

Heretaunga Aquifer Groundwater Model

Executive Summary of Development Report

May 2018

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1 Introduction

1.1 Purpose of this document

This executive summary is a standalone document that complements the Heretaunga Aquifer Groundwater Model Development Report (Rakowski *et al.*, 2018). The purpose of this document is to provide a concise but comprehensive summary of study findings, particularly on the hydrogeological conceptualisation. Detailed discussion is provided in the main development report, along with references to related studies.

1.2 Content of the report

This report summarises the following:

- Hydrogeological conceptualisation, including a summary of historical and recently acquired data;
- Model design;
- Model calibration using automated model calibration software PEST;
- Discussion of model limitations and capabilities.

1.3 Purpose of the study

The overall purpose of the groundwater model was to simulate the Heretaunga Plains gravel aquifer system and associated surface water resources to allow technically defensible groundwater and surface water allocation and water quality limits to be established. A detailed discussion of the objectives is provided in section 2 of the development report.

1.4 Context of the study

The work documented in the development report is a part of a larger groundwater modelling study, which includes modelling scenarios, contaminant transport modelling and uncertainty estimation, which will be documented in separate reports.

This groundwater modelling study is in turn a part of a series of studies supporting the Plan Change for catchments of TANK (Tutaekuri, Ahuriri, Ngaruroro and Karamu Rivers). The Plan change for the TANK catchments will ensure that appropriate limits are established for water resources within the management zones.

The groundwater modelling elements of the TANK study include the following:

- MODFLOW groundwater flow model of the Heretaunga Aquifer System (covered by this report);
- SOURCE surface water flow and quality model in the TANK catchment area, linked to the groundwater flow model;
- IRRICALC recharge and irrigation demand model, providing inputs to MODFLOW and SOURCE;
- MT3D groundwater contaminant transport model (uses MODFLOW model results);
- OVERSEER nutrient loading model, providing inputs to MT3D and SOURCE;
- MODPATH particle tracking model, providing travel times and pathways for contaminants in groundwater (uses MODFLOW model results).

2 Hydrogeological conceptualisation

2.1 Geography

The study area comprises the Heretaunga Plains and surrounding valleys. The alluvial Heretaunga Plains are an area of 300 km², located on the east coast of the North Island of New Zealand. The Plains are bound by steep hills on three sides, and the coast to the east. The Plains have been formed by sediments deposited by the Ngaruroro, Tukituki and Tutaekuri Rivers.

2.2 Geology

The Heretaunga Plains is a fault bounded, deep sedimentary basin, reaching at least 900 m depth (perhaps as deep as 1,600 m) below ground level.

The geology in the hill country surrounding the plains is mostly Pliocene limestone and sandstone. These Pliocene sediments also form the basement of the sedimentary basin. The Pliocene sediments are overlaid by younger Quaternary rocks, mainly of the Kidnappers Group, which consist of a sequence of conglomerate, sandstone and mudstone. Above the Kidnappers Group there is a sequence of younger Quaternary alluvium deposited during interglacial and glacial periods. These alluvial deposits are estimated to be present to depths of 250 m below the Heretaunga Plains and consist of permeable river gravels interlayered with finer deposits, forming the Heretaunga Aquifer System. Younger Holocene deposits form gravel fans where major rivers (Ngaruroro, Tukituki and Tutaekuri) enter the plains. The fan gravels overlie the Last Glacial Gravels (the “Q2-Q4 deposits”), and together these gravel units form the main Heretaunga aquifer, that is highly developed for groundwater extraction. The deeper Heretaunga aquifer (largely undeveloped) is formed by the (“Q5-Q7”) deposits that lie below the Last Glacial Gravels, extending to around 250 m depth. A wedge of fine Holocene sediments (marine, estuarine and lagoon sediments) extends from the coast into the eastern part of the plains, overlying the Q2 deposits and forming a confining layer of the eastern part of the aquifer.

2.3 Geological model

A 3D geological model of the Heretaunga Plains has been developed using Leapfrog software. An example cross-section is provided in Figure 2-1. The Leapfrog geological model used several thousand HBRC bore logs, topographic data, the geological map of Hawke’s Bay, radiocarbon age data and information from published seismic lines.

The geological model defines the following units relevant for this study (Figure 2-1):

- Holocene gravel units, including fan gravels for Ngaruroro, Tukituki, and Tutaekuri Rivers, which form aquifers, particularly in the unconfined (western) areas – in light green in Figure 2-1;
- Holocene marine/estuarine deposits, forming a confining layer above eastern parts of the aquifer system (Figure 2-2, in blue in Figure 2-1);
- Last Glacial Gravels underlying Holocene deposits, forming the main Heretaunga aquifer (i.e. the relatively shallow parts of the overall aquifer, where most aquifer development has occurred) – in dark green in Figure 2-1;
- Quaternary Alluvial units below the Last Glacial Gravels to depths of around 250 m, forming the deeper Heretaunga aquifer that is largely undeveloped – in khaki in Figure 2-1.

The Leapfrog geological model has achieved a reasonable representation of the shallow gravel aquifer and confining layers. This means that it is a realistic representation of the main geological features, and overall it fits the available geological data. However, the base of the Last Glacial gravels and details of the deeper

aquifer system are represented crudely. This is mainly due to limited data availability (most available bores are shallow and only a few bores are more than 100 m deep). Nevertheless, the Leapfrog geological model is useful for informing a conceptual understanding of the subsurface.

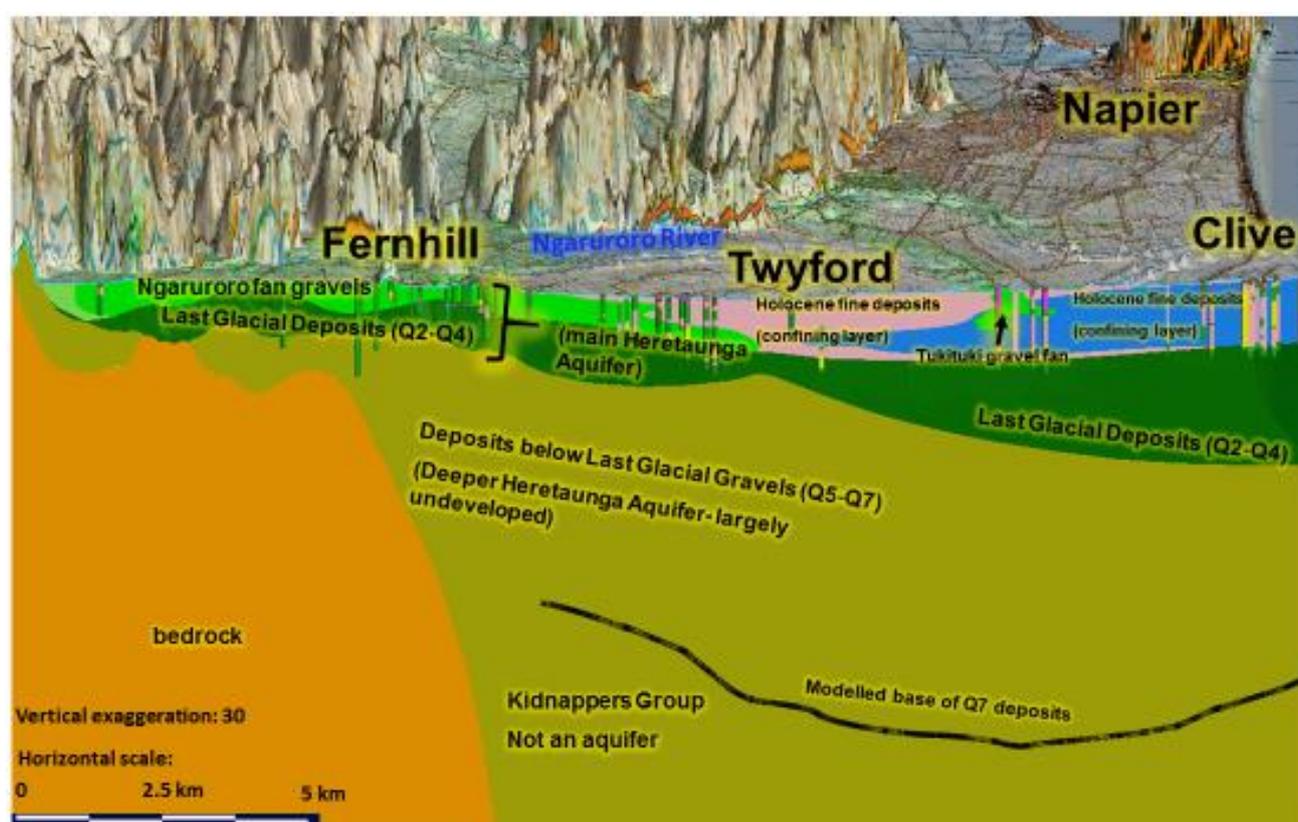


Figure 2-1: Leapfrog 3D geological model. Example of cross-section between Fernhill and Clive

2.4 Aquifers

The Heretaunga Aquifer System has been formed to estimated depths of about 250 m within a much deeper sedimentary basin underlying the Heretaunga Plains. The aquifer consists of alluvial materials deposited by rivers over thousands of years and partially confined or interlayer by fine marine sediments. The deposition of the aquifer material by rivers meandering and changing course suggests heterogeneous nature of the aquifer.

The Heretaunga Aquifer System includes the Heretaunga Aquifer (including Tukituki Aquifer) and a few connected peripheral valley aquifers (Figure 2-2): Moteo, Tutaekuri and the upper Ngaruroro valleys. There is evidence that other aquifers in the vicinity (e.g. Okawa, Poraiti, Ahuriri, Te Awanga and Poukawa valleys) are not connected.

The Leapfrog geological model and available drilling data indicates that the aquifer is stratified, although there is some degree of connection between the deeper and shallower aquifer layers. The deep sedimentary units below 250 m have relatively poor aquifer potential.

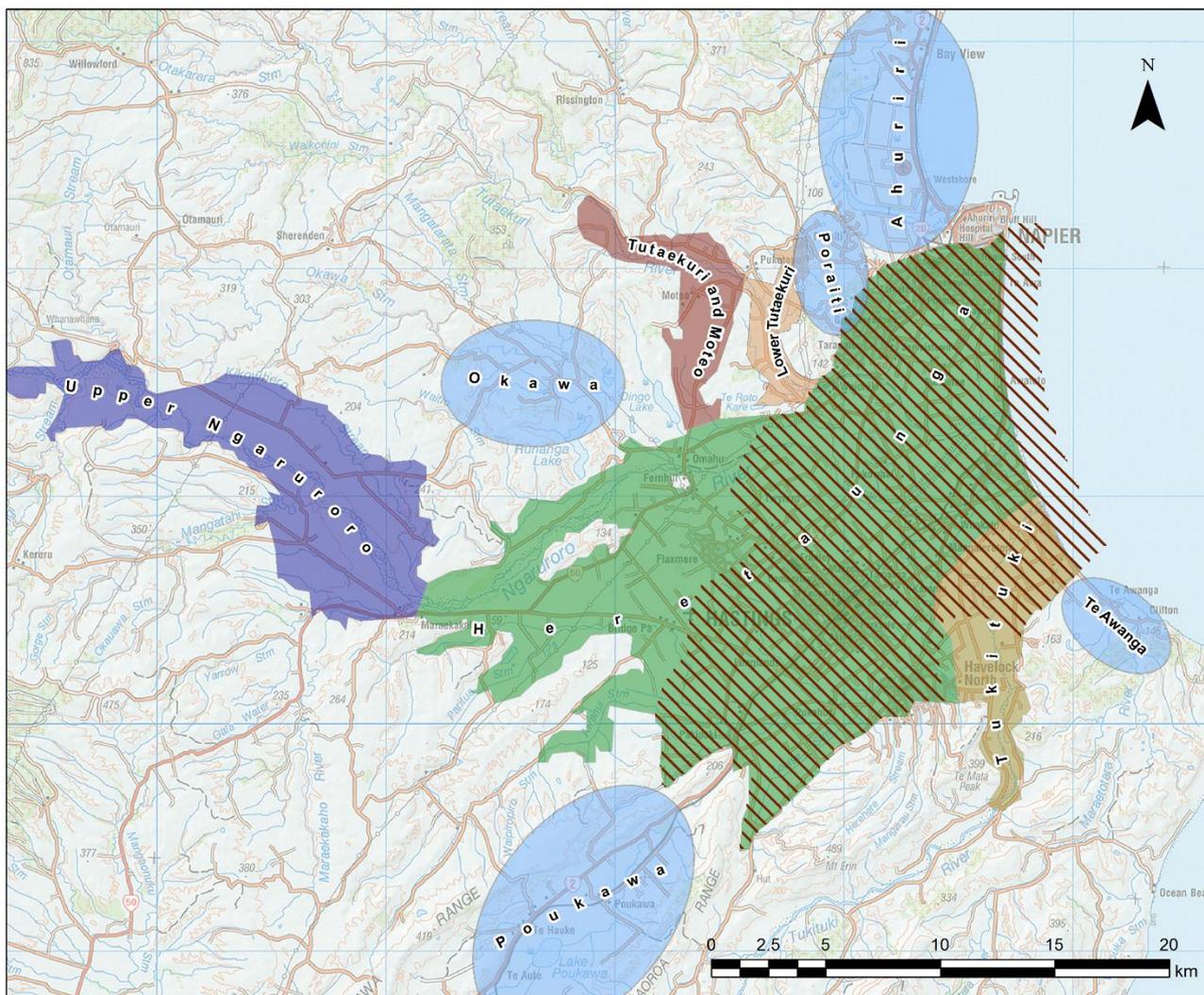


Figure 2-2: Heretaunga Aquifer System Confined area of the aquifer is shown with brown hatched lines. Aquifers that are not considered part of the Heretaunga Aquifer System are shown as blue ovals to indicate their approximate location and size.

2.5 Aquifer type

The eastern part of the main Heretaunga aquifer is confined and artesian. The shallowest layer of the Last Glacial Gravels is confined under a thick wedge of low permeability Holocene sediments. The confined area of the aquifer is shown in Figure 2-2.

In the western part of the aquifer, drilling identified a shallow, unconfined aquifer, predominantly formed by gravel fans associated with major rivers, which allows high rates of rainfall and river recharge to occur. Unconfined conditions have also been encountered where the Tukituki River enters the Heretaunga Plains.

2.6 Aquifer properties

The main aquifer units are formed by highly transmissive alluvial gravels. Aquifer properties are known from numerous pumping tests. Available test data has been compiled and reviewed for the purpose of this study.

2.7 Groundwater flow

The groundwater flow direction is eastwards from the recharge areas towards the coast, with pumping and spring discharges having some effect on the flow pattern. The piezometric map of measured groundwater level contours is shown on Figure 2-3.

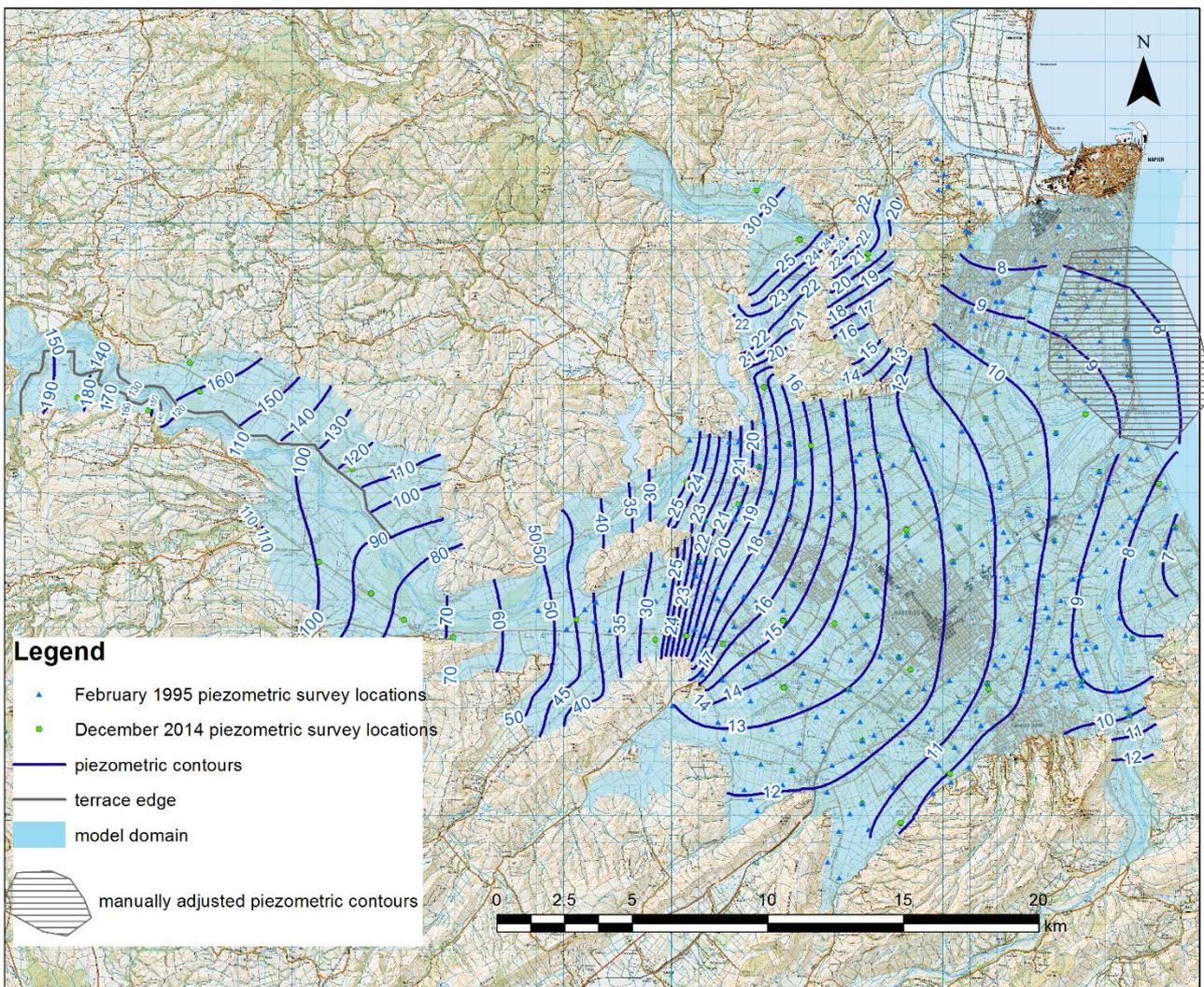


Figure 2-3: Piezometric map of the Heretaunga Aquifer System during summer.

Groundwater levels in the Heretaunga Aquifer have been extensively monitored. For this study, 101 monitoring points with corresponding time series data sets were compiled, and 43 locations were selected for the purpose of model calibration as shown on Figure 2-4. Selection criteria are described in the main report.

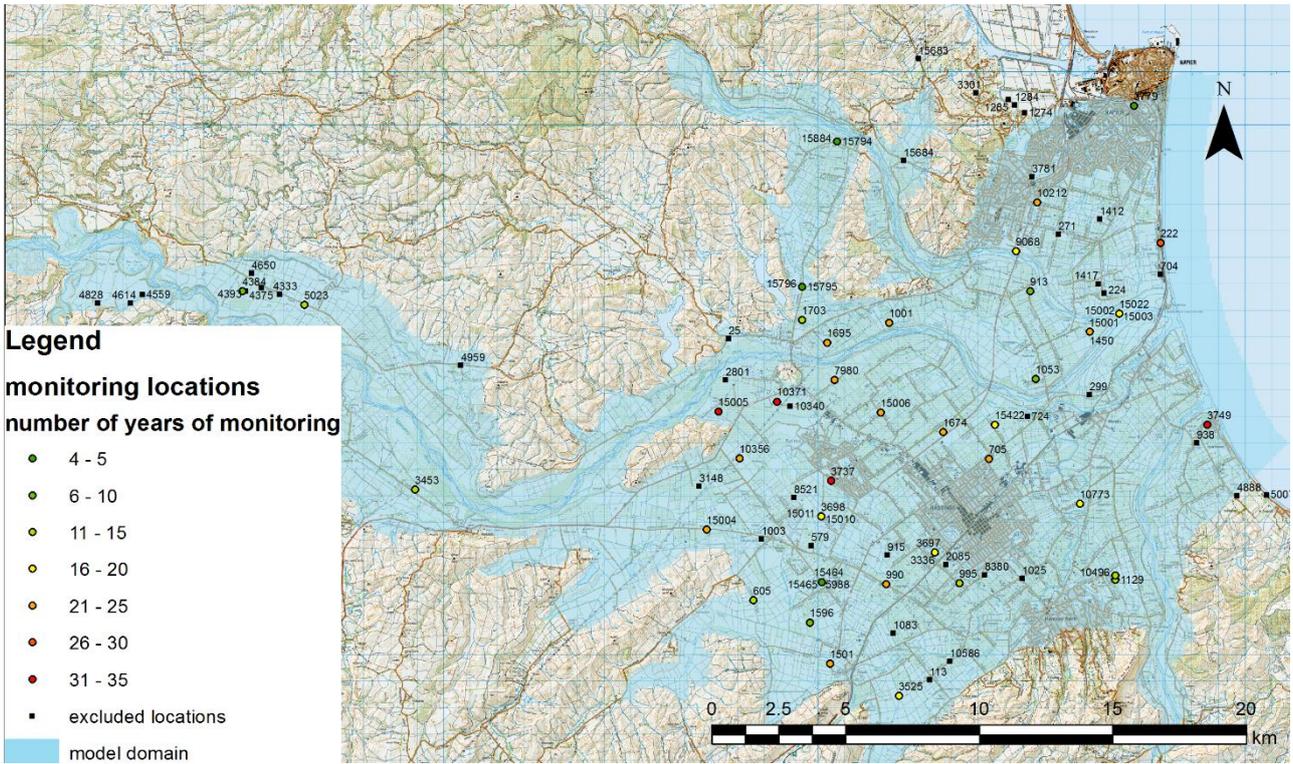


Figure 2-4: Groundwater level monitoring locations and available data.

2.7.1 Seasonality of groundwater levels

Groundwater levels in the Heretaunga Plains show strong seasonality, with groundwater level changes of about 2 m between summer and winter. Selected monitoring records are shown on Figure 2-5, with seasonal variation clearly visible for all bores.

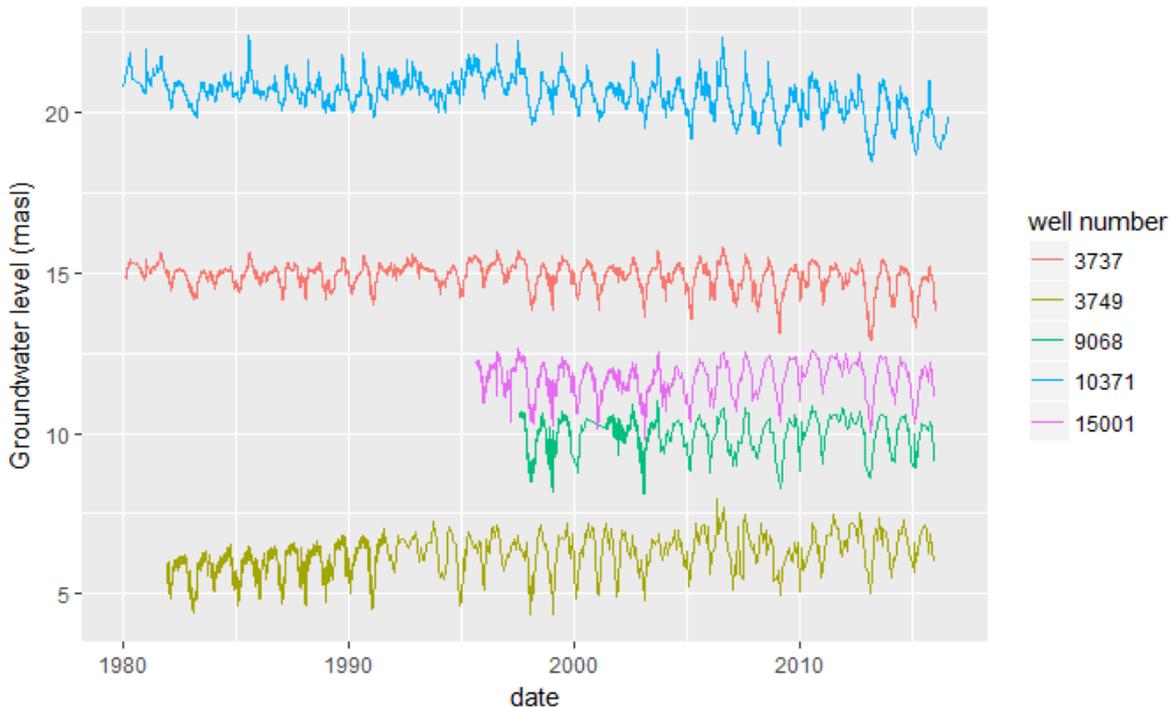


Figure 2-5: Selected long term groundwater monitoring records.

2.7.2 Long term water level changes

A few of the monitoring locations also show long term water level changes, with one location showing a maximum trend equivalent to 2 m decline over 20 years, and smaller declining trends in other locations. Declining trends are localised near Fernhill, as shown on Figure 2-6. Otherwise, statistically significant trends were not detected over most of the Heretaunga Plains. Changes to seasonality over time have also been observed, the amplitude between February and August water levels has increased by about 0.3 m to 0.7 m over 20 years. Selected monitoring records are shown on Figure 2-5, and the declining trend and increasing amplitude between summer and winter can be observed for the long term record of bore 10371.

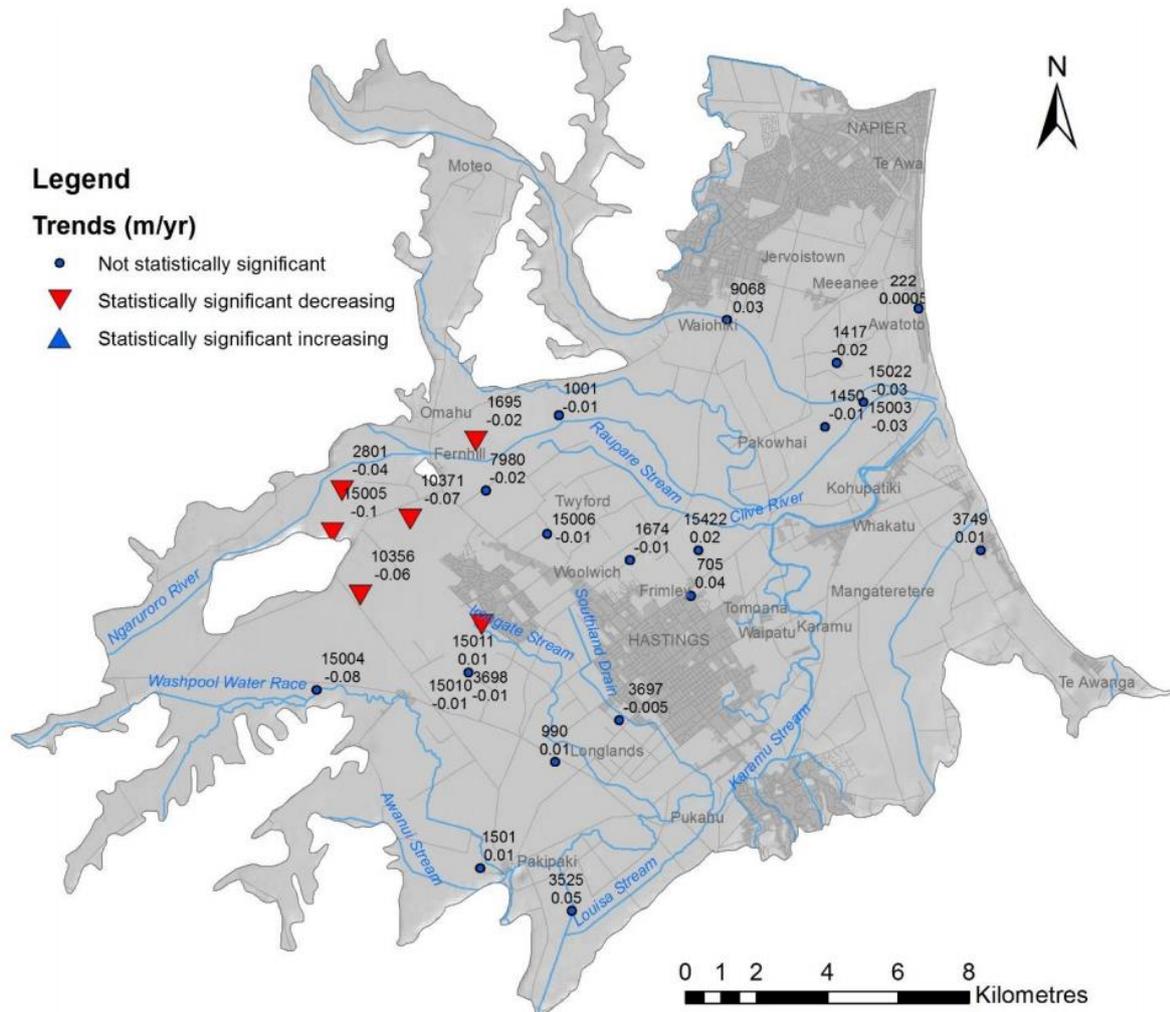


Figure 2-6: Groundwater level trends in Heretaunga Aquifer (after Harper, 2015).

2.8 Hydrology

On the Heretaunga Plains and surrounding valleys there is a complex network of rivers, streams and drains that interact with the underlying Heretaunga Aquifer System (Figure 2-7). There are three main rivers that flow across the Heretaunga Plains: the Ngaruroro, Tutaekuri and Tukituki Rivers. These rivers have braided gravel bed characteristics and originate in the mountains west of the Heretaunga Plains. After entering the plains, the rivers begin losing water (loss rates are shown in Table 2-1), providing recharge to the unconfined parts of the aquifer.

There are also a number of springs, spring fed streams and artificial drains that receive discharge from the aquifer. The largest spring fed streams and their typical summer discharges are summarised in Table 2-2.

A comprehensive and systematic review of the entire stream network of Heretaunga Plains has been undertaken in a recent study by HBRC, which identified all significant river losses and spring locations in the study area.

Table 2-1: Main river losses to the Heretaunga Aquifer System.

	Estimated typical loss to aquifer (L/s)
Ngaruroro	4,400
Tukituki	800
Tutaekuri	780
Total	5,980

Table 2-2: Summer spring discharges in Heretaunga Plains.

Stream	Typical summer spring discharge (L/s)
Tutaekuri-Waimate	1831
Karamu	575
Waitio	566
Raupare	402
Irongate	168
Mangateretere	46
Karewarewa	25
Paritua	-100 (losing section)
Other streams	15
Total	3528

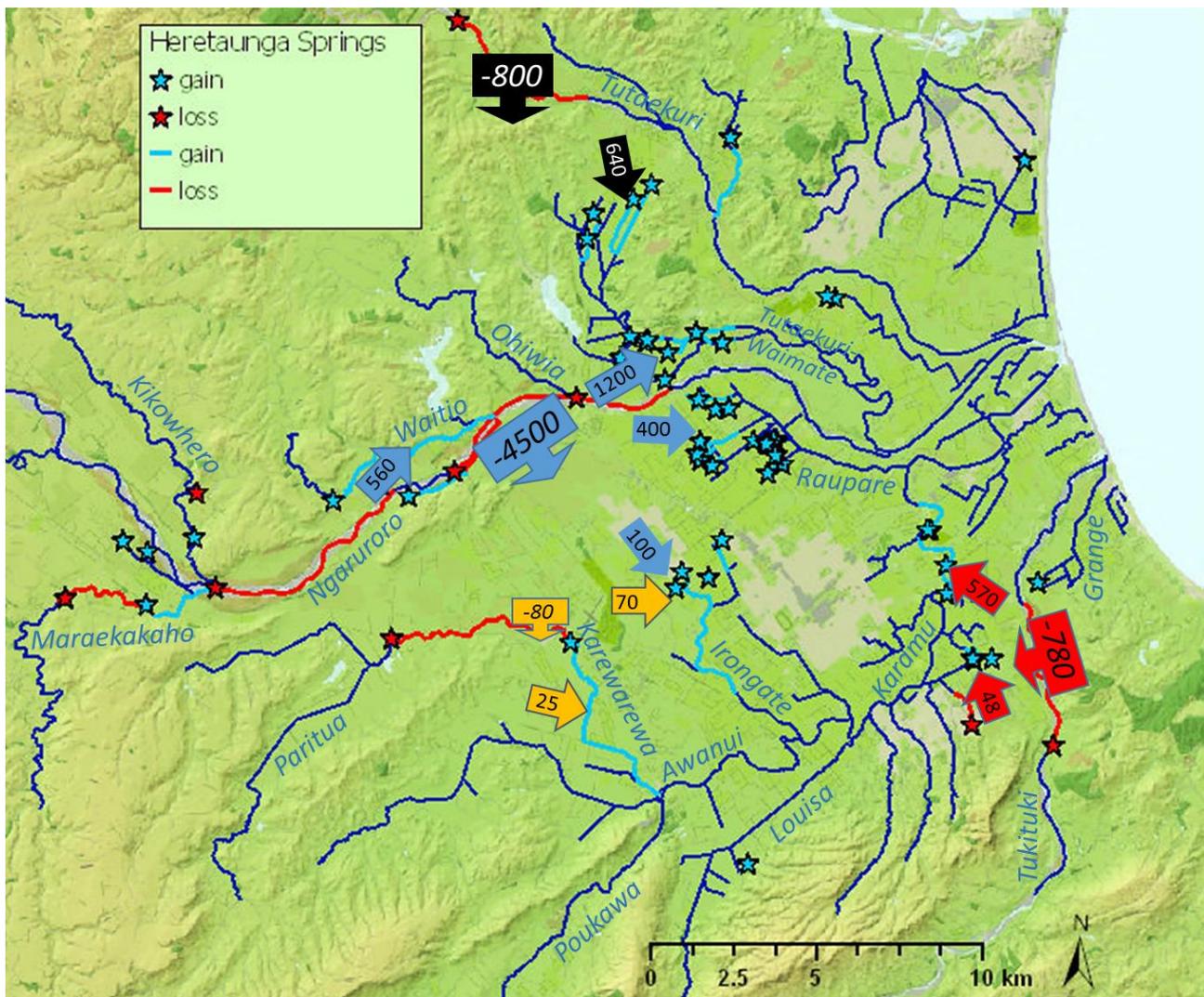


Figure 2-7: Heretaunga Plains hydrology and flows in L/s Red sections of waterways indicate losing reaches, while bright blue sections are gaining reaches.

2.9 Groundwater pumping

Groundwater pumping is a significant component of the groundwater budget for the Heretaunga Aquifer System. Groundwater abstraction is mainly used for public water supply, industrial and irrigation uses, with smaller volumes of water also abstracted for frost protection, stock water and domestic purposes.

A major review of metered pumping data was undertaken to support the model development. Numerous problems were encountered with these data, including issues related to data storage, availability and quality.

Abstraction for irrigation is a significant part of overall groundwater use in the Heretaunga Plains. Irrigation data used in modelling is based on the irrigation demand modelling, due to poor quality and availability of recorded data. Public water supply and industrial groundwater use data is available from HBRC databases and this data is considered of good quality except before 1990. Groundwater use data for Frost Protection, Stock Water and Domestic takes was estimated as data were not available.

Groundwater abstraction for public water supply is approximately 22 million m³/year (Mm³/year) and has been relatively stable since 1980. Industrial use appears to have stabilised in the year 2000 at a level of 13 Mm³/year. Approximately 50 Mm³/year is estimated to be abstracted for irrigation. Groundwater use for irrigation has steadily increased since 1980 (Figure 2-8).

Abstraction from the aquifer system is highly seasonal, with largest abstraction volumes in the summer, when more than 50% of groundwater abstraction is for irrigation (Figure 2-9). There is also considerable variability between the different years.

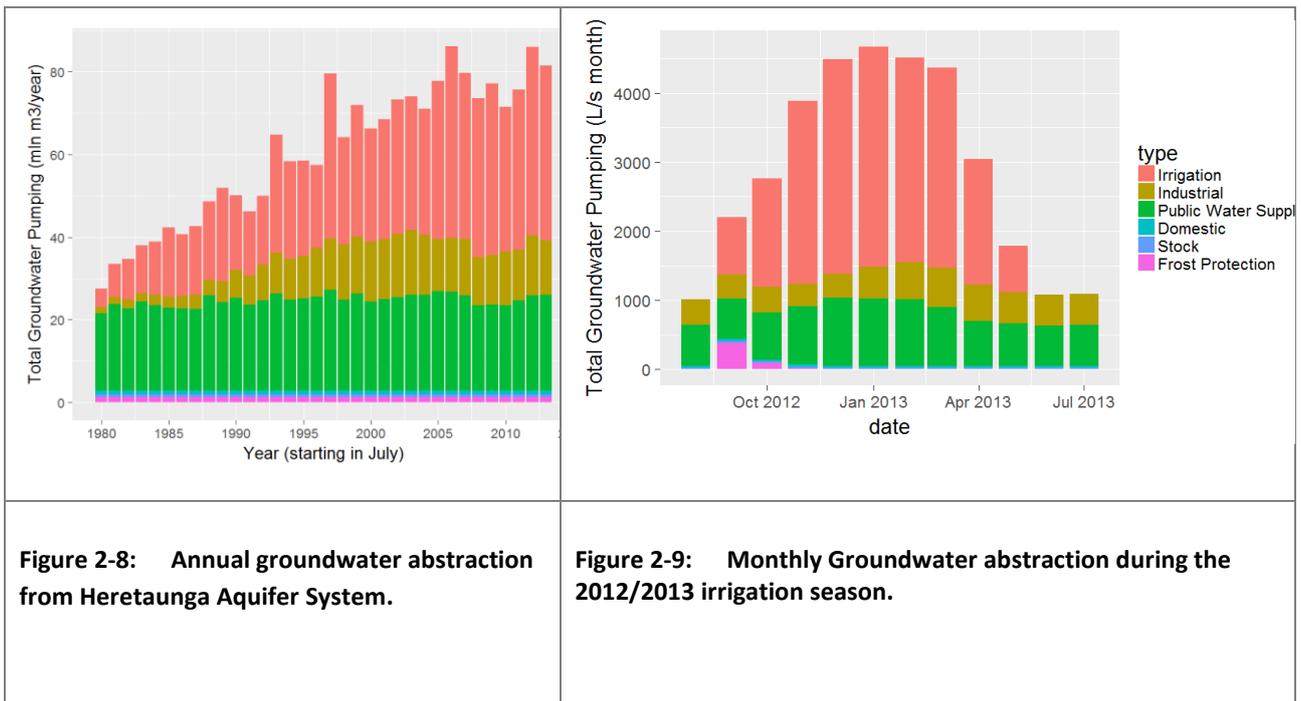


Figure 2-8: Annual groundwater abstraction from Heretaunga Aquifer System.

Figure 2-9: Monthly Groundwater abstraction during the 2012/2013 irrigation season.

Large, concentrated abstractions of groundwater occur for public water supply and industrial takes in several locations, while irrigation takes are relatively evenly distributed across the study area during summer seasons (Figure 2-10).

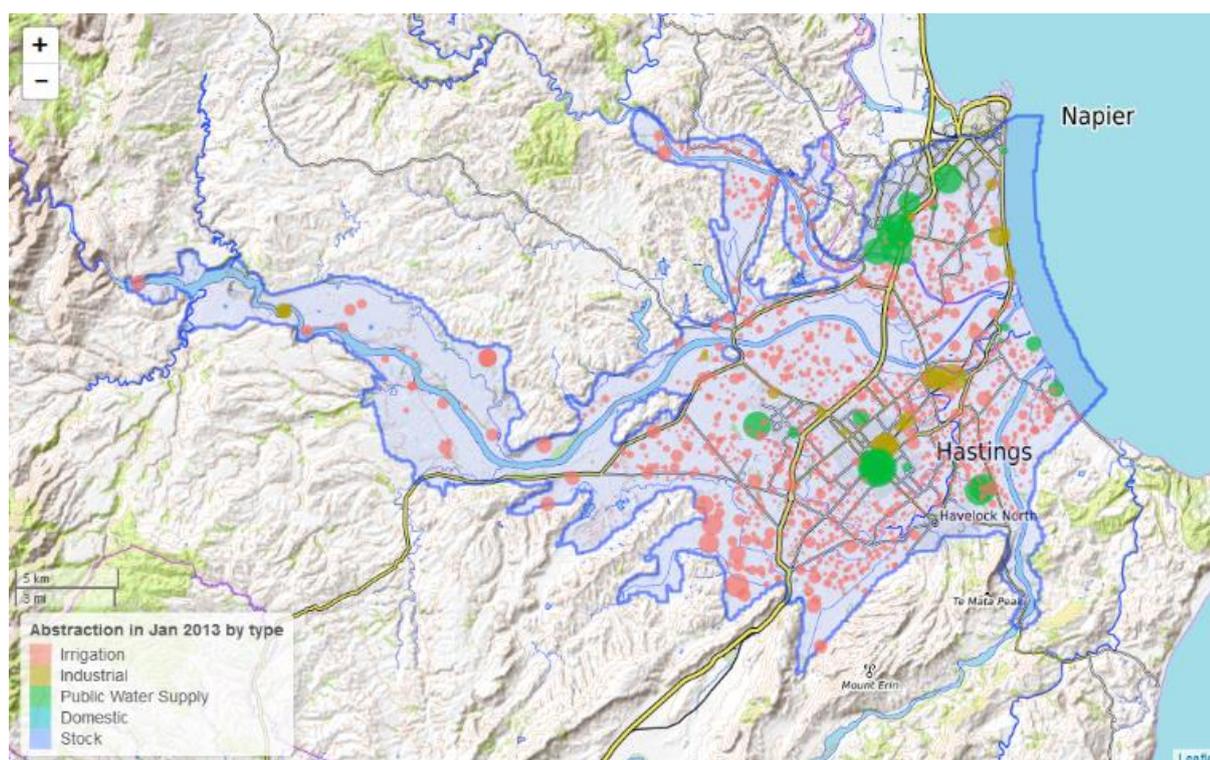


Figure 2-10: Distribution of groundwater pumping from the Heretaunga Aquifer System in January 2013 Dot area is proportional to take size, such that small domestic and stock water takes are indiscernible.

2.10 Land surface recharge

Land surface recharge (derived from rainfall) only occurs in the unconfined area of the aquifer which covers 239 km² (see Figure 2-11). Recharge in the confined aquifer area is limited by the presence of impermeable marine sediments that form a confining layer. Land surface recharge (LSR) was calculated for this study by Aqualinc Research Ltd, as part of their irrigation demand assessment for the Heretaunga Plains.

The study has relied on soil data, climatic data, crop data and irrigated area to calculate daily LSR for each combination of the above variables, which resulted in 3,108 recharge daily time series. The calculations were undertaken using Aqualinc's Irricalc daily soil water balance model, which is accepted and field verified internationally and within New Zealand.

LSR is highly variable over time, with most of this recharge occurring in winter months, but much less LSR occurring during the summer period (see Figure 2-12). There is also variation between years, depending on the rainfall.

The average LSR between 2005 and 2015 is 330 mm/year, which is equivalent to 78.9 Mm³/year across the Heretaunga Plains.

Average rainfall in this period was 769 mm, which means that recharge is 42% of rainfall (on average).

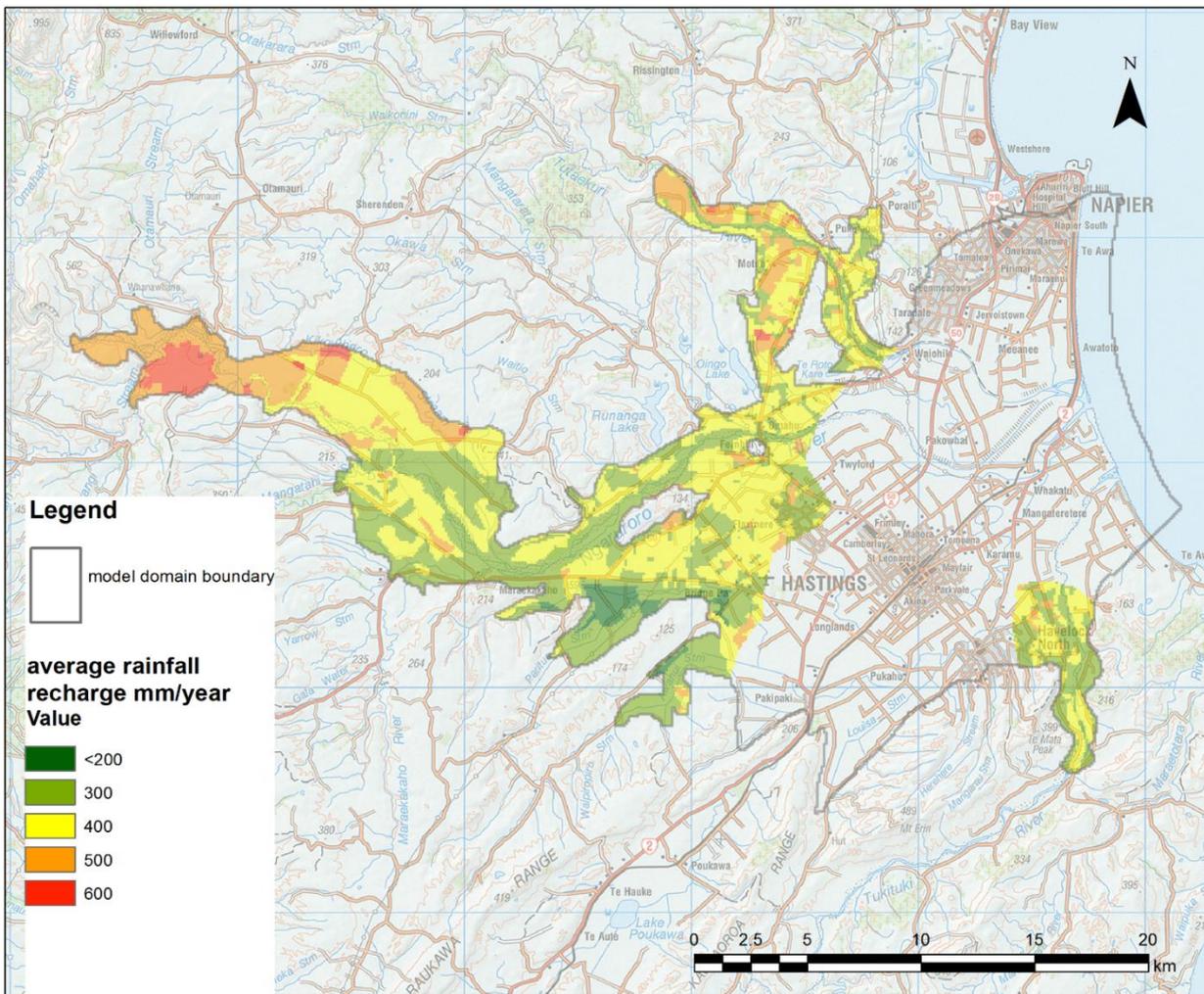


Figure 2-11: Distribution of average annual (2005-2015) land surface recharge (mm/year).

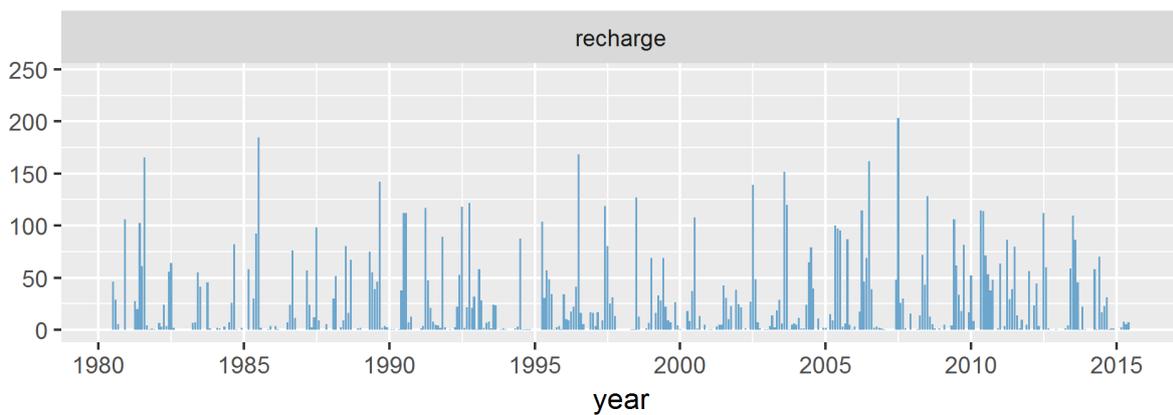


Figure 2-12: Monthly land surface recharge on the Heretaunga Plains (mm).

2.11 Sea discharge

Whether or not the aquifer is hydraulically connected to the sea is uncertain. The geological understanding is that the gravel formations may extend far offshore, suggesting that such connection is possible. Navigational charts indicate the presence of submarine springs perhaps 30 km offshore, but the presence of these springs has not been confirmed in recent investigations, and it is not certain how they were identified originally. High artesian head recorded at the coast indicates there is some hydraulic resistance between the sea and the aquifer.

2.12 Water budget

Most (71%) of the total recharge to the aquifer occurs through river losses (rather directly than from rainfall), most of which is from the Ngaruroro River, with the remainder from the Tukituki and Tutaekuri rivers. In contrast, land surface recharge provides 29% of recharge to the aquifer and occurs in the unconfined area of the aquifer.

Discharge from the aquifer occurs through springs and spring fed streams (42%) along with groundwater pumping (29%), with the remainder most likely occurring via submarine springs.

The groundwater budget is presented in Table 2-3 and Figure 2-13. This budget approximates average or typical conditions, however it needs to be noted that spring discharges are representative of average summer discharge, as winter spring discharges are difficult to measure.

The budget is presented in both L/s to allow for easy comparison with river flow which are typically recorded in this unit, and million m³/year (Mm³/year) which is often used when discussing water allocation.

Table 2-3: Groundwater budget for the Heretaunga Aquifer System.

	Type	Description	Mm ³ /year	L/s	
INFLOWS	River Recharge (to groundwater)	Total river recharge to groundwater (based on observed major river losses by HBRC) including: Ngaruroro loss Tukituki losing Tutaekuri losing	188.6	5,980	71%
			138.8	4,400	
			24.6	780	
			25.2	800	
	Land Surface Recharge from rainfall	LSR calculated by Aqualinc for the unconfined area	78.5	2,489	29%
	TOTAL INFLOWS		267.1	8,469	
OUTFLOWS	Spring discharges	Measured summer discharges	111.0	3,520	42%
	Groundwater pumping	Some data, and estimated from demand modelling	78.1	2,475	29%
	Sea discharge	No observations	78.0	2,474	29%
	TOTAL OUTFLOW		267.1	8,469	

Heretaunga Aquifer System water budget

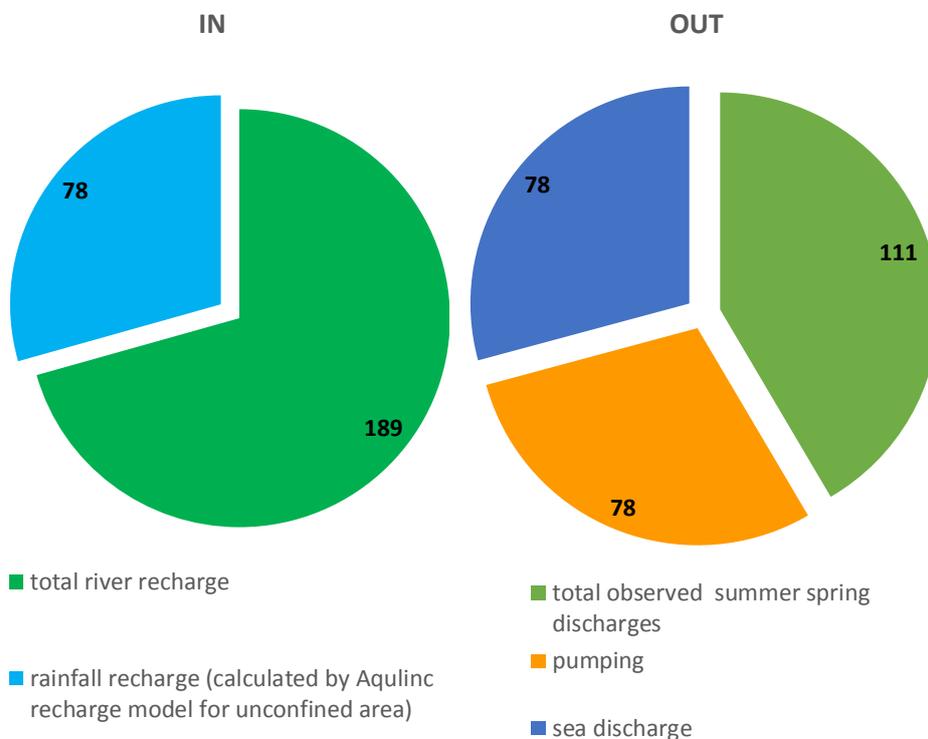


Figure 2-13: Average Water budget for the Heretaunga Aquifer System (in Mm³/year).

2.13 Geochemistry

GNS Science, in collaboration with HBRC, completed an investigation of groundwater age along with the isotopic and hydrochemical composition of water in the Heretaunga Aquifer System. The aims of the investigation were to explore rates of groundwater flow through the aquifer, along with the interaction of groundwater with streams and rivers. The study used available age tracer data for the Heretaunga Plains including: tritium, CFCs, SF₆, δ²H, δ¹⁸O, Ar, N₂, CH₄, radon and major/minor ion hydrochemistry data.

Results of this study helped to identify sources of water in the aquifer and springs, and informed the conceptual model of the aquifer. For example, the study has indicated that groundwater in the Napier area comes from the Ngaruroro River, despite its geographical separation, and confirmed contributions from the Ngaruroro River to recharge the aquifer in other areas.

2.14 Conceptual model summary

The Heretaunga Aquifer System includes the main Heretaunga Aquifer (including Tukituki Aquifer) within the Heretaunga Plains area, along with hydraulically connected surrounding valley aquifer systems including Moteo valley, Tutaekuri valley and the upper Ngaruroro valley. The Heretaunga Aquifer is formed by highly transmissive alluvial gravels. The aquifer is stratified, although there is some degree of connection between deeper and shallower aquifer layers.

A conceptual aquifer cross section (Figure 2-14) shows the main aquifer is confined and artesian in the eastern part, while it is unconfined in the western part and also near the Tukituki River.

Major features of the Heretaunga Aquifer are shown in Figure 2-15, with the main water budget components identified and quantified.

About a third of recharge to the aquifer occurs through river losses, mainly from Ngaruroro River. Land surface recharge in the unconfined area provides remainder of recharge. Discharge from the aquifer occurs mainly through springs and spring fed streams, with about a third through the groundwater pumping, and with the remainder most likely occurring via submarine springs.

Groundwater pumping forms a significant part of the water budget, especially during the summer irrigation season, and is likely to affect other parts of the water budget, such as spring discharges.

The groundwater flow direction is eastwards from the recharge area in the west towards the coast, with pumping and spring discharges having some effect on flow patterns.

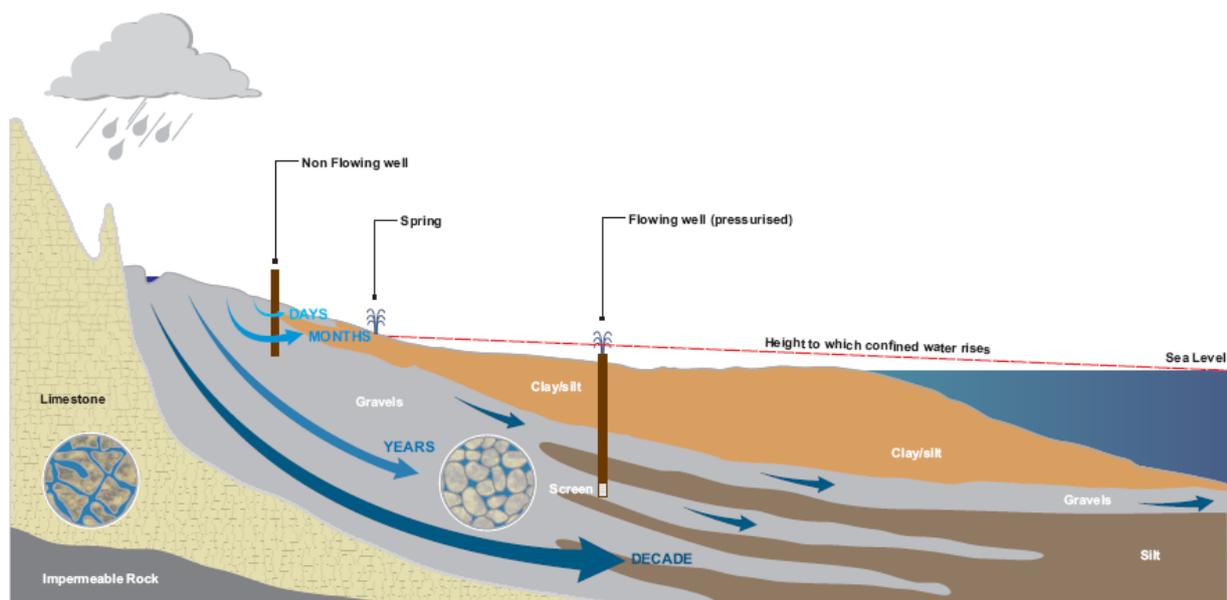


Figure 2-14: Conceptual cross-section through Heretaunga Plains.

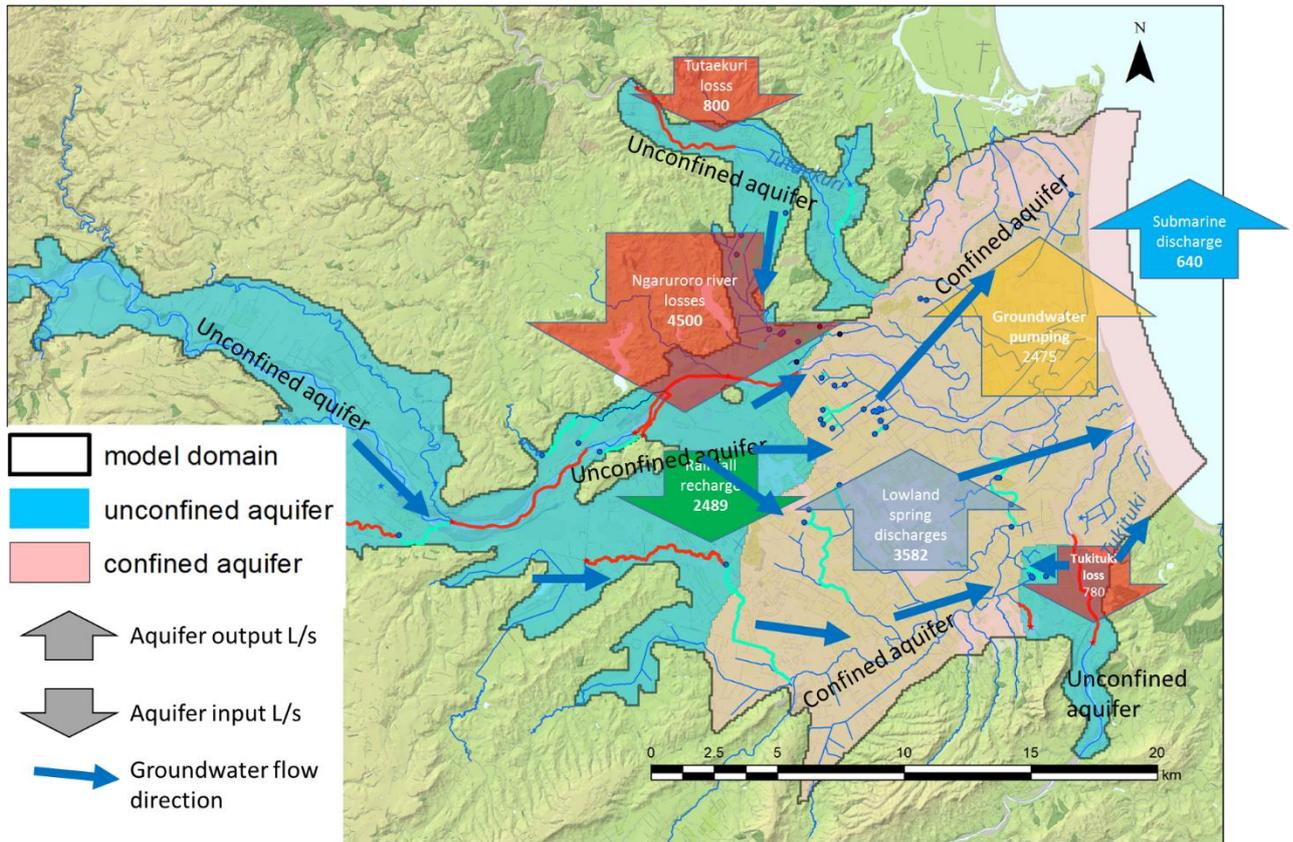


Figure 2-15: Main features of the Heretaunga Aquifer Arrows show typical flow components in L/s, for explanation refer to Section 2.12

3 Description of groundwater model

A detailed description of the model set-up is given in section 5 of the main report (Rakowski *et al.*, 2018).

MODFLOW-2005 was used to simulate groundwater flow under steady-state and transient conditions. The model was designed to cover the period from 1 July 1980 until 30 June 2015, with a monthly stress period (all hydrological stresses are held constant within each stress period, but can vary between stress periods), but for model calibration purposes this time discretisation was modified to reduce model run time. The model covers the area of the Heretaunga Plains and surrounding river valleys that are considered to contain aquifers in hydraulic connection with the Heretaunga Aquifer. The model domain was extended about 1.5 km to the east, to include the sea and enable simulation of submarine springs. The total active area is 506 km², which is larger than the Heretaunga Plains area of 300 km² because the model area includes valley aquifers and the offshore part of the aquifer. The model area is discretised into a 100 m x 100 m uniform grid. The grid consists of 302 rows and 501 columns and the domain contains 87,594 active cells.

3.1 Model layers

The aquifer was discretised vertically into two model layers (Figure 3-1).

Layer 1 represents the combined Holocene gravels (mainly fan gravels where present in the unconfined area) and the underlying Last Glacial Gravels (Q2-Q4 deposits). Layer 2 represents the deeper deposits of the main Heretaunga aquifer (geologically defined as deposits below the Last Glacial Gravels or the Q5-Q7 deposits), to a maximum depth of about 250 m.

Both layers are set as Type 3 using the MODFLOW BCF package which allows for conversion between confined and unconfined conditions. An aquitard separating the two aquifer layers was not explicitly modelled, due to insufficient data that could be used adequately to delineate it. The confining layer above the Last Glacial Gravels, consisting predominantly of low permeability marine clays and silts, was not included in the model layers to reduce model run times (but the confining hydraulic effect was represented in the layer configuration).

3.2 Boundary conditions and parametrisation

Model boundary conditions (Figure 3-2) include rivers, streams and springs, which are represented using the “River” boundary condition (RIV), with main rivers using variable river stage. The Coastal boundary was represented as a line of “General Head Boundary” (GHB) cells, representing the head-dependent flow conditions. Land surface rainfall and/or irrigation recharge is represented by the “Recharge” (RCH) boundary condition. Pumping from the aquifer was simulated using the MODFLOW “Well” package (WEL). Diffuse drainage in the confined aquifer was represented using the “Drain” package (DRN). Parameterisation of spatial variability in K_h , K_z , S_y , and S_s was achieved using Pilot Points (Figure 3-3).

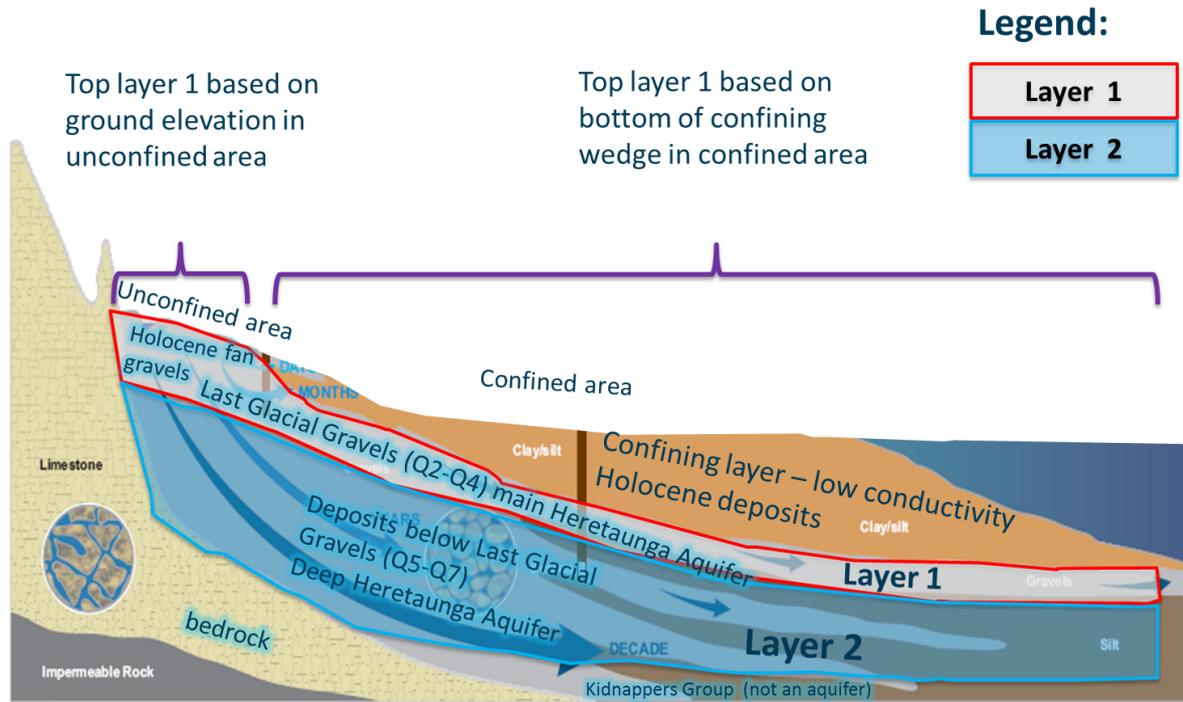


Figure 3-1: Model layer discretisation diagram.

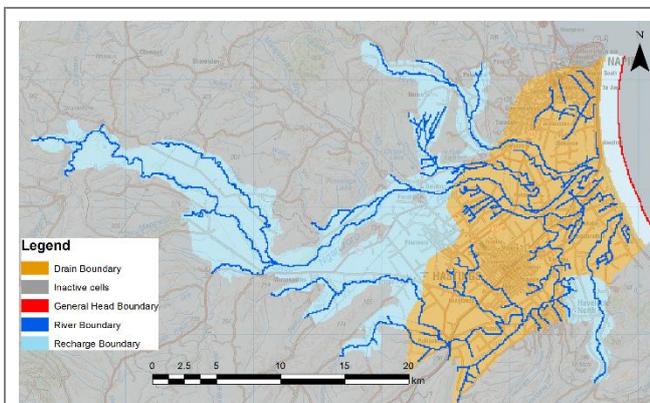


Figure 3-2: Model Domain and Boundary Conditions.

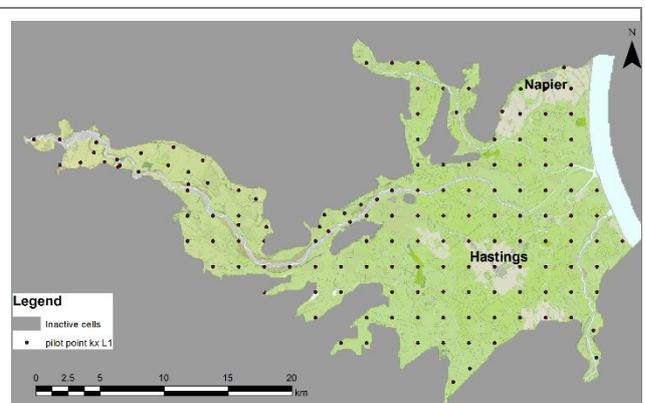


Figure 3-3: Horizontal hydraulic conductivity Pilot Points in Layer 1.

4 Model calibration

4.1 PEST set-up

Estimation of model parameters through calibration was performed using the industry-standard parameter estimation software PEST. The process of calibration is described with detail in Section 5 of the main report.

The model was divided into several sub-models with different time periods and lengths of stress periods, including steady state models. These models were then run together using common model parameters (i.e. the same aquifer properties). This minimised the number of model stress periods and model run times.

Model pre- and post-processing involves the use of several programs. While most of these programs are available within the PEST and Groundwater Data Utilities suite, four programs were written as part of the current work to address specific tasks, including data processing and formatting, using the 'R' programming language.

The integration of all pre- and post-model run processing steps and sub-models, along with a list of the programs executed within the calibration process, was summarised schematically (Figure 4-1).

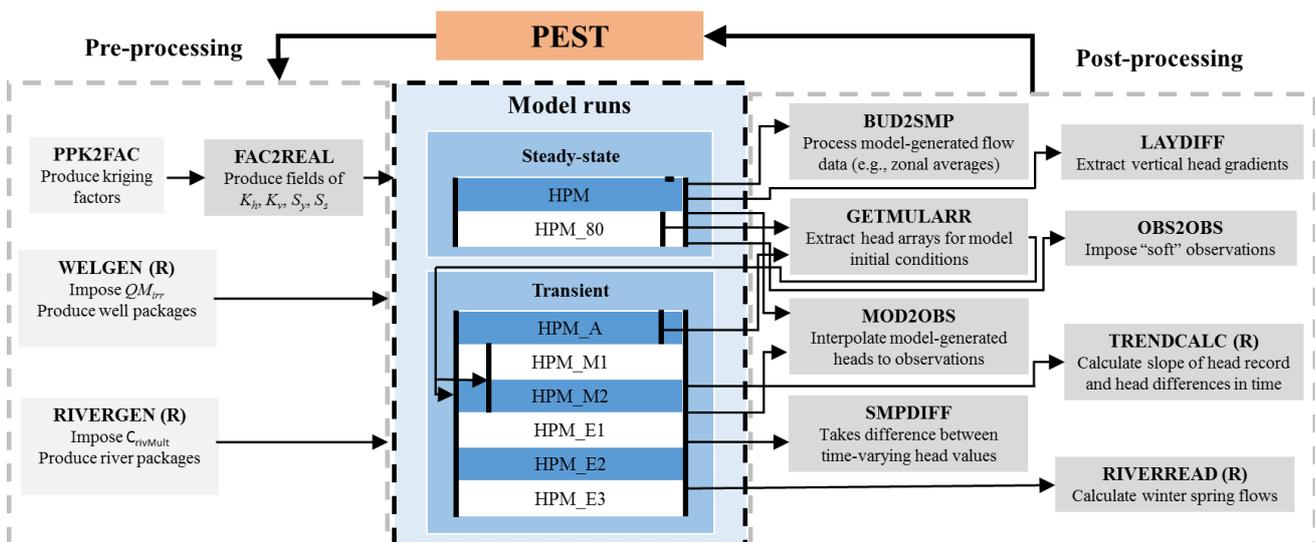


Figure 4-1: Flowchart illustrating pre-processing, model run and post-processing steps within the model calibration process.

4.2 Observations

Observations used in model calibration included (refer also to Figure 4-2, Figure 4-3 and Figure 4-4):

- Groundwater levels;
- Groundwater level changes;
- Long term trends;
- Vertical head differences;
- River losses and gains during different times.

Overall, more than 6,000 observations were used in the model calibration.

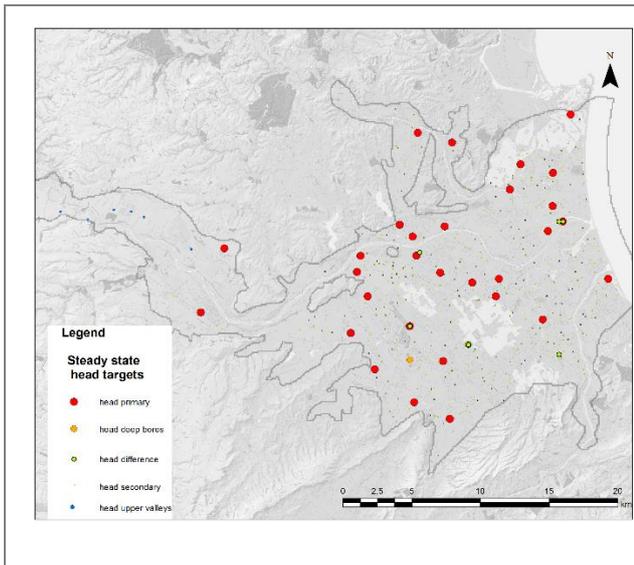


Figure 4-2: Steady state head calibration targets

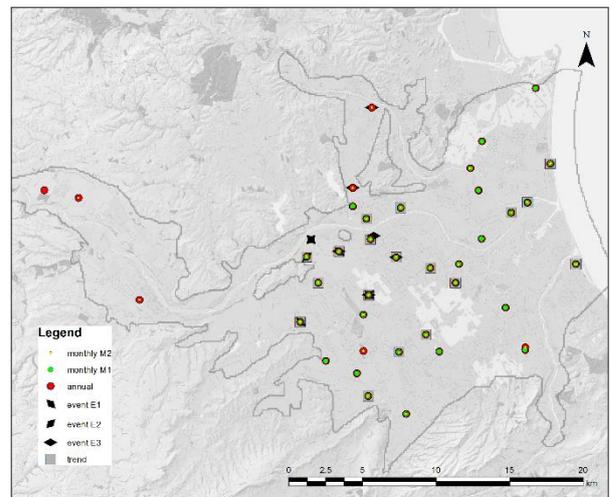


Figure 4-3: Locations of transient modelling targets

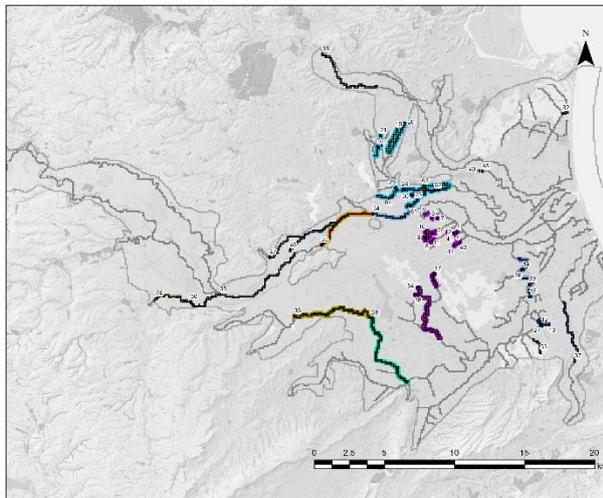


Figure 4-4: Locations of spring and river observations. Coloured cells represent locations where spring flow was used for observations. Numbers represent a spring identification number.

4.3 Parameters

Model parameters included:

- Aquifer properties (K_h , K_z , S_y , and S_s) as pilot points;
- River bed conductances;

- Land surface recharge and irrigation demand multipliers;
- Coastal boundary conductances;
- Drain bed conductances.

Overall, more than 800 parameters were used in the model calibration.

Regularisation (preferred values and SVD) was used to improve the calibration process.

4.4 PEST runs

Due to long model run times and a large number of parameters, PEST runs had to be conducted using a high performance computing facility. A total of nearly 50,000 processing hours was used during PEST runs.

4.5 Calibration outcome

The final calibrated model is able to replicate the observed dynamic of groundwater system (i.e. match seasonal and long-term groundwater level changes, as well as observed spring flows and river losses). Although this match is not perfect, in practice a better level of fit is rarely achieved in groundwater modelling. Therefore, the model can be considered suitable for simulating the effects of groundwater pumping on river flows, along with seasonal and long term changes of groundwater levels. Example calibration plots are presented on Figure 4-5, Figure 4-6, Figure 4-7 and Figure 4-8.

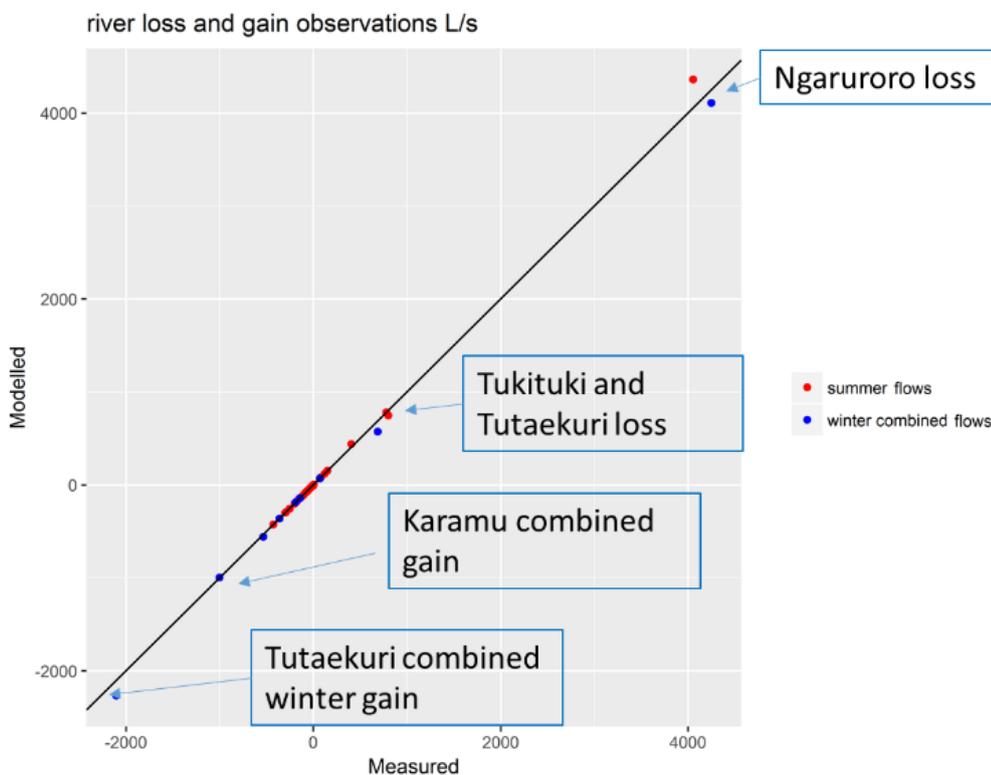


Figure 4-5: Measured and modelled river losses and gains, including springs

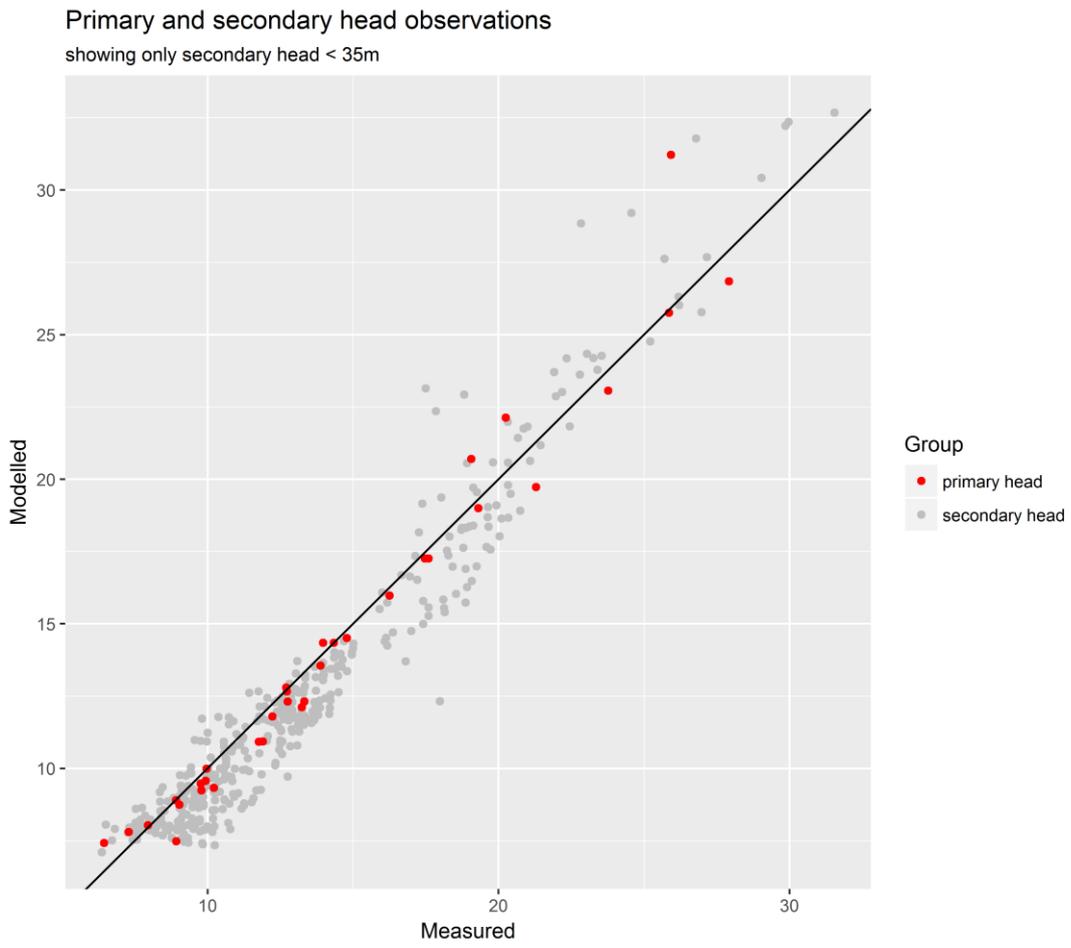


Figure 4-6: Measured and modelled heads for steady state observation groups.

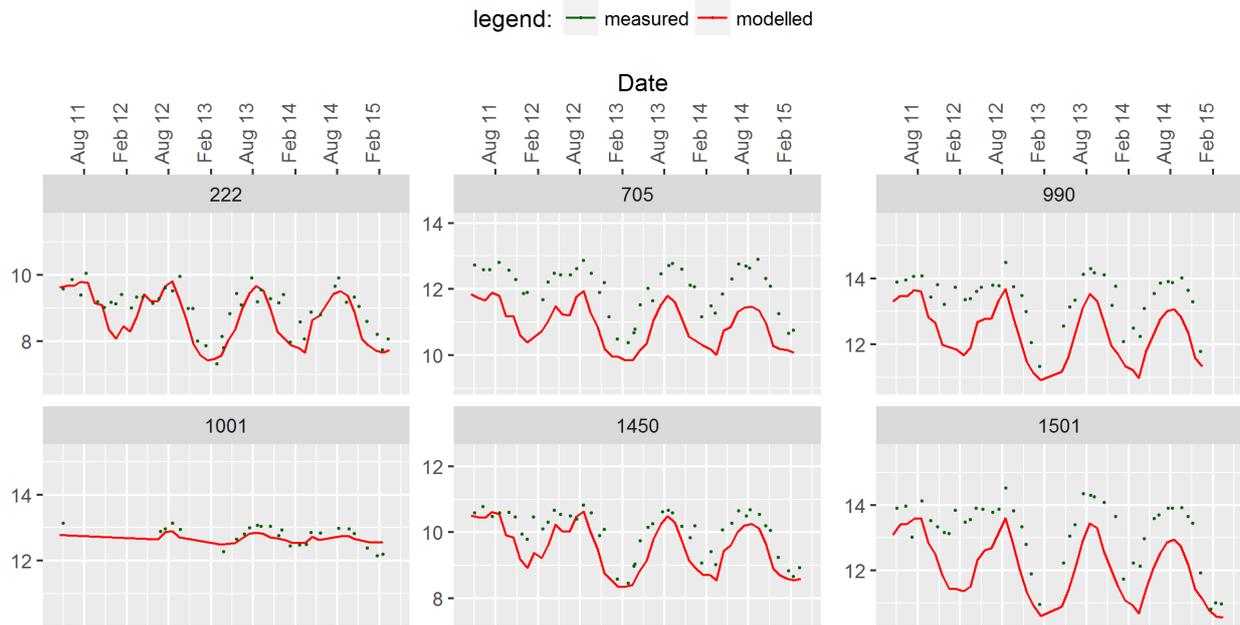


Figure 4-7: Hydrograph of measured and modelled heads (m above sea level) for M2 sub-model.

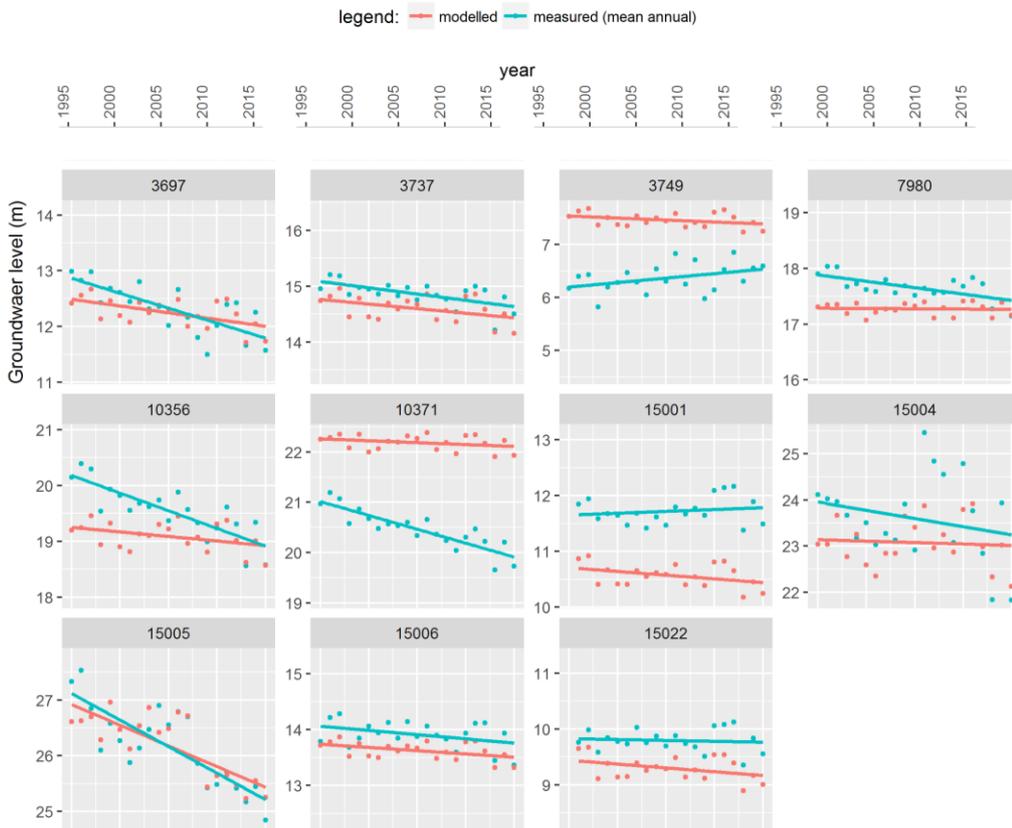


Figure 4-8: Observed vs simulated trends in groundwater levels.

4.6 Limitations

Due to the possibility that the model is not unique (ie, other solutions are feasible), and despite a reasonable calibration, there is a residual uncertainty remaining. This is a common issue with all groundwater models. Uncertainties have been explored using a calibration-constrained Monte Carlo analysis and the impacts on model predictions will be explored in a subsequent report.

Limitations of the model calibration also include:

- Poor match to observation data in some areas;
- Limited observation data in some areas;
- Conceptual uncertainty;
- Uncertainty related to rate of recharge during high rainfall events.

5 References

Rakowski P., Knowling M.(2018) *Heretaunga Aquifer Model Development Report*. HBRC Report No. RM18-14, publication No. 4997