pumping at the maximum consented rate (Q=Qmax) for reaches 2 -5

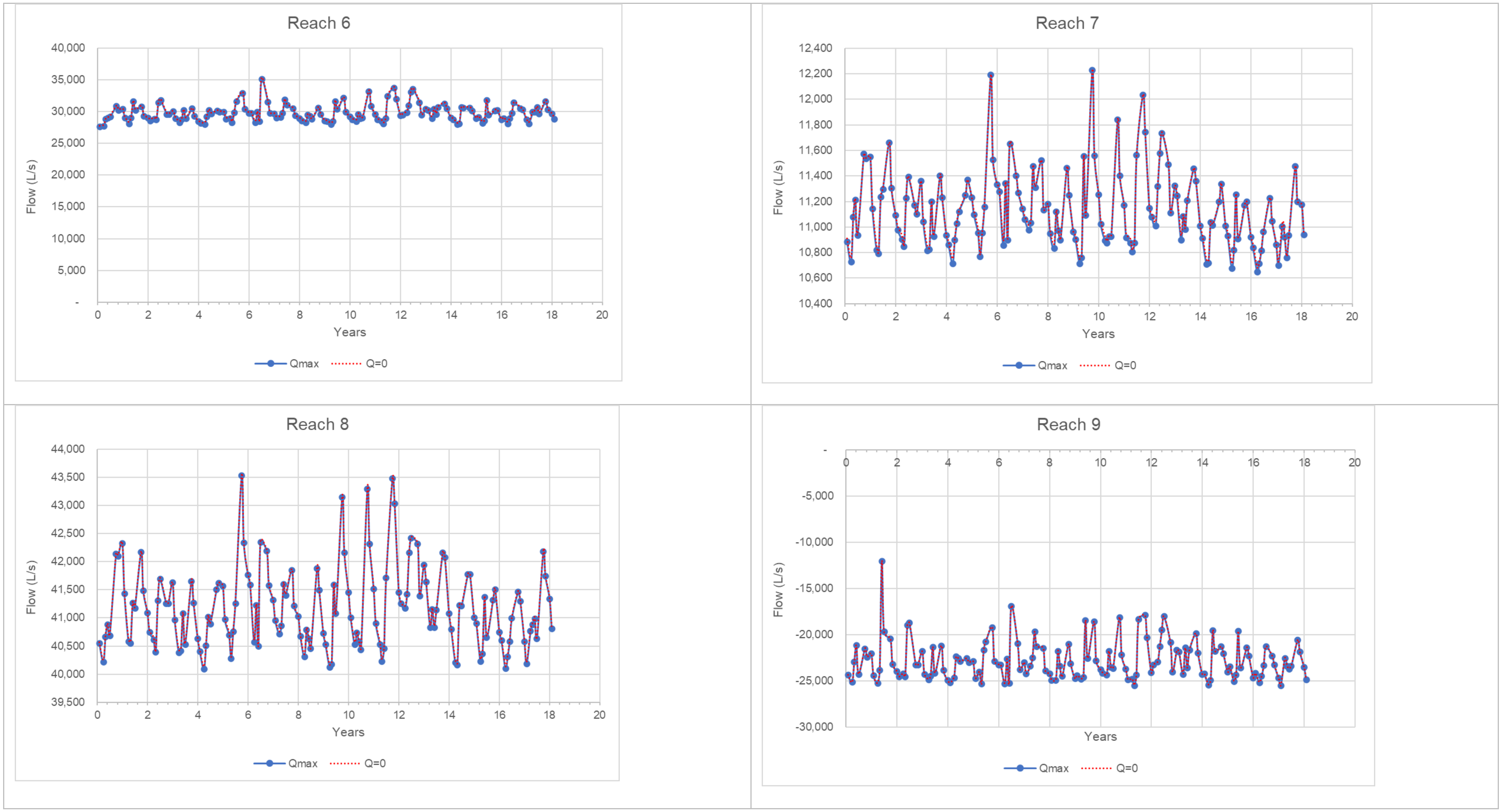


Figure 17. Baseflow for no pumping (Q=0) and pumping at the maximum consented rate (Q=Qmax) for reaches 6 -9

Drawdown assessment

Coastal Heads

Heads for coastal observation wells (existing and virtual ones) were analysed to assess whether the default Environmental Trigger condition (i.e. Heads near the coast remaining above -0.5 m Moturiki for the shallow aquifer system) prescribed by BoPRC was being fulfilled. The first 2 model layers were chosen for this assessment because these layers represent the shallow aquifer system most likely to be impacted by pumping. shows heads for layers 1 and 2 in virtual observation wells (VOB1 – VOB14) and two existing observation wells (OB461 and OB467). Virtual observations wells VOB1 -1 VOB14 are located at about 1km from the coast and are about 2km apart. OB547 and OB461 are located at about 630 m and 2.8 km from the coast, respectively. With a couple of exceptions, all coastal heads were higher than -0.5 m Moturiki for all observation wells in layers 1 and 2. The only exceptions are OB461 in layer 1 which has exhibited a minimum head of -1.0 m Moturiki but, on average, its heads are 0.8 m Moturiki. The other exception is OB547 at Qmax in Layer 1, which has exhibited a minimum head of -4.6 m Moturiki although its average is 1.4 m Moturiki. It is noted that this observation well is located in an area where drains are present, and this could have exacerbated the head drop whilst pumping was taking place, which is evidenced by its higher head (0.1 m) in layer 2 where no drains are present. In addition, VOB9 which is located between OB547 and the coast shows heads higher than -0.2 m Moturiki which is compliant with the prescribed trigger condition.

Table 9. Heads for coastal observation wells (m Moturiki) with no pumping and with wells pumping at their maximum consented rate. Values in red represent values < -0.5 m.

Well	Layer	Model run with nil pumping (Q=0)			Model run with wells pumping at Qmax		
		Min (m)	Max (m)	Average (m)	Min (m)	Max (m)	Average (m)
OB461	1	-1.0	5.2	0.8	-1.0	5.2	0.8
OB461	2	-0.4	8.7	1.3	-0.4	8.7	1.3
OB547	1	3.4	6.9	4.6	-4.6	5.3	1.4
OB547	2	2.6	5.2	3.5	0.1	4.4	2.4
VOB1	1	18.5	33.1	19.8	18.5	33.1	19.8
VOB1	2	18.1	24.5	18.8	18.1	24.5	18.8
VOB2	1	20.9	22.2	21.1	20.9	22.2	21.1
VOB2	2	20.0	21.2	20.2	20.0	21.2	20.2
VOB3	1	21.0	31.4	22.4	21.0	31.4	22.4
VOB3	2	20.9	23.9	21.5	20.9	23.9	21.5
VOB4	1	21.2	34.2	23.1	21.2	34.2	23.1
VOB4	2	21.0	25.1	22.2	21.0	25.1	22.2
VOB5	1	44.2	79.2	48.2	44.2	79.2	48.2
VOB5	2	44.0	68.9	47.3	44.0	68.9	47.3
VOB6	1	23.6	55.4	27.1	23.6	55.4	27.1
VOB6	2	23.3	40.9	25.6	23.3	40.9	25.6
VOB7	1	0.5	12.0	1.3	0.4	10.8	1.3
VOB7	2	0.5	7.7	1.1	0.5	6.9	1.1
VOB8	1	-0.4	6.1	0.4	-0.4	6.1	0.4
VOB8	2	-0.2	4.0	0.5	-0.2	4.0	0.5
VOB9	1	-0.2	11.3	1.3	-0.2	11.0	1.3
VOB9	2	0.3	8.8	1.6	0.3	8.5	1.6
VOB10	1	-0.2	2.7	0.4	-0.2	2.7	0.4
VOB10	2	-0.1	2.3	0.4	-0.2	2.2	0.4
VOB11	1	0.8	9.1	1.9	0.5	8.3	1.5
VOB11	2	0.8	7.2	1.6	-0.2	6.4	1.1
VOB12	1	2.9	9.4	4.0	2.9	9.0	3.9
VOB12	2	2.4	7.2	3.3	2.3	6.9	3.2
VOB13	1	0.6	7.0	1.7	0.6	7.0	1.7
VOB13	2	0.7	5.2	1.6	0.7	5.1	1.6
VOB14	1	0.0	7.8	1.1	0.0	7.8	1.1
VOB14	2	0.2	5.4	1.0	0.2	5.3	1.0

Spatial distribution of drawdown

Hydrographs showing modelled drawdown for layer 3 observation wells 845, VOB11, 547, 461, 2518, 2541, and 2509 (**Figure 18**) were analysed as a first step to examine the spatial distribution of drawdown in the Rangitāiki Plains. These observation wells were selected because a preliminary analysis indicated they were in close proximity to groundwater extraction wells and are expected to be within the cones of depression. Layer 3 was selected because the majority of the pumping wells are screened within this layer. Similarly, the analysis focused on the Rangitāiki Plains because most of the pumping wells are located within this basin, thus generating the highest drawdown within the model area (e.g. drawdown over large areas in the Upper Rangitāiki, Galatea, Waiohau, and Taneatua basins is not significant nor extensive).

Drawdown hydrographs for observation wells 845, VOB11, 547, 461, 2518, 2541, and 2509 are presented in **Figure 19** and **Figure 20**. These hydrographs exhibit drawdown fluctuations due to seasonal pumping, with the highest drawdown values generally occurring from January to March, and the lowest drawdown values occurring from September to December. The maximum drawdown values from these graphs is presented in **Table 10**. The wells exhibiting the highest drawdown are 2541 and 2509 (3.5 m and 4.6 m respectively) at stress period 138 (17.25 years). Although these wells are near existing pumping wells, it was checked that the cone of depression at 17.25 years is indeed the most extensive one. This check was carried out by visually inspecting the resulting drawdown contours for various elapsed times in **Table 10.** Stress period 138 (17.25 years) corresponds to a period of summer pumping (Jan-Feb) which would be subject to irrigation and municipal groundwater extraction.

The spatial distribution of modelled drawdown at stress period 138 (17.25 years) for layer 3 is presented in **Figure 21**. Layer 3 has been selected because this layer hosts most pumping wells (e.g. screen termination depth). Modelled drawdown for the remaining layers (layers 1-2 and 4-10) are presented in **Figures A.2** to **A.10** (**Appendix A**). **Figure 21** shows the distribution of drawdown and highlights 5 areas of interest (A-E) within the Rangitāiki Plains. Area A consists of four areas delimited by the 0.5 m drawdown contour line, and with further pumping these areas could merge into an single ellipsoidal area (approximal dimensions 9 km in the S-N direction and 6.5km in the W-E direction). There are19 Irrigation and 4 municipal wells within area A. Area B is an area of about 3 km in diameter (0.5 m contour) in the southern section of the Rangitāiki Plains, next to Kawerau (2 Irrigation wells and 1 municipal well). Towards the centre of the Rangitāiki Plains, area C is a small area (2 km in diameter) and solely due to the presence of three irrigation wells. Finally, area D practically covers the totality of the Rangitāiki Plains between the Rangitāiki River and the Raungaehe Range. This elongated area is about 1.5 km – 3 km in width and about 15 km in length, and it includes at least 58 irrigation wells and 4 municipal extraction wells.

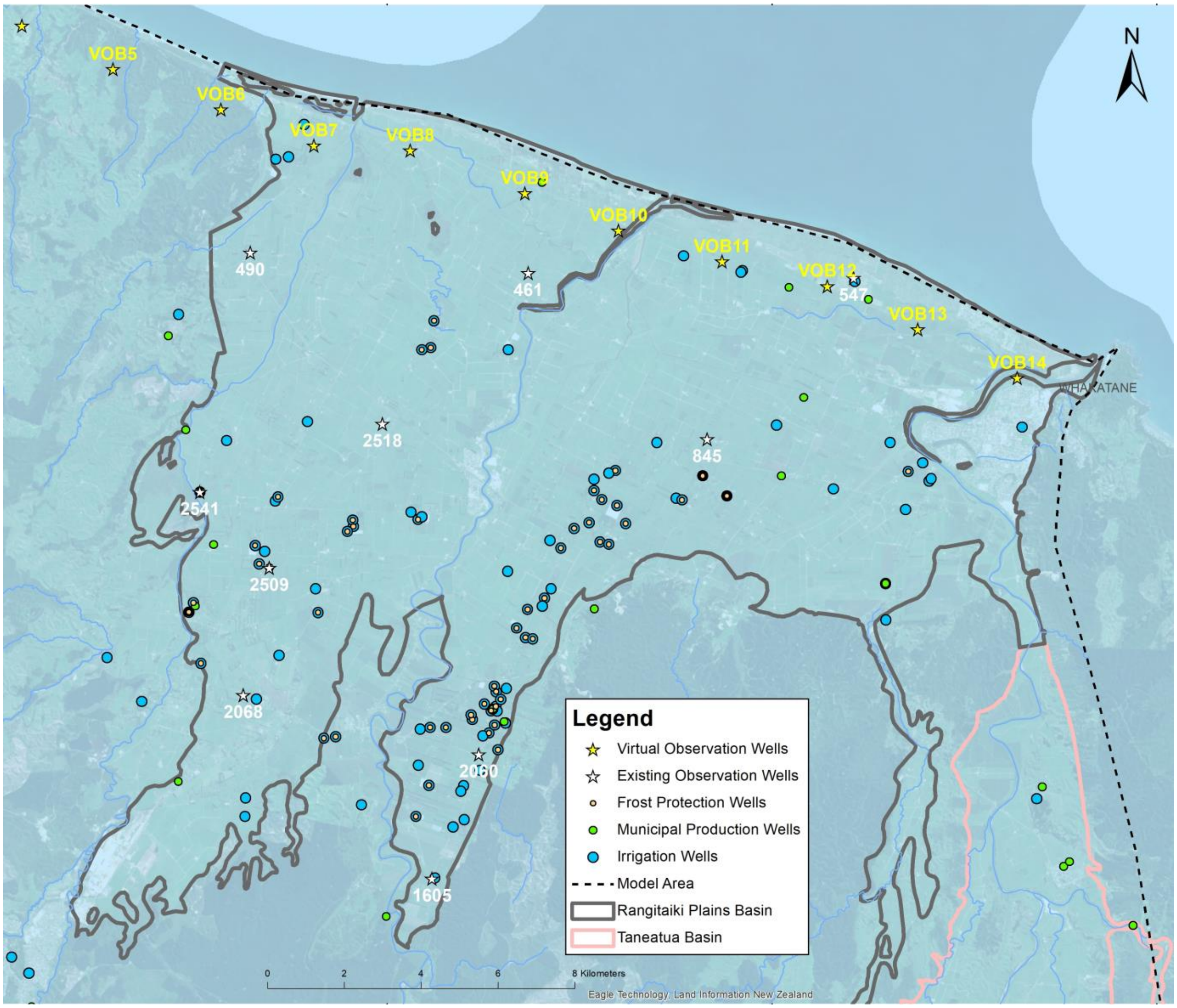


Figure 18. Observation wells in the Rangitāiki Plains

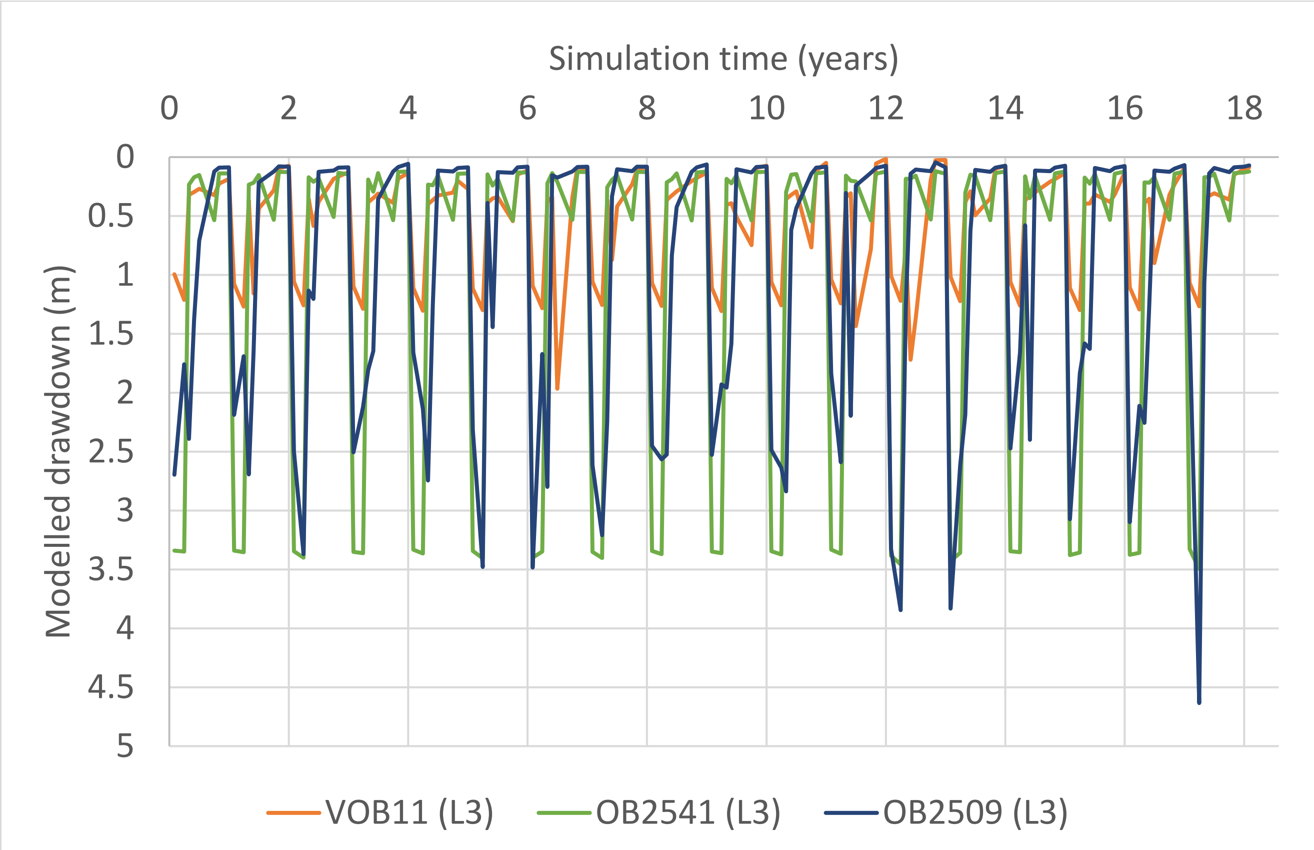


Figure 19. Hydrographs showing modelled drawdown for wells VOB11, 2541, and 2509 (Layer 3)

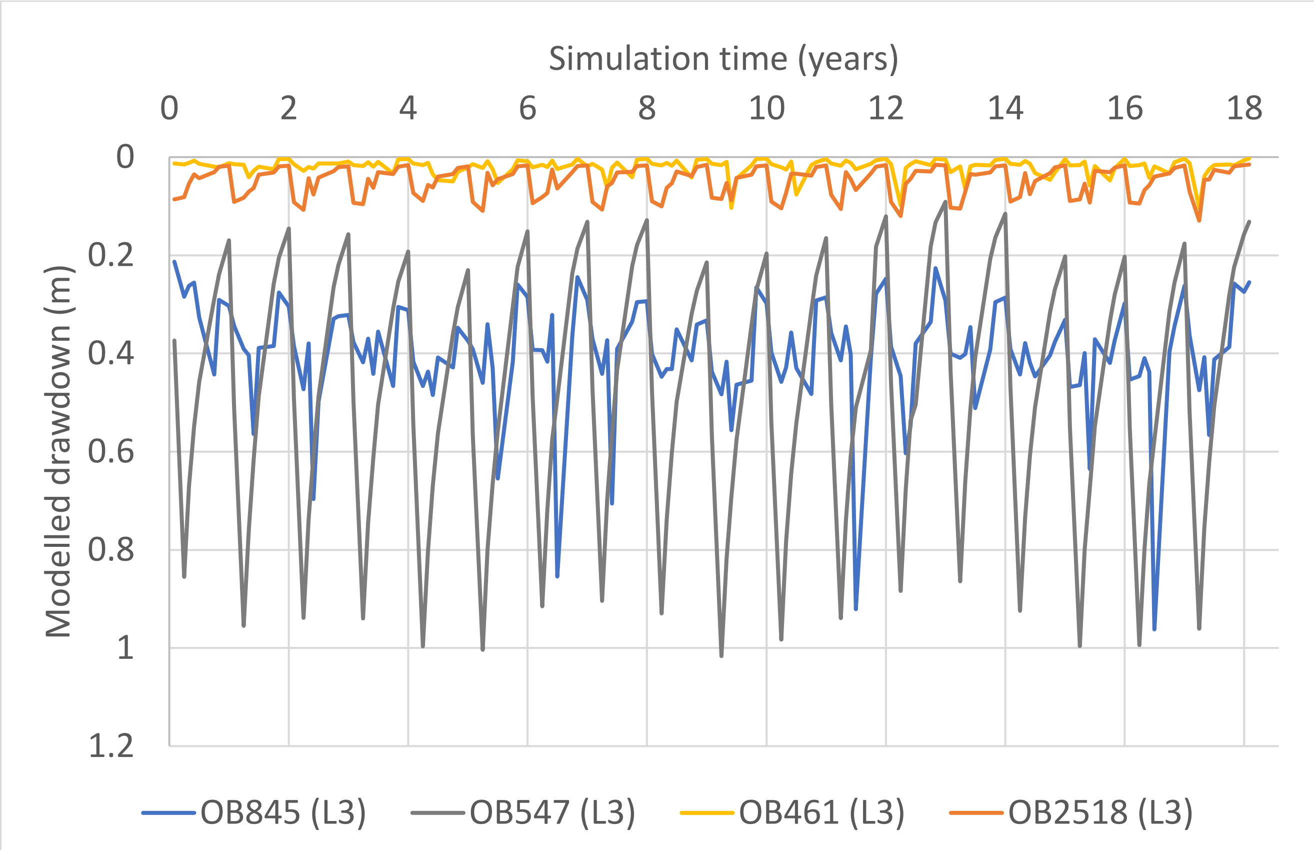


Figure 20. Hydrographs showing modelled drawdown for wells 845, 547, 461, and 2518 (Layer 3)

Table 10. Maximum drawdown at selected observation wells

Observation bore	Max Drawdown	Elapsed Time (years)
845	0.96	16.50
VOB11	1.97	6.50
547	1.02	9.25
461	0.10	9.41
2518	0.13	17.25
2541	3.50	17.25
2509	4.63	17.25

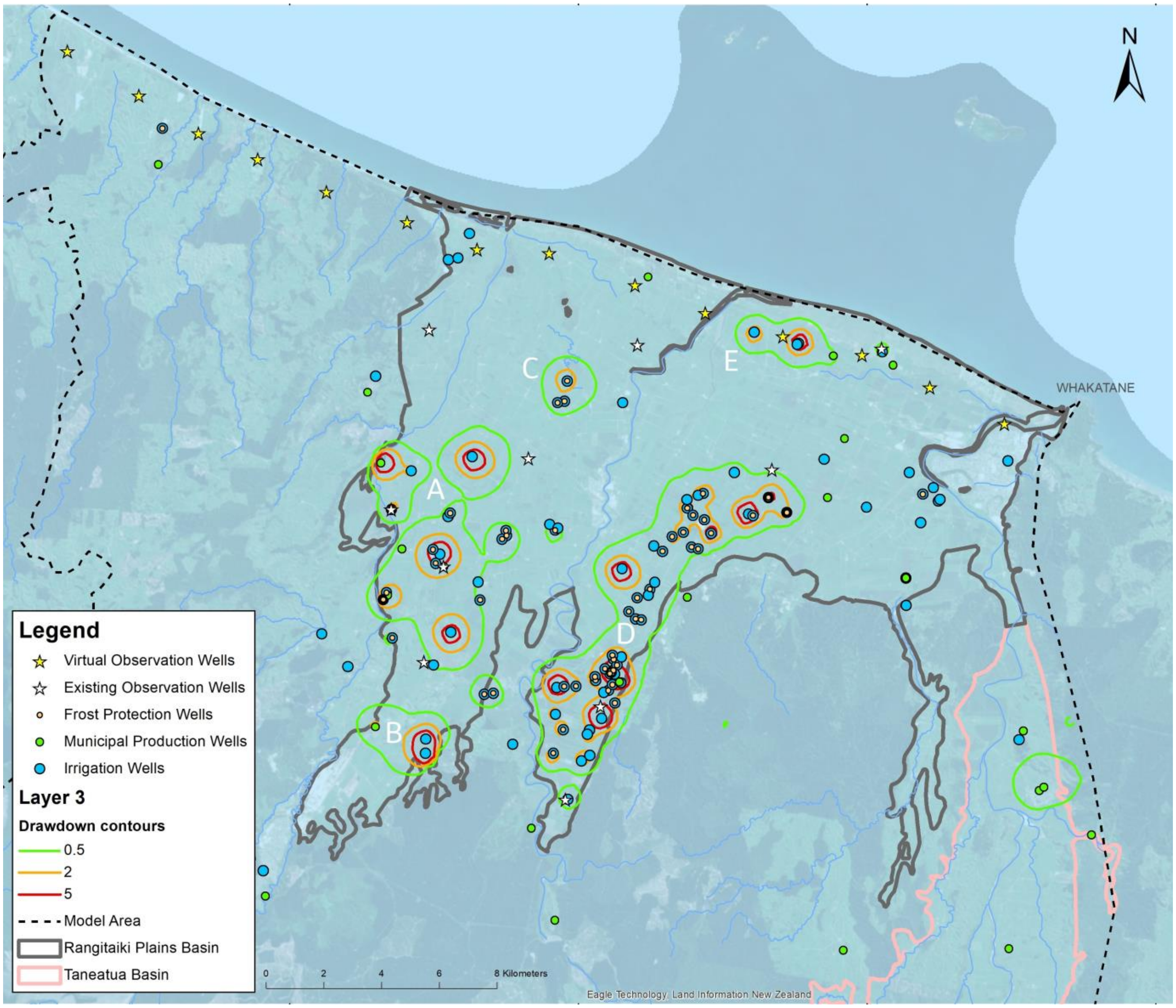


Figure 21. Model predicted drawdown contours (Qmax) for Rangitāiki Plains and lower Taneatua Basin in Layer 3 (layer elevation from about -104 m Moturiki to -67 m Moturiki), stress period 138.

Zonal Water Balance

A mass balance analysis using the MODFLOW's USG Zone Budget tool was carried out for the 6 HSU zones in **Figure 1**. The average fluxes into and out of the model (in Mm^3/year) are presented for these zones for the simulation period (**Figure 22 - Figure 27**). These figures show that recharge is the highest in HSU6 (1,036 Mm^3/year), HSU2 (892 Mm^3/year), and HSU3 (665 Mm^3/year) which is not surprising as these zones corresponds to units present at the surface over extensive areas within the model domain. Well extraction is the highest in HSU 1 (26 Mm^3/year) and HSU 2 (8 Mm^3/year). HSU 1 corresponds to superficial Holocene deposits present in the Rangitāiki Plains, Taneatua, Wiohau, and Galatea basins. Most wells are present in the Rangitāiki Plains. In addition, the mass balance shows losses to coastal discharge (constant heads) mainly occurring in HSU 5 (356 Mm^3/year) and HSU 2 (271Mm^3/year). Total coastal discharge from all zones is about 709 Mm^3/year.

Figure 22 shows that, on average, HSU 1 experiences higher losses through groundwater discharge to rivers (baseflow) than gains from river recharge (299 Mm^3/year net losses). This zone also experiences losses through drains (present near the coast) and evapotranspiration. Storage fluxes in and out of the groundwater system are fairly equal. In addition, "flows in" from adjacent zones tend to be higher than "flows out" of neighbouring zones. Most significantly, there is a net contribution of about 62 Mm^3/year for HSU2 and 116 Mm^3/year for HSU 6.

HSU 2 (Upper Volcanics, **Figure 23**) exhibits significant fluxes through the river system with a net loss of 4,259 Mm^3/year. Also, the main zones contributing to this zone are HSU 3 and HSU 5. There is a net loss of about 599 Mm^3/year to HSU 3 and a net gain of 4,503 from HSU 5.

Apart from recharge, HSU 3 exhibits reasonably balanced fluxes (**Figure 24**). There is a net river flux contribution of 377 Mm^3/year in this zone. The main zones contributing to fluxes in and out of this zone are HSU 2, HSU 5, and HSU 6.

Fluxes in and out of HSU 4 (Early to mid-Pleistocene Sediments, **Figure 25**) are fairly low in comparison to other zones. There is a small contribution from the Kaituna model (shared general head boundaries (59 Mm^3/year net flux). This zone exhibits losses/gains from HSU2 (net gain 329 Mm^3/year), HSU 5 (net loss 299Mm^3/year) and HSU6 (net loss 31 Mm^3/year).

HSU 5 (Lower Volcanics, **Figure 26**) exhibits significant gains from river contribution (net gains 2,459 Mm^3/year) and flows in and out of HSU2 (net loss of 4,503 Mm^3/year), HSU3 (net gain of 1,448 Mm^3/year), and HSU6 (net gain of 545 Mm^3/year).

HSU 6 (Undifferentiated Basement, **Figure 27**) shows fluxes in the same order of magnitude for rivers (net loss of 416 Mm^3/year), storage (net gain 34 Mm^3/year), and adjacent zones (HSU1, HSU2, HSU3, HSU4, and HSU5).

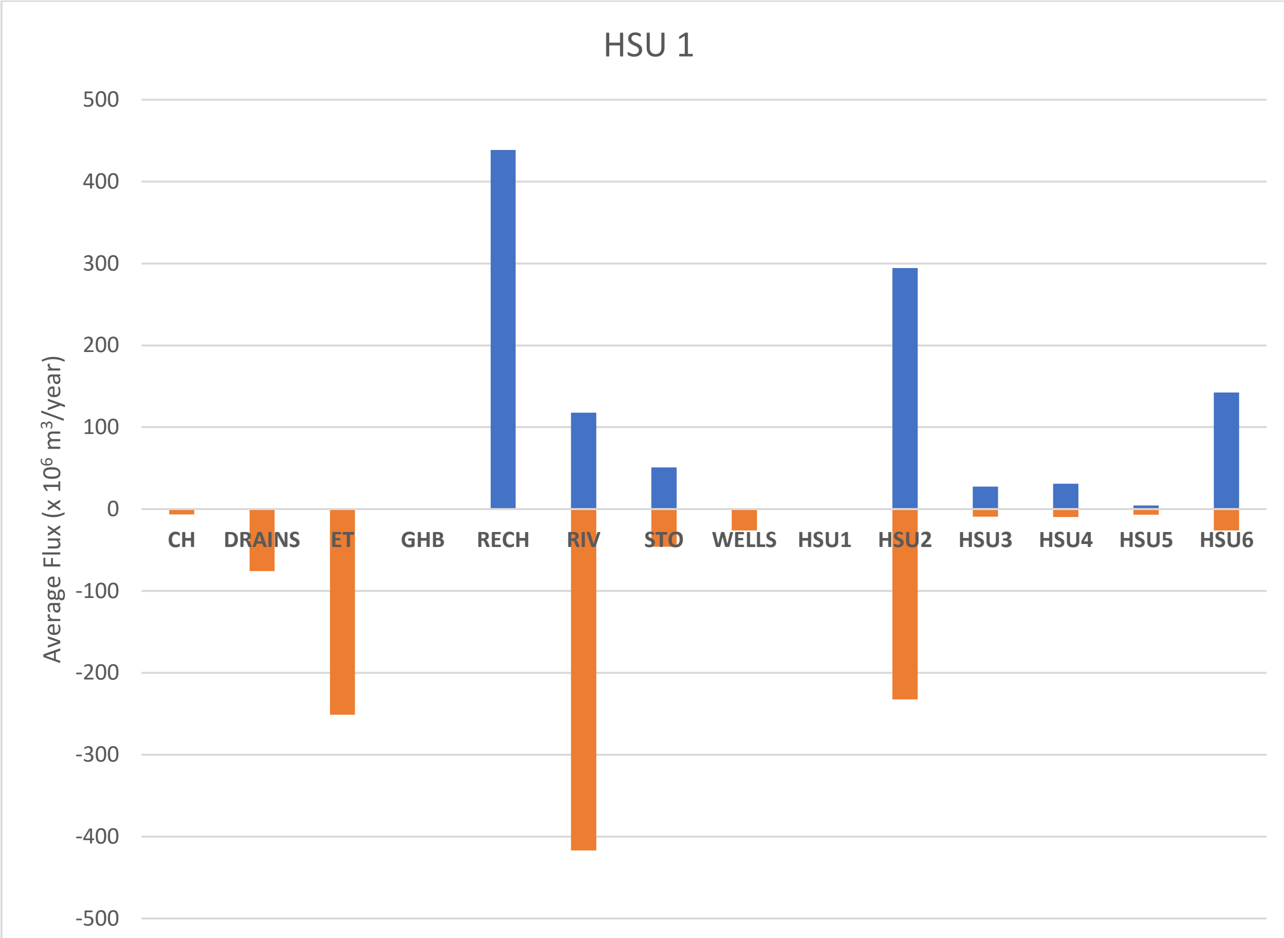


Figure 22. Water balance for HSU 1. Positive flux indicates water flux into the HSU and negative flux indicates water flux out.

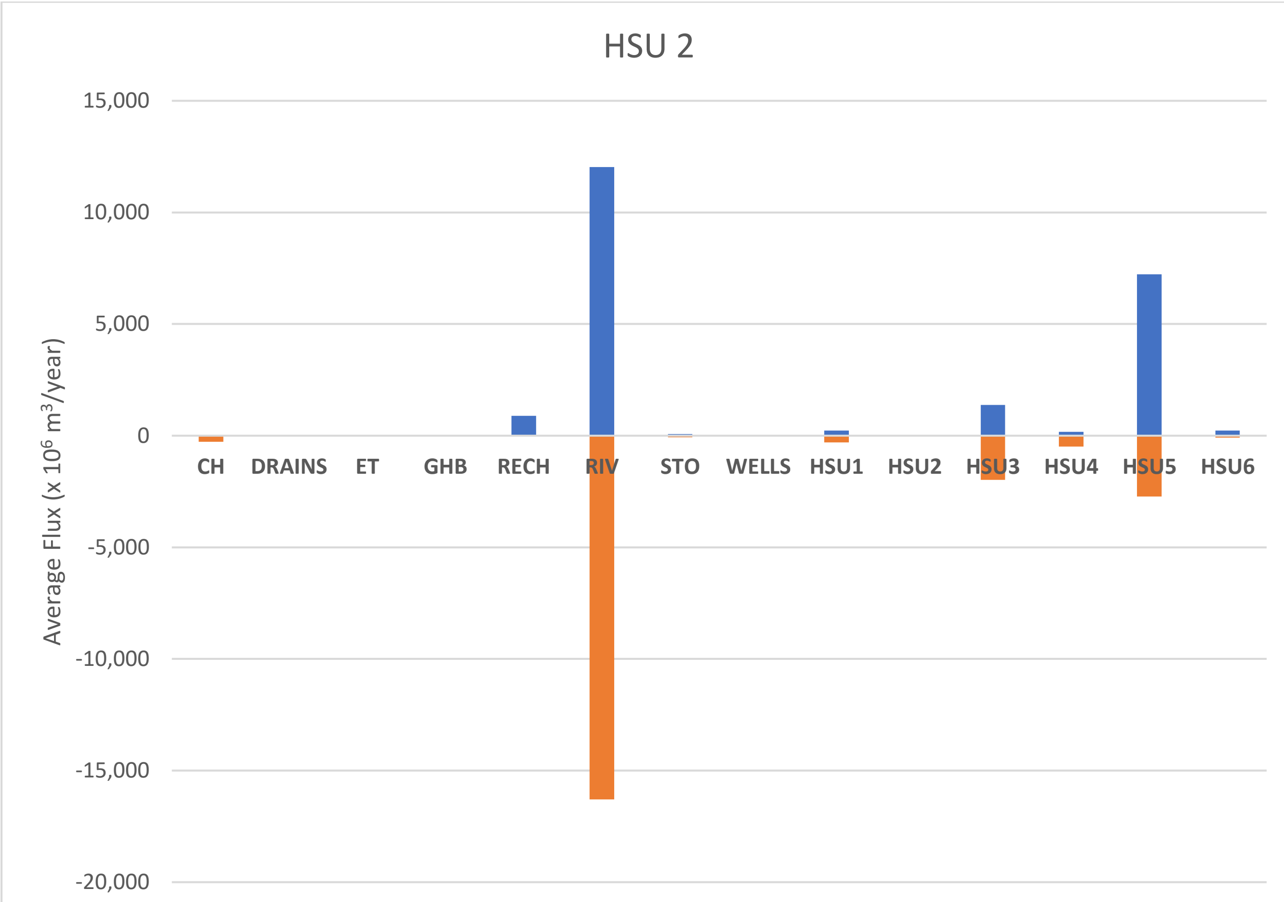


Figure 23. Water balance for HSU 2. Positive flux indicates water flux into the HSU and negative flux indicates water flux out.

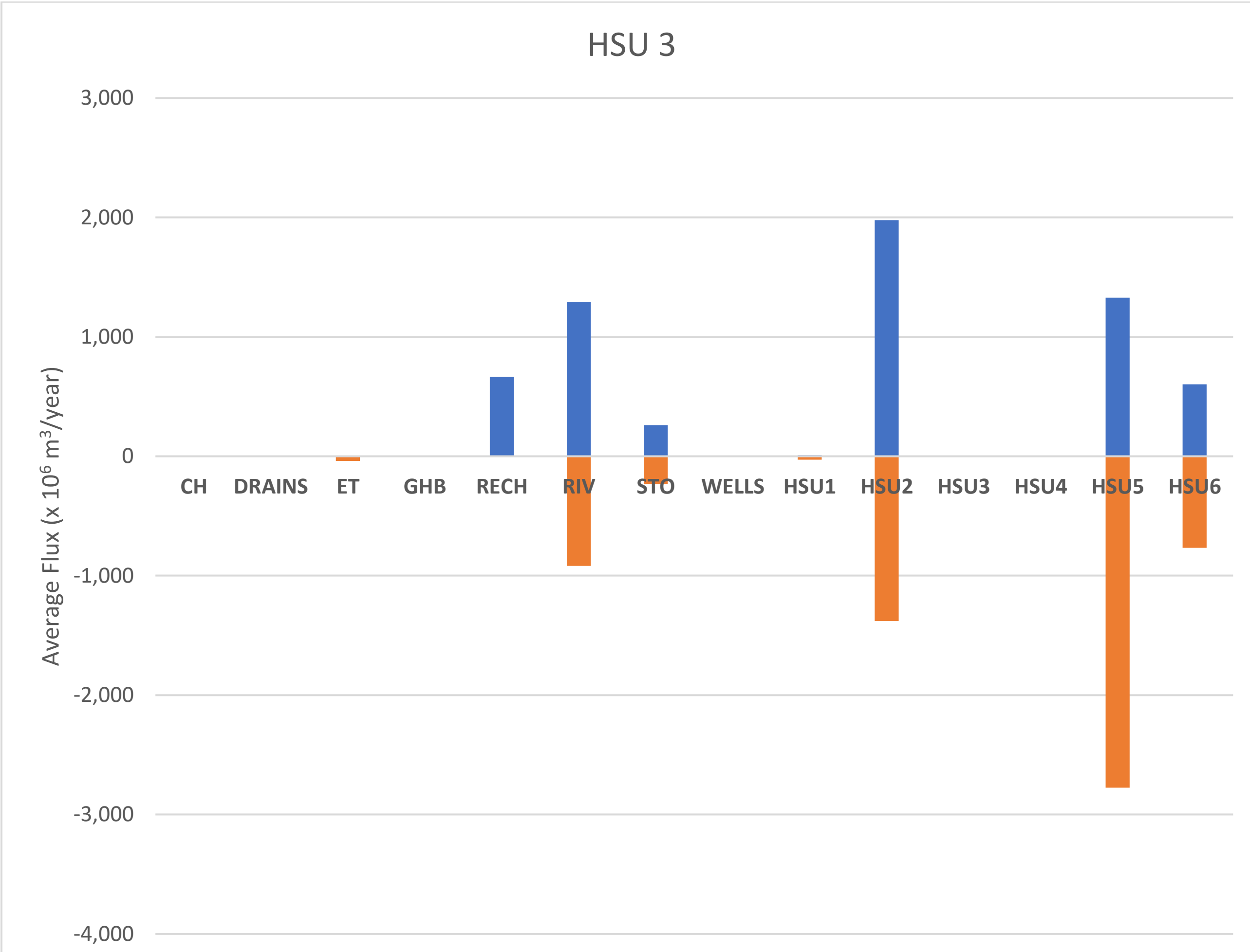


Figure 24. Water balance for HSU 3. Positive flux indicates water flux into the HSU and negative flux indicates water flux out.

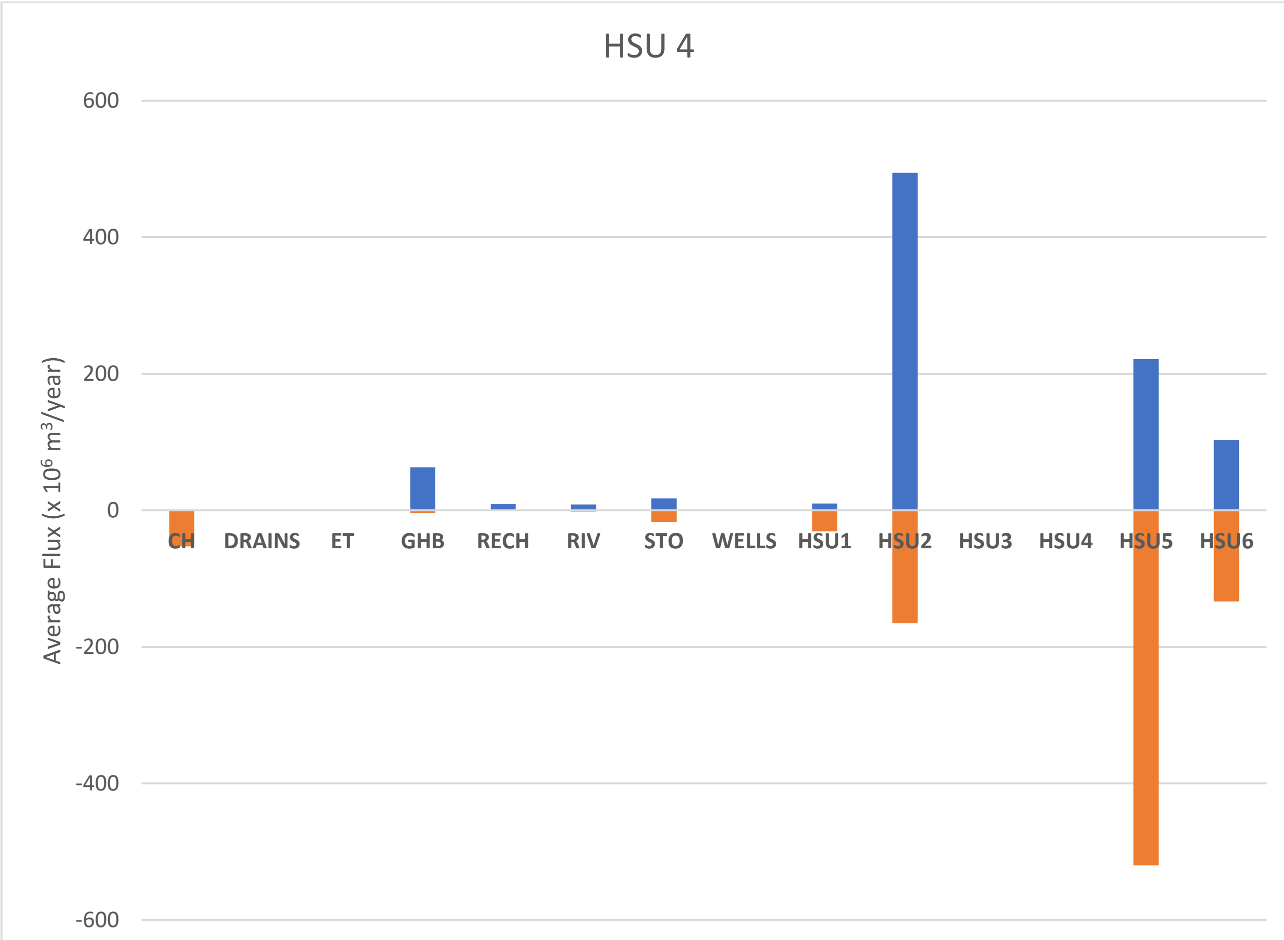


Figure 25. Water balance for HSU 4. Positive flux indicates water flux into the HSU and negative flux indicates water flux out.

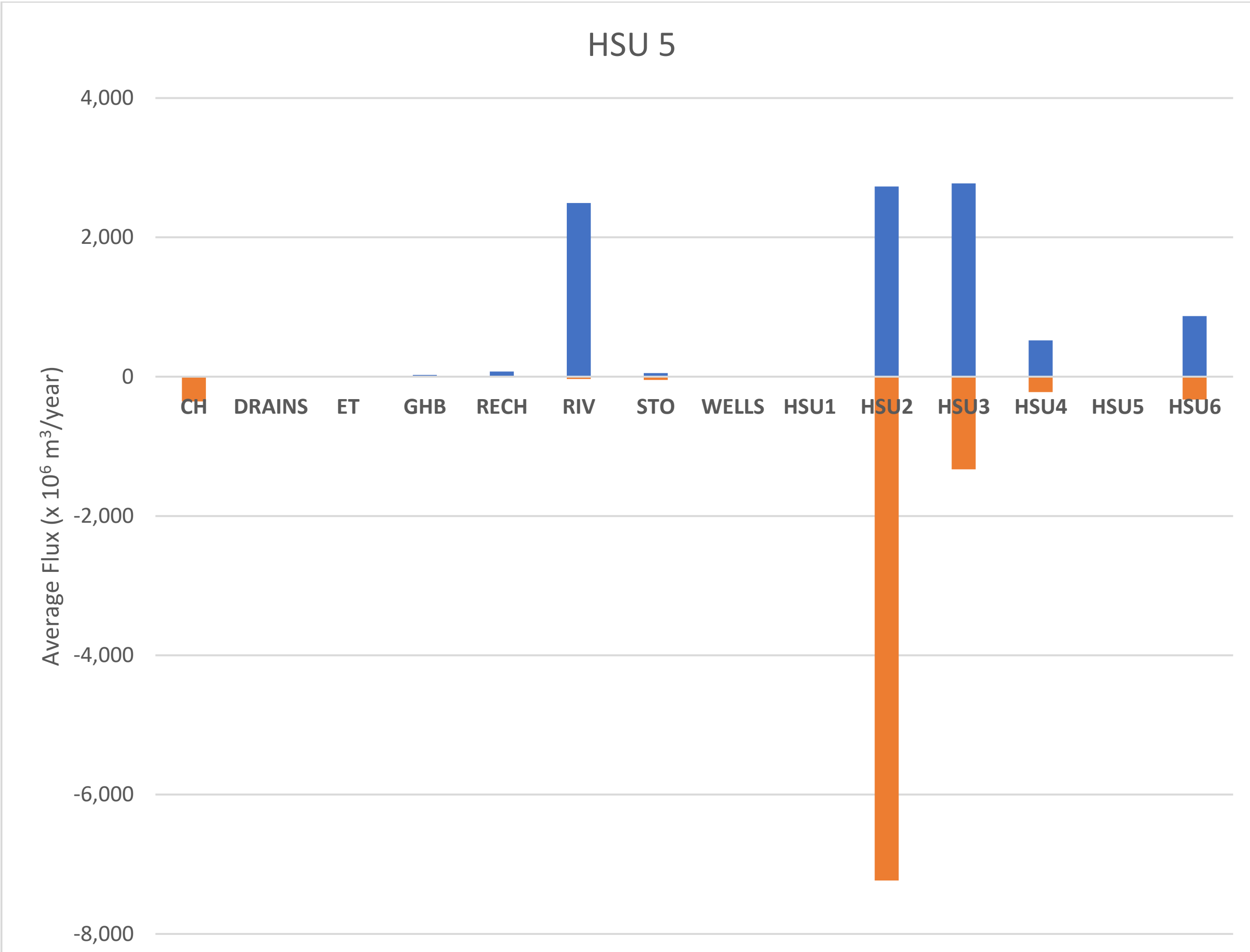


Figure 26. Water balance for HSU 5. Positive flux indicates water flux into the HSU and negative flux indicates water flux out.

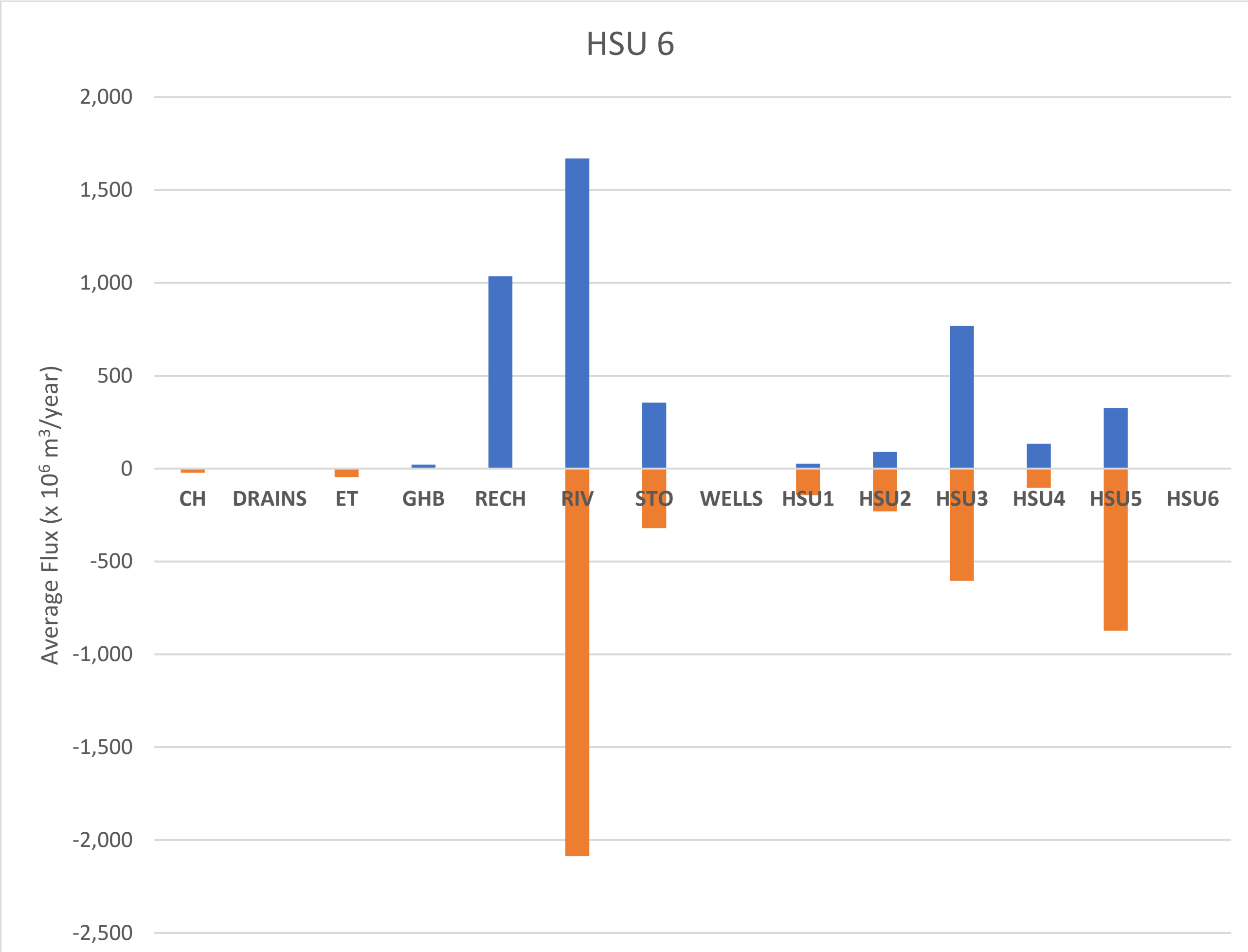


Figure 27. Water balance for HSU 6. Positive flux indicates water flux into the HSU and negative flux indicates water flux out.

5.3 Model Prediction 7

5.3.1 Methodology

This model prediction focuses on increasing water production in excess of Qmax and involved a number of model runs in which groundwater extraction was progressively increased:

a) This scenario considers additional pumping from existing wells only.

b) To estimate additional groundwater extraction the model is run by progressively increasing Qmax to 1.5Qmax, 2Qmax, and 4Qmax for all pumping wells, until the prescribed Environmental Trigger values are just exceeded. Groundwater hydrographs predicted in the virtual model observation wells are assessed against trigger levels to determine whether the modelled outcome has acceptable groundwater level impacts. To assess baseflow impacts, river cells in the reaches upgradient of the gauging station are analysed using a mass balance approach. This step results in the selection of an upper groundwater extraction limit.

c) Model fluxes were calculated for each of the zones within the RTW Model domain when the model is run at the upper groundwater extraction limit. These show the average rate at which water flows in and out of each of the zones for all model stress periods.

d) Increased Allocation Estimate. The potential for increased groundwater allocation for the different zones is determined by comparing the model results from MP7, against the base case in which wells are pumping at the current maximum allocated rate (MP6).

5.3.2 MP7 Results

Impacts on rivers

Table 11 presents groundwater surface water exchange fluxes (L/s) and average baseflow reduction and increase in river seepage (%) for scenario runs with no pumping, pumping at the maximum consented rate (Qmax), and pumping at 1.5Qmax, 2Qmax, and 4Qmax. **Table 11** shows the average change in river exchange fluxes as pumping increases for reaches 1, 2, 4-8. Reaches 3 and 9 have negative exchange flux values because streams are losing to groundwater at these locations. With increasing pumping, river seepage (to groundwater) at reaches 3 and 9 keeps increasing in absolute magnitude, which in turn results in lower stream and river flow.

For the Rangitāiki Plains (Reach 6) baseflow reduction, relative to the no-pumping case, increases to 1.0% when wells are pumping at 1.5Qmax. However, when wells are pumping at 2Qmax baseflow reduction is greater than 1% and it doubles when wells are pumping at 4Qmax (**Table 11**). In general, for the remaining reaches, baseflow reduction does not increase significantly at 1.5Qmax but for subsequent increments (2Qmax and 4Qmax) baseflow reduction tends to nearly double. This is particularly noticeable for Reach 5 which already exceeds the 1% trigger with no pumping and nearly doubles at twice the maximum consented rate (2.3% baseflow reduction). Baseflow reduction at this reach doubles again when wells are pumping at four times the maximum consented rate (4.5% baseflow reduction).

Table 11. Baseflow (L/s) and baseflow reduction percentage (%) for various model runs

	Average Baseflow (L/s)					Baseflow reduction (%)			
Reaches	**Q = 0**	**Qmax**	**1.5Qmax**	**2Qmax**	**4Qmax**	**Qmax**	**1.5Qmax**	**2Qmax**	**4Qmax**
1	40.70	40.69	40.69	40.69	40.67	0.02	0.03	0.04	0.07
2	9,950	9,948	9,948	9,947	9,946	0.01	0.02	0.02	0.04
3	-42,181	-42,315	-42,381	-42,442	-42,614	-0.3	-0.5	-0.6	-1.0
4	15,759	15,716	15,694	15,673	15,594	0.3	0.4	0.5	1.1
5	24,801	24,507	24,360	24,219	23,674	1.2	1.8	2.3	4.5
6	30,059	29,854	29,761	29,694	29,460	0.7	1.0	1.2	2.0
7	11,188	11,175	11,169	11,164	11,144	0.1	0.2	0.2	0.4
8	41,321	41,296	41,283	41,321	41,270	0.1	0.1	0.1	0.1
9	-22,615	-22,635	-22,646	-22,651	-22,670	-0.1	-0.1	-0.2	-0.2

Drawdown assessment

Coastal Heads

Table 12 presents groundwater heads (m Moturki) for layers 1 and 2 in virtual observation wells (VOB1 – VOB14) and two existing observation wells (OB461 and OB467) all of which are located near the coastline. In general, coastal heads tend to decrease as pumping increases with a few wells having heads lower than -0.5 m Moturiki (OB461, OB547, and VOB11). For the pumping rates considered in Scenario MP7, the minimum and average heads are identical to the heads predicted in MP6 as presented in **Table 9** (the only exceptions are the minimum heads at 4Qmax which breach the -0.5 m trigger values in layer 2).

For OB547, the minimum head values breach the -0.5 m trigger limit at 1.5Qmax, 2Qmax, and 4Qmax in layers 1 and 2 but the average head values breach the -0.5 m limit at pumping rates at 2Qmax and 4Qmax. At 1.5Qmax, the average coastal heads for OB547 satisfy the -0.5 m limit.

For VOB11, the minimum head values breach the -0.5 m trigger limit at 1.5Qmax, 2Qmax, and 4Qmax in layer 2. This trigger is also breached in layer 1 but only at 4Qmax. However, the average head values do not breach the -0.5 m limit for the scenarios presented in **Table 12**.

.

Table 12. Heads for coastal observation wells (m Moturiki) with wells pumping at 1.5Qmax, 2Qmax, and 4Qmax. Values in red represent head values < -0.5 m.

Well	Layer	Pumping rate = 1.5Qmax			Pumping rate = 2Qmax			Pumping rate = 4Qmax		
		Min (m)	Max (m)	Average (m)	Min (m)	Max (m)	Average (m)	Min (m)	Max (m)	Average (m)
OB461	1	-1.0	5.2	0.8	-1.0	5.2	0.8	-1.0	5.2	0.8
OB461	2	-0.4	8.7	1.3	-0.4	8.7	1.3	-0.5	8.7	1.3
OB547	1	-8.9	4.9	-0.4	-13.2	4.7	-2.3	-30.9	3.1	-10.1
OB547	2	-1.3	4.1	1.7	-2.7	3.8	1.1	-8.3	2.9	-1.8
VOB1	1	18.5	33.1	19.8	18.5	33.1	19.8	18.5	33.1	19.8
VOB1	2	18.1	24.5	18.8	18.1	24.5	18.8	18.1	24.5	18.8
VOB2	1	20.9	22.2	21.1	20.9	22.2	21.1	20.9	22.2	21.1
VOB2	2	20.0	21.3	20.2	20.0	21.3	20.2	20.0	21.3	20.2
VOB3	1	21.0	31.4	22.5	21.0	31.4	22.5	21.0	31.4	22.5
VOB3	2	20.9	23.9	21.5	20.9	23.9	21.5	20.9	23.9	21.5
VOB4	1	21.2	34.2	23.1	21.2	34.2	23.1	21.2	34.2	23.1
VOB4	2	21.0	25.1	22.2	21.0	25.1	22.2	21.0	25.1	22.2
VOB5	1	44.2	79.2	48.2	44.2	79.2	48.2	44.2	79.2	48.2
VOB5	2	44.0	68.9	47.3	44.0	68.9	47.3	44.0	68.9	47.3
VOB6	1	23.6	55.4	27.1	23.6	55.4	27.1	23.6	55.4	27.1
VOB6	2	23.3	40.9	25.6	23.3	40.9	25.6	23.3	40.9	25.6
VOB7	1	0.4	10.4	1.3	0.4	9.9	1.3	0.4	8.8	1.2
VOB7	2	0.5	6.6	1.1	0.4	6.2	1.0	0.4	5.3	1.0
VOB8	1	-0.4	6.1	0.4	-0.4	6.1	0.4	-0.4	6.1	0.4
VOB8	2	-0.2	4.0	0.5	-0.2	4.0	0.5	-0.2	4.0	0.5
VOB9	1	-0.2	10.9	1.3	-0.2	10.8	1.3	-0.2	10.5	1.2
VOB9	2	0.3	8.4	1.6	0.3	8.3	1.5	0.3	8.0	1.5
VOB10	1	-0.2	2.7	0.4	-0.2	2.7	0.4	-0.2	2.7	0.4
VOB10	2	-0.2	2.2	0.4	-0.2	2.2	0.4	-0.2	2.2	0.4
VOB11	1	0.3	7.7	1.3	0.2	6.9	1.2	-0.6	4.6	0.6
VOB11	2	-0.7	5.9	0.9	-1.1	5.1	0.7	-2.8	3.3	-0.1
VOB12	1	2.8	8.7	3.9	2.8	8.3	3.8	2.5	7.3	3.6
VOB12	2	2.2	6.6	3.2	2.1	6.3	3.1	1.7	5.4	2.8
VOB13	1	0.6	7.0	1.7	0.6	7.0	1.7	0.6	6.9	1.7
VOB13	2	0.7	5.1	1.6	0.7	5.1	1.6	0.7	5.0	1.6
VOB14	1	-0.0	7.7	1.1	-0.0	7.7	1.1	-0.1	7.6	1.1
VOB14	2	0.2	5.3	1.0	0.2	5.3	1.0	0.2	5.1	1.0

Spatial distribution of drawdown

The predicted drawdown contour map when wells are pumping at 1.5Qmax (in stress period 138) is presented in **Figure 28.** Stress period 138 has been previously identified (see MP6) as the stress period in which the highest drawdowns are predicted. A pumping rate of 1.5Qmax has been selected as the basis for the drawdown map as this pumping increment results in baseflow reduction and coastal drawdown impacts that are considered to be acceptable. When comparing **Figure 28** against **Figure 21**, it is noted that the 0.5 m drawdown contour zones (A-E) have expanded by approximately 200 m. The only exception is the western 0.5 m drawdown contour for area D which has expanded by about 1 km due to the presence of Upper Volcanics sediments with high hydraulic conductivity at this location. In addition, it is noted that area A previously consisted of 4 separate drawdown cones in close proximity to each other but, with pumping increased to 1.5Qmax, these areas are now connected resulting in one area with a small mound in the middle. Area E, which is associated with pumping wells 4872, 3371, and 1000021, has expanded outwards but its 0.5 m drawdown contour is about 420 m from the coast. For these zones, the 2 m drawdown contour is generally between 0.5 and 1 km from the central pumping wells but the southern section of zone D can potentially expand beyond 1 km with additional pumping.

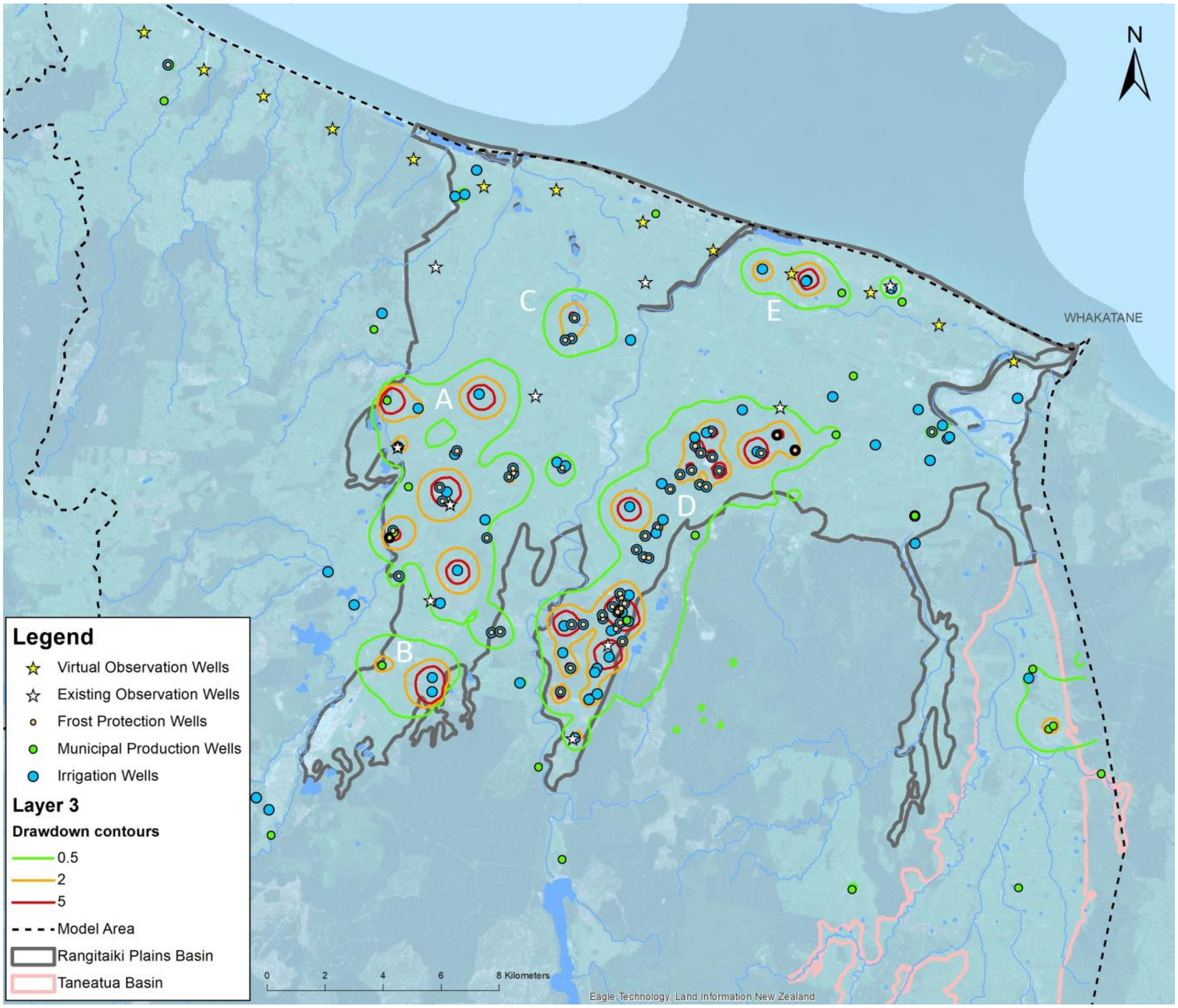


Figure 28. Drawdown contours (1.5 Qmax) for Rangitāiki Plains and lower Taneatua Basin in Layer 3 (layer elevation from about -104 m Moturiki to -67 m Moturiki), stress period 138.

Additional allocation

An estimate of additional groundwater allocation has been carried out with a water balance calculation for the 6 HSUs defined in the model, with wells pumping at 150% of their maximum allocation rate (1.5Qmax). The existing and additional allocation results are presented in **Table 13.** This table shows that the vast majority of pumping is occurring in HSU 1 which is the superficial Holocene deposits unit associated with the Rangitāiki Plains and Galatea basins, and the additional extraction resulting from a 50% increase in allocation is about 12 Mm^3/year. The second HSU with the highest groundwater extraction is HSU 2 (Upper Volcanics). These wells are located in the south of the Rangitāiki Plains and in deeper sections of the Rangitāiki Plains and Galatea basins.The additional extraction resulting from a 50% increase in allocation for HSU 2 is about 4 Mm^3/year.

For HSUs 3 and 5 (Whakamaru Group and Lower Volcanics) there is practically no additional extraction. The Whakamaru Group only hosts a few wells within the model domain and there are no pumping wells in the Lower Volcanics group.

Finally, for HSUs 4 and 6 the additional extraction only amounts to about 0.4 Mm^3/year in both cases as these units do not host a significant number of pumping wells.

Table 13. Average annual extraction for existing maximum allocation (Qmax) and for the scenario with wells pumping an additional 50% (1.5Qmax). Note: Mm^3/year refers to Million m^3 per year.

HSU Zone	Wells pumping at existing allocation rate (Qmax, Mm3/year)	Wells pumping an additional 50% (1.5Qmax, Mm3/year)	Additional extraction (Mm3/year)
1 (Superficial Holocene Deposits)	26.2	38.1	11.9
2 (Upper Volcanics)	8.2	12.2	4.1
3 (Whakamaru Group)	0.05	0.08	0.03
4 (Early and Mid-Pleistocene Sediments)	0.8	1.2	0.39
5 (Lower Volcanics)	0	0	0
6 (Undif. Basement)	0.75	1.13	0.38

5.4 Predictive uncertainty

Groundwater models include uncertainties associated with the complexities of the underground environment, most of which are unknown and cannot be adequately represented in a regional groundwater model. The uncertainties present in the RTW Model are illustrated in calibration as the differences between the modelled heads and fluxes compared to the observed heads and fluxes (as reported in Section 4.2). A formal uncertainty analysis has not yet been undertaken and should be considered as part of future model up-grades.

6. Conclusion

Transient calibration of the Rangitāiki Tarawera Whakatāne model (RTW Model) has produced statistics and residuals that are very similar to the Steady State model (RMSE 1.7% Transient vs 1.9% Steady State). In general, transient hydrographs and seasonal trends for both heads and baseflow show that the calibration is successful at matching observed historic behaviour. It is noted however that the model does not replicate the observed seasonal fluctuations in groundwater heads observed in some wells – however for a model of this size and given the objectives of assessing sustainability of groundwater extraction, such fluctuations are of little importance.

While the main areas of interest are close to the coastal area (Rangitāiki Plains), the model itself covers a much bigger area. Calibration efforts have focused on obtaining the best match to observed heads and flows over the entire model domain with emphasis on the coastal area.

The model exhibits most attributes of a Class 2 Confidence Level Classification under the Australian Groundwater Modelling Guidelines (Barnett et al, 2012).

In terms of the available data, the Guidelines identify the significance of metered groundwater extraction data base (metered data) for Class 2 models. In particular, the Guidelines state that "extraction data may be available but spatial and temporal coverage may not be extensive". For the RTW Model, metered data is incomplete in terms of temporal coverage, and this has led to some uncertainty in calibration. In addition, it is noted that there is not a clear understanding of irrigation and frost protection application rates that makes it difficult to determine enhanced recharge rates beneath irrigated or frost protected land (i.e. excess water not taken up by plants which results in additional aquifer recharge). Furthermore, some model areas (e.g. Galatea and Upper Rangitāiki) have a low density of observation wells with adequate data for calibration. Some parts of the model (e.g. south western section of Rangitāiki Plains and Upper Rangitāiki) exhibit a poor calibration.

In terms of the calibration itself, the overall head matching statistics are reasonable but there are areas where there are significant differences between measured and modelled heads. Seasonal fluctuations in observed data have been replicated reasonably well in the model calibration along with long term trends.

The Guidelines suggest that the Class 2 model is suitable for evaluation and management of medium risk impacts. The classification can be improved by the collection of more data to:

1) improve the conceptual understanding of the Rangitāiki Tarawera Whakatāne area,
2) improve the reliability of groundwater extraction data (metered data),
3) improve the reliability of groundwater monitoring data (survey existing observation wells and include additional ones, implement telemetry in key observation wells and implement extensive QA/QC of these data).
4) help to constrain model parameters and reduce non-uniqueness.

In sum, transient calibration of the RTW Model meets all reasonable calibration expectations for a model of this size and range in topography and heads. Transient calibration of the RTW Model is in line with current industry standards.

The average annual flow through the RTW model is about 21,700 M m^3/year. With such a large volume of water flowing through this aquifer system, there is scope for further development of reliable groundwater supplies to support agriculture, town water supplies, and industry (continued investment in regulation and monitoring is required to achieve this sustainably). The main flux component into the model is recharge from rainfall (3,170 M m^3/year) and the main flux component out of the model is through rivers (2,177 M m^3/year) and discharge to the sea (modelled using Constant Head boundaries and having an average of 711 M m^3/year), followed by evapotranspiration (349 M m^3/year). Groundwater abstraction, on average, accounts for about 0.08 % of the total fluxes out of model (18 M m^3/year).

Transient calibration has involved adjustment of parameters that also influence the Steady State solution. Therefore, it is noted that the previously reported Steady State model is no longer consistent with the transient calibration and transient predictions. If BoPRC want to continue to use the Steady State model – it should be updated with the new calibrated values so that there are no inconsistencies.

This report presents two model predictions (MP6 and MP7) to assess the expected impact with maximum consented groundwater extraction and to explore increased allocation that may be sustained without breaching environmental triggers.

MP6 considers wells pumping at their maximum consented rate (Qmax) and assesses baseflow reduction and groundwater heads near the coastline as Environmental Triggers. This prediction assesses the spatial distribution of drawdown and provides an estimate of groundwater allocation for groundwater management zones based on geological units as defined in the model HSU zones. In general, when the model includes pumping at the maximum consented rate, for river reaches receiving average net baseflow contribution (reaches 2, 4-8), predicted baseflow reduction ranges from 0.01% to 1.2% of the no-pumping modelled baseflow. Also all coastal heads, apart from a few exceptions at specific moments in time, were higher than -0.5 m Moturiki for all observation wells in layers 1 and 2. In addition, MP6 has identified 5 areas of interest (A-E) where drawdown could potentially impact users within the Rangitāiki Plains.

A mass balance analysis using the MODFLOW's USG Zone Budget tool was carried out for the 6 HSU zones included in the model. Recharge is the highest in HSU6 (1,036 Mm^3/year), HSU2 (892 Mm^3/year), and HSU3 (665 Mm^3/year) which is not surprising as these zones corresponds to units present at the surface over extensive areas within the model domain. Well extraction is the highest in HSU 1 (26 Mm^3/year) and HSU 2 (8 Mm^3/year). HSU 1 corresponds to superficial Holocene deposits present in the Rangitāiki Plains, Taneatua, Wiohau, and Galatea basins. In addition, the mass balance shows losses to coastal discharge (constant head boundary conditions) mainly occurring in HSU 5 (356 Mm^3/year) and HSU 2 (271Mm^3/year). Total coastal discharge from all zones is about 709 Mm^3/year.

MP7 has assessed the potential to increase current allocation limits by progressively increasing the maximum rate of extraction from all pumping wells, until baseline Environmental Triggers are breached. Predicted river baseflow reduction does not increase significantly at 1.5Qmax but for subsequent increments (2Qmax and 4Qmax) baseflow reduction tends to nearly double. In addition, coastal heads tend to decrease as pumping increases with a few locations identified where head are predicted to be lower than -0.5 m Moturiki at 1.5Qmax. At pumping increments higher than 1.5Qmax coastal heads at some locations are predicted to decrease significantly. As a result, 1.5Qmax has been identified as the maximum rate of groundwater extraction from existing wells that can be sustained without triggering the prescribed environmental limits. In terms of drawdown, it is noted that the 0.5 m predicted drawdown contour zones previously identified with MP6 (A-E) have expanded by approximately 200 m with MP7.

MP7 has resulted in an estimate of additional groundwater allocation for the 6 HSUs, with wells pumping at 1.5Qmax. The most important additional allocation takes place in HSU 1 (Superficial Holocene Deposits in the Rangitāiki Plains and Galatea basins) and this is about 12 Mm^3/year. Wells in HSU2 (Upper Volcanics) are located to the south of the Rangitāiki Plains and in deeper sections of the Rangitāiki Plains and Galatea basins; the additional extraction resulting from a 50% increase in allocation for these wells is about 4 Mm^3/year. The remaining HSUs hold either no additional allocation of additional extraction less than 0.4 Mm^3/year.

7. References

Barnett et al. (2012). *Australian groundwater modelling guidelines.* Canberra: Waterlines report, National Water Commission.

GNS. (2010/113). *Groundwater resource investigations of the Rangitaiki Plains stage 1 - conceptual geological model, groundwater budget and preliminary groundwater allocation assessment.* GNS.

Jacobs. (2019). *Rangitaiki Tarawera Whakatane Groundwater Model (Steady State).*

USGS, P. S. (2019, February 27). MODFLOW-USG version 1.5.00: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation: U.S. Geological Survey Software Release.

Appendix A. Additional Figures

<u>Take schedule</u>

The year is divided into three stress periods depending on the take type schedule:

- Municipal takes occur all year-round.
- Irrigation takes occur between December and April; and,
- Frost occurs in October and November

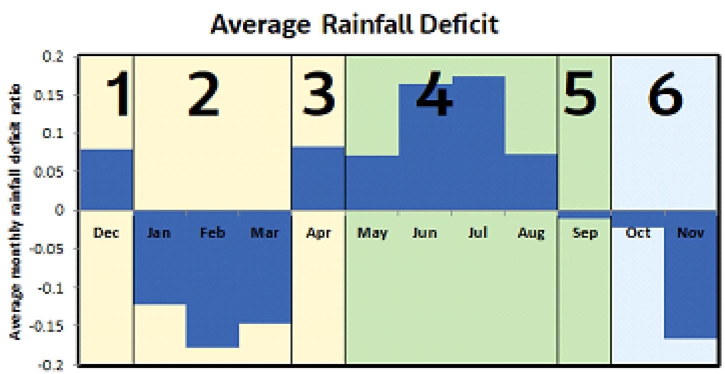
Considering the take schedule alone results in three stress periods.

<u>Seasonal recharge pattern</u>

Lysimeter data was analysed for each of the 4 basins within the model domain (Rangitaiki Plains, Taneatua, Waiohau, and Upper Rangitaiki). Their overall seasonal response was similar and was averaged in order to generate a generalized response.

Lysimeter data showed that recharge as a percentage of rainfall changed seasonally:

- December: 8% above average rainfall
- January to February (summer) and March are below average (up to 18% less rainfall);
- April is 8% above average rainfall;
- May, June to August (winter) are up to 17% above average rainfall
- September is almost identical to average rainfall but in fact only 1% lower; and,
- October and November (second part of spring) are below average rainfall and November is up to 17% below average.



Combining the seasonal recharge pattern with the take schedule produces a total of four stress. periods.

<u>Monthly average rainfall pattern</u>

The monthly seasonal rainfall was compared to the average rainfall deficit graph. This resulted in:

· Monthly rainfall is above average in December, and between April and August.

· Monthly rainfall is below average between January-March, and October-November.

Combining the seasonal recharge pattern with the rainfall deficit pattern and the take schedule produces a total of eight stress periods.

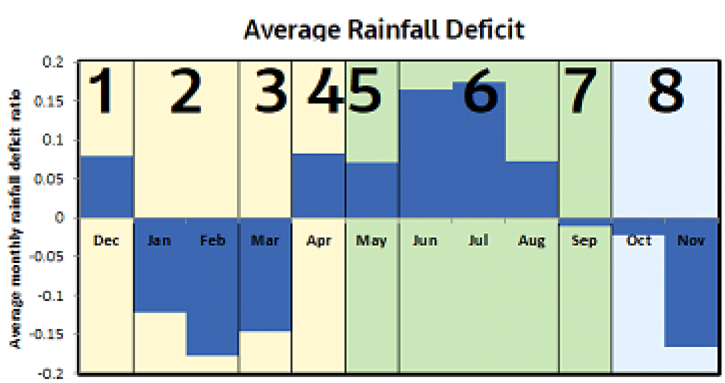


Figure A.1. Derivation of stress periods for the RTW transient model

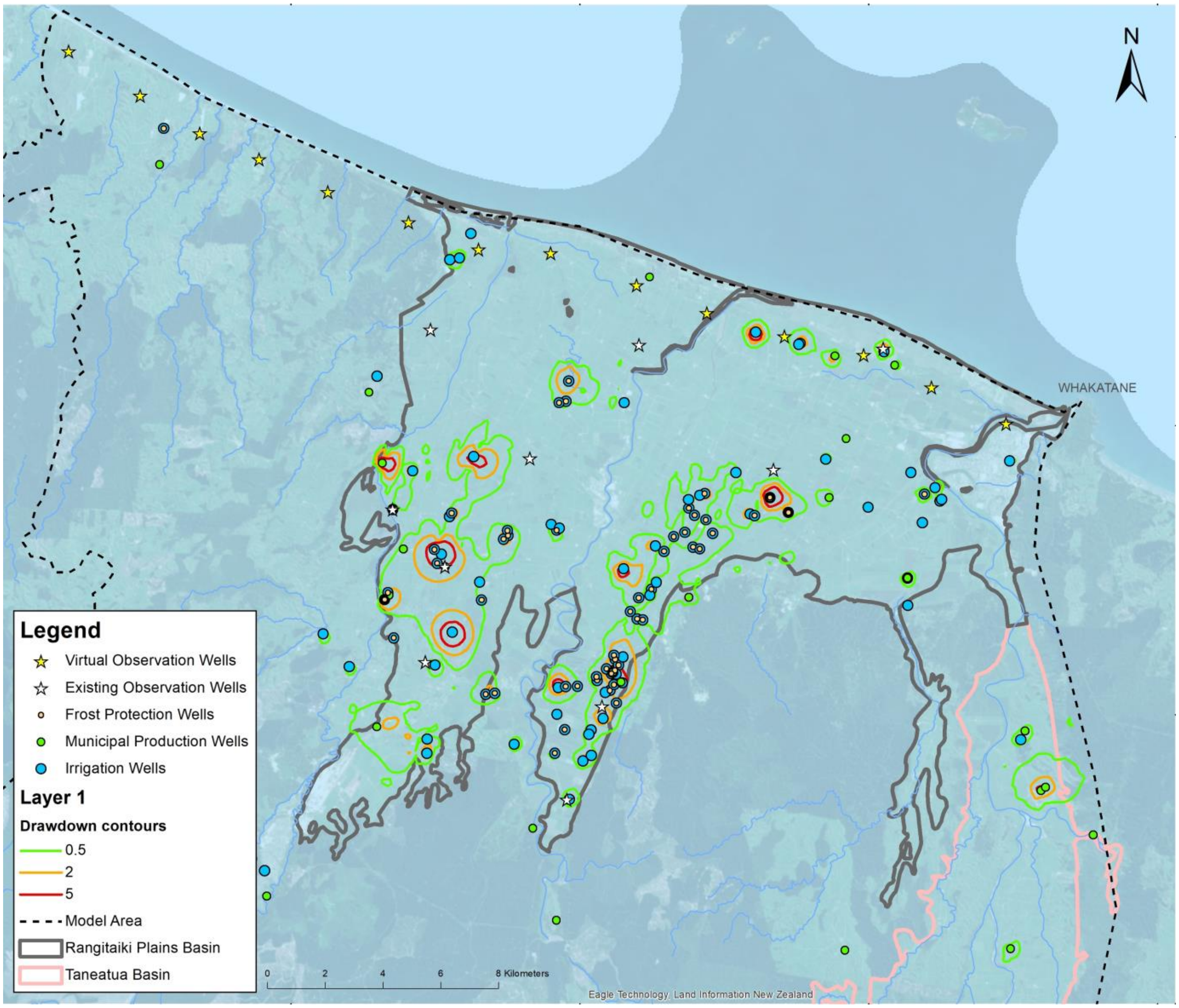


Figure A.2. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 1 (layer elevation at natural surface elevation, from about -4 m Moturiki to 32 m Moturiki), stress period 138.

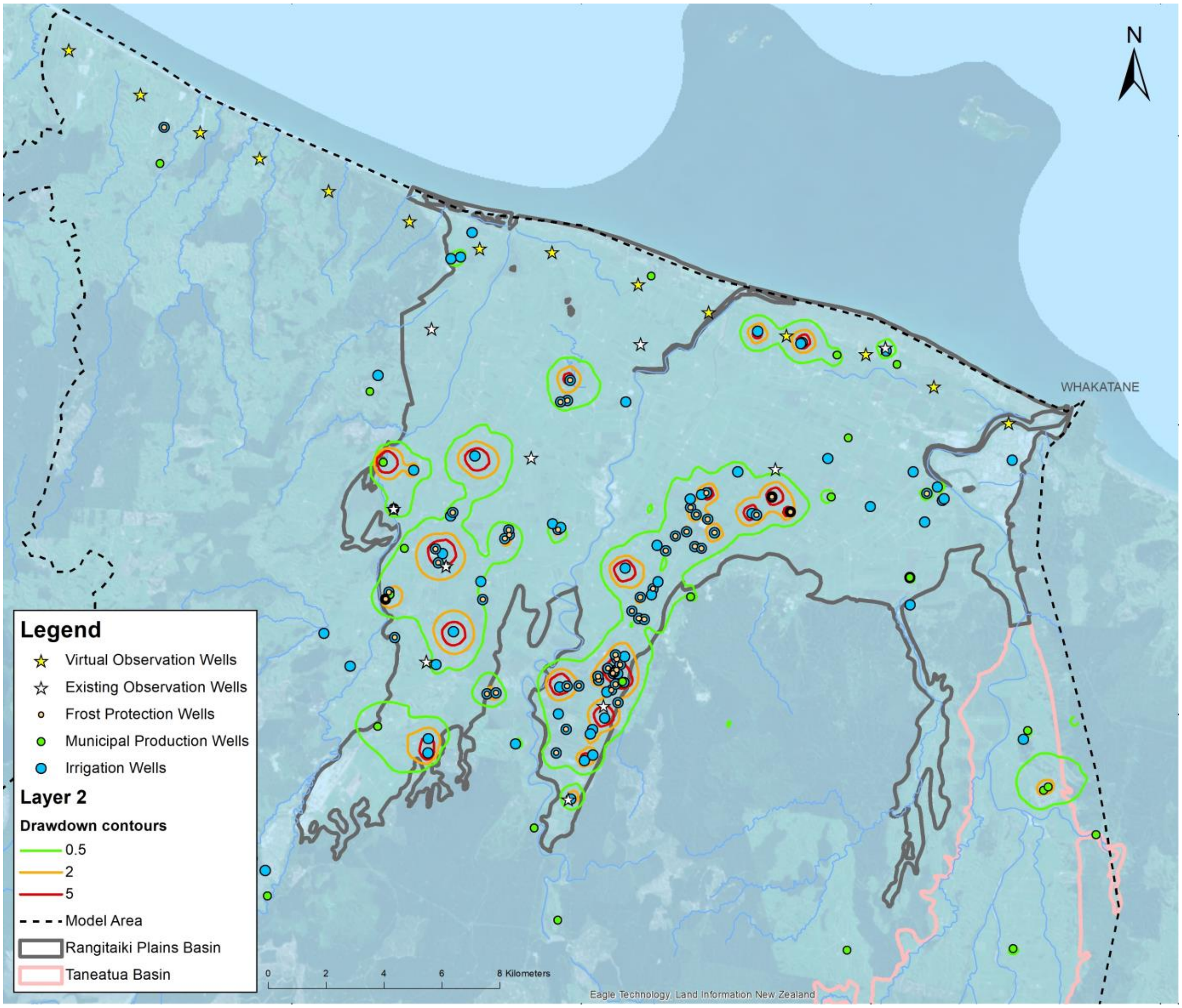


Figure A.3. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 2 (layer elevation from about -54 m Moturiki to -17 m Moturiki), stress period 138.

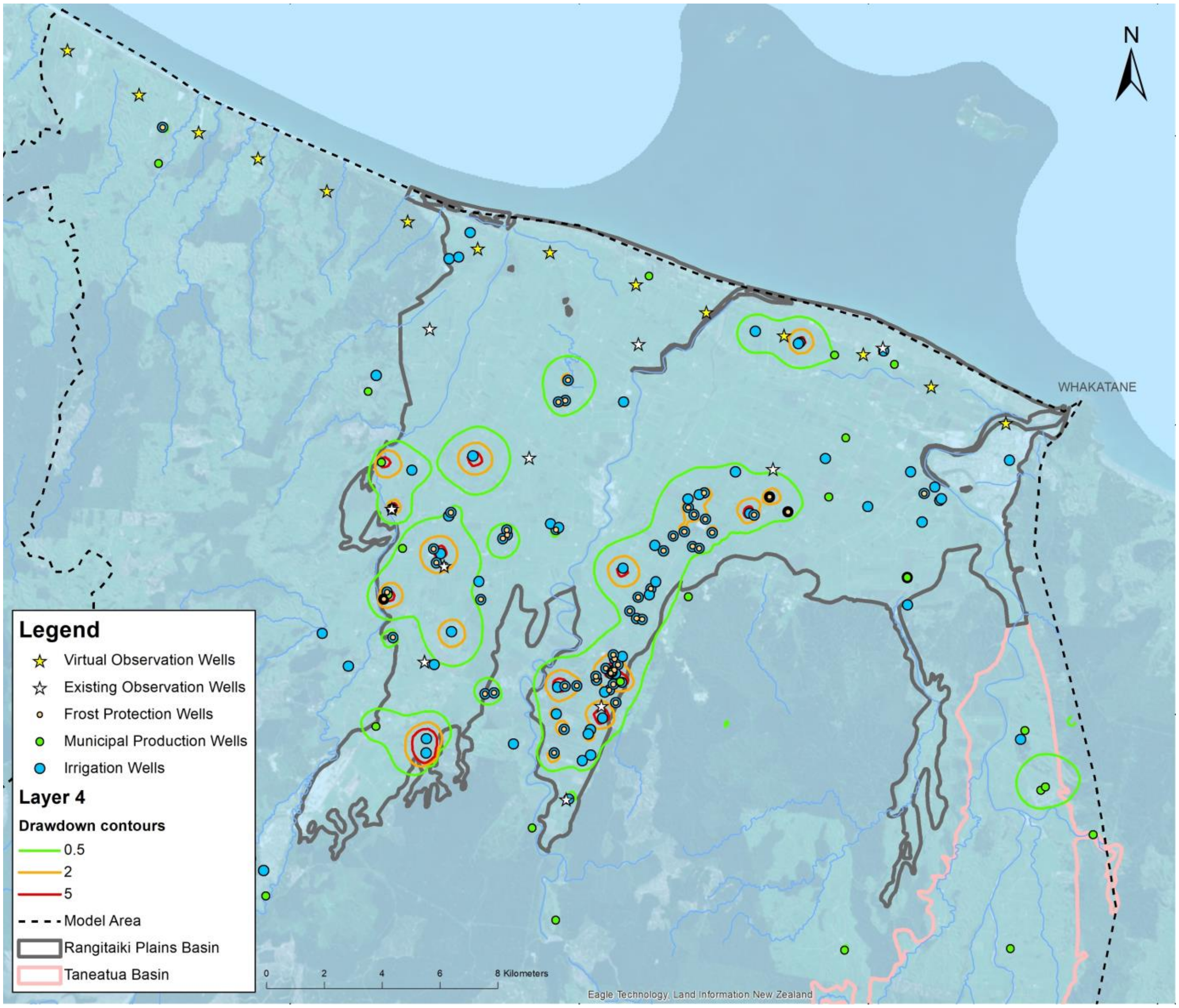


Figure A.4. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 4 (layer elevation from about -154 m Moturiki to -117 m Moturiki) , stress period 138.

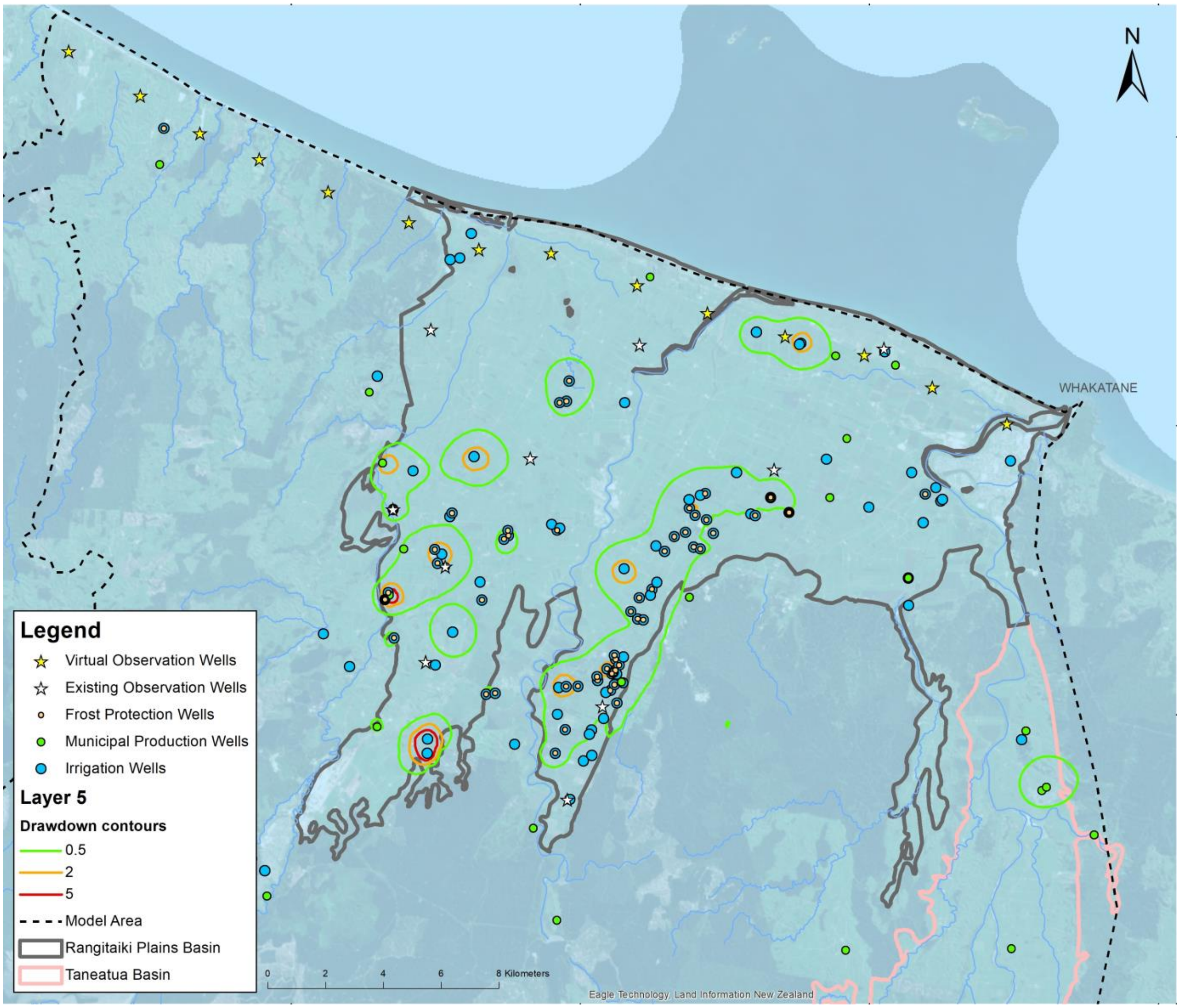


Figure A.5. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 5 (layer elevation from about -204 m Moturiki to -167 m Moturiki), stress period 138.

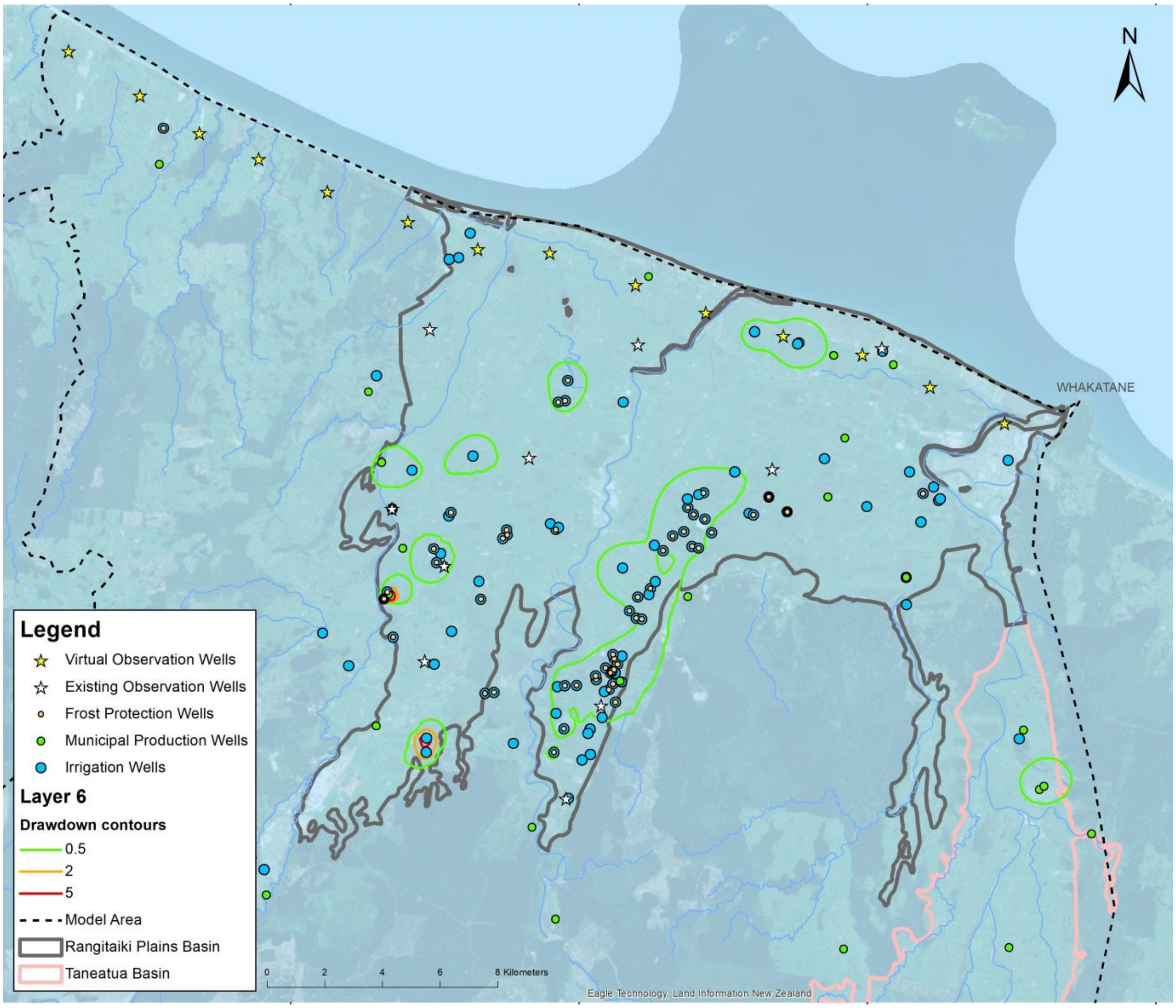


Figure A.6. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 6 (layer elevation from about -254 m Moturiki to -217 m Moturiki), stress period 138.

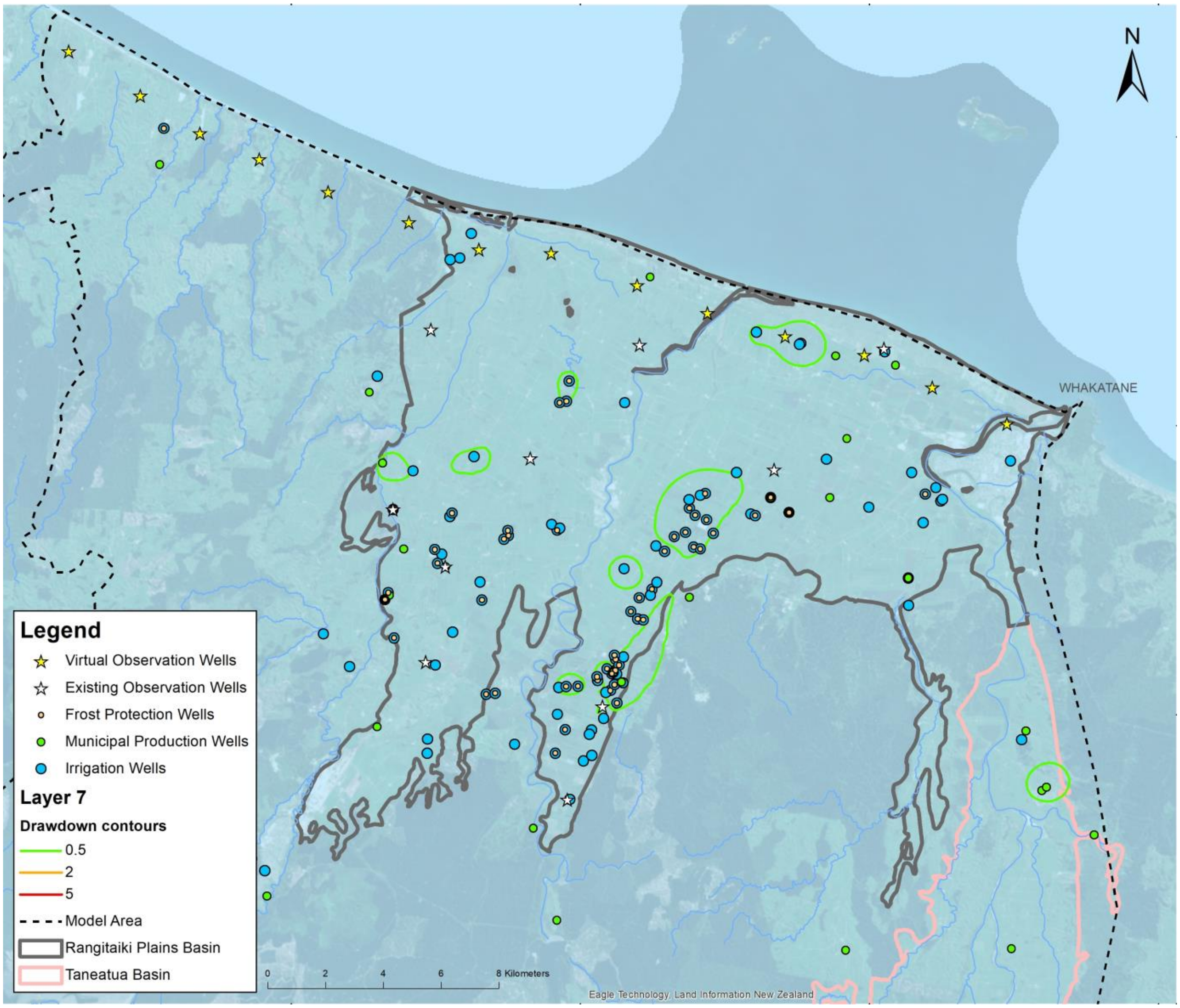


Figure A.7. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 7 (layer elevation from about -304 m Moturiki to -267 m Moturiki), stress period 138.

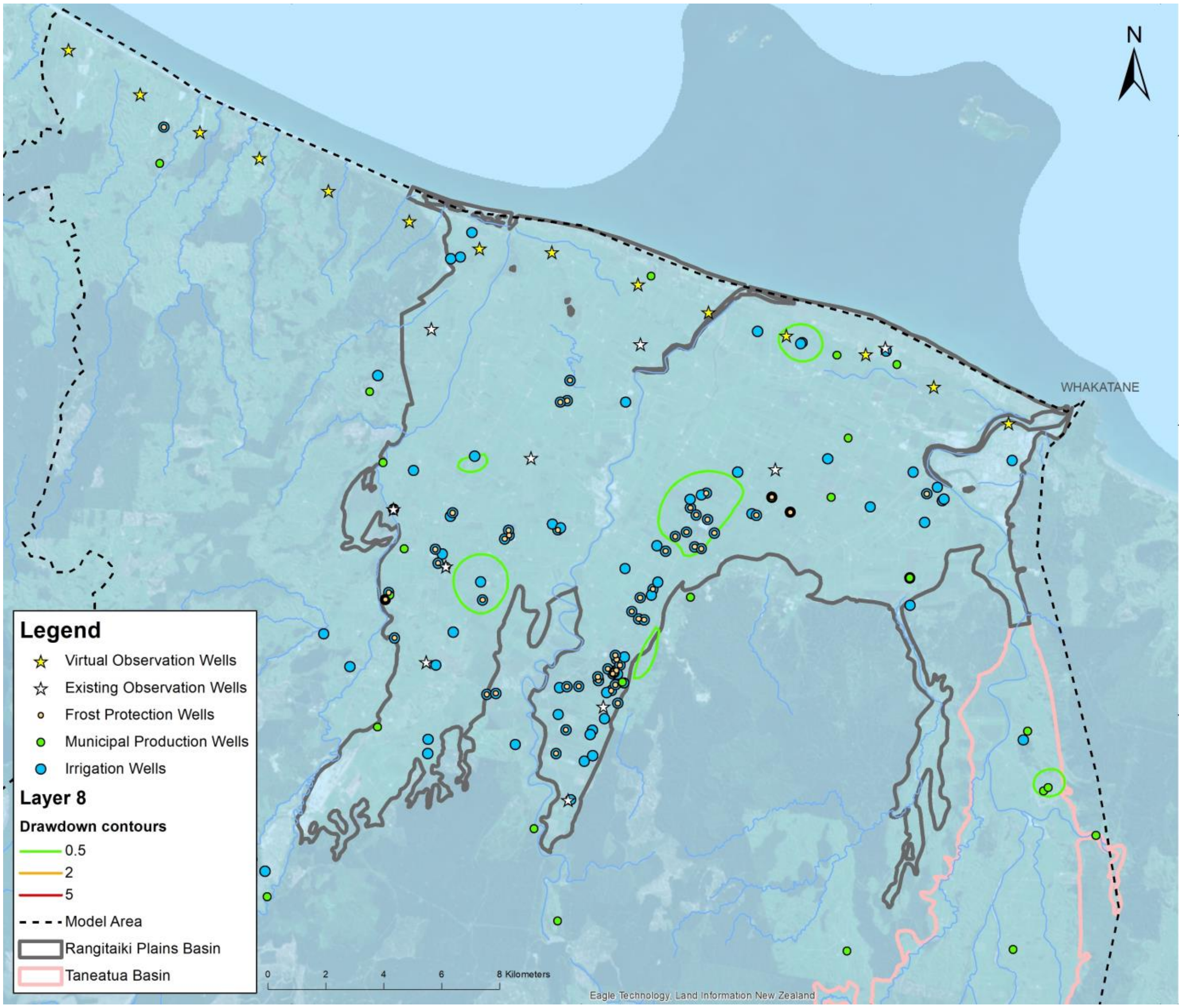


Figure A.8. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 8 (layer elevation from about -354 m Moturiki to -317 m Moturiki), stress period 138.

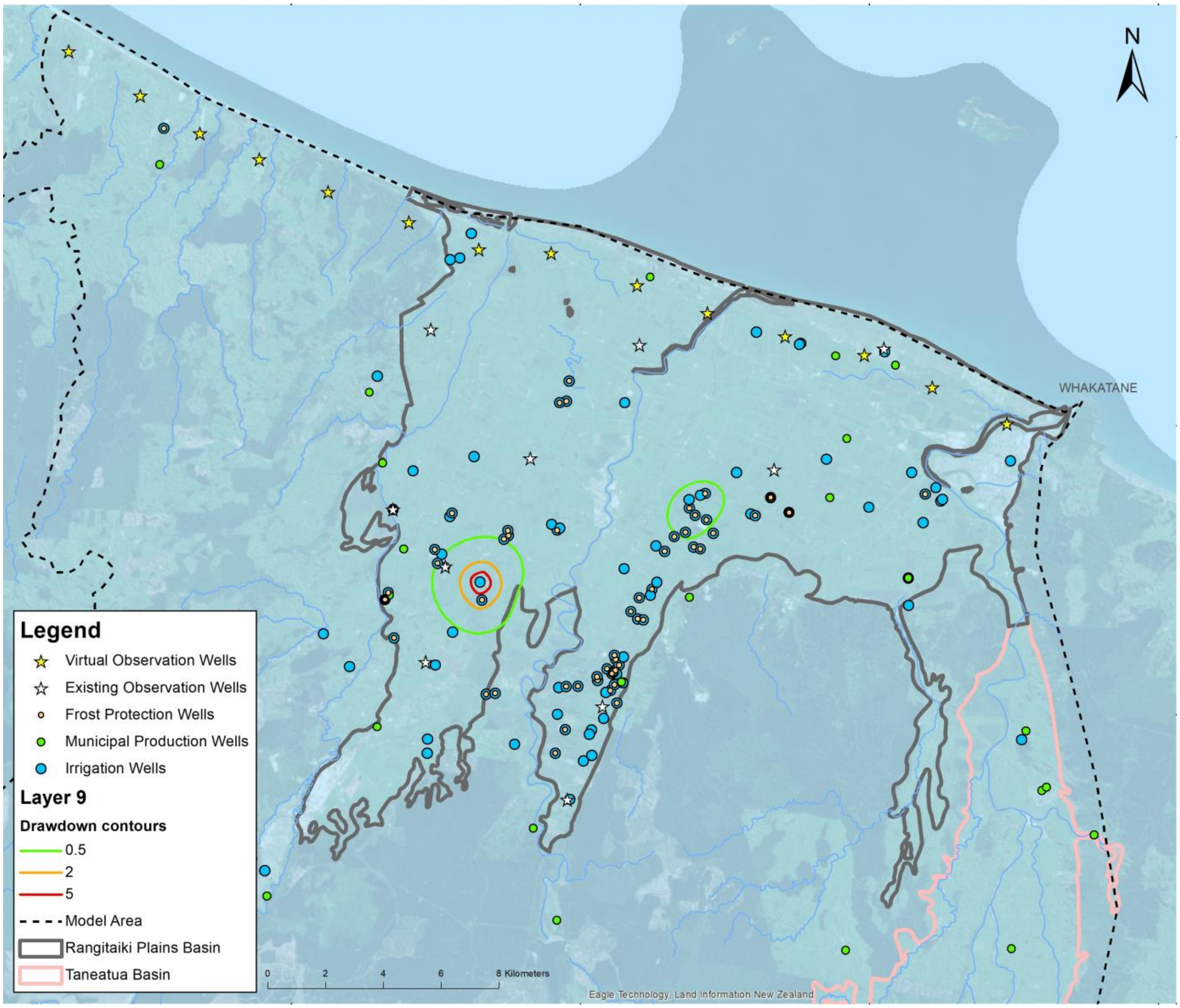


Figure A.9. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 9 (layer elevation from about -404 m Moturiki to -367 m Moturiki), stress period 138.

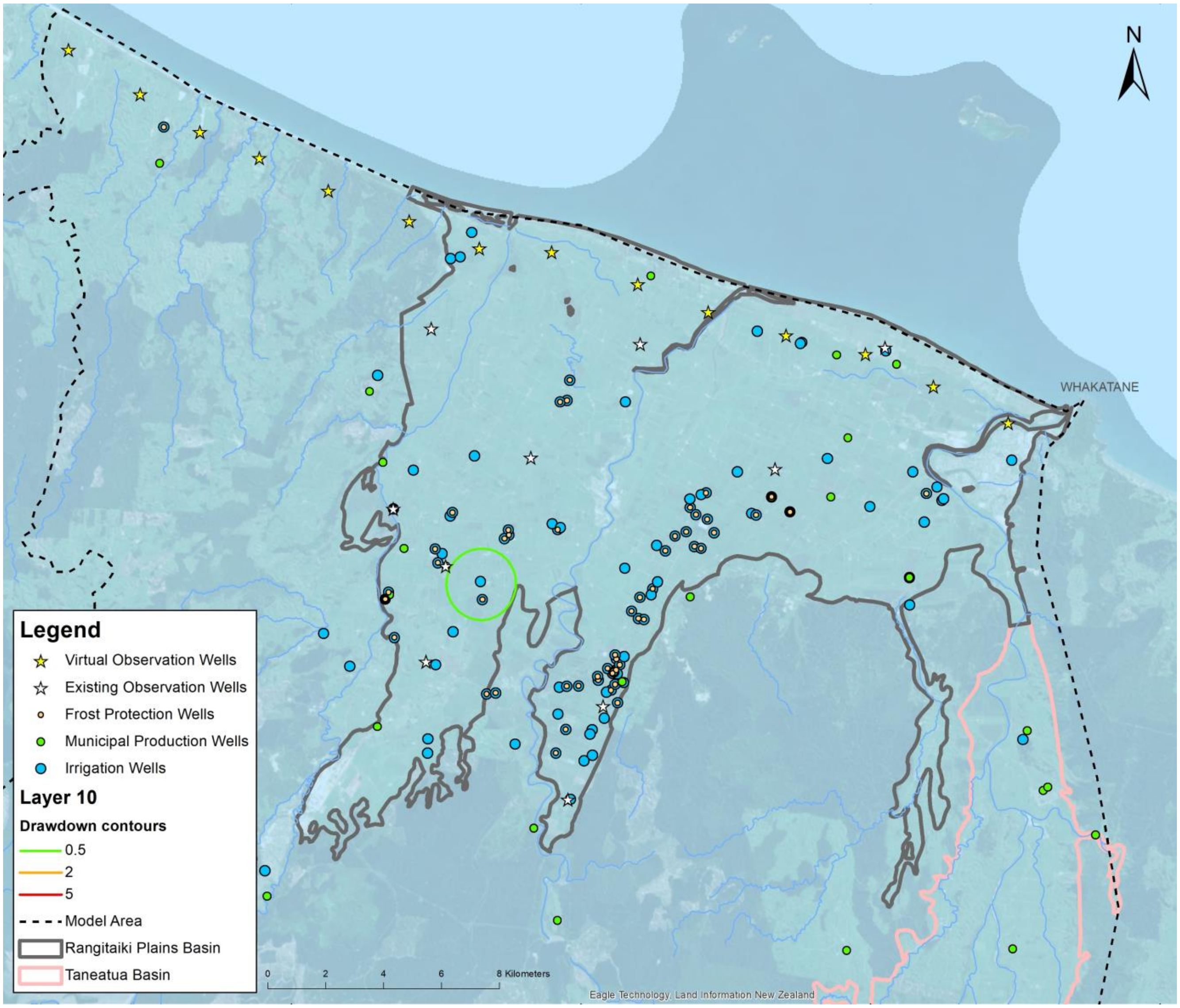


Figure A.10. Drawdown contours for Rangitāiki Plains and lower Taneatua Basin in Layer 10 (layer elevation from about -604 m Moturiki to -567 m Moturiki), stress period 138.