Waikato Regional Council Technical Report 2012/13

Groundwater modelling of the upper Waikato catchment: stage 2

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

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July 2011

Document #: 2154581

Approved for release by:
Ed Brown Date April 2012

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Groundwater Modelling of the Upper Waikato Catchment: Stage 2

Prepared for Waikato Regional Council

Report No C11131/1

July 2011

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Quality Control			
Client:	Waikato Regional Council		
Report reference:	Title: Groundwater Modelling of the Upper Waikato Catchment: Stage 2		No: C11131/1
Prepared by:	Julian Weir (Aqualinc) and Catherine Moore (ESR)		
Reviewed by:	Channa Rajanayaka (Aqualinc)	Approved for issue by:	Greg Barkle
Date issued:	July 2011	Project No:	C11131

Document History							
Version:	1	Status:	Draft	Author:	JW	Reviewer:	CR
Date:	21-07-11	Doc ID:	WRC_Upper_Waikato_GW_Model_Staeg 2_Draft 1.docx	Typist:	JW	Approver:	JW
Version:	2	Status:	Draft	Author:	JW	Reviewer:	CR
Date:	19-12-11	Doc ID:	WRC_Upper_Waikato_GW_Model_Staeg 2_Draft 2.docx	Typist:	JW	Approver:	JW
Version:	3	Status:	Draft	Author:	JW	Reviewer:	JH & VB
Date:	11-01-12	Doc ID:	WRC_Upper_Waikato_GW_Model_Staeg 2_Draft 4.docx	Typist:	JW	Approver:	JW
Version:	4	Status:	Final	Author:	JW	Reviewer:	JH & VB
Date:	5-03-12	Doc ID:	WRC_Upper_Waikato_GW_Model_Staeg 2_Final.docx	Typist:	JW	Approver:	JW

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EXECUTIVE SUMMARY

Groundwater in the Upper Waikato catchment is a valuable resource for agriculture, water supply, forestry and industry. Groundwater quality is naturally high. However, there are indications that this quality is deteriorating as a result of existing land use intensification and deforestation. Compounding this concern is the very substantial lag time between land use changes and the realisation of subsequent effects on groundwater and surface water quality. Consequently, Waikato Regional Council has proposed a comprehensive programme to develop a groundwater model to assist managing water quality and appropriate policy development within the catchment.

The study area of the investigation comprises the upper Waikato River catchment from Lake Taupo outflow through to Lake Karapiro (Karapiro Dam). This is an area of approximately 434,000 ha and includes all eight hydro-electric dams on the Waikato River. Due to rock outcropping in some areas (particularly to the east), the effective area of the groundwater catchment is less than the surface water catchment. The groundwater catchment totals approximately 371,000 ha.

Stage 1 Investigation

Stage 1 of the long-term investigation was completed in 2010 which focussed on choosing a suitable modelling platform. The model platform must not inhibit the needs of future decision making and it should allow an accurate representation of reality as feasible. Given this, the performance of two modelling platforms, FEFLOW and MODFLOW (with MT3DMS), were compared alongside various selection criteria including complexity of model set-up and development, computational burden, ease and accuracy of representing surface water-groundwater interactions, precision in predictive scenarios and ease with which the model input and output files could be interrogated external to the modelling graphical user interface. This latter criteria is essential for the thorough assessment of predictive uncertainty with third-party software, such as PEST (Doherty, 2010).

Primarily due to the ease of interrogating input and output files, MODFLOW/MT3DMS was selected as the preferred platform. Other advantages and disadvantages of the two modelling platforms were somewhat balanced. Subsequently, a preliminary MODFLOW model of the Upper Waikato catchment was constructed. Geological interpretations were provided by GNS Science, and other model inputs were derived by data supplied primarily by Waikato Regional Council.

Stage 2 Investigation

The first task under Stage 2 was to investigate the use of a finer MODFLOW grid size than what used under the Stage 1 investigation. Grid size affects both model run times and numerical stability and accuracy. A uniform size of 1 km x 1 km square was selected as the optimum size to minimise run times while maximising precision and numerical stability.

Model Development and Calibration

Upon selecting a suitable grid size, the preliminary model developed under Stage 1 was further developed by revising the geological interpretation (greater focus was placed on the upper layers) and incorporating more measured data (including river flows and geometry, groundwater levels, groundwater age and aquifer test data). Calibration of the flow model was subsequently completed. Calibration of the transport model was not included at this stage as it was recognised that attenuation processes were not sufficiently known.

Groundwater Flow

The groundwater flow model was calibrated using PEST (Doherty, 2010) with a combination of pilot points and parameter zones. The model was calibrated against measured groundwater levels in 548 wells and river flow gains along eight reaches of the Waikato River.

A good fit to both groundwater levels and river gains was achieved. A normalised root means square error of 4.7% was achieved for groundwater level calibration and 1.7% for Waikato River flow gains. These errors are less than accepted industry standards and are within the criteria stipulated by Waikato Regional Council's Contract for Services. Water balance discrepancies much less than 1% were achieved. Calibration resulted in a wide range of values for aquifer hydraulic conductivity suggesting that formation type may not be a good indicator of hydraulic properties. Parameter sensitivity and uncertainty were also analysed as part of the PEST calibration process.

Contaminant Transport

As discussed above, groundwater transport is not calibrated at this stage of the investigation, though some indicative conservative transport simulations were run to provide an initial indication of the transport process. Mass transport budget errors[1] were much less than 1%.

The transport simulations suggested that travel times through the groundwater system are quite variable, ranging from a few years to a few hundred years, depending on distance from the water source. The time for the effects of regional scale land use to reach a new equilibrium was predicted to be in the order of 350-400 years, though 90% of the change is predicted to occur after approximately 160 years.

Travel times do not account for time lag through the vadose (unsaturated) zone nearer the surface. Approximations of this time lag vary between 0.2-20 years, and average 6 years over the entire catchment.

Because denitrification is not accounted for, modelled contaminants entering the groundwater system from the land surface eventually make their way to the Waikato River. Therefore, modelled concentrations are likely to be larger than actual. The areas of greatest groundwater concentrations occur in areas of intensive land use and relatively low rainfall, such as Reporoa.

[1] Mass transport budget errors refer to the calculated differences between modelled mass inputs and outputs as a result of numerical error.

Summary of Key Findings

The following key findings are summarised from the Stage 2 modelling work:

- The Waikato River and the regional groundwater system are closely linked.
- Groundwater flow is consistently towards the Waikato River. Over its length, the Waikato River gains water from groundwater as it passes through the catchment. The long-term average flow in the Waikato River at Lake Karapiro is approximately 247 m^3/s. Based on modelling, this flow is comprised of the following approximate components:
    - 161 m^3/s (65%) of surface water from lake Taupo;
    - 40 m^3/s (16%) of groundwater entering the Waikato River directly;
    - 17 m^3/s (7%) of groundwater entering via the main tributaries; and
    - 29 m^3/s (12%) (the remaining balance) of surface water flow via the tributaries.
- River bed properties and aquifer properties near the river have a large influence on regional groundwater levels.
- Modelled aquifer properties cover a larger range than measured, but there is only a small set of field measurements to compare to. Further field work is required to enable a more meaningful comparison of parameters.
- Geological formation may not be a good indicator of hydraulic property. It is likely that other hydrogeologic properties that vary within each formation (such as extent of welding and hence fracturing of ignimbrites) also contribute to hydraulic performance.
- Depths to basement rock vary over the study area from zero depth in the west (where bedrock outcrops) to over 3 km depth in the southern and eastern areas. Approximately 90% of bores are shallower than 440 m with deeper bores predominately used for geothermal use.
- The properties of deep layers have little influence on regional groundwater levels.
- Modelled groundwater gradients are steepest in the upper catchments where the land surface gradients are steepest. Groundwater gradients range from 0.003-0.005 in the plains and lower catchment to 0.05-0.07 in the upper catchment (nearer Lake Taupo and also above Tokoroa).
- Though not calibrated, groundwater travel times range from a few years to a few hundred years.
- The time for the effects of an instantaneous regional scale land use change to reach a new equilibrium (assuming conservative transport) was predicted to be in the order of 350-400 years, though 90% of the change is predicted to occur after approximately 160 years.
- Travel time lag through the unsaturated zone is variable, and has been estimated between approximately 0.2-20 years (with an average of 6 years) depending on the depth to shallow groundwater (which varies between 0.4-41 m depth). Flow through the unsaturated zone is outside the scope of the Stage 2 investigation and has not been calibrated.
- The MODFLOW (with MT3DMS) software is an efficient and flexible tool for modelling regional scale groundwater flow and contaminant transport in the Upper Waikato region. Currently the greatest constraint to simulation of groundwater flow and

contaminant transport in the Upper Waikato is data availability rather than the software used.

Considerations for Future Work

The Stage 2 modelling work has highlighted areas where additional data and research would be beneficial. Given this, it may be necessary to focus much of the short-term field work on collecting this additional data, allowing time for the data to 'catch up' to the level required by the model. However there is still field data that can be readily collected that would greatly assist with model development and refinement. The following, in order of development logic, summarises all recommendations for future data collection and model development.

- Investigate the relationship between rivers and adjacent groundwater, such as conducting stream-depleting aquifer tests with appropriate analyses;
- Update well datums with measured levels and locations where these have not been measured;
- Include lysimeter data for estimating land surface recharge flows and concentrations;
- Expand the set of aquifer tests to better describe formation properties and the range of properties possible within the formations;
- Incorporate key transport processes such as denitrification, unsaturated flow, dispersion and preferential flow;
- Include measured aquifer porosities to assist calibrating the transport model; and
- Use age and concentration data to assist calibrating the transport model;

The importance of a specific set of data collection should be determined jointly with the groundwater modelling team and Waikato Regional Council to balance data needs with financial, time and resource demands.

1 INTRODUCTION

Groundwater in the Upper Waikato catchment is a valuable resource for agriculture, water supply, forestry and industries (NZHS, 2001). The primary water feature in this catchment is the Waikato River which supports eight hydro-electric power stations and associated reservoirs.

Groundwater quality in the Upper Waikato catchment is naturally high. However, there are indications that this quality is deteriorating as a result of existing land use intensification and deforestation (Environment Waikato, 2010). Compounding this concern is the lag time between land use changes and the realisation of subsequent effects on groundwater and surface water quality. It is expected that the effects of land use changes have not yet fully manifested, and additional intensification may take years to fully develop, further compounding the deterioration. Consequently, Waikato Regional Council has proposed a long-term programme to develop a groundwater model to assist managing water quality and appropriate policy development within the catchment.

1.1 Project Purpose

One of the most important parts of any modelling exercise is the definition of the model purpose which implicitly defines appropriate model approaches and model questions. For this project, the need for a model relates to potential and already occurring deterioration in water quality in the study area. Although background water quality is naturally high in the upper catchment, there is some evidence of deterioration, with trends of increasing nutrient levels occurring within some hydro lakes and tributary streams. Concerns regarding increased nutrient loads in groundwater, which would occur after some time lag, and understanding how this may affect water resources (particularly rivers and lakes) in the area, are the motivation behind the project. Therefore this long-term project has the following purposes:

1. Broad scale analysis of the impacts of current land uses on groundwater and surface water and the prediction of the effects from the identified land use changes (intensification and deforestation);

2. Identification of gaps in the existing data to guide future investigative programmes to reduce uncertainties in the predictions; and

3. Scenario testing to support planning, management and policy development to protect identified water quality values for an envelope of anticipated land use changes.

1.2 Stage 1 Investigation

The first stage of the investigation was completed in 2010 and marked the beginning of the longer-term investigative and modelling programme. The Stage 1 work focussed on choosing a suitable modelling platform for the long-term investigative programme. The performance of two modelling platforms, FEFLOW and MODFLOW (with MT3DMS), were compared under the following criteria:

- Complexity of model set-up and development;
- Computational burden as determined by model run times;
- Ease of defining and the accuracy of representing surface water and groundwater interactions;
- Domain constructions required and/or simplifications necessary to describe complex geologic, hydrogeologic and surface water features;
- Precision in predictive scenarios; and
- Ease with which the model input and output files (including unformatted files) could be interrogated to obtain specific details for the modelling questions.

MODFLOW (with MT3DMS) was selected as the most appropriate platform to achieve the long-term modelling objectives. Subsequently, a preliminary MODFLOW model of the Upper Waikato catchment was constructed. Further detail and discussion of the Stage 1 work is documented in Aqualinc (2010a).

1.3 Stage 2 Investigation

The purpose of the Stage 2 investigation was to construct a numerical groundwater model (both flow and transport) for the study area. The Stage 2 investigation comprised the following modelling scope (as specified under the Contract for Services):

- Simulate three-dimensional steady state flow and transient transport using MODFLOW and MT3DMS (as selected under the Stage 1 investigation);
- Surface waters to be included in the model are the Waikato River and major tributaries;
- The contaminant for the work is nitrogen, treated as a conservative solute (no denitrification). Contaminant input is to be via spatially distributed surface loading at rates derived from work undertaken by Waikato Regional Council;
- Investigate the use of a finer grid discretisation than that determined in Stage 1;
- Flow calibration should achieve a water balance discrepancy of less than 1% and hydraulic head root means square fit of less than 10%. Head residuals should be normally distributed. Nitrogen concentration calibration criteria are not imposed as denitrification is not accounted for; and
- Project outputs include a calibrated soft copy of the model, and a model report documenting model development, calibration, sensitivity and uncertainty analyses, and recommendations for future enhancements.

This report documents work completed on Stage 2 and makes recommendations for future investigations.

1.4 Study Area

For the Stage 2 investigation, the study area is the same as for Stage 1 which comprises the upper Waikato River surface water catchment from Lake Taupo outflow through to Lake Karapiro (Karapiro Dam). This is an area of approximately 434,000 ha and includes all eight hydro-electric dams on the Waikato River. Figure 1 (reproduced from Aqualinc, 2010a), shows the location of the study area in relation to New Zealand and the Waikato region. Figure 2 (also reproduced from Aqualinc, 2010) presents greater detail of the study area and model boundary. Due to rock outcropping in some areas (particularly to the east), the effective area of the groundwater catchment is less than the surface water catchment. The groundwater catchment totals approximately 371,000 ha.

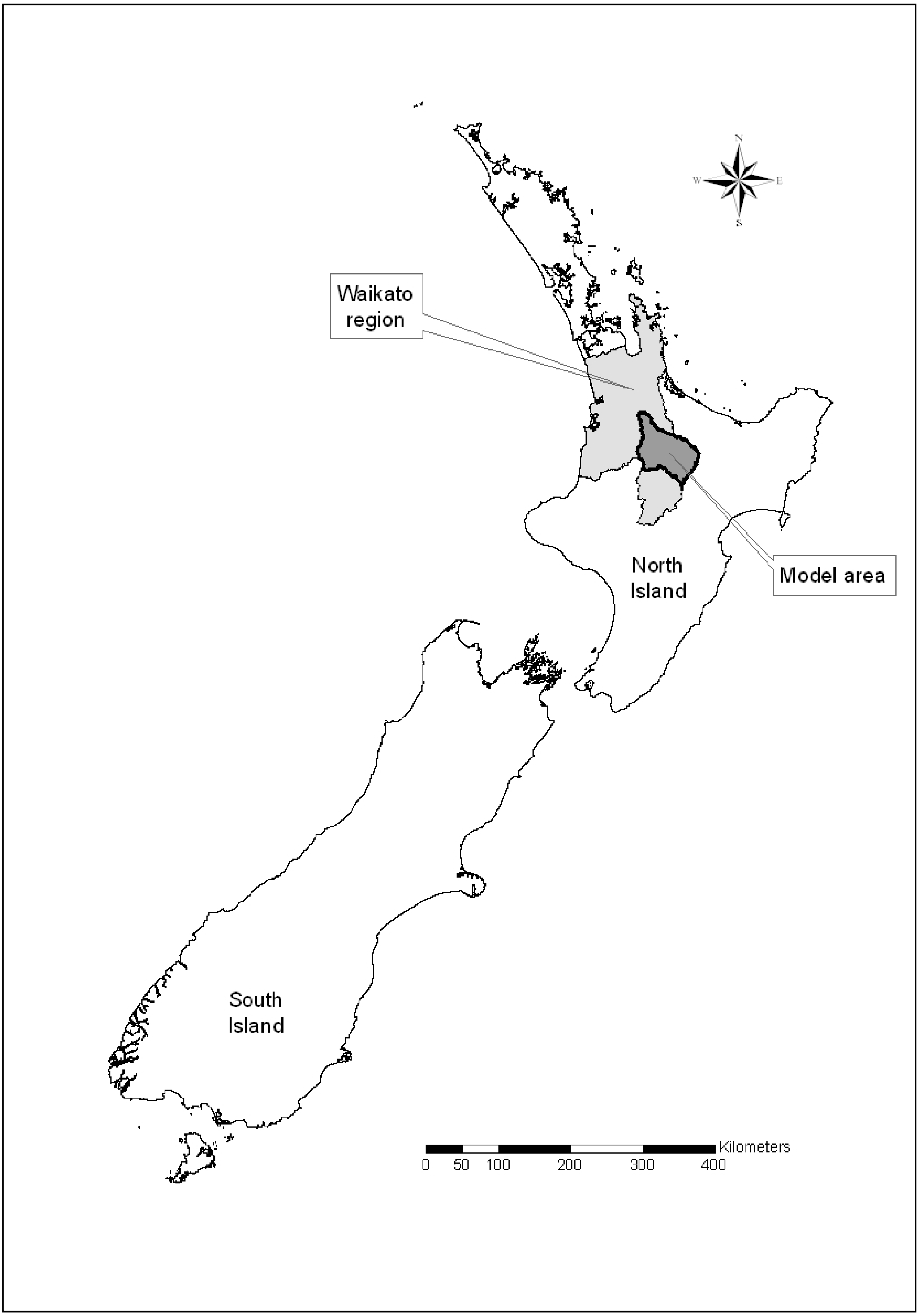


Figure 1: Model location
(reproduced from Aqualinc, 2010a)

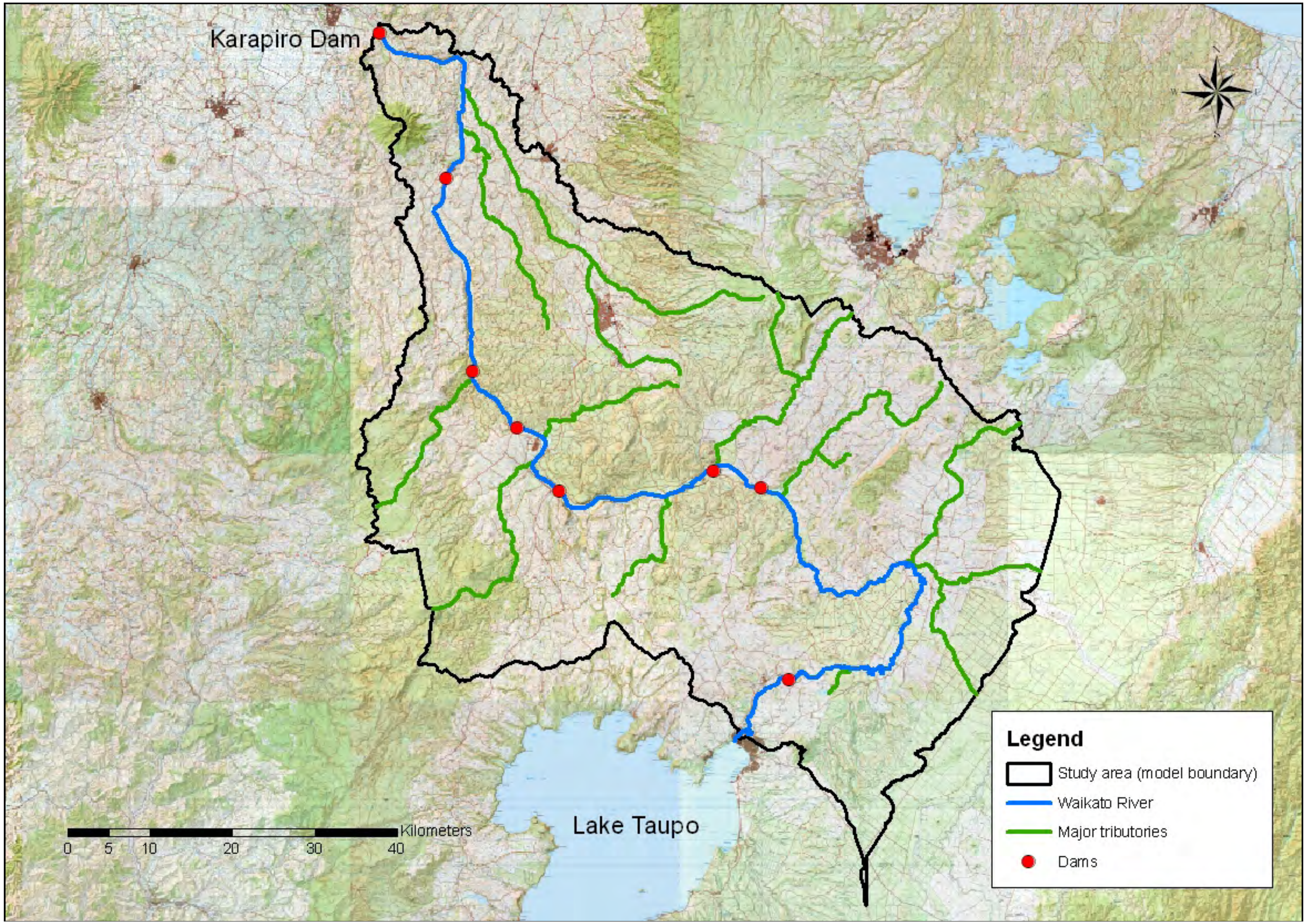


Figure 2: Study area and numerical model boundary (reproduced from Aqualinc, 2010a)

1.5 Project Collaboration

As occurred under the Stage 1 investigation, this Stage 2 work has been completed as a partnership between Aqualinc Research Ltd (Aqualinc), Environmental Science and Research Ltd (ESR) and Dr. Vince Bidwell (formerly of Lincoln Ventures Ltd., now Sole Practitioner). The Institute of Geological and Nuclear Sciences (GNS Science) has supplied geological information relevant to the groundwater modelling project. This partnership provides Waikato Regional Council with a team of highly experienced engineers, modellers and scientists skilled in water research, policy direction and practical applications.

1.6 Key Personnel

Management of the model development project has been jointly undertaken by John Hadfield (of Waikato Regional Council) and Julian Weir (of Aqualinc). Model development was completed primarily by Julian Weir with technical support by Dr. Catherine Moore (via ESR). Project technical support and direction was also supplied by Dr. Bidwell. Additional contributions in various forms (primarily data collation and processing) have been received from other Waikato Regional Council and Aqualinc support staff.

1.7 Disclaimers, Acknowledgements and Copyright Statements

The following disclaimers, acknowledgments and copyright statements apply to data collated under this project.

1.7.1 Data Supplied by Waikato Regional Council

Environmental Data Location information was sourced from Waikato Regional Council's databases and may be subject to Privacy regulations. COPYRIGHT RESERVED. Data collated under this Stage 2 investigation remains the property of Waikato Regional Council.

1.7.2 Land Resource Inventory

Land resource information was derived from the New Zealand Land Resource Inventory (NZLRI) database maintained by Landcare Research NZ Ltd. COPYRIGHT RESERVED. Approved for internal reproduction by Waikato Regional Council, Digital License No. 9532.

1.7.3 Geological Information from GNS Science

Geological formation data has been supplied by GNS Science.

1.8 Data Collation and Analysis

Data for construction of the preliminary upper Waikato groundwater model has been collated from various sources, with Waikato Regional Council being the primary supplier of groundwater and surface water data. An overview of each of the following data sources and the transformations applied to the data is presented in Appendix A. Information on data sets common to the Stage 1 investigation have been reproduced from Aqualinc (2010a) and updated where new data has been gathered for Stage 2. Data used for the Stage 2 investigation include:

- Topographical and geological data;
- Climate data;
- Land use and slope;
- Agricultural soil characteristics;
- Soil water balances;
- Land surface recharge;
- Existing irrigation;
- Groundwater bores information and groundwater levels;
- Surface water data;
- Dams and lakes;
- Aquifer transmissivity;
- Groundwater age; and
- Nitrate nitrogen data.

1.9 Report Structure and Objectives

This report is structured as follows:

- Grid discretisation and transport time step trials;
- Model development;
- Model calibration;
- Predictive transport simulations; and
- Considerations for future work.

The main purpose of this report is to document the model development work including the collated data.

2 GRID DISCRETISATION AND TRANSPORT TIME STEP TRIALS

Under Stage 1 of the investigation, a generic grid size of 2 km was used, which resulted in a stable running model with short run times. However, further investigations into finer grid sizes were completed to assist potential future sub-catchment investigative work. A finer grid size was also expected to improve the numerical stability of the transport solver, so long as run times were not excessive. Therefore, finer grid discretisations were trialled.

2.1 Grid Sizes and Transport Time Steps Trialled

Square and spatially uniform horizontal grid sizes of 1 km, 500 m, 250 m, 200 m and 100 m were trialled. In addition, transport time steps of 1 day intervals and 10 day intervals were trialled. The model used for these trials was similar to the Stage 1 model, but with modifications to the geological representation as described in Section 3.1 of this report. As was used in Stage 1, GMS (2011) was used as the graphical user interface (GUI) for developing, running and post-processing the models. GMS provides for rapid re-discretisation of the model domain in space and time.

2.2 Results

The software did not cope with grid sizes of 100 m, 200 m and 250 m, reporting an error due to too many cells and insufficient memory. The computer used to run the software is a high-spec (by today's standards) 64-bit desktop machine with 8GB of physical memory. So, it is likely that the error message is due to a software (GMS) limitation rather than a physical memory problem. However, a grid size of 250 m resulted in over 3.6 million cells and a grid size of 100 m resulted in over 22.5 million cells. With such large numbers of cells, it is not surprising that the software had trouble managing the task it was being asked to complete. Grid sizes of 250 m or less are too small for the regional domain being considered.

Models were successfully constructed for grid sizes of 500 m and 1 km. For direct comparison, the 2 km gridded model was also run. Plan views of the three MODFLOW grids are presented in Appendix C. Table 1 lists the run times for both the flow and transport models.

Table 1: Model runs times for various grid discretisation

Grid size (m)	Total number of cells	Run times		
		Flow[1]	Transport[2]	
			1-day time steps	10-day time steps
2,000	56,259	5 seconds	~ 15 minutes	30 seconds
1,000	225,036	23 seconds	1 hour	~ 2 minutes
500	900,144	~ 5 minutes	4^{+} hours	31 minutes

1 Flow run times are to convergence of the steady state model.
2 Transport run times are to complete a 100-year transient simulation.

Model runs times need to be sufficiently short to allow robust analyses by PEST (Doherty, 2010). PEST (the parameter estimation software that is used to calibrate the model) needs to run a model many times, and the more parameters that are required to be calibrated, the more runs that are needed. Therefore, model run times need to be short, particularly if pilot points are employed (there could potentially be hundreds of pilot points that require calibration). Hill (1998) reports that model run times should not exceed 15 minutes, if a model calibration effort is to be robust.

The runs times of the flow models for all three grid sizes are sufficiently quick that all would be suitable for calibration within PEST. However, the 500 m grid flow model showed signs of instability and struggled to reach convergence as a result. Careful editing of the iteration parameters was required. Further instability as a result of predictive scenarios is a concern, and should be avoided if possible.

Conversely, transport run times are substantially longer. For 1-day transport time steps, the four hour run time for the 500 m grid is far too long to result in manageable PEST calibration. Even the one hour run time for a 1 km grid is a little too long, but could be managed with careful PEST construction and computer resource assignment. The 10-day transport time steps are much quicker, but still the 1,000 m grid size provides the maximum transport simulation time that would be appropriate for robust calibration (less than 15 minutes).

Within Stage 2 of the investigation, the transport model is not being calibrated. But, transport calibration may occur in the future, and so the model development in Stage 2 should not preclude this possibility. Hence, reasonable model run times are necessary.

Considering the above, the preferred grid size is 1 km. All further model development has been based on this grid discretisation. However, if future work required a finer grid (say for further precision at a sub-catchment scale), and the transport model runs times were either not important or could be overcome, then re-discretisation can be undertaken relatively easily via GMS (2011). For the modelling work completed using the 1 km grid, calibration run times for the flow model using PEST (discussed later) have exceeded 2 days, and this is based on a model that takes 23 seconds for each model run. Hence, longer run times (by using a finer grid) would substantially hinder the model calibration process.

3 MODEL DEVELOPMENT

The MODFLOW model developed under the Stage 1 investigation has been further developed in the following areas:

- The geological representation has been revisited, with greater focus placed on the upper layers;
- Additional groundwater level data has been collated for calibration;
- Rivers have been refined and measured gains from groundwater along the Waikato River have been added as a calibration dataset; and
- Aquifer test data has been considered as part of model calibration.

These are discussed below.

3.1 Re-Assessment of the Geological Representation

The geological interpretation provided by GNS Science (Appendix B) describes geological formations to depths in excess of 3 km. This is too deep for consideration of regional groundwater transport resulting from land use changes within the catchment. Therefore, the formations have been condensed into an upper zone that is important for regional transport, and a deeper zone which is less important.

The thickness of the upper zone has been determined using bore depth as an indicator. Figure 3 shows the distribution of bore depths in the study area. Bore depths vary from between 1 m and 3.3 km below ground level; bore depths increase sharply beyond the 90 percentile depth of about 440 m[2]. Therefore, an upper thickness of 400 m has been selected as a suitably representative depth above which most of the bores in the study area are installed. Figure 4 depicts the modelled geological formations.

The shallow zone has been divided into 20 numerical layers of equal thickness. Where the top layer is 400 m thick, each numerical layer within this top zone is 20 m thick. In some areas, the basement rock is shallower than 400 m, so in these areas the numerical layer thicknesses are less than 20 m each. One geological formation has been assigned to each model cell, this being the formation that is fully contained by the cell, or contains the greatest proportion of the formation (for example along formation boundaries).

The deeper zone has been assigned a single parameter set representing a homogeneous formation. The deeper layer is not a true representation of actual formations but instead provides for the presence of deeper layers without requiring detail. Future transport simulations will validate (or not) the importance of this deeper layer to regional groundwater flow and transport.

[2] Deeper bores are predominantly for geothermal use.

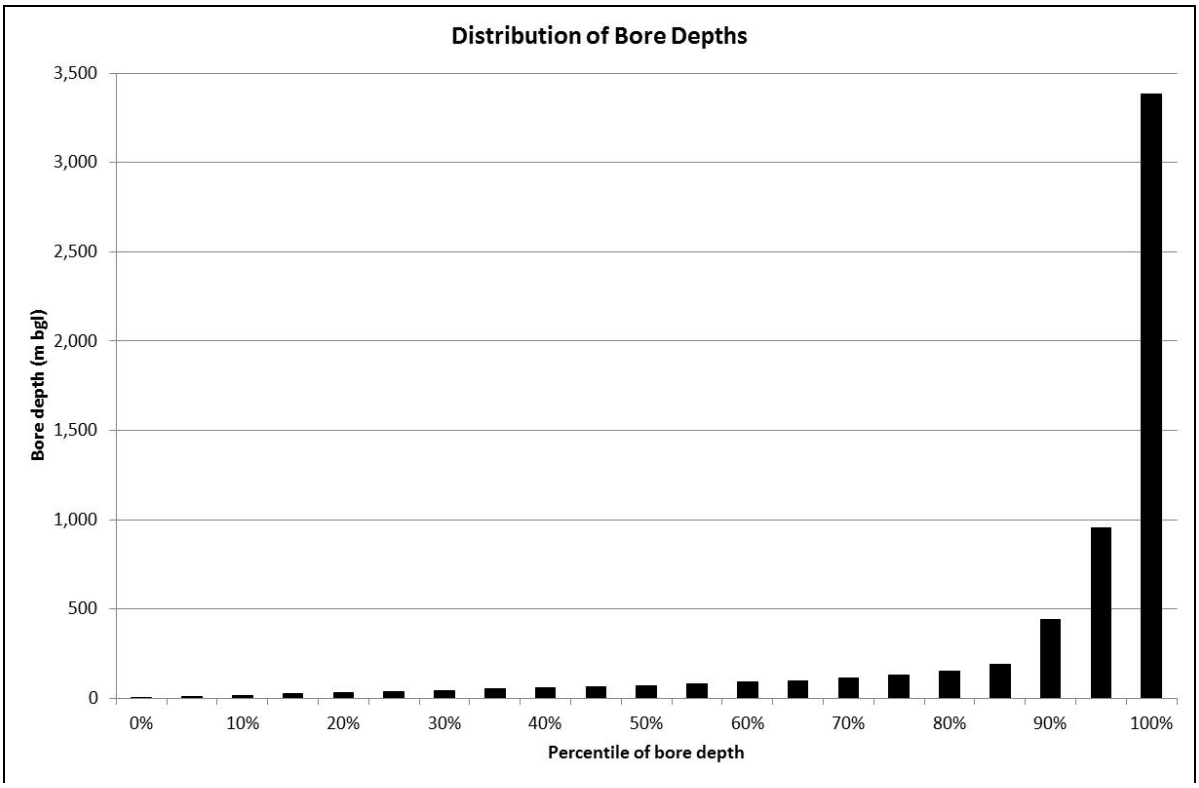


Figure 3: Distribution of bore depths

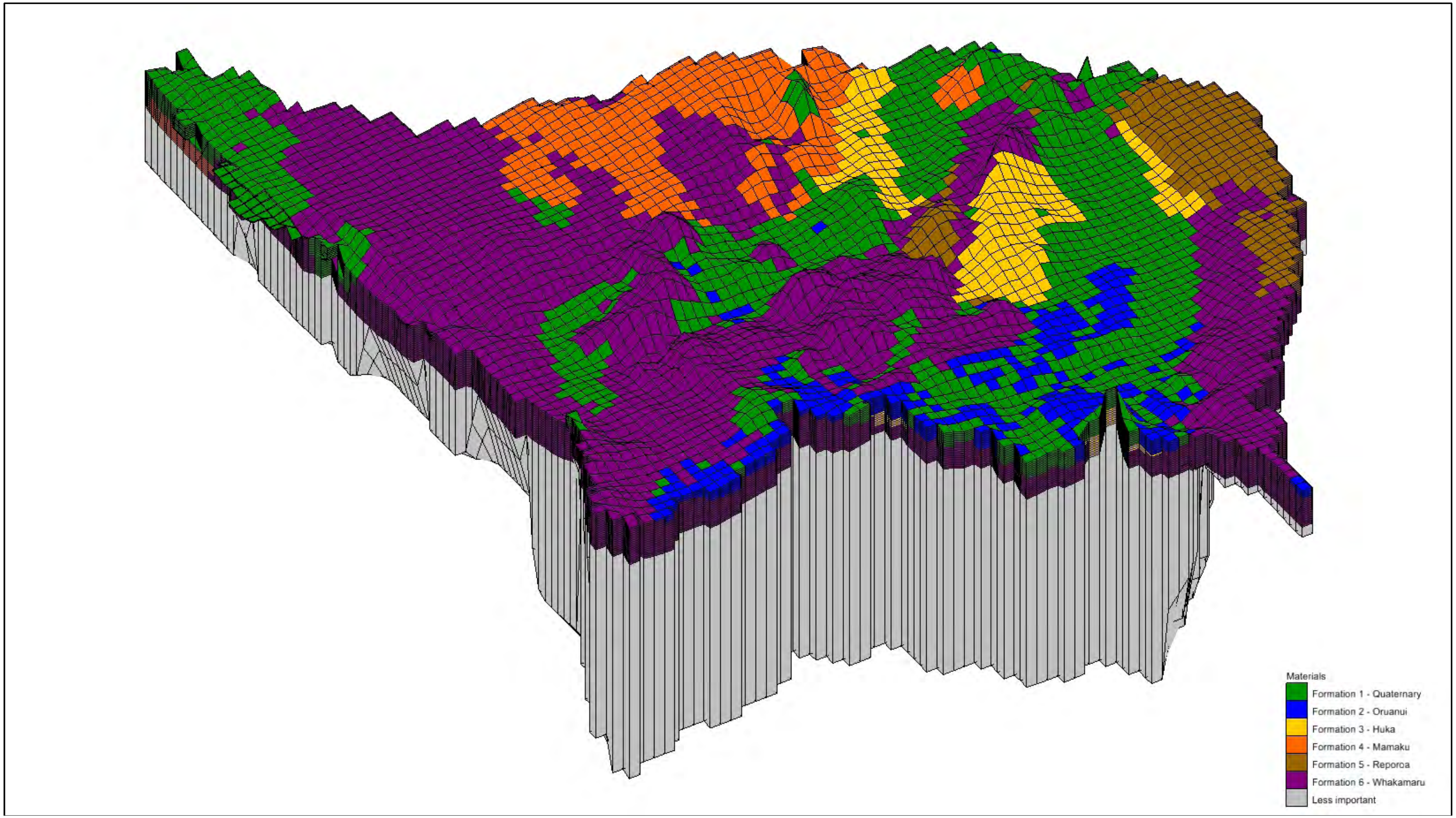


Figure 4: Revised geological representation

3.2 Groundwater Level Data

Further to the bores used for calibration in Stage 1, additional groundwater level measurements have been supplied by Waikato Regional Council. Groundwater level measurements have been supplied from the following sources (listed in order of reliability):

- Wells with multiple measurements of groundwater levels, most of which are collected by Waikato Regional Council, but some from external suppliers. Records have been averaged;
- One-off measurements of static groundwater levels taken for specific monitoring such as water quality sampling, aquifer testing and spot inspections;
- Measurements supplied by drillers, typically taken after the well has been installed.

A total of 548 measurements from unique wells were collated and used to calibrate the MODFLOW flow model.

3.3 Refinement of the River Boundaries and Measured River Gains

Measured river elevations (stage and bed elevations) have been supplied by WRC and the model river properties updated accordingly.

In addition, long-term average measured gains along the Waikato River have been derived from Collier *et al.* (2010). Figure 3.2 of Collier, reproduced in Appendix D, summarises the long term average flows in the Waikato River and major tributaries. From this information, the gains from groundwater along the Waikato River have been derived. In reality, there are smaller streams and drains that flow into the Waikato River between the major rives. However, there are no (or very few) measurements of flows from these sources and so they cannot be quantified. Therefore, it has been assumed that the flows between the sites documented in Appendix D are sourced from groundwater.

Considering this, the gains for various reaches along the Waikato River have been derived and are summarised in Table 2. The model name assigned to the bed conductance of each reach is also shown for later reference.

Table 2: Long term average flow gain from groundwater for various reaches of the Waikato River

Reach	Model name assigned to bed conductance	Downstream site	Upstream site	River flow gain from groundwater (m^3/s)
1	Waikato River 1	Karapiro	Arapuni	3.7
2	Waikato River 2	Arapuni	Waipapa	4.0
3	Waikato River 3	Waipapa	Maraetai	1.3
4	Waikato River 4	Maraetai	Whakamaru	1.8
5	Waikato River 5	Whakamaru	Atiamuri	12.0
6	Waikato River 6	Atiamuri	Ohakuri	9.0
7	Waikato River 7	Ohakuri	Aratiatia	4.5
8	Waikato River 8	Aratiatia	Taupo gates	4.0
Total groundwater flow gain directly to the Waikato River				*40.3*
N/A	Other rivers	All other rivers combined		Unknown

3.4 Aquifer Test Data

Aquifer test data supplied by Waikato Regional Council has been used to assist model calibration. Since the groundwater flow model is steady state, aquifer storativity is not required for this part. Therefore, only aquifer transmissivity has been used to assist calibration of the flow model. Aquifer porosity is used to model transport and has been manually adjusted (discussed later).

Transmissivity data from 37 tests in the study area have been supplied. These are documented in Appendix A12. Saturated aquifer thicknesses have been determined from stratigraphic logs from the pumped bores and have been used to derive aquifer hydraulic conductivity, which is the parameter used in the groundwater model.

4 MODEL CALIBRATION

The revised groundwater model has been calibrated to the measured data presented in Section 3. The calibration process and results are described below.

4.1 Parameterisation and Observation Weighting

Model calibration has been conducted using PEST (Doherty, 2010) with a combination of pilot points and parameter zones. Pilot points have been used to calibrate aquifer parameters of the upper model zone. A separate set of pilot points has been assigned to each of the six geological formations (Figure 4). A single parameter zone has been assigned to the deeper, less important layer. Vertical anisotropy has been calibrated for each of the six pilot point groups and also the deeper layer. So in total, seven vertical anisotropy values have been calibrated.

The values for pilot points at the location of aquifer tests (Section 3.4) have been fixed as the test value. Other pilot point values have been allowed to vary.

Bed conductances have been calibrated, one for each of the eight reaches of the Waikato River where gains have been measured (Table 2), plus an additional bed conductance term that covers all of the other tributaries (combined).

There are eight reaches where measured flow gains are calibrated (Table 2) and 548 sites where measured groundwater levels are calibrated. Therefore, groundwater levels outweigh river gains substantially. However, groundwater levels and Waikato River gains are equally important data sets to the calibration process. Therefore, in PEST, the weighting of the observation group for Waikato River gains has been set to give equal importance as the groundwater levels observation group. Therefore, both observation groups contribute equally to the model objective function.

4.2 Calibration Results

Calibration of groundwater levels and river flow gains has been achieved. The results of this calibration are presented below along with discussion on model water budgets, and the calibration of groundwater age and nitrate-nitrogen concentrations.

4.2.1 Fit to Measured Groundwater Levels

Figure 5 presents a plot of simulated versus measured groundwater levels for the observation wells used for calibrating the groundwater model. For a model perfectly calibrated at every observation well considered, all points would lie exactly along the solid line running diagonally through the plot. The amount of scatter either side of this line provides an indication of the goodness of fit. Some scatter around this line is normal for any model that simplifies a complex real world system. The scatter results from measurement and model structural error. The distribution of head residuals are presented in Figure 6 along with theoretical curves showing normally distributed residuals.

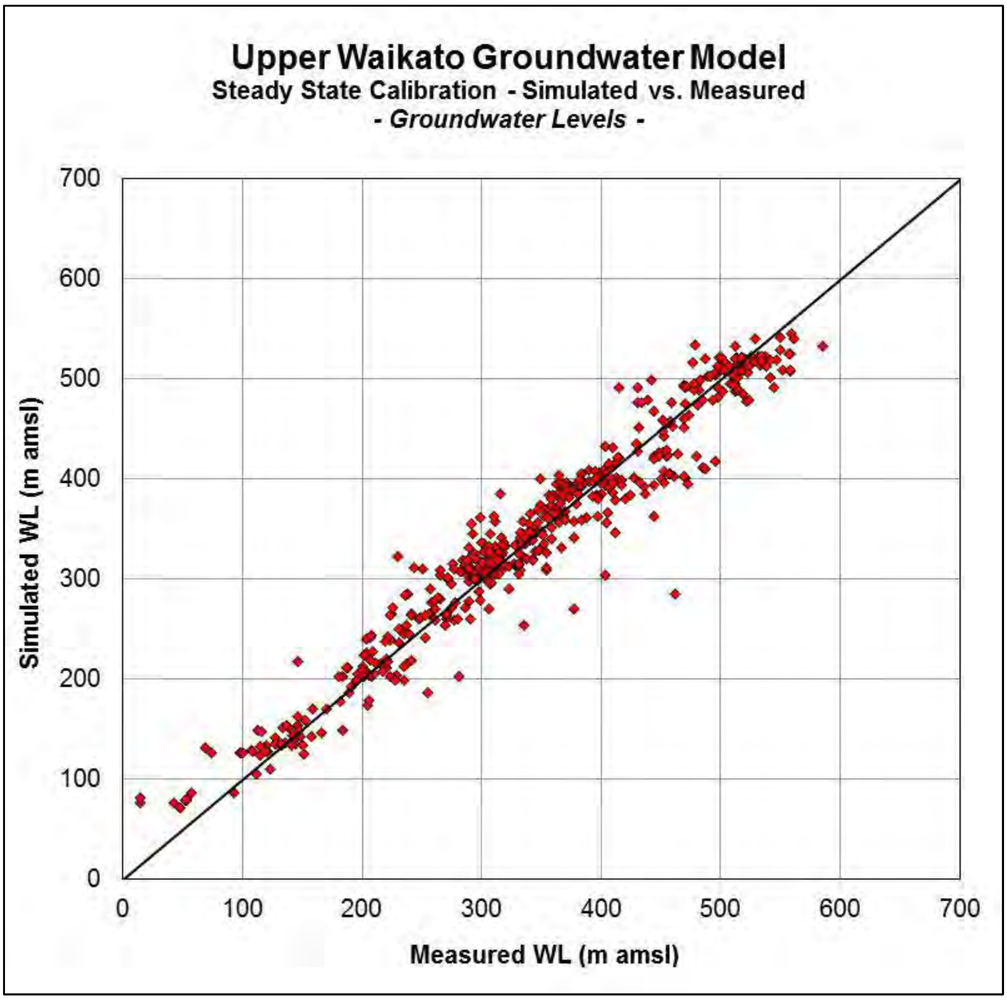


Figure 5: Simulated versus measured groundwater levels

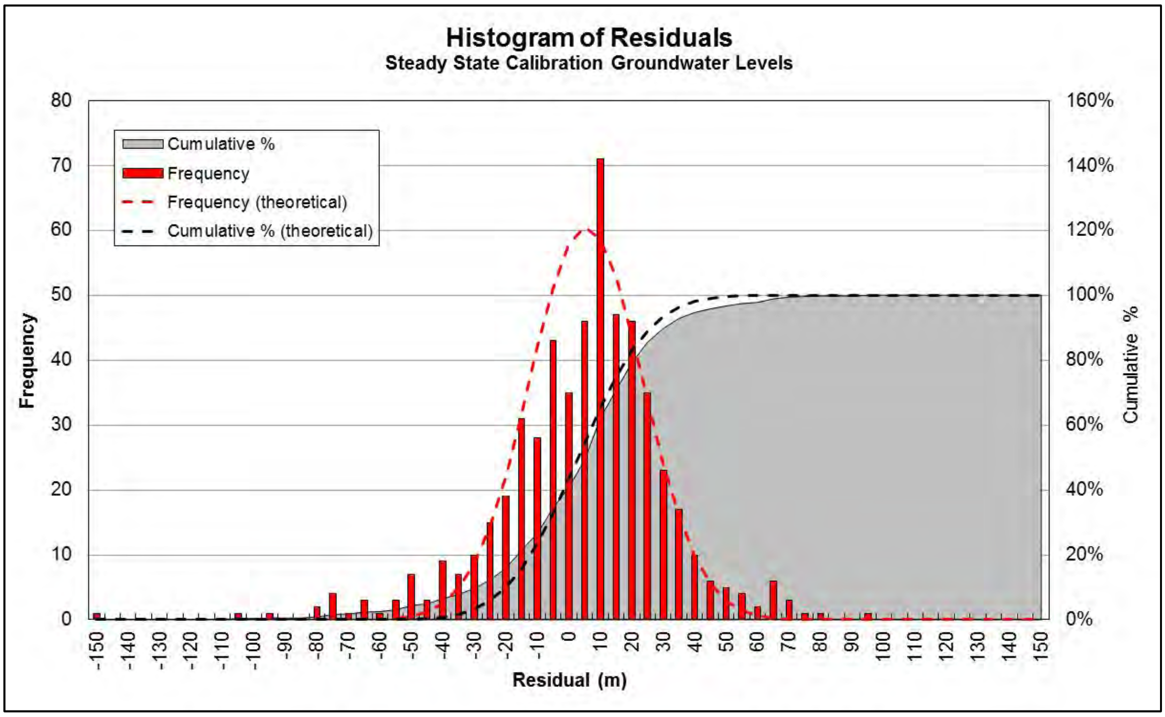


Figure 6: Distribution of head residuals

The fit to measured groundwater levels results in the calibration statistics presented in Table 3.

Table 3: Groundwater level objective function values and other statistics for the calibrated steady state model

Objective function or statistic	Value
Mean error (ME)	1.89 m
Root mean square error (RMS)	27.4 m
Normalised RMS	4.8%
R^2	0.95

The project's Contract for Services specifies that the hydraulic head root means square error is to be less than 10% and that head residuals should be normally distributed. Based on Table 3 and Figure 6, these criteria are met.

The resulting piezometric contours derived for the uppermost layer of the calibrated model are presented in Figure 7. Based on Figure 7, the Waikato River is the dominating feature of the groundwater system. Groundwater flow is generally towards the Waikato River (and main tributaries). Horizontal groundwater gradients are steepest in the upper catchments where the land surface gradients are steepest. Groundwater gradients range from 0.003-0.005 in the plains and lower catchment to 0.05-0.07 in the upper catchment (nearer Lake Taupo and also above Tokoroa).

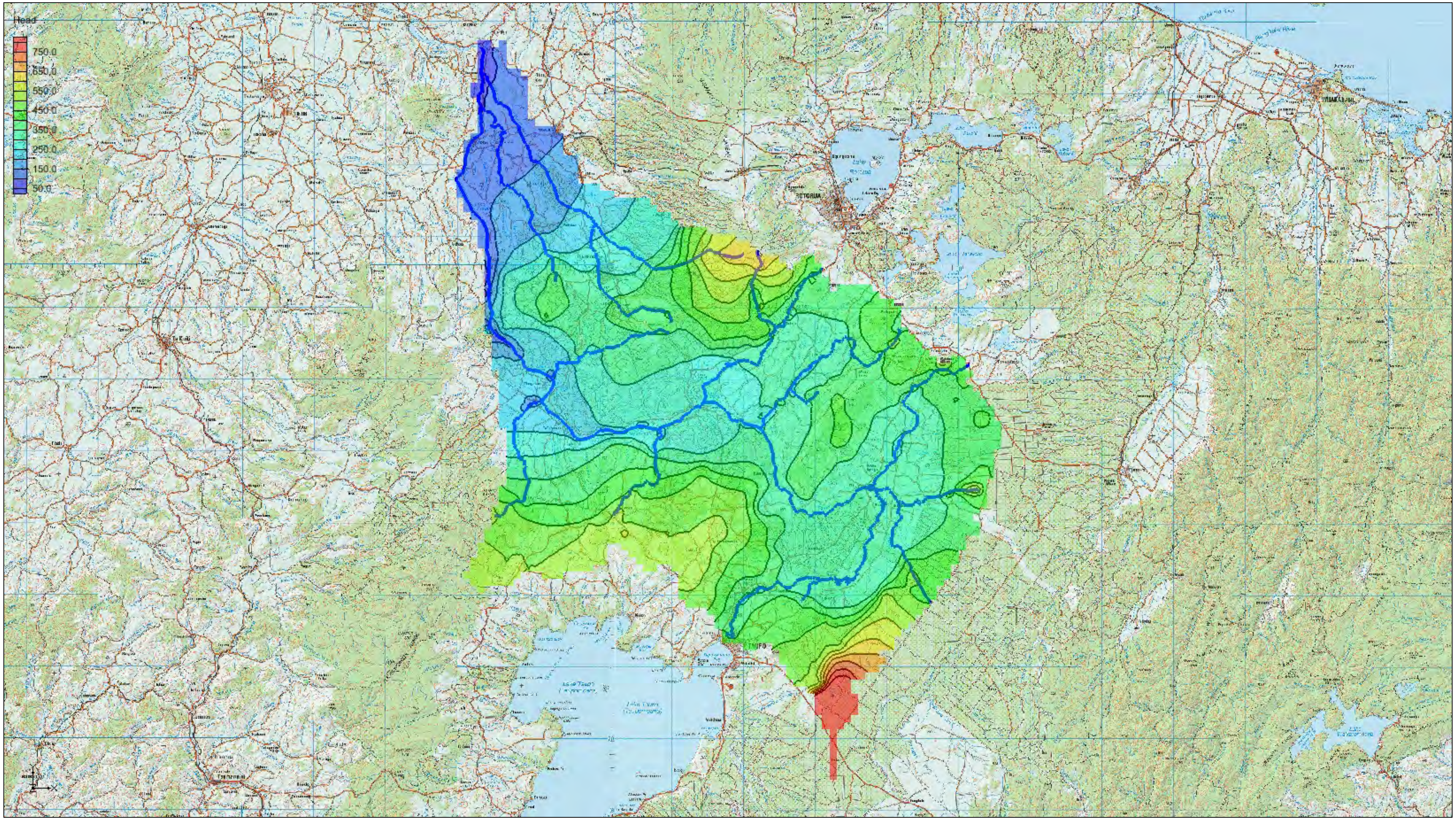


Figure 7: Calibrated piezometric contours for the uppermost layer

4.2.2 Fit to Measured Flow Gains in the Waikato River

In addition to measured groundwater levels, the groundwater model was calibrated against measured long-term gains in the Waikato River, as discussed in Section 3.3. A plot of simulated versus measured gains for the Waikato River is provided in Figure 8. There are insufficient data points to determine a meaningful distribution of residuals.

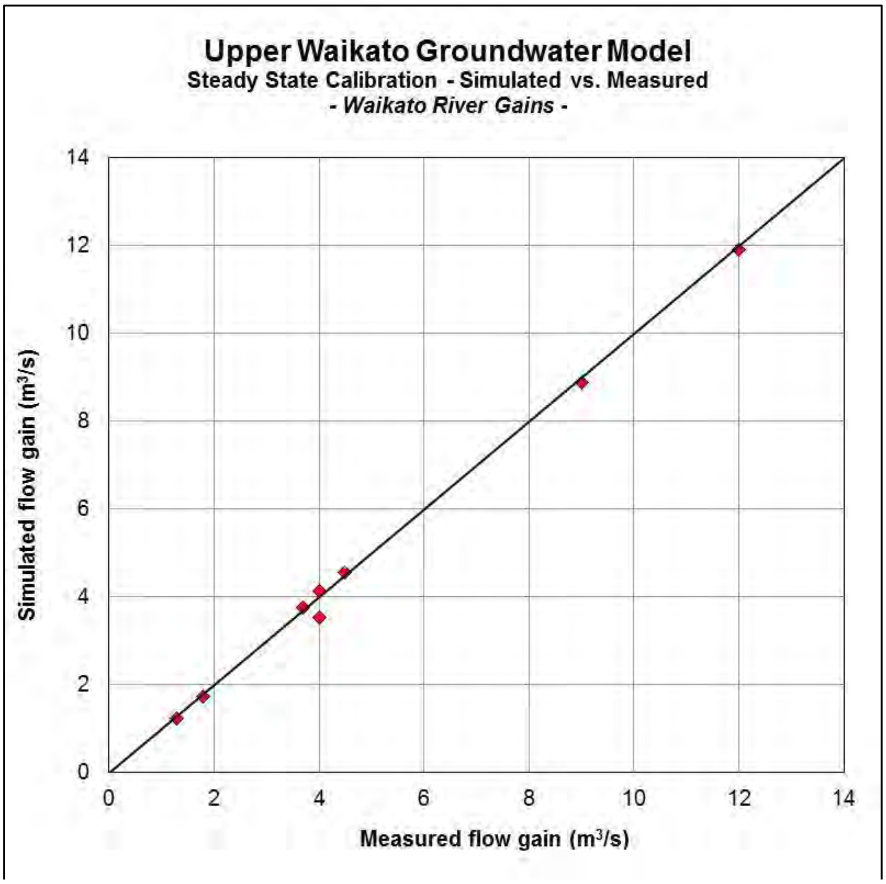


Figure 8: Simulated versus measured flow gains for the Waikato River

The fit to measured river gains resulted in the calibration statistics presented in Table 4.

Table 4: River gains objective function values and other statistics for the calibrated steady state model

Objective function or statistic	Value
Mean error (ME)	-0.1 m^3/s
Root mean square error (RMS)	0.2 m^3/s
Normalised RMS	1.7%
R^2	0.998

The project's Contract for Services does not stipulate a calibration criteria for river gains. However, the modelled gains for the Waikato River meet the error criteria specified for groundwater levels.

4.2.3 Model Groundwater Budgets

The groundwater budget for the calibrated mode is shown in Table 5. The project's Contract for Services requires that flow calibration should achieve a water balance discrepancy of less than 1%. This has been achieved.

Table 5: Model groundwater budgets

Flow (m^3/day) (steady state)		
	(m^3/day)	(m^3/s)
Ins		
Rivers	12,169,383	140.8
Land surface recharge	4,915,263	56.9
Total in	**17,084,646**	**197.7**
Outs		
Rivers	17,084,645	197.7
Land surface recharge	0	0
Total out	**17,084,645**	**197.7**
Summary		
In-Out	1	0
% discrepancy	0.000006	0

Based on Table 5, a net flow of approximately 57 m^3/s is contributed to the rivers from groundwater. This equates to 23% of the 247 m^3/s average river flow at Lake Karapiro (Appendix D). Of the 57 m^3/s groundwater contribution, approximately 40 m^3/s is groundwater flow that has entered the Waikato River directly (Table 2), and remaining 17 m^3/s is groundwater flow that has entered via the main tributary rivers.

4.2.4 Calibrated Parameter Values

Model calibration by PEST resulted in various parameter values. The values for all block parameters, as determined by PEST through the calibration process, are presented in Table 6. Similarly, the values for each pilot point are present in Figure 9. Table 7 summarises the range of pilot point values for each formation and compares these to measured values (where available). The measured values are from a smaller subset of the overall formation than what is represented by the pilot points; hence a true comparison is not possible. However, the comparison between measured and modelled values of the Quaternary formation suggests that modelled conductivities are typically greater than measured.

Given the large range of pilot point values for each formation (Figure 9 and Table 7), formation type may not be a good indicator of hydraulic properties. All pilot points in all formations have the same upper and lower limits. Hence, the hydraulic conductivity properties are effectively independent of the formation type.

Differences between measured and modelled properties may be due to model structural error (including errors interpreting formation layering and thicknesses), or simply a lack of measured values. Further investigation is required to reduce this uncertainty. Aligning the upper and lower bounds of the pilot points during calibration with the range of measured values would be a step towards reducing this uncertainty. However, this requires confidence in the range of measured values, which is not provided by the relatively small set of existing aquifer tests. Further tests are required.

Table 6: Calibrated block parameter values

Parameter	Value	Unit
Formation 1 (Quaternary) Kh/Kv	1.0	-
Formation 2 (Oruanui) Kh/Kv	47.7	-
Formation 3 (Huka) Kh/Kv	5.9	-
Formation 4 (Mamaku) Kh/Kv	1.7	-
Formation 5 (Reporoa) Kh/Kv	101.3	-
Formation 6 (Whakamaru) Kh/Kv	1.1	-
Deeper Kh	1×10^{-4}	m/day
Deeper Kh/Kv	14.8	-
Waikato River bed 1	1.0	m/day
Waikato River bed 2	3.3	m/day
Waikato River bed 3	0.9	m/day
Waikato River bed 4	1.8	m/day
Waikato River bed 5	4.3	m/day
Waikato River bed 6	141.3	m/day
Waikato River bed 7	0.7	m/day
Waikato River bed 8	20.5	m/day
Other river beds	34.1	m/day

Table 7: Pilot point value statistics for each formation

<table>
<tr><th rowspan="2">Formation</th><th colspan="4">Horizontal hydraulic conductivity (k) (m/day)</th></tr>
<tr><th>Average</th><th>Minimum</th><th>Maximum</th><th>Measured (range)</th></tr>
<tr><td>Formation 1 (Quaternary)</td><td>362</td><td rowspan="6">0.001 [1]</td><td>10,000 [2]</td><td>0.1 – 46
(10 measurements)</td></tr>
<tr><td>Formation 2 (Oruanui)</td><td>44</td><td>706</td><td>0.2 – 97
(4 measurements)</td></tr>
<tr><td>Formation 3 (Huka)</td><td>2</td><td>28</td><td>None</td></tr>
<tr><td>Formation 4 (Mamaku)</td><td>3</td><td>31</td><td>None</td></tr>
<tr><td>Formation 5 (Reporoa)</td><td>440</td><td>6,109</td><td>67
(1 measurement)</td></tr>
<tr><td>Formation 6 (Whakamaru)</td><td>65</td><td>2,811</td><td>0.03 – 52
(8 measurements)</td></tr>
<tr><td>Deeper layer</td><td colspan="2">0.0001
(block parameter, Table 6)</td><td></td><td>0.1 – 17
(11 measurements)</td></tr>
<tr><td colspan="5">(1) The minimum horizontal hydraulic conductivity for all formations was the same value of 0.001 m/day, which was the lower limit specified in the PEST control set up; at least 1 pilot point in all formations reached this minimum limit during calibration.
(2) A value of 10,000 was set as the upper limit to horizontal hydraulic conductivity; at least one pilot point in the Quaternary formation reached this upper limit during calibration.</td></tr>
</table>

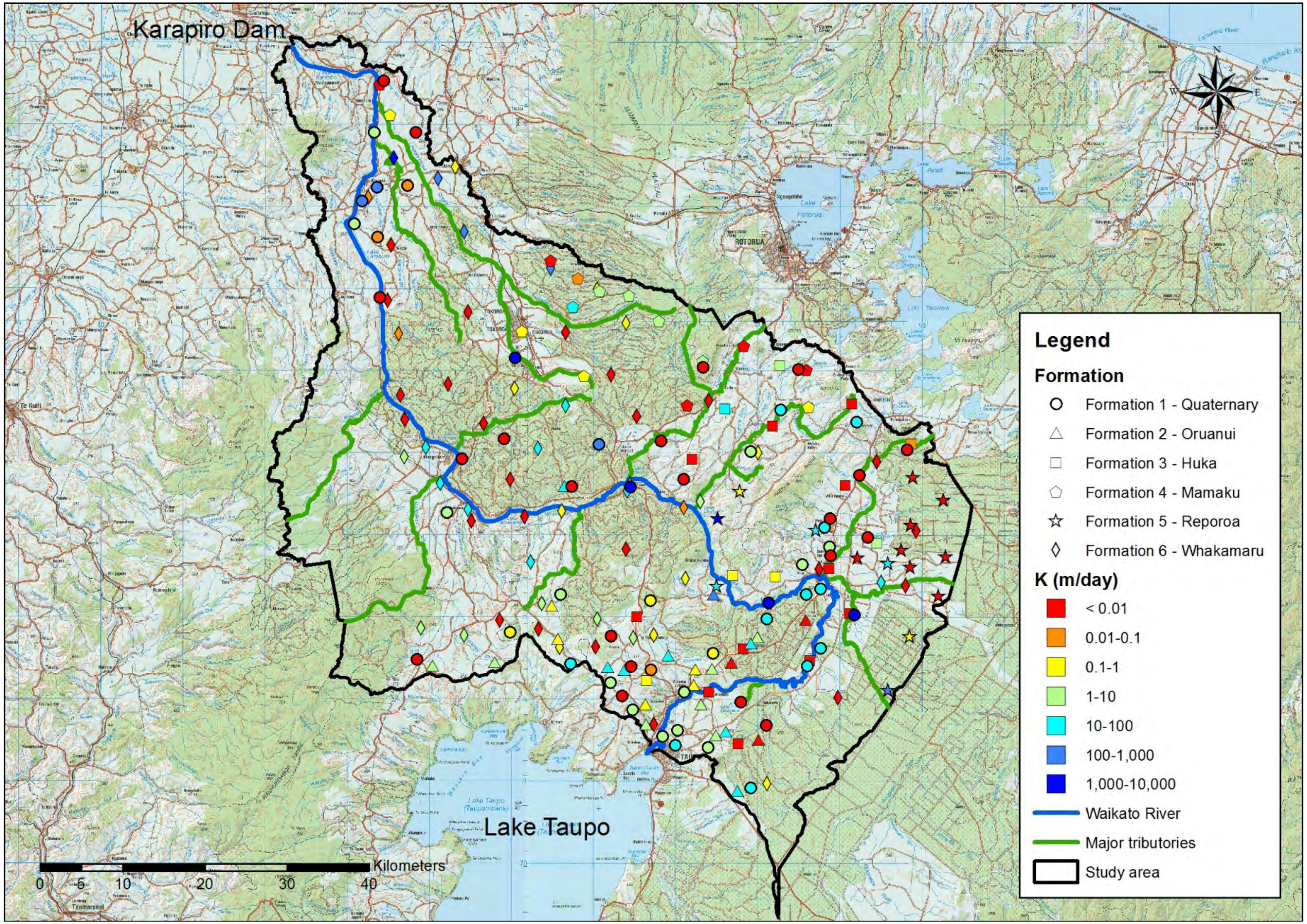


Figure 9: Calibrated pilot point conductivity values

4.2.5 Parameter Sensitivities: Calibration

A sensitivity analysis of a model determines which parameters are most receptive to the information contained in the observation dataset. Sensitivity analyses can also be used to guide assessments of aquifer behaviour, where this behaviour is described in the same terms as the data comprising the calibration dataset. Sensitivity analyses also form one of the building blocks used for assessing future field investigations and monitoring[3].

The sensitivity of all block parameters are presented in Figure 10. Parameter names for formation hydraulic conductivities are shown in Figure 4. Parameter names for river bed conductances are listed in Table 2. Considering the block parameters, the overall model fit is more sensitive to river bed conductances than groundwater hydraulic parameters. In addition, river gain outputs (the 2nd graph in Figure 10) are more sensitive to river bed parameters than groundwater hydraulic properties. By comparison, groundwater level outputs (the 1st graph in Figure 10) are less sensitive to all parameters and more equally influenced by both river bed properties and groundwater hydraulic properties.

The sensitivities of pilot points to groundwater level and river gain outputs are presented in Figure 11 and Figure 12 respectively. The composite sensitivities of all pilot points are presented in Figure 13. Consistent with the sensitivity of the bulk parameters, the more sensitive pilot points tend to be those adjacent to rivers, and river gain outputs (Figure 12) are most sensitive to these parameters. However, groundwater level outputs are more sensitive to a wider range of pilot points than the river gains.

Overall, the river parameters and pilot points near rivers dominate the modelled fit to measured groundwater levels and river gains. In addition, regional model calibration is relatively insensitive to the properties of the deeper layer.

[3] The other building blocks include assessments of parameter variability/heterogeneity, parameter correlations, and prediction sensitivities to the model parameters.

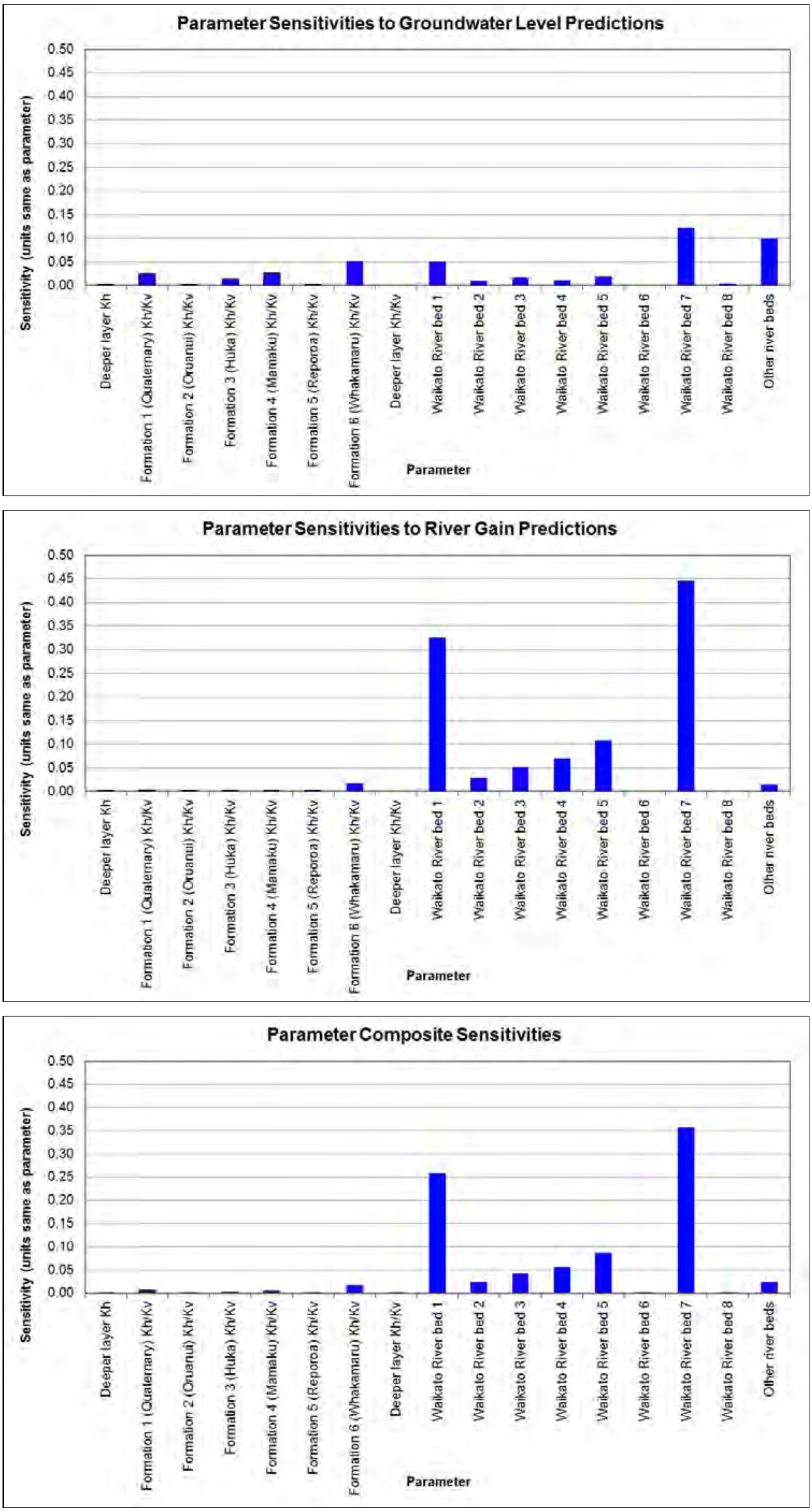


Figure 10: Block parameter sensitivities

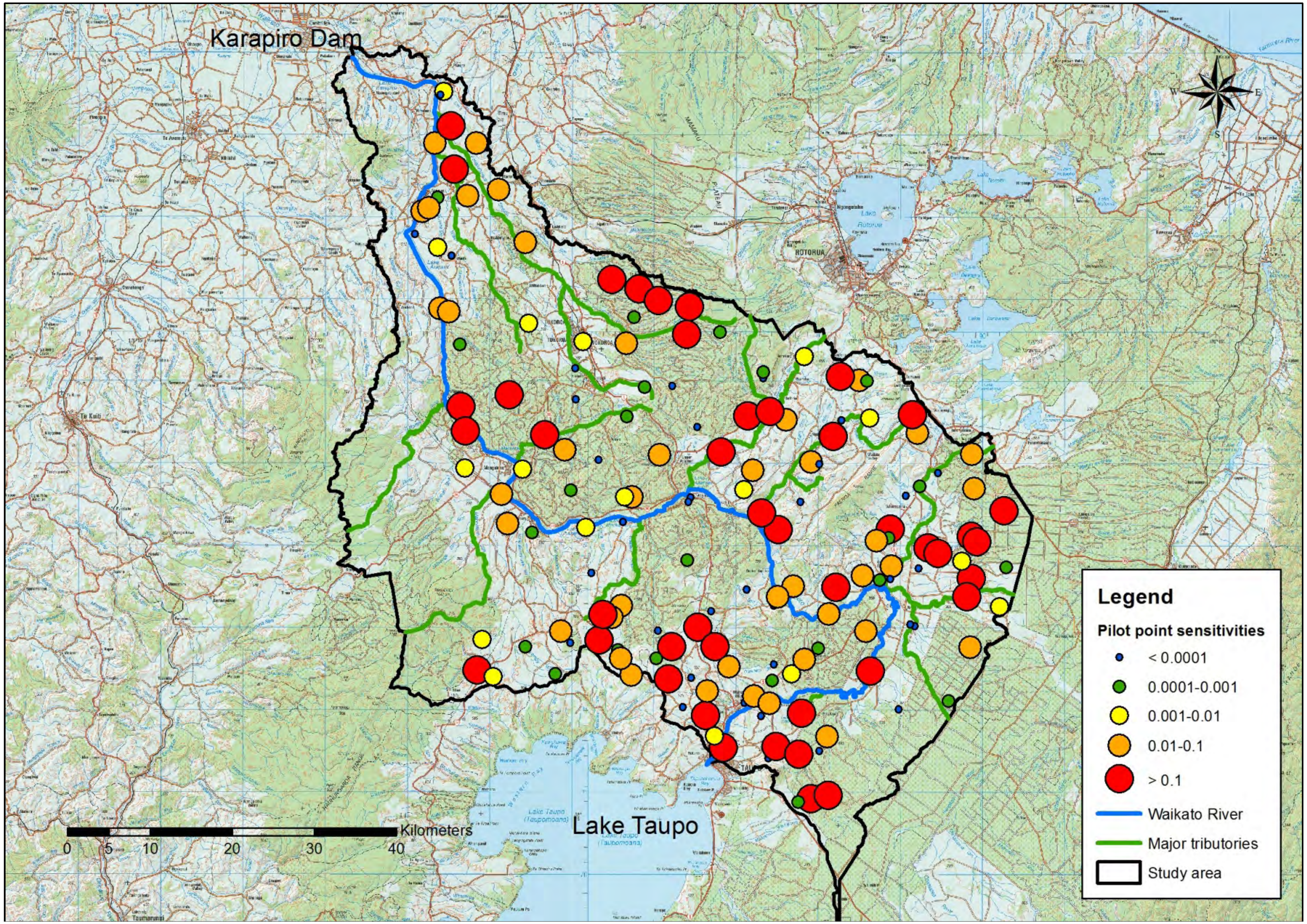


Figure 11: Pilot point sensitivities to groundwater level outputs

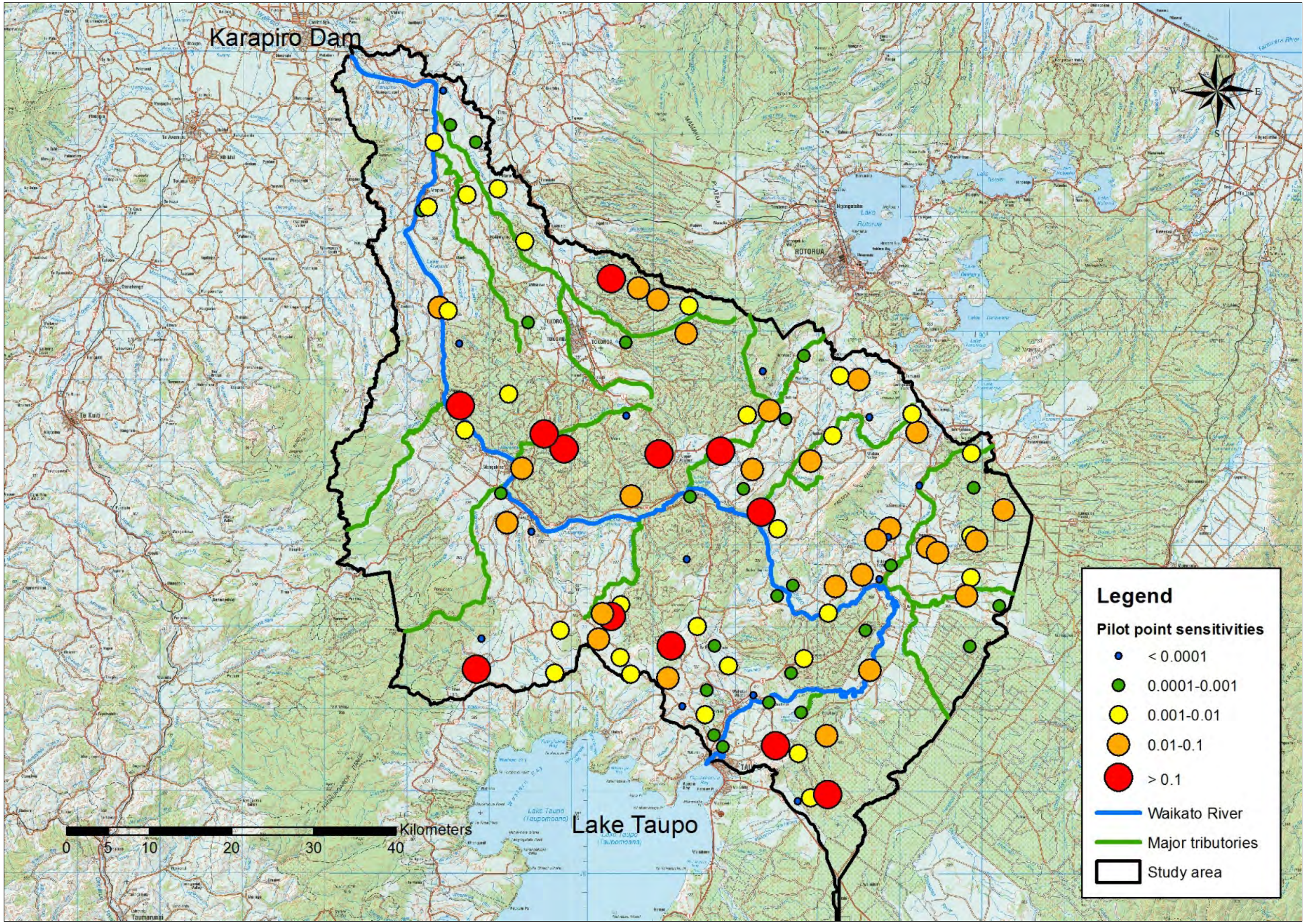


Figure 12: Pilot point sensitivities to river gain outputs

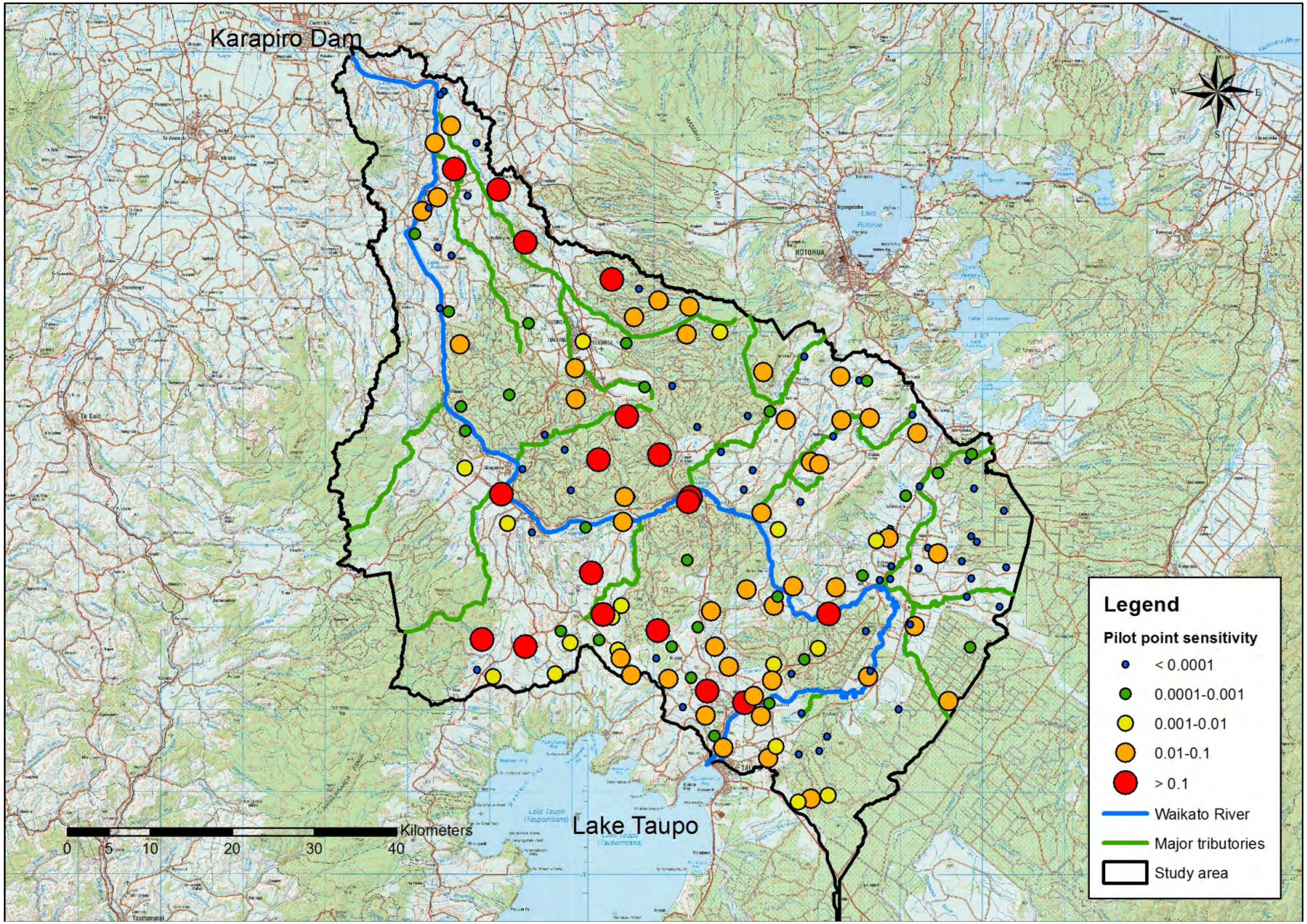


Figure 13: Pilot points composite sensitivities

4.2.6 Parameter Uncertainty

The uncertainty of model parameters can be estimated as a function of:

i) The estimated prior parameter variability measured within the field; and

ii) The reduction in this parameter variability achieved by information encapsulated in the calibration dataset.

Prior estimates of the uncertainty of the calibration parameters (i.e. vertical and horizontal hydraulic conductivity distributions in each formation, and river bed conductances) were explored on the basis of aquifer test data supplied by WRC. However, further work to refine these estimates is recommended. To provide an initial exploration, the bulk parameter distribution of log-hydraulic conductivity values for all formations was estimated in a variogram analysis. The resulting variogram is depicted in Figure 14. The variogram indicates that the bulk variance of log hydraulic conductivity values is tending to a value of around 1.5 log (m^2/day) or a standard deviation of log hydraulic conductivity of around 1.23 log (m^2/day).

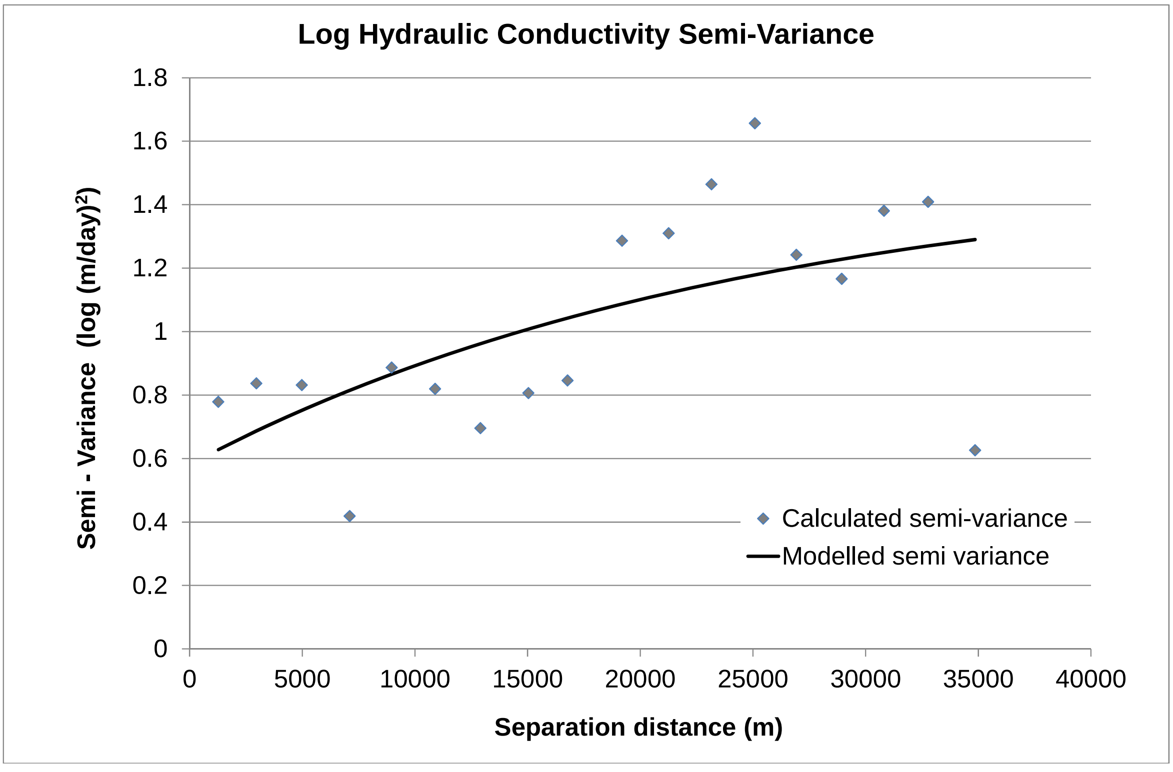


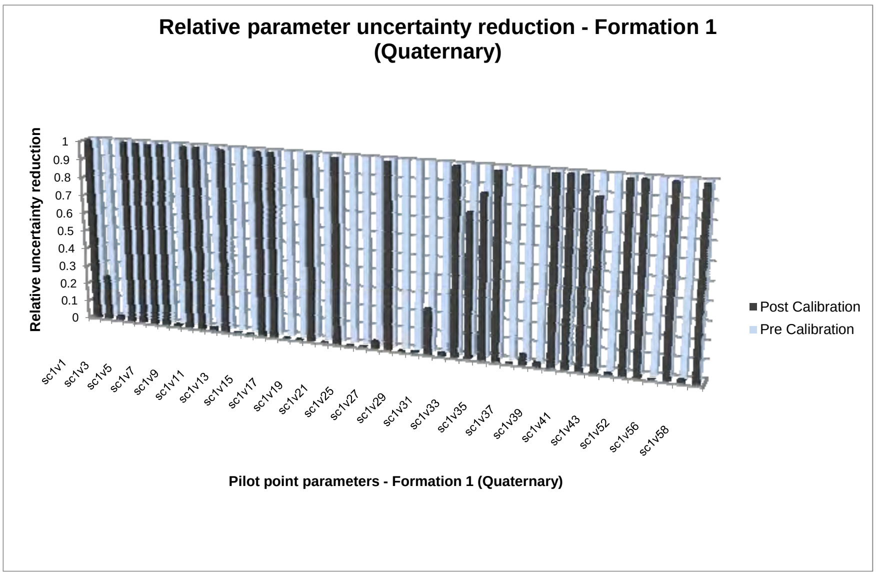
Figure 14: Semi-variance of log-hydraulic conductivity

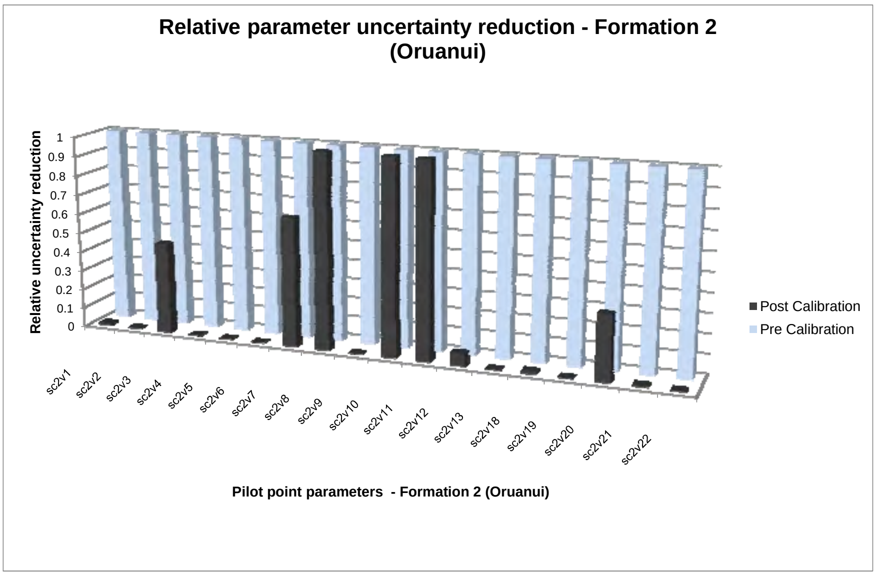
There was no measurement data provided for river bed conductance parameters. For the purposes of this analysis, it was assumed that these conductance parameters had a standard deviation one order of magnitude greater than that calculated on the basis of the aquifer test hydraulic conductivity values. This is a conservative estimate and will tend to overestimate the calibrated parameter uncertainties.

Using these estimates of prior parameter variance, the model-observation misfits, and the calculated model sensitivities, estimates of the relative reduction in parameter uncertainty achieved through the calibration dataset were derived using a linear parameter uncertainty formulation of Bayes Theorem (Moore & Doherty, 2005). The results of this analysis is depicted in Figure 15, Figure 16 and Figure 17.

Those parameters with the greatest sensitivities (as discussed in Section 4.2.5), and therefore most receptive to the information in the calibration dataset (i.e. the most sensitive), incurred the greatest reduction in uncertainty via the calibration process (e.g. the river conductance parameters). In contrast, for those parameters that were least sensitive (e.g. the hydraulic conductivity parameters in some locations), the calibration process did little to reduce the parameter uncertainties. The uncertainties of these parameter estimates could be reduced by gathering field measurements in these areas. The extent to which each parameter impacts on the predictions being made determines whether the post calibration uncertainty is irrelevant or of concern.

Therefore, it is recommended that further work be undertaken to assess the relative extent to which this suite of current calibration parameters and their uncertainty will impact on the predictive simulations for this project. Such an assessment would indicate the relative importance of each parameter (and its estimate uncertainty) to the predictive simulations assessing the long term nitrate fluxes in surface water ways and the groundwater system. A strategy could also be developed to assess which type of additional field measurement (e.g. isotope studies, additional aquifer tests, surface water loss gaugings, tracer tests, groundwater levels etc.) would be most beneficial for reducing the uncertainty of the parameter estimates (e.g. Moore, Wohling and Wolf (2011); Turnadge (2010); Dausman (2010)).





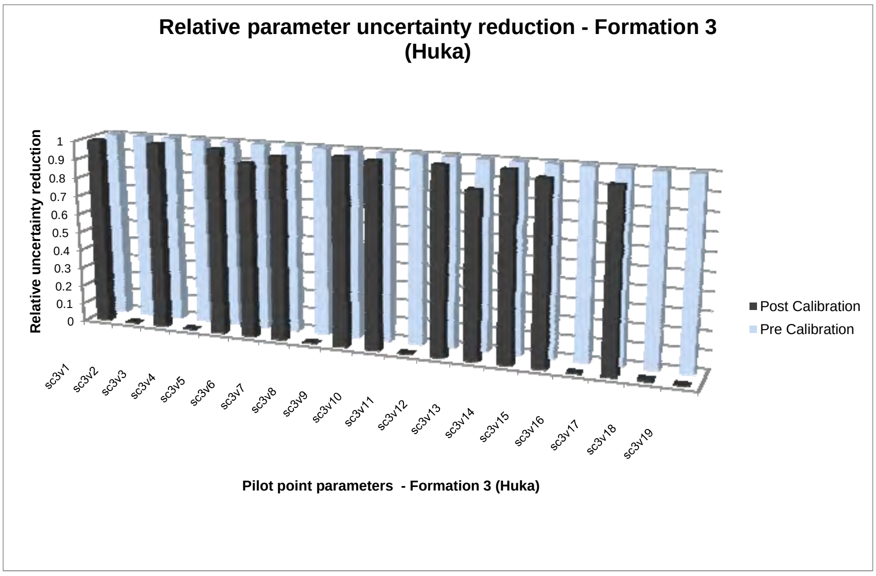
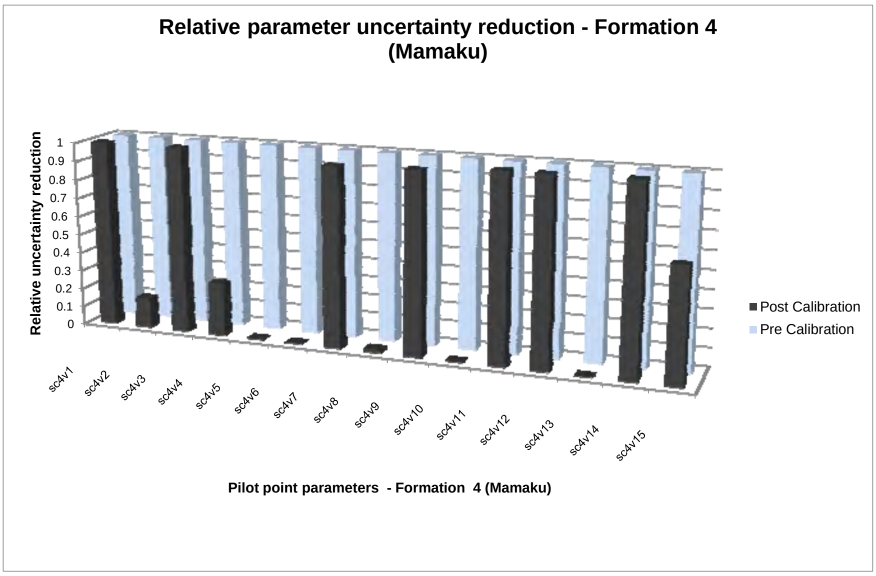
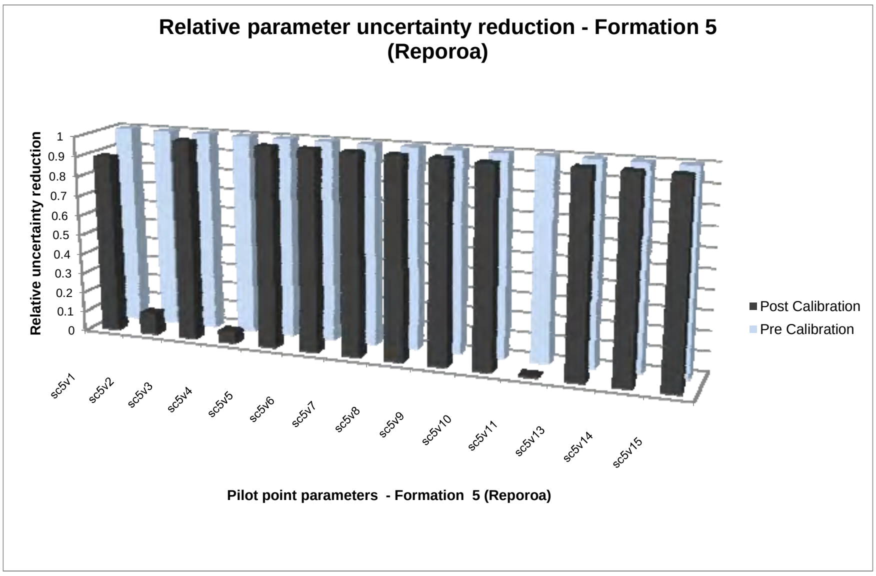


Figure 15: Relative parameter uncertainty reductions (1-3 of 7)





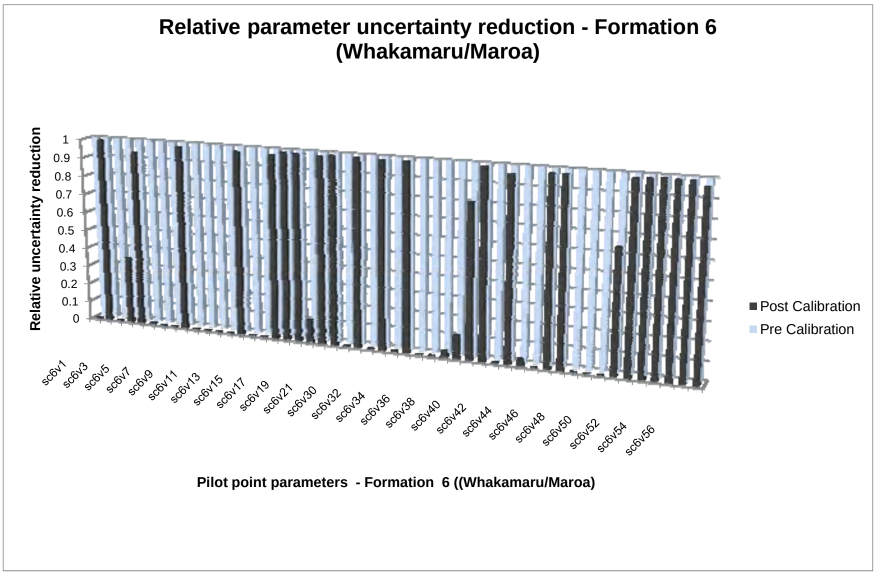


Figure 16: Relative parameter uncertainty reductions (4-6 of 7)

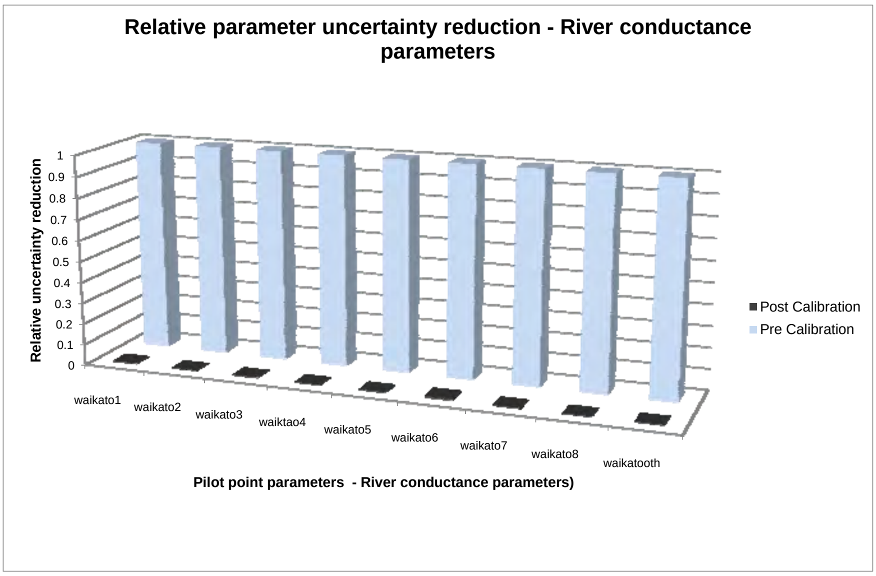


Figure 17: Relative parameter uncertainty reductions (7 of 7)

4.2.7 Parameter Confidence Intervals and Parameter Uncertainty

Confidence intervals can be calculated on the basis of model sensitivities and model to measurement misfit. Where the model is a perfect representation of the real world, these confidence intervals can also be used to express parameter uncertainty. Where the model is not a perfect real world representation, then the real world parameter variability that is simplified in the model must also be considered in a formal uncertainty analysis.

Below, parameter confidence intervals are presented. It is recommended that the uncertainty analysis presented in the previous section be extended to the calculation of parameter uncertainties when a thorough analysis of the hydraulic property variability (heterogeneity) is undertaken. This can only be considered in an approximate relative sense, given the underdetermined/non-unique nature of the model (further discussed below).

The calculated confidence intervals vary greatly throughout the model domain. Parameters with low sensitivities have very large confidence intervals, and higher uncertainty estimates. As noted above, the sensitivity analyses above indicate that the river parameters were the most receptive to the information in the calibration dataset, and particularly to the river flow gain observations. This resulted in the river conductance terms achieving the greatest uncertainty reductions via the calibration process. The 95-percentile confidence intervals of the river parameters are presented in Figure 18. The wider the range between the upper and lower confidence interval, the less certain the parameter value is for the given model.

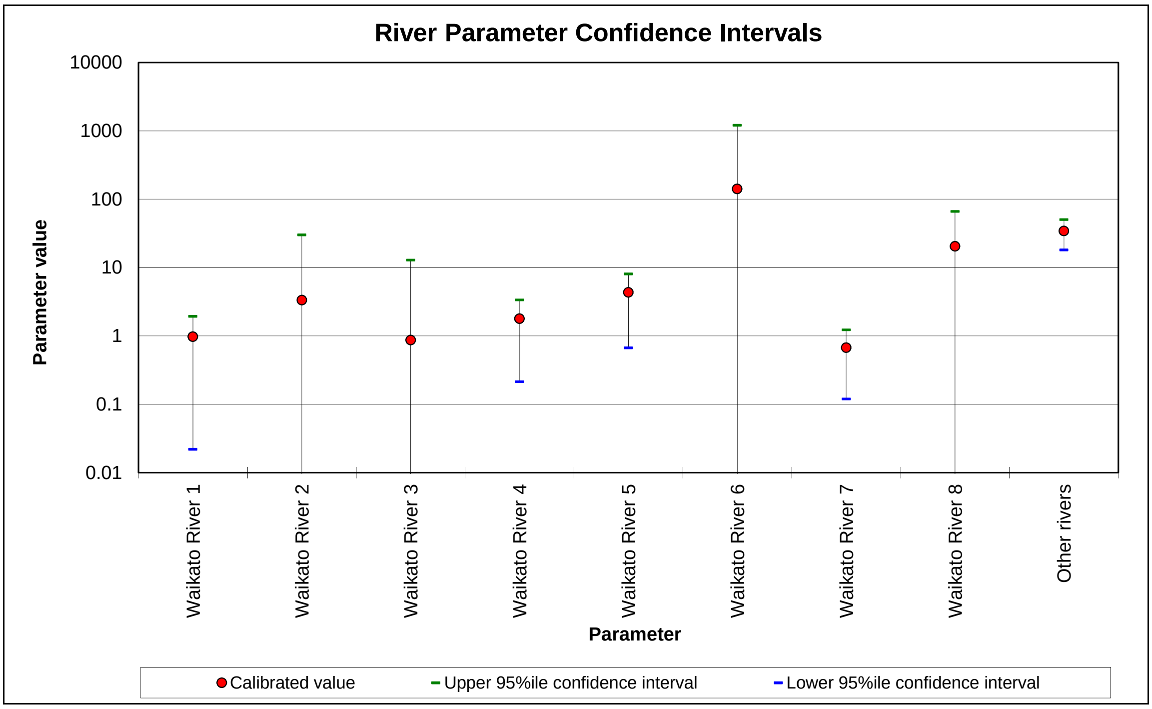


Figure 18: River parameter confidence intervals

The lower bound for the parameters Waikato River 2, 3, 6 and 8 extend beyond a reasonable value due to violation of a linearity assumption in estimating the bounds. Based on Figure 10, model calibration is less sensitive to these river parameters than the other river parameters.

4.2.8 Parameter Correlations and Eigen Values

The analysis completed by PEST provides an assessment of parameter correlations. If parameters are highly correlated (positive or negative), they are non-unique, interdependent and difficult to calibrate, as changing one parameter can give the same effect (or inverse effect) as changing a correlated parameter. The weaker the correlations, the more the model approaches a unique parameter solution. In general the less data there is available to inform the model of the real world system, the greater the tendency for parameter correlation.

There are 180 parameters considered for the Upper Waikato model. This results in a correlation matrix of 32,400 values, which is too large to reproduce herein. However, approximately 290 of these correlations are considered high (they have correlation coefficients of 0.5 or greater, either directly or inversely correlated). This suggests there is a degree of non-uniqueness present.

Further, there are 180 eigen values (one for each parameter). The ratio of maximum to minimum eigen values is approximately 4 x 10^{12}. Doherty (2004) states that if the ratio of highest to lowest eigen values is greater than approximately 10^{8}, then there is a chance the model is non-unique. With a ratio of 10^{12}, it can be concluded that the model parameterisation is non-unique. This is typical for regional groundwater models such as this. This conclusion is supported by the 290 high parameter correlations. To reduce model non-uniqueness, alternative modelling techniques (such as prior information) can be trialled in the first instance. However, additional data acquisition would be required to reduce the non-uniqueness and associated uncertainty of the model in any significant way. The additional data that could be considered includes isotope analyses, aquifer tests, tracer test data, and additional flux and water level measurements.

4.2.9 Calibration of Groundwater Age, Travel Times and Model Porosity

Particle travel times have been used to set approximate values for model porosity. Among other parameters, travel times are a function of the groundwater transport volume, which is a function of both porosity and layer thickness. However, layer thicknesses have been defined by the geological information. Hence, it is appropriate to calibrate porosity to particle travel times (Dr Vince Bidwell, *pers. com.*).

Modelled particle travel times (derived by the steady state model) have been compared to the age data presented in Appendix A13. The reported age dates stem from a mixture of methods, some of which have been subject to simple transport modelling (Dr Vince Bidwell, *pers. com.*). The reporting of a range of ages and the lack of reported measurement error further implies the approximate nature of the datings. Consequently, the reported dates are not precise and should only be considered as indicative.

Travel through the vadose zone has not been simulated in the groundwater model and is likely to be significant given the depths to groundwater in some areas of the catchment (Dr Vince Bidwell, *pers. com.*). An estimate of the regional-scale travel time lag through the vadose zone can be derived from tracer experiments completed at the Taupo SPYDIA site (Barkle *et al*, 2011). Tracer experiments in the Taupo Ignimbrite horizon have yielded travel distances of 4.1 mm for every 1 mm of drainage (below the root zone) (Dr Greg Barkle, Aqualinc, *pers. comms.*). The long-term average recharge for the study area is approximately 500 mm/year (Appendix A7). Assuming that the Taupo Ignimbrite travel times derived from the SPYDIA tracer experiment are representative of the entire study area, then the 500 mm/year recharge would travel approximately 2.1 m/year. Therefore, given a regional-scale average depth to shallow groundwater of 13 m (with a range between 0.5-41 m) (Appendix A9), the average travel time through the vadose zone would be approximately 6 years (ranging between 0.2-20 years).

In addition, the modelled particle travel times do not account for dispersive mixing (Dr Vince Bidwell, *pers. com.*). Consequently, the comparison is only approximate.

Because some travel process are not simulated and because of the approximate nature of the age datings, the Contract for Services does not specify calibration criteria for particle travel times or groundwater age. However, the groundwater age data has been used to constrain the range of plausible model porosity values by matching as best as possible particle travel times. Model porosities have been manually adjusted so that the reported average and range of ages within the model domain are approximately matched. The resulting average and range of ages are summarised in Table 8 for both modelled and measured, which have been derived from measurements in 19 different bores. From Table 8, the modelled average groundwater age is approximately 5 years younger (i.e. quicker travel times) than measured. This can be accounted for by the 6-year approximate average travel time through the vadose zone (discussed above).

Table 8: Approximate comparison between measured and modelled groundwater age

Age (years)	Measured	Modelled (steady state)
Average	52	47
Minimum	3	2
Maximum	200	361

Although the values presented in Table 8 compare favourably (particularly when vadose travel time is allowed for), there are in some cases large discrepancies for individual wells. These discrepancies cannot be improved without the modelling of key transport process. This is earmarked for future stages of the long-term study.

The resulting approximate effective porosity values are presented in Table 9 which are compared with the porosity values reported by GNS Science (Appendix B).

Table 9: Approximate effective porosity values for each formation

Formation	Approx. effective porosity	Porosity values reported by GNS Science (Appendix B)
Formation 1 (Quaternary)	0.02	0.5-0.7
Formation 2 (Oruanui)	0.3	0.4-0.6
Formation 3 (Huka)	0.01	0.4-0.6
Formation 4 (Mamaku)	0.3	0.3
Formation 5 (Reporoa)	0.2	0.3
Formation 6 (Whakamaru)	0.3	0.3
Deep layer	0.3	0.02-0.2

Some of the porosity values reported by GNS Science (Table 9) are large (up to 0.7) which suggests that these values may be total porosity, rather than effective. Given this, a direct comparison is not possible as the modelled are effective.

4.2.10 Comparison of Groundwater Nitrate-Nitrogen Concentrations

As was the case for groundwater age and particle transport times, nitrate-nitrogen concentrations cannot be reliably calibrated because some key flow processes are not provided. Instead, the transport model has been run once with the porosity values determined from the groundwater age approximation (see Section 4.2.4) and the land use described in Appendix A3. Table 10 lists the rate of nitrate-nitrogen assumed to leach under the different land uses.

Table 10: Assumed rate of nitrate-nitrogen leaching under different land uses

Land use	Assumed rate[1] (kg N/ha/yr)
Crops	35[2]
Dairy	35
Forest	2
Less intensive pasture	15
Other	0.1

Notes:
(1) John Hadfield, WRC, *pers. Coms*
(2) There is very little cropping within the study area (<0.5% - Appendix A3). Therefore for simplicity, the rate of nitrate-nitrogen for crops has been assigned the same as for dairying.

The leaching rates in Table 10 were applied to the model surface.

Concentrations of nitrate-nitrogen for various reaches of the Waikato River were assigned as the 5-year mean concentration reported by WRC (2010). Tributaries of the Waikato River were assigned the same concentration as the reach of the Waikato River into which they flow.

Dispersivity was assigned the same values as determined by Aqualinc (2005).

For comparing measure and modelled nitrate-nitrogen concentrations, the transport model was run as steady state. This gives very fast model run times and concentrations as a result of long-term unchanged land use, but can result in an over prediction of the concentrations for shorter durations. However, the steady sate transport model is sufficient to show indicative patterns. It is also useful for indicating the long-term changes when considering predictive scenarios.

The average nitrate-nitrogen concentrations reported from measurements in 120 different bores was 2.4 g/m^3. The average modelled steady state concentrations in the same set of bores was 4.7 g/m^3. There are greater discrepancies for some individual wells. Discrepancies cannot be improved without the modelling of key transport process, which will be targeted in future work.

The calculated nitrate nitrogen concentrations for the upper most layer of the model are presented in Figure 19. The concentrations at depth, towards the base of the shallow layers of interest (see Section 3.1), are presented in Figure 20. A mass budget for the steady state model is summarised in Table 11.

Table 11: Model mass budgets

Mass (kg/day) (steady state)	
Ins	
Rivers	2,407
Land surface recharge	22,265
Total in	**24,672**
Outs	
Rivers	24,672
Land surface recharge	0
Total out	**24,672**
Summary	
In-Out	0
% discrepancy	0

4.2.11 Comparison of Waikato River Nitrate-Nitrogen Concentrations

Net mass into the modelled rivers has been compared to measured mass gain between Lake Taupo and Lake Karapiro.

The average measured flow at Lake Taupo gates is 161 m^3/s (Appendix D) with a concentration of 0.006 g/m^3 (WRC, 2010). At lake Karapiro, the flow is 247 m^3/s (Appendix D) with a concentration (at 'Narrows') of 0.301 g/m^3 (WRC, 2010). These changes in flows and concentrations between Lake Taupo and Lake Karapiro result in a mass gain through the catchment of approximately 6,340 kg/day.

From Table 11, the transport model reports a steady state (long-term) net mass gain to the rivers (i.e. 'out' from groundwater less 'in' to groundwater) of approximately 22,265 kg/day. This is approximately 3.5 times greater than the current measured mass gain. The following may contribute to the over prediction:

- This modelling is for steady state, therefore transport time lags are not simulated;
- Denitrification is not included (both land-based denitrification and lake processes); and
- Land surface recharge concentrations are assumed based on current land use, whereas measured river concentrations are a function of actual time-varying land use which could potentially have lower historically concentrations than present.

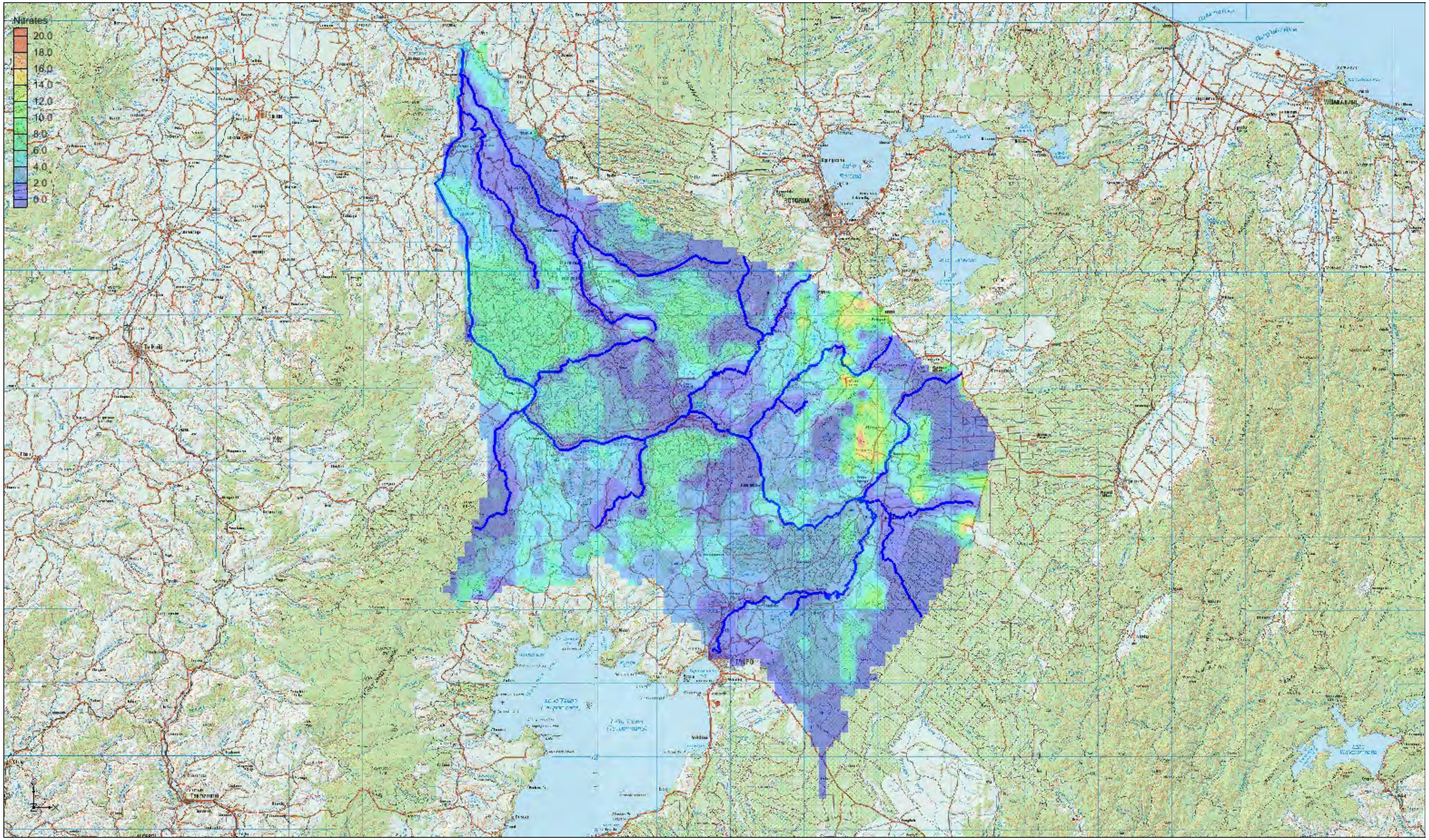


Figure 19: Indicative groundwater nitrate-nitrogen concentrations for the uppermost layer

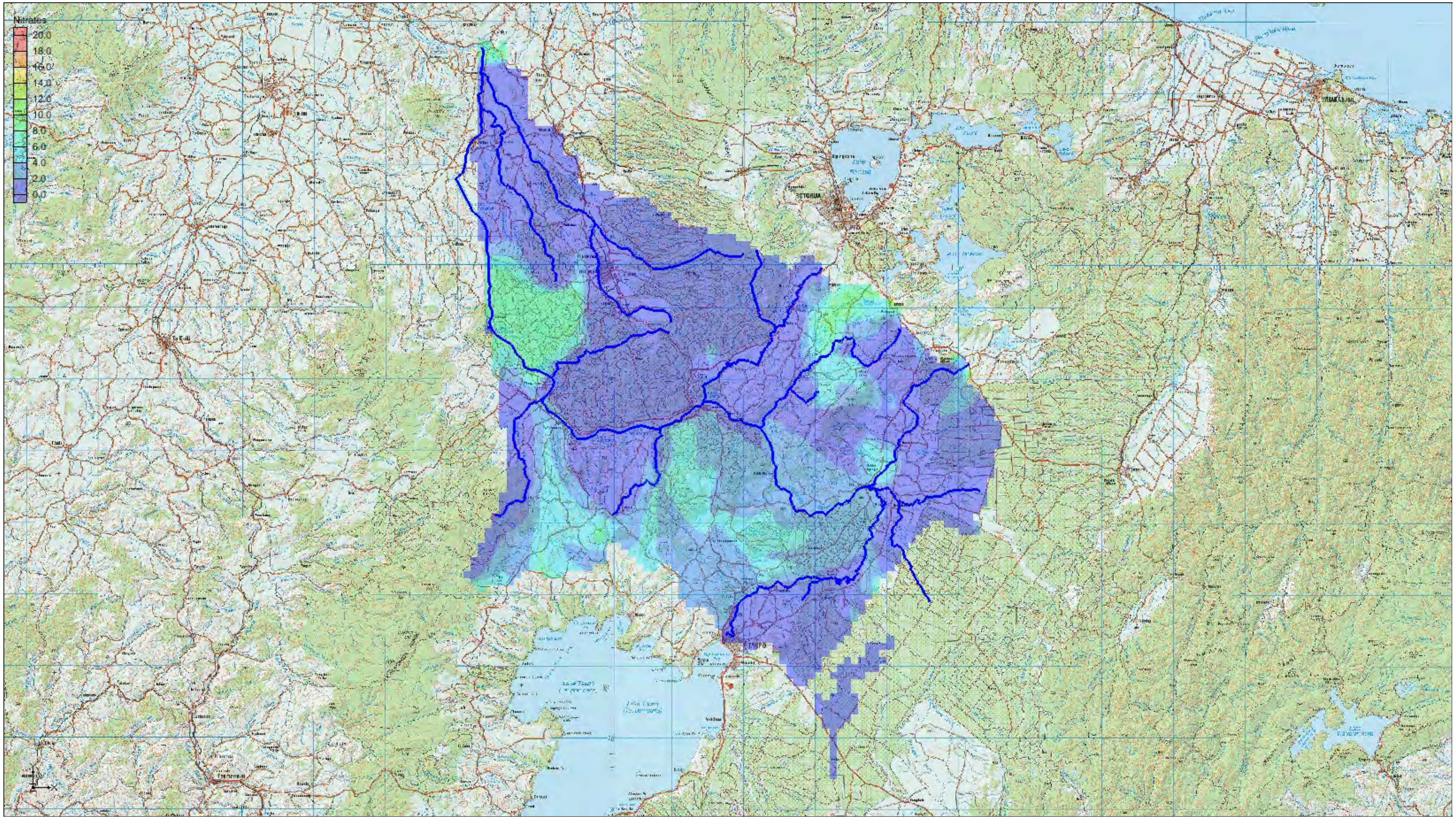


Figure 20: Indicative groundwater nitrate-nitrogen concentrations at depth, towards the base of the shallow layers of interest

5 PREDICTIVE TRANSPORT SIMULATIONS

The calibrated flow model and the assumed transport model have been used to run two predictive scenarios. First the steady state model was used to predict the potential long-term changes in concentrations of groundwater nitrate-nitrogen if the entire study area was converted to intensive dairying. Secondly, a transient transport model was used to estimate the time it would take for the effects of the existing land use on the Waikato River to reach steady state given a relatively 'natural' starting condition. These are discussed below.

5.1 Predictive Scenario 1: Intensive Dairying Everywhere

This scenario assess the potential changes in groundwater nitrate-nitrogen concentrations if the entire study area was converted to intensive dairying. Currently, approximately 45% of the study area is dairying and the remainder is a mixture of less intensive pasture, forest, crops and other land uses (Appendix A3). If all of the non-dairying areas were convert to dairying with the same leachate rate as Table 10, then groundwater nitrate-nitrogen concentrations in the uppermost layer are predicted to increase by approximately the amounts shown in Figure 21. Overall the greatest changes occur where the existing land use has the lower rates of nitrate-nitrogen in the leachate (primarily the existing forested areas). The areas of greatest concentrations tend to occur in areas with greatest LSR concentrations (which are those areas with the lower recharge rates[4]).

Table 12 summarises the mass budget for this predictive scenario. Since the flow scenario is the calibrated model, the water budget is the same as presented in Table 5. All model inputs are daily values, and so outputs will also be on a daily time step. Therefore, the steady state budgets for flow (Table 5) and transport (Table 12) represent daily rates.

Table 12: Model mass budget for predictive scenario where all land use is dairying

Mass (kg/day) (steady state)	
Ins	
Rivers	2,407
Land surface recharge	35,475
Total in	**37,882**
Outs	
Rivers	37,883
Land surface recharge	0
Total out	**37,883**
Summary	
In-Out	-1
% discrepancy	0.003

[4] Because the assumed rates of nitrate-nitrogen leaching under different land uses is specified as a mass per area per unit time (Table 10), the areas with lower LSR rates require larger mass concentrations to result in the 'correct' mass loading.

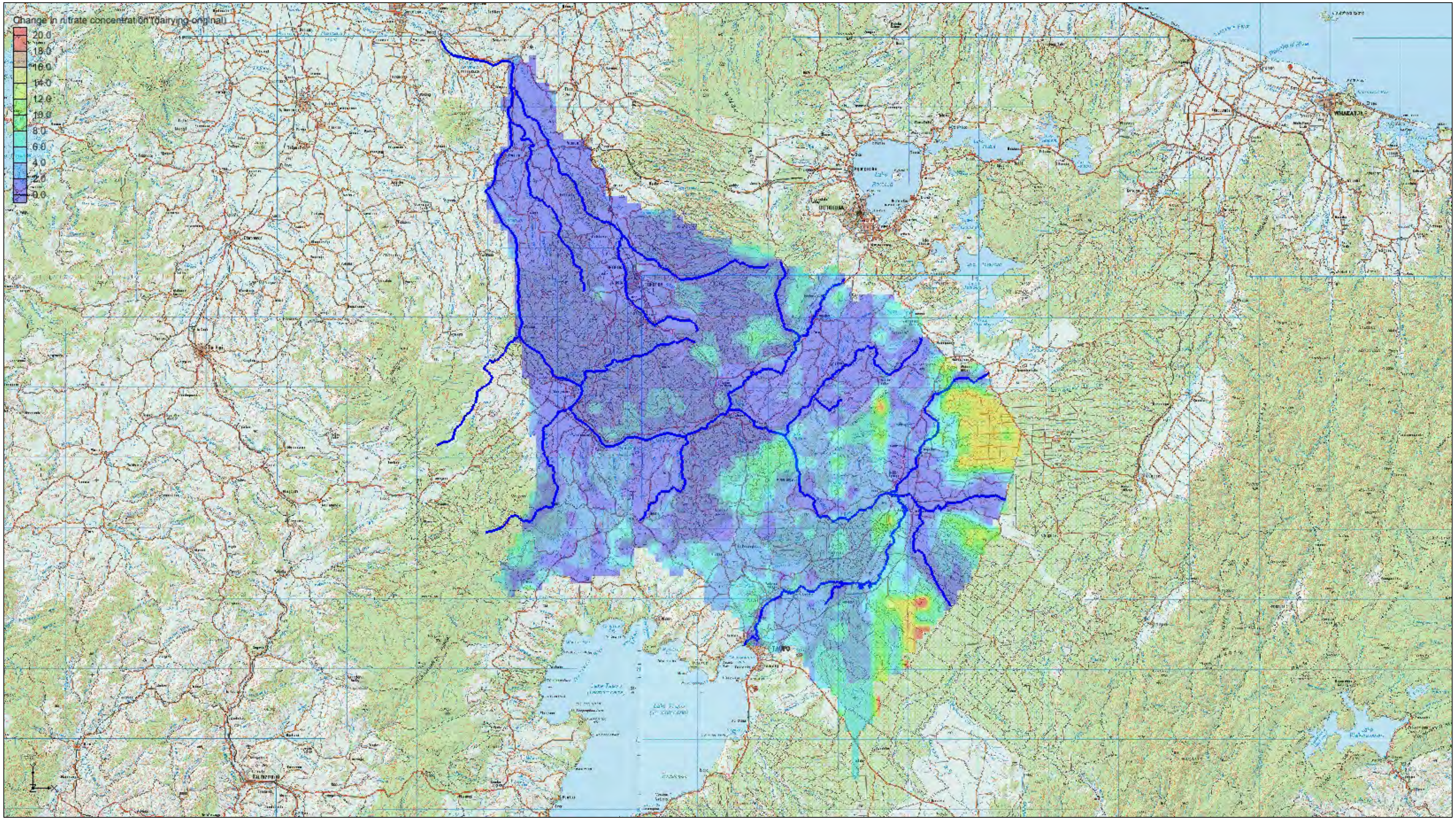


Figure 21: Indicative changes in groundwater nitrate-nitrogen concentrations for the uppermost layer if all land use was changed to dairying

Given the above, the predicted change in nitrate-nitrogen concentration in the Waikato River near Lake Karapiro as a result of converting all existing land use to intensive dairying can be estimated. From Table 11, the status quo net loss of mass to the rivers (i.e. gain to the rivers) for the entire model is approximately 22,265 kg/day. Under the scenario where all land use is converted to intensive dairying (Table 12), the equivalent mass gain for the rivers is 35,475 kg/day. This is an increase of 13,210 kg/day.

From Appendix D, the long-term average flow at Lake Karapiro is 247 m^3/s. From WRC (2010), the existing concentration of nitrate-nitrogen in the Waikato River near Lake Karapiro is 0.301 g/m^3 (based on the records from 'Narrows'). Assuming complete mixing, the long-term (steady state) concentration of nitrate-nitrogen in the Waikato River near Lake Karapiro is predicted to increase to approximately 1.7 g/m^3 if all land use was converted to intensive dairying. This is an increase of approximately 1.4 g/m^3 over and above existing concentrations (which are a measure of the time-varying land use, not steady state). These calculations assume that the change in land use makes no change to river flows and that the change in river concentration is directly proportional to the change in mass entering the river.

5.2 Predictive Scenario 2: Timing of Regional Effects on Rivers

This scenario assesses the time it may take for the full effects of the current land use to be realised in the modelled rivers. To do this, a transient transport model was constructed to run for 500 years. Initial conditions were set as an equivalent steady state model based on all land surface recharge concentrations equivalent to forestry (2 kg N/Ha/year - Table 10). River concentrations were specified as zero. Model results were recorded at 10-yer intervals.

Figure 22 presents the time-varying modelled response of nitrate-nitrogen gains to all rivers (combined) in the model. This is effectively the modelled gain of nitrate-nitrogen to rivers at the lower boundary of the model domain (i.e. into Lake Karapiro). Both the rate of gain and the change in the rate of gain are presented. Even though the transport model is not calibrated, this gives an order of effect for the time it may take for the full effects of large-scale regional land use change to be realised.

From the start of the simulation, the change in mass gain to the rivers is rapid. Though the simulation does not reach complete steady state until after 500 years, steady state conditions are approached after 350-400 years. Approximately 90% of the rate at 400 years is predicted to be reached after 160 years.

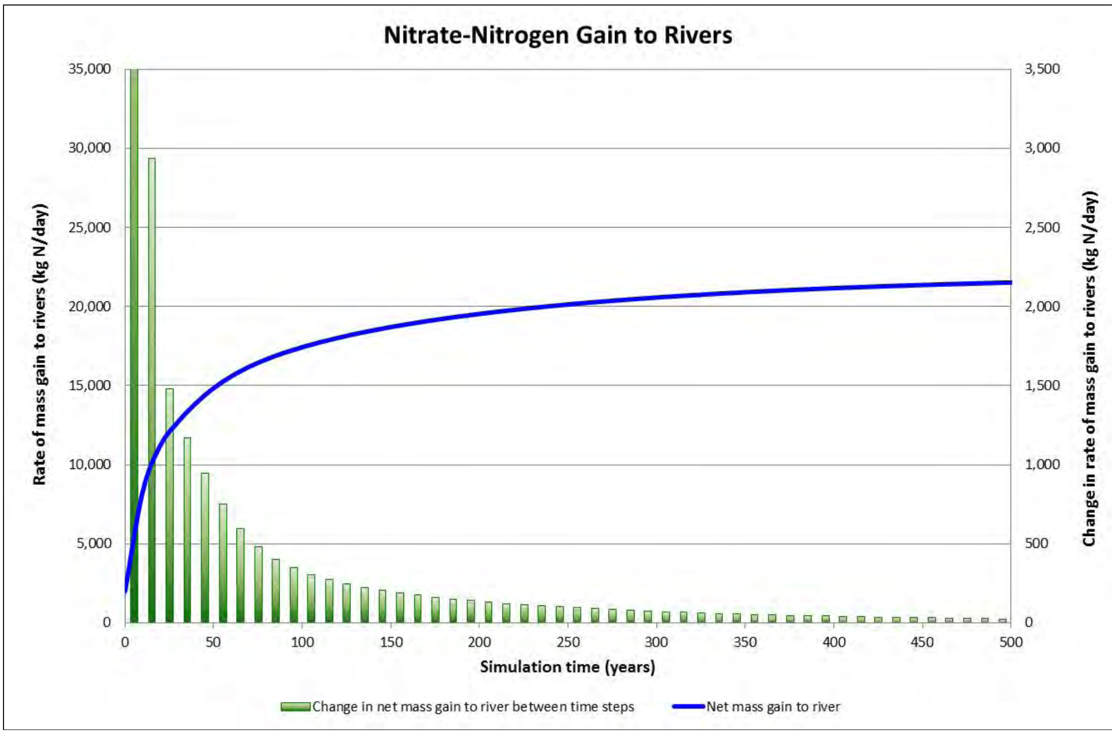


Figure 22: Simulation of nitrate-nitrogen gain to modelled rivers

6 CONSIDERATIONS FOR FUTURE WORK

The Stage 2 modelling work has highlighted areas where additional data and research would be beneficial. In some respects, the overall level of data now required to take the groundwater model forward is greater than what is currently available. Given this, it may be necessary to focus much of the short-term field work on collecting this additional data, allowing time for the data to 'catch up' to the level required by the model. However there is still field data that can be readily collected that would greatly assist with model development and refinement. The following, in order of development logic, summarises all recommendations for future data collection and model development.

- Investigate the relationship between rivers and adjacent groundwater, such as conducting stream-depleting aquifer tests with appropriate analyses;
- Update well datums with measured levels and locations where these have not been measured;
- Include lysimeter data for estimating land surface recharge flows and concentrations;
- Expand the set of aquifer tests to better described formation properties and the range of properties possible within the formations. This will assist in reducing uncertainty associated with hydraulic parameter values;
- Incorporate key transport processes such as denitrification, unsaturated flow, dispersion and preferential flow;
- Include measured aquifer porosities to assist calibrating the transport model; and
- Use age and concentration data to assist calibrating the transport model;

The importance of a specific set of data collection should be determined jointly with the groundwater modelling team and WRC to balance data needs with financial, time and resource demands. In addition, a 'data worth' optimisation exercise could be used to provide focus on which of these measures would most reduce the uncertainty around the predictive simulations of nitrate flux entering groundwater and surface water.

Once a suitably calibrated transport model has been developed, future predictive scenarios can be used to assess the effects of changing land use within individual sub-catchments. A catchment towards the upper part of the model (such as the Reporoa area) and another further down the catchment (such as the Tokoroa area) could be separately modelled to consider how changes in different parts of the region affect downstream water quality. In addition, backward particle tracking can be used to determine the capture zones of the various dams. This will assist in determining which areas of future land use change may affect water quality at the specified dam location.

7 REFERENCES

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Appendix A: Data collection and analysis

A1 Topographical and Geological Data

A three-dimensional model of the upper Waikato geology was supplied by GNS Science. This data was supplied as X-Y-Z Ascii data on a 500 x 500 m grid, clipped to a polygon slightly larger than the study area. Each of the following geological contacts were supplied (in order from the land surface down):

- Land surface DEM (digital elevation model)
- Quaternary sediments and volcanic layer
- Huka group
- Oruanui group
- Mamaku group
- Reporoa group
- Whakamaru/Maroa group
- Basement rock

A description of the hydrogeological characteristics of these formations was also supplied by GNS Science and this is reproduced in Appendix B.

A2 Climate Data

Climate data was sourced from NIWA's gridded virtual climate station (VCS) which is currently the best available source of climate data for regional water studies. The data retrieved from NIWA were reference evapotranspiration (ET) and rainfall. Approximately 230 VCS were available for the study area. Aqualinc (2009) provides further discussion on the VCS network for Waikato; this will not be reproduced herein.

Mean annual rainfall across the study area varies between 1,100-1,800 mm per year. Mean reference ET varies from 575-850 mm per year. Contours of mean annual rainfall and reference ET are provided in Figure 23 and Figure 24, respectively.

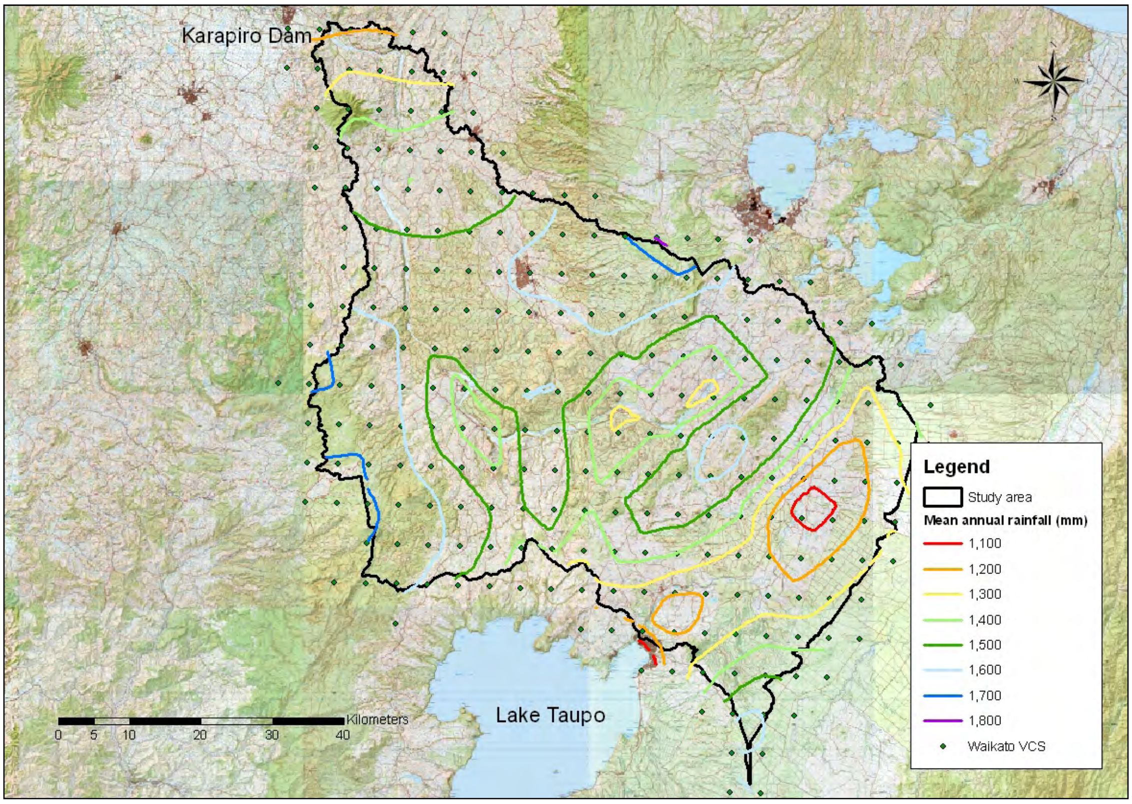

Figure 23: Mean annual rainfall from NIWA's VCS network

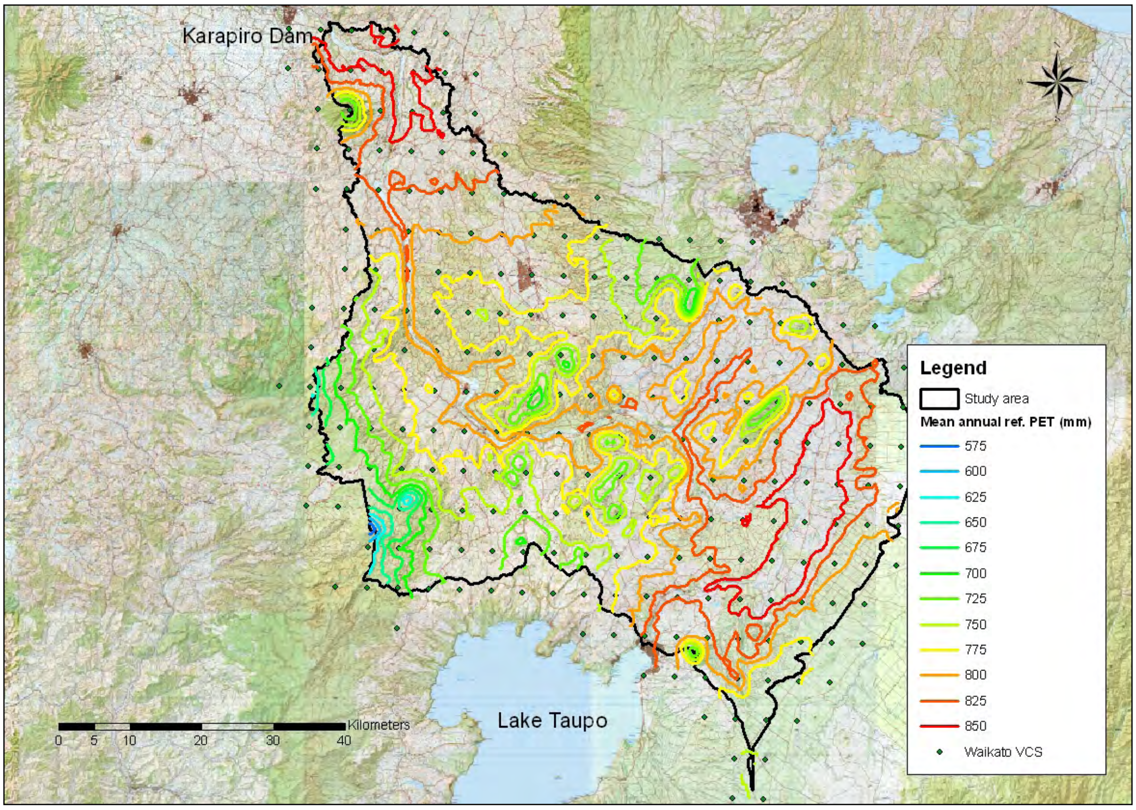

Figure 24: Mean annual reference evapotranspiration from NIWA's VCS network

A3 Land Use

Land use in the study area is dominated by pasture and pine plantations. Land use information was obtained from a combination of Terralink's Land cover Database (Version 2) and from Waikato regional Council, and is summarised in Table 13 and Figure 25. Land cover has been aggregated into the following classes:

i) Crops (cropping is a very small proportion of the total land area (less than 0.5%) and so for simplicity it has been assigned as intensive dairying);
ii) Pasture for intensive dairy;
iii) Forest (this includes both pine plantations and native forest);
iv) Pasture for less-intensive purposes (such as sheep, beef etc.); and
v) Other (including open water and other land covers.

Table 13: Land cover

Land cover	Percent of study area
Crops	< 0.5%
Dairy	45%
Forest	22%
Less intensive pasture	30%
Other	3%

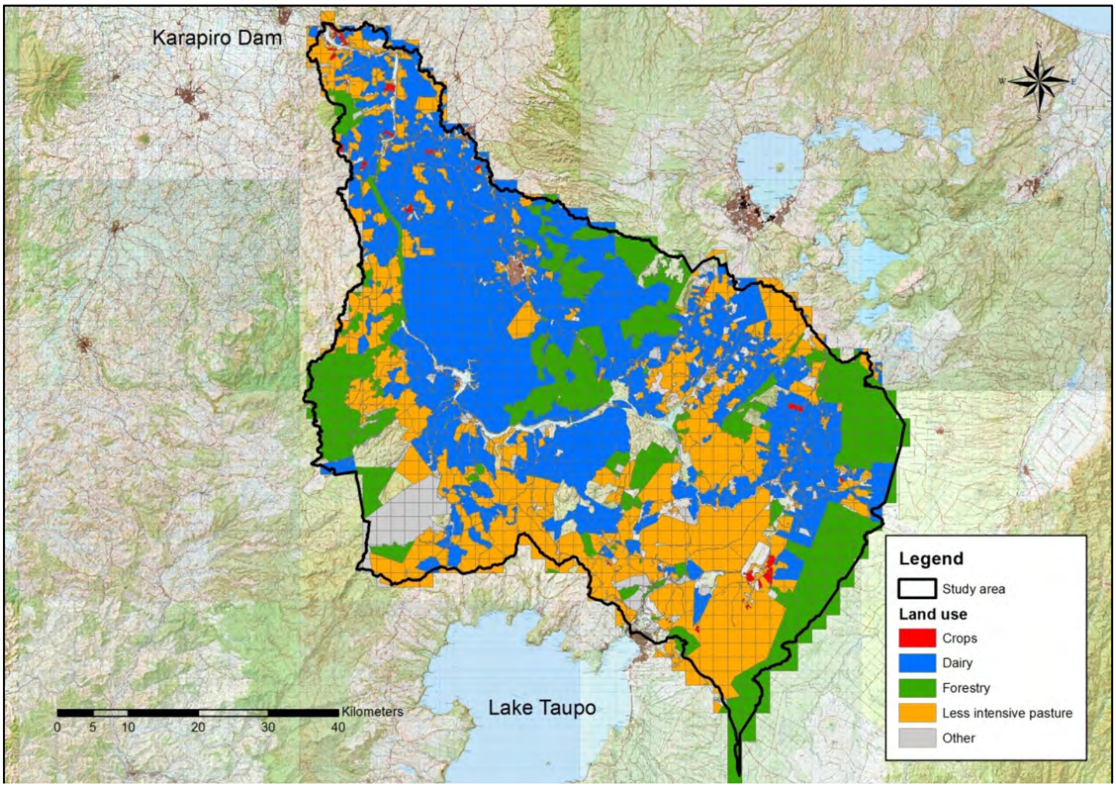

Figure 25: Land use

A4 Land Slope

Land slope, together with land cover, affects the likelihood of direct surface runoff. Significant portions of the study area are steep (Figure 26) which increases the chance of runoff. Runoff increases the likelihood that water will flow directly to streams and rivers rather than recharging groundwater.

Runoff is reduced beneath pine plantations due to rainfall interception by the tree canopy and water storage in the organic litter (this impedes overland flow). Runoff is most likely to occur in pasture land and where the land slope is greater than 15 degrees. Approximately 25% of the study area has pasture slopes greater than 15 degrees (Figure 27). In these areas, the land surface recharge (LSR) to groundwater may be overestimated.

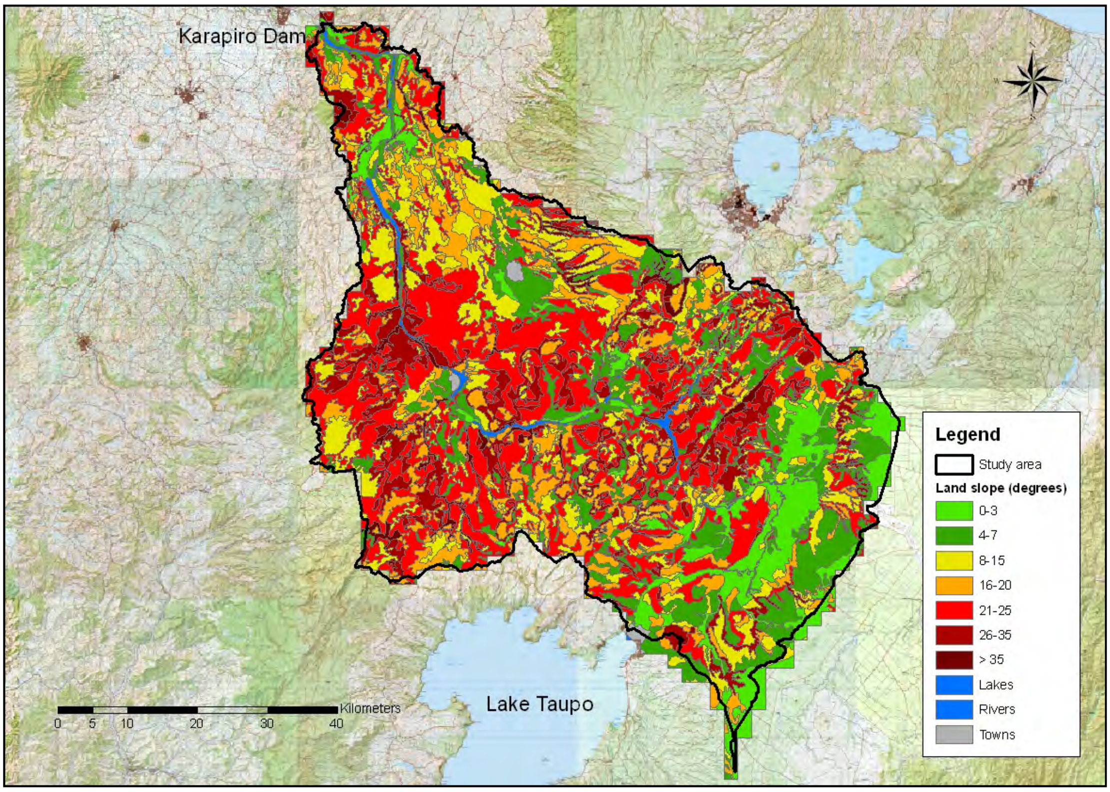

Figure 26: Land slope

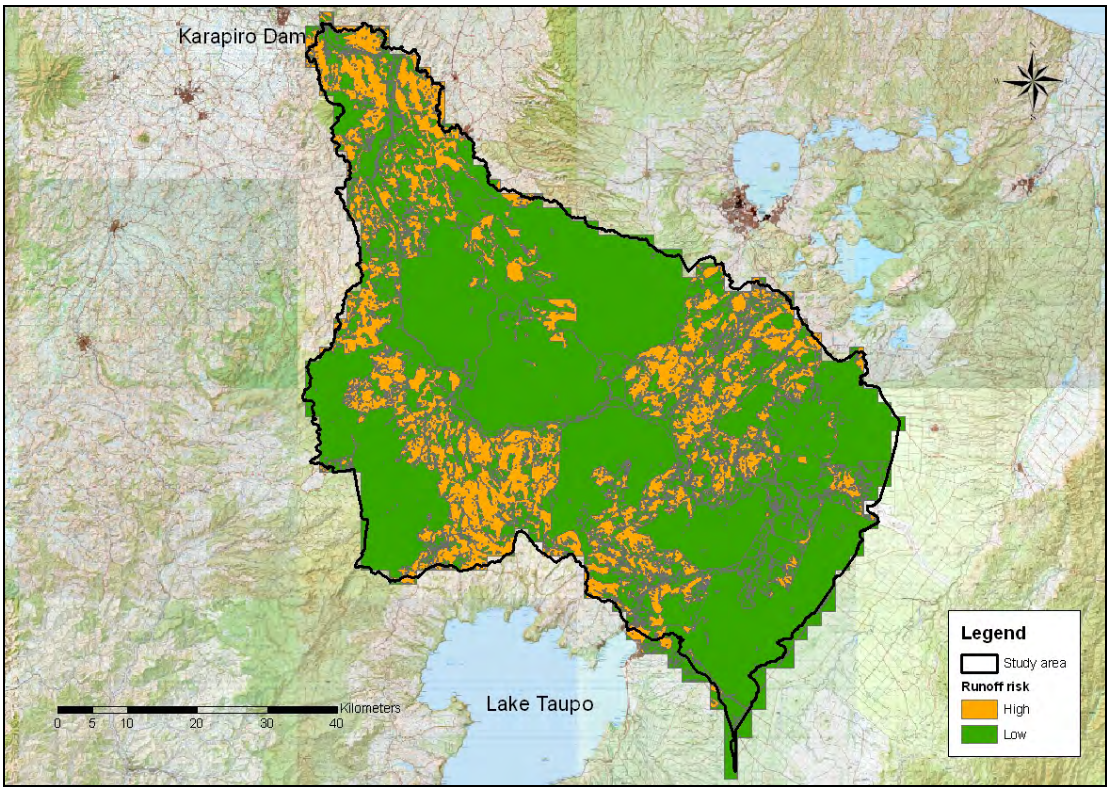

Figure 27: Runoff risk

A5 Agricultural Soils

Soils information for pasture was obtained from Landcare's Fundamental Soils Layer, which is generally based on a rooting depth of 900 mm. Soils were aggregated into three plant available water (PAW) classes (Table 14).

Table 14: Soil classes for pasture

Soil class (mm)	PAW range (mm)
40	25-65
90	66-120
50	>120

For forests, PAW was assumed to be about 530 mm, based on fitting calculated LSR to field measurements by Whitehead and Kelliher (1991). No allowance was made for spatial variations in PAW, since no reliable information is available to typical rooting depths for pine (3-5 m).

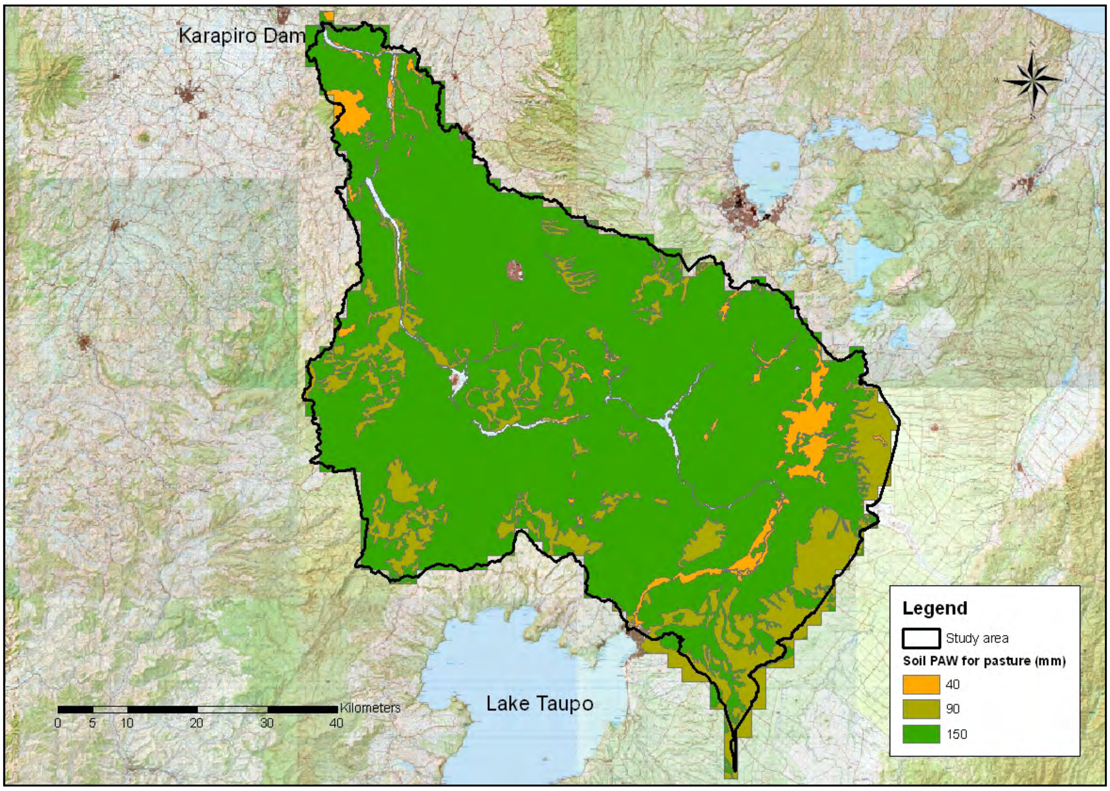

Figure 28: Soil plant available water for pasture

A6 Soil Water Balances

Aqualinc's in-house crop-soil water balance model has been used to generate time series of varying land surface drainage. The crop-soil water balance model simulates the variable use of water in agriculture with differing crops, agricultural soil types, representative daily climatic conditions and irrigation strategies. The basis of the model is a daily soil moisture balance with an irrigation scheduling component, though for the upper Waikato groundwater model, the irrigation component has not been used (refer to Section A8 below).

The crop-soil water balance model was developed by Lincoln Environmental as part of a research project funded by the Foundation for Research, Science & Technology (FRST). It has been based on New Zealand field data and tested on Canterbury irrigation schemes. More recently, the model has been tested by Aqualinc (2010b).

For the purposes of the upper Waikato groundwater study, the soil water balance model was used to calculate groundwater recharge. Data inputs were:

- Reference evapotranspiration (ET);
- Rainfall;
- Land cover; and
- Soil plant available water.

Actual ET was derived from the reference ET using the relationship by Allen *et al.* (1998) described in Equation 1.

$$\text{Actual ET} = k_s \times k_c \times \text{reference ET} \quad (1)$$

Where: k_s = the water stress reduction factor; and
k_c = the evapotranspiration crop coefficient.

The water stress reduction factor is a function of soil moisture. As recommended by Allen *et al.* (1998), it was assumed that k_s equalled 1.0 when the soil moisture deficit was less than the plant readily available water, and k_s reduced linearly down to a value of zero at wilting point, when the soil moisture deficit was greater than the plant readily available water. Readily available water was assumed to be equal to 50% of the plant available water at field capacity (PAW). Each day soil moisture was calculated as:

$$ASM_{\text{day } i} = ASM_{\text{day } i-1} + (\text{rain} + - \text{actual ET} - \text{drainage})_{\text{day } i} \quad (2)$$

Where: ASM = plant available soil moisture.

The ET crop coefficient (k_c) for pasture was set at 1.0. For forests, k_c was estimated to be approximately 1.45 based on fitting calculated land surface recharge (LSR) to field measurements by Whitehead and Kelliher (1991) for a pine catchment located in the centre of the study area.

The model assumes that the maximum water the soil can hold is the PAW. Any rain in excess of that required to reach field capacity was assumed to drain beyond the root zone.

Modelling assumed soils were free draining, and the depth to groundwater was greater than plant rooting depths. Model simulations were run from 1 June 1972 to 31 May 2010, a total of 38 years.

A7 Land Surface Recharge

The long-term average annual land surface recharge (LSR) as calculated by the soil water balance model is presented in Figure 29. Average annual recharge for the whole study area is estimated to be approximately 70 $m^3/s \pm 10\ m^3/s$ and averages at approximately 500 mm/year. Of this, approximately 13 m^3/s occurs in areas where bedrock outcrops or comes close to the surface[5] (particularly to the eastern areas of the model) and does not recharge the regional groundwater system. In reality this water would flow more directly to streams and rivers via shallow soil flow paths.

The largest source of uncertainty in the calculations is associated with actual evapotranspiration (AET). Field measurements suggest estimated annual average AET for both pasture and forestry has about ±10% uncertainty which correlates to approximately ±15% uncertainty in cumulative average annual recharge for the whole study area. At a smaller scale, uncertainty in the rainfall distribution means that LSR uncertainty for individual locations may vary from this.

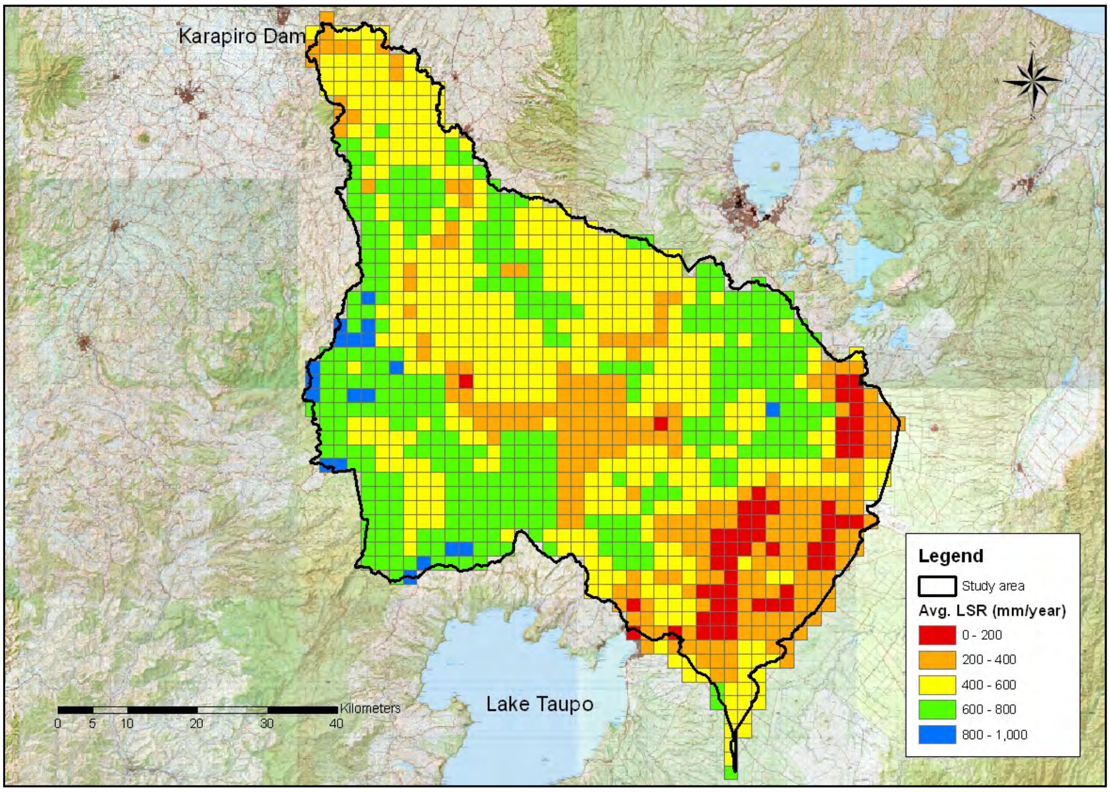

Figure 29: Estimated average annual land surface recharge

[5] Model cells in these areas are assigned as inactive, rather than low conductivity, to encourage stable model running.

A8 Existing Irrigation

Information on existing irrigation has been sourced from Waikato Regional Council. Within the study area there is approximately 4,600 ha of irrigation (Figure 30) which equates to 1% of the total study area. Of the 4,600 ha of irrigated area, approximately 80% is supplied from surface water and 20% from groundwater.

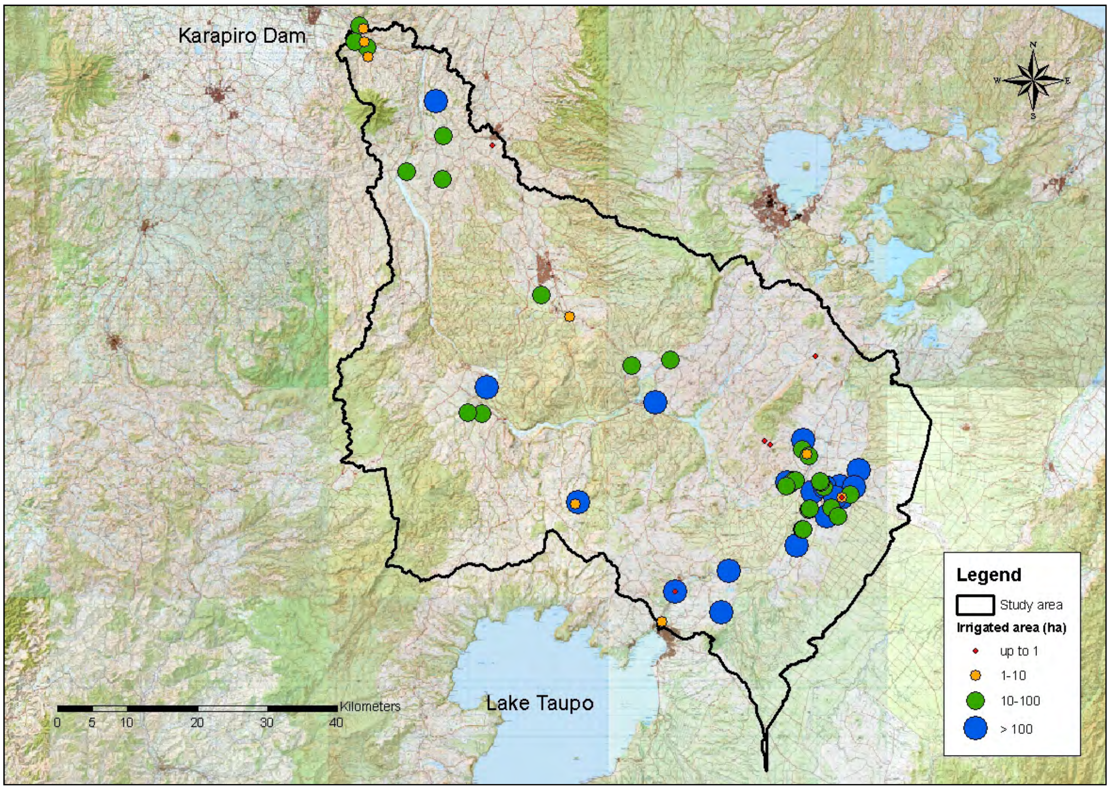

Figure 30: Existing irrigated areas

Irrigation from surface water increases the LSR; irrigation from groundwater increases the LSR and reduces the net amount of water flowing through the groundwater system (accounting for the taken water and the returned water). To determine the effects irrigation has on the regional water balance, the soil water balance model was used to compare the relative changes in LSR.

The soil water balance model suggests that, on average, irrigation from surface water results in an increase in LSR of approximately 2,000 m^3/ha/y; irrigation from groundwater results in a net reduction in groundwater flow of about 2,000 m^3/ha/y. Given this, the expected increase in LSR over the entire study area is approximately 0.18 m^3/s [((4,600 ha × 80% surface water × 2,000 m^3/ha/y) – (4,600 ha × 20% groundwater × 2,000 m^3/ha/y))/(365 × 60 × 60 × 24 seconds/year)].

In comparison, the calculated long-term average recharge for the entire study area is estimated to be approximately 70 m^3/s ± 10 m^3/s (see Appendix A7). The effects of additional recharge from irrigation are very small (an increase in groundwater recharge of approximately 0.3%). Since the increase is very small (particularly compared to the uncertainty in calculating LSR), the contribution from irrigation has been ignored; land surface recharge has been calculated based on un-irrigated land use only.

A9 Groundwater Bores and Groundwater Levels

The location of existing known bores, their depths and groundwater level measurements were provided by Waikato Regional Council. Figure 31 presents the locations of the known bores and their depths. Figure 32 shows the average measured depth to groundwater levels for bores with measurements. The depth to groundwater for all bores with measurements varies between approximately 0.5-165 m depth with an average of approximately 35 m. However, this average is likely to be skewed by deeper bores with deep measurements but which have shallower water tables overlying the deeper layers within which the groundwater level is measured. Therefore considering shallower bores only provides a truer indication of the average depth to groundwater for the first (shallow) water bearing layer. The depth to groundwater for bores less than 50 m deep varies between 0.5 and 41 m deep with an average of approximately 13 m.

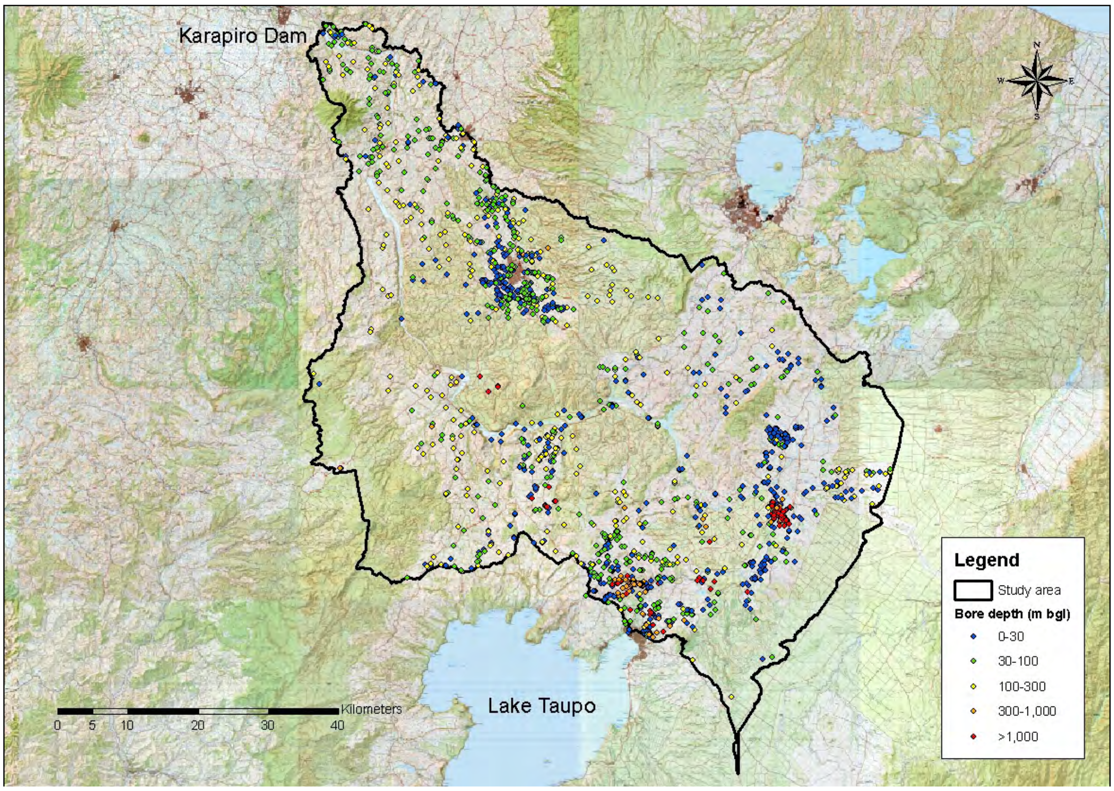

Figure 31: Groundwater bores

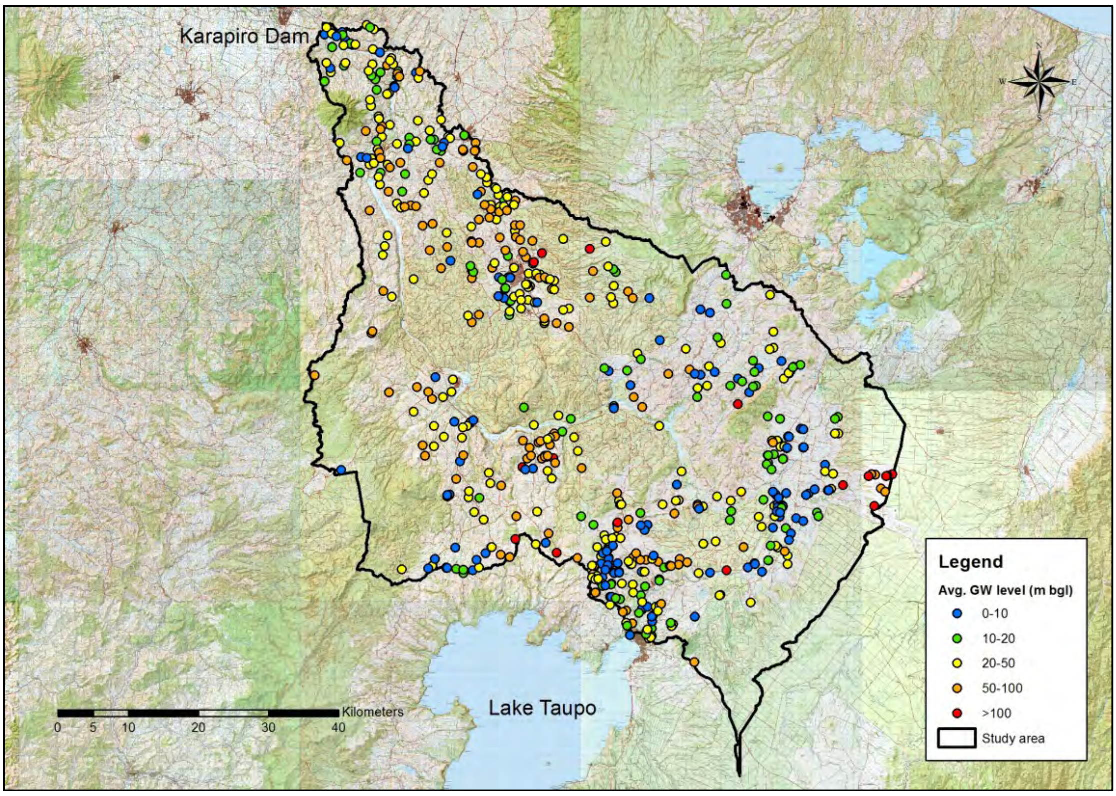

Figure 32: Average depth to groundwater

A10 Surface Water Data

The Waikato River and major tributaries have been included in the regional groundwater model. River courses were digitised from 1:50,000 topographic maps and are shown in Figure 33. Also shown in Figure 33 are the locations of river measurement sites, both rated sites (with automatic recorders) and gauged-only sites (with occasional spot measurements). River levels and river flows (where available) at these sites were supplied by Waikato Regional Council.

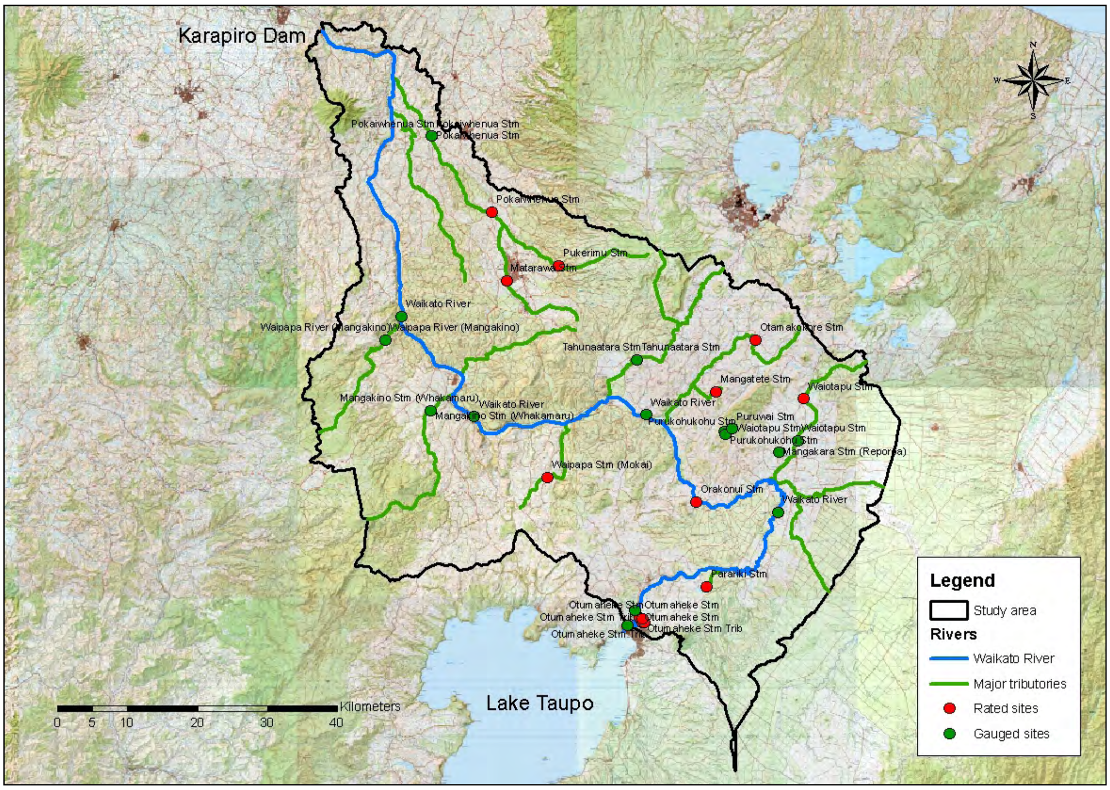

Figure 33: Rivers

A11 Dams and Lakes

The location of dams and their respective lakes were digitised from 1:50,000 scale topographic maps. These are shown in Figure 34. The lakes formed behind the dams follow very closely to the general shape of the Waikato River. Consequently specific lakes have not been included in the model, except by that provided in representing the rivers. The river stage heights in the vicinity of the lakes have been assigned as the lake level elevations, which were supplied by Waikato Regional Council.

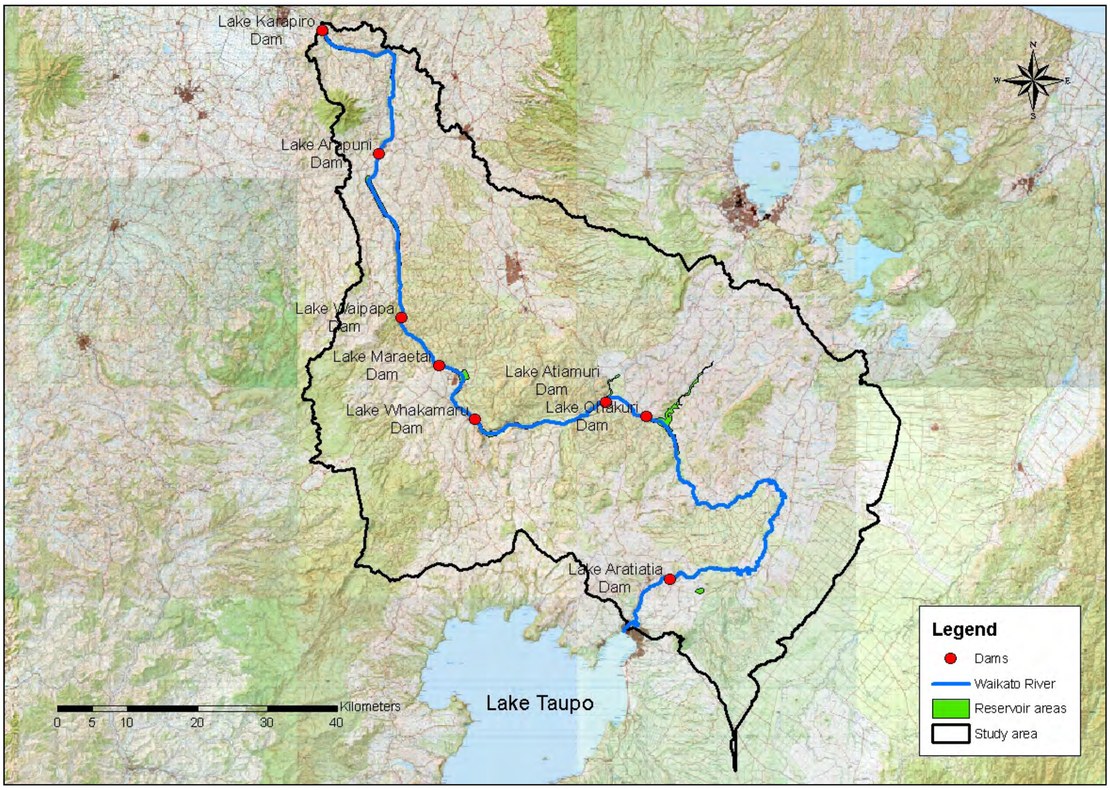

Figure 34: Dams and lakes

A12 Aquifer Transmissivity

Transmissivity data derived from aquifer tests has been supplied by Waikato Regional Council for 37 bores. Aquifer saturated thicknesses have been interpreted from the pump bore stratigraphy logs to yield an aquifer hydraulic conductivity. These numbers are listed in Table 15.

Table 15: Aquifer transmissivity and hydraulic conductivity

Bore name	T (m^2/day)	Approx. sat thickness from bore logs (m)	K (m/day)	Formation
68_268	770	30	25.67	Whakamaru
68_45	30.8	12	2.57	Oruanui
68_46	178	28	6.36	Quaternary
68_47	30.8	25	1.23	Quaternary
68_48	46.7	16	2.92	Whakamaru
68_494	3.2	20	0.16	Whakamaru
68_579	1.7	11	0.15	Oruanui
68_6	1.2	20	0.06	Quaternary
68_66	79.9	25	3.20	Quaternary
68_71	915	20	45.75	Quaternary
68_711	3.2	119	0.03	Whakamaru
68_77	210	18	11.67	Quaternary
68_844	270	21	12.86	Whakamaru
72_1565	1200	23	52.17	Whakamaru
72_2725	581	6	96.83	Oruanui
72_3036	254	10	25.40	Quaternary
72_3037	300	13	23.08	Quaternary
72_3114	1.12	12	0.09	Whakamaru
72_3191	660	19.5	33.85	Oruanui
72_3318	408	27	15.11	Quaternary
72_3341	1685	120	14.04	Deep
72_3566	8.7	30	0.29	Deep
72_3647	3.29	11	0.30	Deep
72_3654	76.4	9	8.49	Deep
72_3657	8.5	60	0.14	Deep
72_3658	101	6	16.83	Deep
72_3663	3.8	68	0.06	Deep
72_3667	21.3	132	0.16	Deep
72_3848	38	72	0.53	Whakamaru
72_3984	4000	60	66.67	Reporoa
72_4004	444	27	16.44	Deep
72_4159	151	68	2.22	Deep
72_4391	1240	39	31.79	Quaternary
72_4555	22.3	34	0.66	Deep

A13 Groundwater Age

Waikato Regional Council have collated measurements of groundwater age data, primarily from bores, but with a few measurements taken from springs. Some age datings were completed directly by Waikato Regional Council and others have been provided by external suppliers. The datings typically consist of a range in likely age, and in some instances a recommended age is provided. The recommended age has been used to guide model calibration. Where no recommended age is provided, an average within the range reported has been selected as the chosen age. The ranges (where reported), recommended ages, and the chosen ages for various sites with age data are summarised in Table 16. The site locations and chosen age are presented in Figure 35.

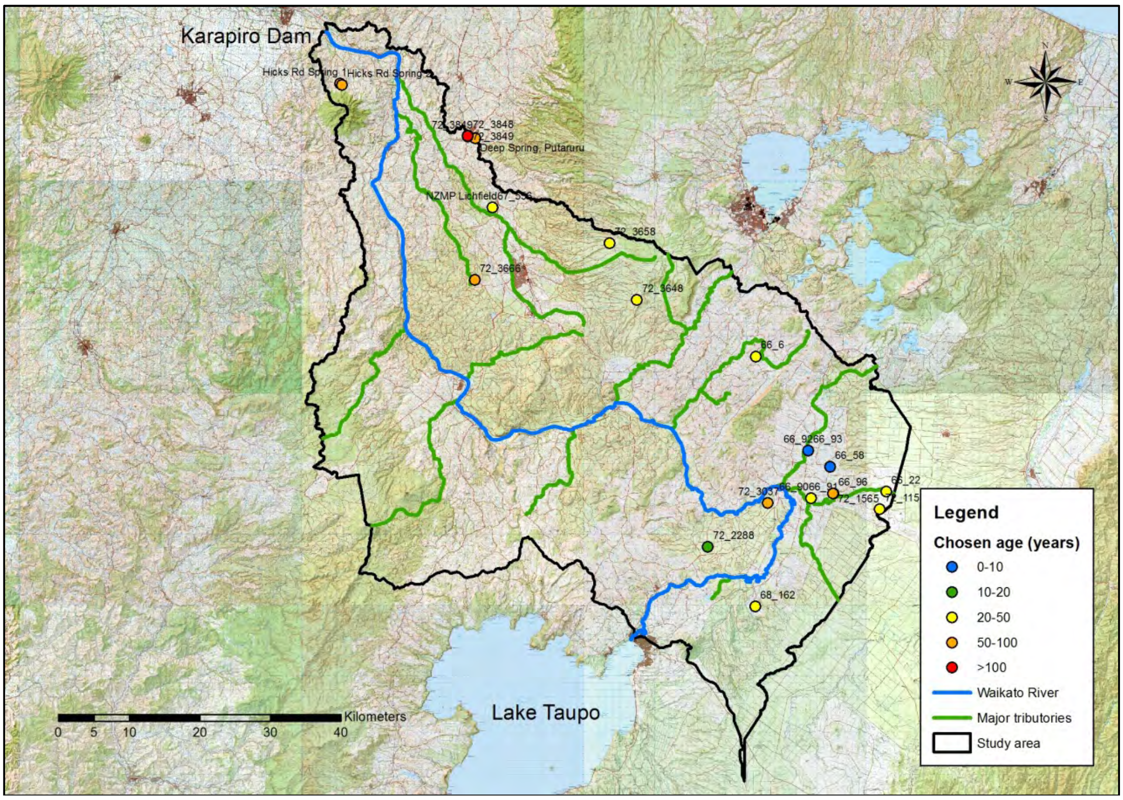

Figure 35: Groundwater chosen age

Table 16: Summary of groundwater age data

Site name	Source depth (m bgl)	Reported age range (years)	Recommended age (years)	Chosen age (years)
66_22	110.0	22-28	25	25
66_58	38.0	0.08-7.7	>170	5(1)
66_6	38.0	1.26-189.2	30	30
66_90	6.0	9-13	11	11
66_91	4.5	16-27	26	26
66_92	48.5	0.032-5.4		3
66_93	8.0	1.66-279.5		Ignore(2)
66_96	120.0	0.9-66.3	200	200
67_11	18.5	8.32-643.3	2.5	3
67_15	20.0	16-45	45	45
68_162	43.0	35-61		48
67_556		14-19	20	20
72_1153	210.0	28-65		47
72_1565	112.4	54-65	58	58
72_2288	52.5	8-14		11
72_3037	55.2	50->83		75
72_3648	124.0	15-45	45	45
72_3658	72.0	4-46	46 & 4	46
72_3666	154.0	57-102	102	80
72_3849		34-73	90	90
72_3849	70.0		55	55
72_3848	180.0		125	125
Deep Spring NZ, Putaruru	spring	14-63	30 - 80	55
Hicks Rd Spring 1	spring	50 - 157	20-90	55
Hicks Rd Spring 2	spring	49 - 126	20-90	55
NZMP Lichfield	71.0	55 - 62	20 - 80	50

1 The recommended age is not consistent with the reported age ranges, so a value within the range has been chosen.

2 Because the age range for this site is so large, it is meaningless to select a single representative age. Therefore, the results have been ignored.

A14 Groundwater Nitrate-Nitrogen Concentrations

Waikato Regional Council's database includes records of groundwater nitrogen measurements in various forms including nitrate, nitrite, total and organic nitrogen. Nitrate-nitrogen is the more commonly referred to form, and has the greatest count of measurements available. Nitrate-nitrogen concentrations are listed as being derived via four methods, these being 'nitrogen FIA', 'ion chromat', 'unknown' and 'calculation'. Where multiple measurements are reported for the same well, the data is taken in preference of this same order, which is an approximate order for analytical accuracy. Also, where wells only have nitrate and nitrite concentrations reported as a combined measurement, then these value are assumed to be equivalent to nitrate-nitrogen alone, as the concentrations of nitrite-nitrogen in groundwater are likely to be low (Dr. Greg Barkle, Aqualinc, *pers. com*).

Figure 36 presents the locations of wells with nitrate-nitrogen measurements, their average concentrations, and the number of measurements from which the average is derived.

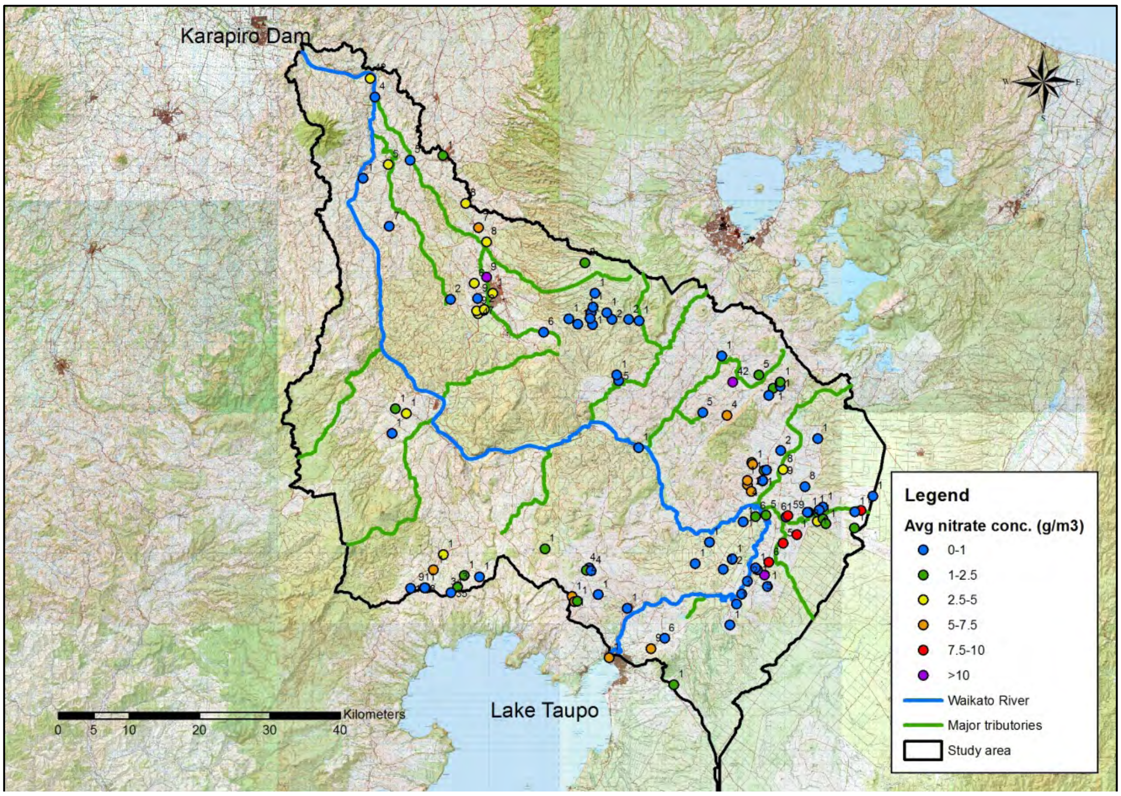

Figure 36: Average nitrate-nitrogen concentrations

(the number of measurements from which the average is derived is noted beside the location)

In this Stage 2 study, these nitrate-nitrogen concentrations are not used to directly calibrate the transport model. However, they are used to make qualitative assessments regarding spatial distribution of concentrations and possible areas of interest.

Appendix B: Hydrogeological descriptions supplied by GNS Science

Letter Report No: 2010/128LR
Project No: 632W0105

8 July 2010

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Dear Julian

RE: HYDROGEOLOGICAL CHARACTERISTICS OF MAJOR GEOLOGICAL UNITS IN THE UPPER WAIKATO CATCHMENT

1.0 INTRODUCTION

Environment Waikato is investigating impacts of current and potential land use in the Upper Waikato River catchment. As part of these investigations, Environment Waikato has commissioned AquaLinc to develop a preliminary three-dimensional (3D) numerical groundwater flow and contaminant transport model covering the Upper Waikato River catchment. A depiction of the 3D geological structure of the study area is required for the numerical groundwater flow model, along with an understanding of the relevant hydrogeological properties of each geological unit (layer) defined within the groundwater flow model.

This letter report provides hydrogeological descriptions of the following seven geological layers that are relevant to the Upper Waikato River catchment; these geological layers are all represented in a 3D geological model of the Taupo Volcanic Zone that has been developed by GNS Science (White et al. 2009).

- Basement layer
- Whakamaru/Maroa layer
- Mamaku layer
- Reporoa layer
- Huka Group layer
- Oruanui layer
- Quaternary sediments and volcanics layer

The description of each geological layer is constrained to characteristics relevant to the application of groundwater flow modelling and is presented from the oldest to youngest layer. A revised surficial geological map of the area is currently under development (Leonard et al., in prep.), from which some of the information is obtained. The summary of aquifer hydraulic information for each layer is not included in the description (although it is fundamental for groundwater flow modelling purposes), because it is understood that AquaLinc will acquire this information directly from Environment Waikato. GNS Science has previously provided digital output files of easting, northing and depth coordinates of layer boundaries to AquaLinc.

The hydrogeological characteristics of each layer are summarised in Table 1. An estimate of effective porosity of each layer is provided if known, based on typical values, or range of values, obtained from geothermal well drilling investigations. All mention of porosity in this letter report pertains to effective porosity. References for the values are provided if known. Unreferenced values were provided anecdotally by Michael Rosenberg (GNS Science geothermal geologist) and are indicative only. The typical range of porosity for ignimbrite, tuff or pyroclastic deposits is 0.1 to 0.4. The porosity of unwelded ignimbrite deposits is generally about 0.3. Groundwater movement in welded ignimbrite layers is via fracture flow with porosity dependent on the density and openness of the fracture system.

The surface exposure of layers in the grids provided approximates the geological map data of Leonard et al. (in prep.). Estimates of errors associated with the elevation of the grid layers are provided in the corresponding layer section. These errors are indicative and should not be considered absolute. The errors provided are based on depth below ground surface, not on elevation, with magnitude of the error generally increasing with depth.

Table 1. Summary of hydrogeological characteristics of model layers

Layer	Units, Formations, Groups or Terranes included in layer	Range of effective porosity values	Nature of porosity	Aquifer type	Hydraulic conditions	Recharge
Basement	Waipapa and Torlesse (composite) terranes (common name greywacke)	0.02 to 0.2	Fracture	No flow boundary	n/a	n/a
Whakamaru/Maroa	Pakaumanu, Whakamaru and Maroa groups	0.3	Intergranular in non-welded zones, fracture in welded zones	Aquifer	Confined at depth	Rainfall, river
Mamaku	Mamaku Plateau Formation	0.3	Intergranular in non-welded zones, fracture in welded zones	Aquifer	Confined at depth	Rainfall
Reporoa	Kaingaroa Formation	0.3	Intergranular in non-welded zones, fracture in welded zones	Probably dry	n/a	Rainfall
Huka Group	Waiora and Huka Falls formations	0.4 to 0.6	Intergranular	Aquiclude and confining layer	Generally regarded as an aquiclude but contains a shallow unconfined aquifer, confined aquifer at depth. Has high porosity but low permeability within Quaternary sediments	Rainfall, river
Oruanui	Oruanui Formation	0.4 to 0.6	Intergranular	Aquifer	Shallow unconfined, confined at depth	Rainfall, river
Quaternary sediments and volcanics	Taupo Formation, Tauranga Group, Kapenga Volcanic Centre pyroclastics	0.5 to 0.7	Intergranular	Aquifer	Generally unconfined	Rainfall, river

2.0 HYDROGEOLOGICAL DESCRIPTION OF MODEL LAYERS

2.1 Basement layer

The basement comprises a series of low-grade metamorphosed sedimentary terranes that are approximately 145 million years old. They are commonly named as greywacke. Greywackes consist of thin-bedded alternating sandstone and mudstone in the southwest of the model area (Grindley 1960, Edbrooke 2005). Basement rocks west of Tokoroa are part of the Waipapa (composite) terrane, which are described as 'massive to poorly bedded, fine - to medium - grained sandstone' (Edbrooke 2005). Basement rocks in the Reporoa and Taupo areas are part of the Torlesse (composite) terrane.

Greywackes typically have very low intergranular permeability. While groundwater may occur in fractures within the basement greywackes, specific yield is likely to be very low over much of the model area. The typical range of porosity for greywacke is 0.02 to 0.2 (Wood et al. 2001). It is likely that very few wells draw groundwater from greywacke in the model area due to significant depth of the deposits over much of the model area and low groundwater yield. Therefore, it is appropriate that the basement layer be considered a no flow boundary for regional groundwater modelling purposes.

Where basement is exposed at the ground surface in the provided grid, error is estimated at +/- 2 m. The source of the data for the ground surface grid was NZMG 20 m contours. In the Ohaaki area, the error associated with the top of the layer where it occurs below ground surface is estimated to be +/- 10 m, as several wells intersect greywacke in this area. Elsewhere the error is estimated to be +/- 30% of depth as the surface was based on interpolation of gravity surveys.

2.2 Whakamaru / Maroa layer

This layer includes the following mapped geological groups: Pakaumanu Group, Whakamaru Group and Maroa Group.

The Pakaumanu Group comprises a series of welded and non-welded ignimbrite deposits with inferred ages spanning approximately 1.68 Ma to 1.0 Ma, (Edbrooke 2005). They are exposed to the west of Waikato River between Arapuni (Healy et al. 1964) and west of Lake Taupo (Grindley 1960); and between Putaruru and Karapiro to the east of the Waikato River. Three regionally mapped ignimbrite formations (and several other local formations) are included in the Pakaumanu Group (Grindley 1960): the Ongatiti, Ahuroa and Rock Hill formations.

Whakamaru Group deposits in the Reporoa area are plateau-forming ignimbrite sheets up to several hundred meters thick erupted from a major caldera in the Taupo-Maroa area. These sheets include the Whakamaru, Rangitaiki and Paeroa Range units. Despite some proposed correlations (e.g. Brown et al. 1998) relationships amongst these units (also referred to variably as 'Ignimbrite', 'Formation' and 'Group' themselves) are unclear. In the Mangakino – Tokoroa area Whakamaru Group ignimbrites, erupted from the Mangakino Volcanic Centre, generally outcrop against Mamaku Plateau Formation and Maroa Volcanic Centre deposits in the east and generally outcrop against Pakaumanu Group in the west.

Whakamaru Group ignimbrites are deposited from Putaruru in the north to the western side of Lake Taupo in the south. Whakamaru and Rangitaiki ignimbrites in the Lake Taupo catchment are variably welded and have inferred or measured radiometric ages between 320ka and 340ka (Houghton et al., 1995). Mostly poor to moderately-welded lithologies, the Whakamaru Group has a low intrinsic permeability. The upper contact of the Whakamaru Group ignimbrites is often a zone of low permeability (Hadfield et al. 2001).

The Maroa Volcanic Centre, located mostly south of Atiamuri, is generally associated with lava domes and pyroclastic deposits. Lava domes were 'erupted mostly over a short 29 kyr period starting at 251 ± 17 ka' (Leonard 2003). Six pyroclastic deposits are described by Leonard (2003); the largest by volume are the Mokai pyroclastics. Pyroclastic deposits include unwelded and welded ignimbrites, dated at 283 ka to 196 ka (Leonard 2003).

Generally, the layer is considered to be groundwater bearing. Inter-granular flow is likely to occur within unwelded ignimbrite sheets. Welded ignimbrite sheets will form localised confining layers where they are unfractured and fracture flow aquifers where fractured. Lateral extent of welded ignimbrite sheets are in the order of 10's of km. The porosity of non-welded ignimbrite sheets ranges between 0.4 to 0.7 depending on grain-size and/or distribution, and 0.1 to 0.3 for fractured welded sheets. Porosity of the entire layer is likely to be about 0.3.

Recharge to the aquifer is from both the infiltration of rainfall and river flow loss. Whakamaru Ignimbrite is a key unit for cold groundwater flow as rainfall recharge on this unit flows to Lake Taupo and to the Waikato River and supports baseflow in streams. Many wells take water from this unit in the Lake Taupo catchment, and probably in other catchments in the Upper Waikato.

Where the layer is exposed at the ground surface in the provided grid, elevation error is estimated at +/- 2 m. The source of the data for the ground surface grid was NZMG 20 m contours. In the Reporoa Basin area, the error associated with the top of the layer where it occurs below ground surface is estimated to be +/- 20% of depth. Elsewhere the error is estimated to be +/- 50% of depth. The existence of the volcanic units at depth associated with the Maroa Volcanic Centre is highly speculative.

2.3 Reporoa layer

This layer includes only the Kaingaroa Formation, which consists of three ignimbrite units and a minor basal tephra deposit.

The formation extends radially 20-30 km from its inferred source at Reporoa Volcanic Centre and underlies an 800 km^2 area mainly to the east and southeast of the caldera, where it forms the capping unit of the Kaingaroa Plateau by overlying the older Rangitaiki Ignimbrite. Eruption of the circa 100 km^3 Kaingaroa Ignimbrites occurred at 230 ka (Ar-Ar dating; Houghton et al. 1995).

The ignimbrite is typically tens of meters thick and has a densely welded upper facies near the top. The lateral extent of the welded upper facies is unknown due to the absence of drill log data on the plateau, but it is at least on the order of 10's of km.

While the layer is considered to be a potential aquifer, it is likely that the layer is predominantly dry, with the poteniometric surface occurring below the base of the layer. The layer is likely to be confined at depth where it is water bearing. Recharge to the aquifer is from infiltration of rainfall. Porosity of the layer is likely to be about 0.3

Where the layer is exposed at the ground surface in the provided grid, elevation error is estimated at +/- 2 m. The source of the data for the ground surface grid was NZMG 20 m contours. In the Reporoa Basin, the error associated with the top of the layer where it occurs below ground surface is estimated to be +/- 10 m, as it is intersected by drill holes in this area.

2.4 Mamaku layer

This layer includes only the Mamaku Plateau Formation. It is comprised of outflow sheets of ignimbrite, erupted from the Rotorua caldera 220 ka, covering the Hauraki Rift in the south and forming the Mamaku–Kaimai Plateau (White et al. 2004). The surface of this plateau dips gently to the northwest and the ignimbrite thins westwards towards the Hauraki Rift (Milner et al. 2003).

The Mamaku Plateau Formation consists of the following three main subunits (Milner et al., 2003). A geological model of the Mamaku Plateau Formation in the Mamaku Plateau area, reported on by White et al. (2007), incorporated the three subunits and used the following layer thicknesses, which were based on field measurements of outcrop and/or drill log information:

- Upper, non-welded predominantly fine-grained ignimbrite sheet. A 5 m thickness was assumed, based on median thickness of this unit in drill logs of wells and field measurements of outcrop.
- Middle, welded ignimbrite sheet with cooling joints. A 60 m thickness was assumed, based on median thickness of this unit in drill logs of wells.
- Lower, non-welded predominantly fine-grained ignimbrite sheet. A 45 m thickness was assumed, based on drill logs of wells. Most wells take groundwater from this lower unit.

The Mamaku Plateau Formation is very thick in the Lake Rotorua catchment due to the proximity to the Rotorua source caldera. Rogan (1982) analysed an airborne gravity survey and concluded a maximum thickness of Mamaku Plateau Formation of greater than 1 km immediately north of Rotorua City.

Groundwater is commonly abstracted from Mamaku Plateau Formation and the layer is considered to be an aquifer. In places the aquifer is confined at depth by the welded ignimbrite unit. Porosity of the layer is likely to be about 0.3.

Recharge to the Mamaku Plateau Formation aquifer is from the infiltration of rainfall. Dell (1982b), in summarising a water balance study for the western Mamaku Plateau, calculated that rainfall recharge of 990 mm was required to support stream baseflow of 10 $m^3 s^{-1}$ in the study area. Evapotranspiration loss was estimated to be 906 mm in each of 1979/80, 1980/81 and 1981/82 years, for rainfall of 1896 mm per $year^{-1}$. This equates to a groundwater rainfall recharge of 52% of rainfall. Similarly, a rainfall recharge rate of 49% of ground-level rainfall was reported by White et al. (2007) for an infiltration lysimeter at Kaharoa, located on the northern rim of the Rotorua caldera.

Specific discharge of streams flowing across the Mamaku Plateau Formation generally increases with distance down river from the headwaters (Dell 1982a, 1982b). For example, specific discharge in the headwaters of the Waihou River is 6.7 L s^{-1} km^{-2}, while it is 132 L s^{-1} km^{-2} when the river is at Whites Road on the Hauraki Plains. Specific discharge estimates are generally largest at the sites on the Hauraki Plains. Specific discharge appears to increase as streams pass through the base of the Mamaku Plateau Formation. For example, specific discharge in the Waihou River increases from 14.8 L s^{-1} km^{-2} (at E276000, N6346750) to 29 L s^{-1} km^{-2} (at E2759750, N6347250) over an approximately 1 km reach in the vicinity of Harris Road, approximately 5 km east of Putaruru (Dell 1982b). This increase in specific discharge may indicate that groundwater is leaving the ignimbrite via spring flow in this region.

A groundwater flow model of the Lake Rotorua caldera (White et al. 2007) suggests that all groundwater flowing in the Mamaku Plateau Formation discharges to surface water. A groundwater budget for the Hauraki Plains (White et al. 2009 in prep.) also suggests that no groundwater flows from Mamaku Plateau Formation to Pleistocene sediments; in effect, all groundwater recharge to the Mamaku Plateau Formation discharges to surface water.

Where the layer is exposed at the ground surface in the provided grid, error is estimated at +/- 2 m. The source of the data for the ground surface grid was NZMG 20 m contours. The error associated with the top of the layer where it occurs below ground surface is estimated to be +/- 20% of depth.

2.5 Huka layer

This layer contains only what was previously referred to as Huka Group sediments (Grindley 1965). The Huka Group was defined at Wairakei by Grindley (1965) as all sediments, pyroclastics, interbedded flow rocks and ignimbrites deposited between the top of the Wairakei Ignimbrite (belonging to the Whakamaru group ignimbrites) and the base of the Wairakei Breccia (belonging to the Oruanui Formation) between 26.5 and 320 ka. It has also been used to refer only to lacustrine sediments in previous mapping. In drill cores the Huka Group comprises two formations called Waiora and Huka Falls Formations.

In geothermal drill cores the name Huka Falls Formation (or Huka Formation) is given to sediments and pyroclastic rocks lying between the top of the Waiora Formation and the base of the Wairakei Breccia. It includes mudstones, siltstones, fine sandstones and minor gravels, which were deposited in lakes that periodically extended over the Taupo-Reporoa area.

These sediments extensively underlie the Wairakei and Ohaaki geothermal fields and are important as they form a cap to the geothermal aquifers, due to their abundance of low permeability lacustrine silts.

Primary permeability in the Huka Falls Formation is likely to be highly variable but mostly low; jointing is sparsely present in the finer units, but not likely to contribute much to overall permeabilities (Hadfield et al. 2001). Reported porosity values for the formation range between 0.36 and 0.65 (Rosenberg and Hunt 1999).

The name Waiora Formation is given to pyroclastic rocks, ignimbrites and interbedded sediments between the base of the Huka Falls Formation and the top of the Wairakei Ignimbrite. This formation is a sequence of pumice sandstone, pumice breccia and ignimbrite layers, with interbedded sediments and interlayered extrusive rhyolite lava flows, including Karapiti Rhyolite. At least some of these units likely correlate to differently-named regionally mapped formations attached to specific eruptive events. Waiora Formation partially filled the basin that existed in the area prior to the formation of the lake that deposited the Huka Falls Formation.

Almost all production at Wairakei and Ohaaki geothermal fields comes from within the Waiora Formation where active faults have been intercepted by drillholes. Reported porosity for the formation ranges between 0.05 to 0.5, with mean porosity about 0.3 (Wood et al. 2001).

While cold groundwater is abstracted from the Waiora Formation in the northern Taupo area, the Huka Falls Formation is generally regarded as an aquiclude and confining layer. Porosity of the layer is likely to be about 0.4 to 0.6

Groundwater recharge to aquifers within the layer is from both infiltration of rainfall and river flow loss.

In the Reporoa Basin, the error associated with the top of the layer is estimated to be +/- 20 m, as it is intersected by drill holes in this area. Elsewhere the error is estimated to be +/- 20% of depth.

2.6 Oruanui layer

This layer contains only the Oruanui Formation. The formation represents the largest eruption (Oruanui) from the Taupo Volcanic Centre, which produced 300 km^3 of ignimbrite, 500 km^3 of pumice and ash fall and an unknown volume of material inside the caldera (Wilson 1993). The Oruanui eruption is thought to have formed the caldera now filled by Lake Taupo (Wilson 2001).

Products of the Oruanui eruption (pumice breccia, lapilli tuff and ignimbrite) are described by Wilson (2001) in terms of 10 phases, nine mappable fall units and a tenth, poorly preserved, but volumetrically dominant, fall unit. The Oruanui event is radiocarbon dated at 22,590 ± 230 yr B.P (Wilson et al. 1988) equivalent to about 26.5 calendar ka (Wilson 1993).

This ignimbrite is composed of landscape-mantling veneer deposits and landscape-forming material (Wilson 1991). In the Taupo area thickness of this unit was between 50 and 240 metres when it was deposited, but a large amount of the Oruanui ignimbrite has been removed by erosion.

In the Reporoa and Southern Hauraki Plains areas, reworking of Oruanui pyroclastics by the Waikato River led to the deposition of the Hinuera Formation, dated 16-23 ka.

The Oruanui Formation is characterised by an almost complete lack of jointing, but, in comparison with the Taupo ignimbrite, is somewhat finer grained and somewhat less permeable (Hadfield et al. 2001).

This layer is aquifer-bearing. Shallow aquifers within the formation are typically unconfined, and deeper aquifers generally confined. The porosity of units within the formation varies between about 0.4 to 0.6. Bulk porosity of the layer is considered to be about 0.5.

Groundwater recharge to aquifers within the layer are from both infiltration of rainfall and river flow loss.

Where the layer is exposed at the ground surface in the provided grid, error is estimated at +/- 2 m. The source of the data for the ground surface grid was NZMG 20 m contours.

2.7 Quaternary sediments and volcanic layer

This layer includes: the Taupo Formation; sedimentary deposits associated with the Waikato River; superficial pumice, breccia and lacustrine deposits; and pyroclactics from the Kapenga Volcanic Centre. These formations and units have been grouped together in one layer as they are likely to have similar hydrogeological properties. The formations and units can be provided as separate layers at a later date should AquaLinc or Environment Waikato require refinement of the model.

Deposits included in this layer generally contain unconfined aquifers. Groundwater recharge to aquifers within the layer is from both infiltration of rainfall and river flow loss.

Taupo Formation

The Taupo Formation contains the products from the 181 A.D. Taupo eruption including the Taupo plinian pumice and the early ignimbrite flow units, the Taupo ignimbrite and airfall deposits. The Taupo ignimbrite represents the end product of a single vent-generated flow and has a volume of ca. 30 km^3 (Wilson and Walker 1985). This ignimbrite extended in all directions from Lake Taupo for about 80 km and covered an area of 20,000 square kilometres. The ignimbrite is divisible into several layers (Wilson 1985) including: pumice generated by the expulsion of material from the flow front; landscape-mantling layers; valley-ponded ignimbrite forming a flat-topped terrace in nearly all the valleys and depressions out to 70-90 km from the vent; and airfall ash thought to be deposited by the dilute ash cloud present above the moving flow.

The ignimbrite shows great lateral variation with distance from the vent. All deposits systematically decrease in thickness with distance from the vent. The thickness of the airfall deposits is as much as 5 m in places. It is assumed that nearly all the airfall material was blown east of the vent by south-westerly to westerly winds (Wilson and Walker 1985).

Gully erosion of Taupo Formation pumice is observed where land is converted from native forest to pasture (Selby 1973). Increased runoff, particularly during intense rainfall, is associated with this land conversion.

Porosity for unwelded Taupo Formation deposits is high and typically ranges between 0.5 to 0.7.

Sedimentary deposits associated with the Waikato River

In the Mangakino-Tokoroa and Southern Hauraki Plains areas, sedimentary deposits associated with the Waikato River include Pleistocene Hinuera Formation (Healy et al. 1964) and Holocene deposits associated with the Taupo eruption.

Manville and Wilson (2004) identified phases of deposition of the Hinuera Formation including:

- Hinuera A deposited after the 220 ka Mamaku eruption and before the Oruanui eruption from the Lake Taupo area 26,500 years ago when the Waikato River flowed into Hauraki Plains;
- Hinuera B deposited mostly in the Hauraki Plains between 26,500 years ago and about 24,000 years ago before the Waikato River moved to its present course;
- Hinuera C deposited on the Hauraki Plains and Hamilton Basin by the break-out flood from Lake Taupo after the Oruanui eruption.

Holocene sediments in the Waikato River valley include those deposited by the post-Taupo eruption break-out flood.

Superficial Deposits

In the Reporoa basin these deposits are also referred to in the literature as pumice and breccia, surficial deposits, recent pumice cover and Taupo pumice. Superficial deposits include pyroclastic deposits from the Taupo eruption and fluviatile and lacustrine sediments post-dating the Oruanui eruption.

Emplacement of the eruption products led to the damming of the Lake Taupo outlet, and thus caused the lake to fill above its present level. During this lake highstand, sediment deposition occurred, along with the formation of the present day terrace. Along the Waikato River valley, sedimentary aggradation occurred supported by enhanced sediment yields in the immediate aftermath of the eruption. Typical deposits include ignimbrite and primary volcanic ash beds mixed with recent pumiceous sands and gravels. These sediments are unconsolidated with high primary permeability. They are usually also layered with paleosols and loess.

Kapenga Volcanic Centre

The Kapenga Volcanic Centre south of Rotorua is the source of the Tikorangi, Matahana, Rahopaka and Waiotapu pyroclastic deposits (Houghton et al. 1995) in the Mangkino-Tokoroa area.

This centre has filled, in large part, with sediments including: Ohakuri Group pumice, tuffs, freshwater siltstones and sandstones; and Huka Falls Formation freshwater siltstones and sandstones.

Where the layer is exposed at the ground surface in the provided grid, error is estimated at +/- 2 m. The source of the data for the ground surface grid was NZMG 20 m contours.

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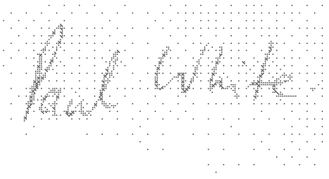
Yours sincerely



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Hydrogeologist

P White
Senior Hydrogeologist

C Daughney (Reviewer)
Section Manager Groundwater

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Appendix C: MODFLOW grids for the grid discretisation trials

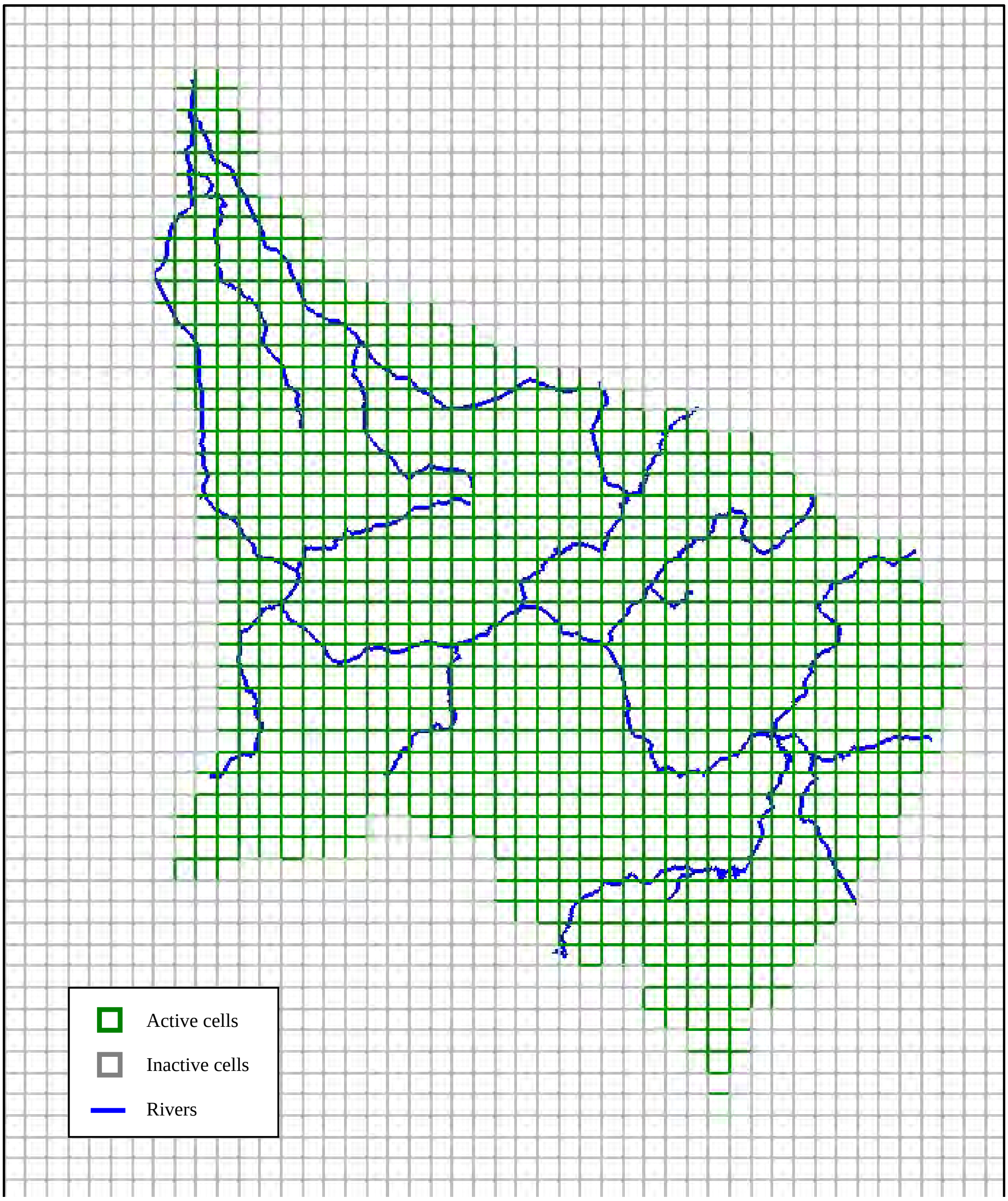


Figure 37: 2km grid

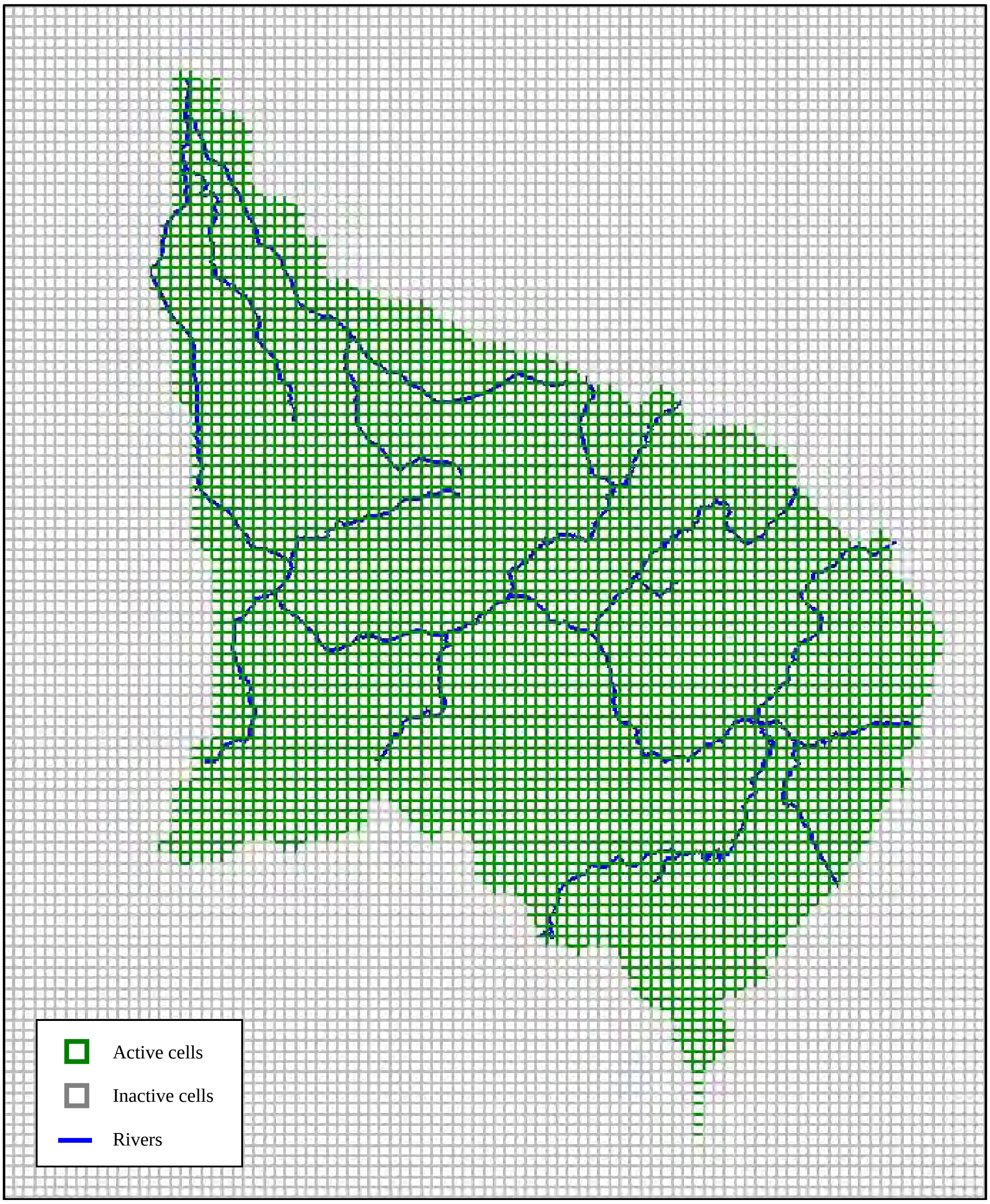


Figure 38: 1km grid

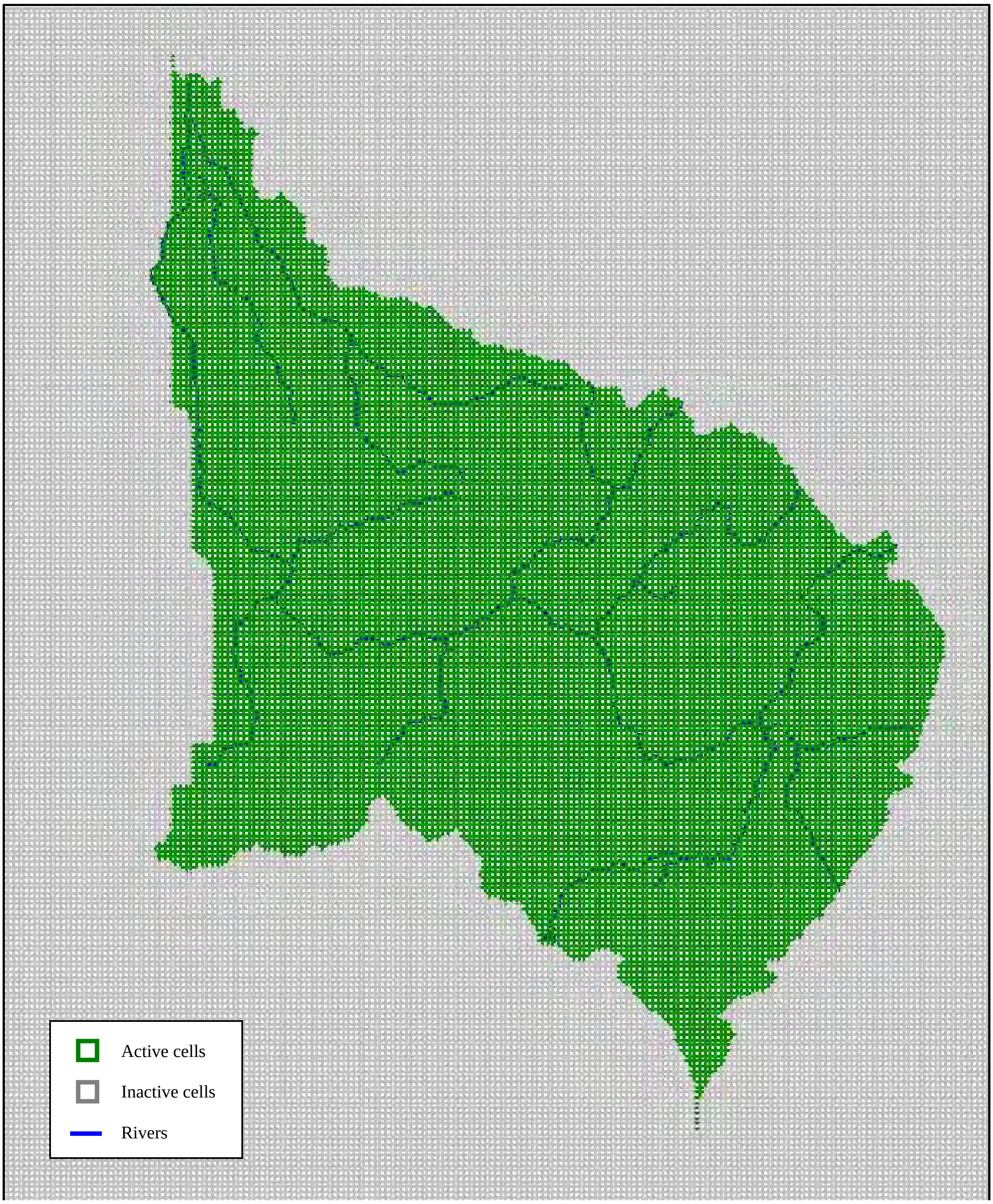
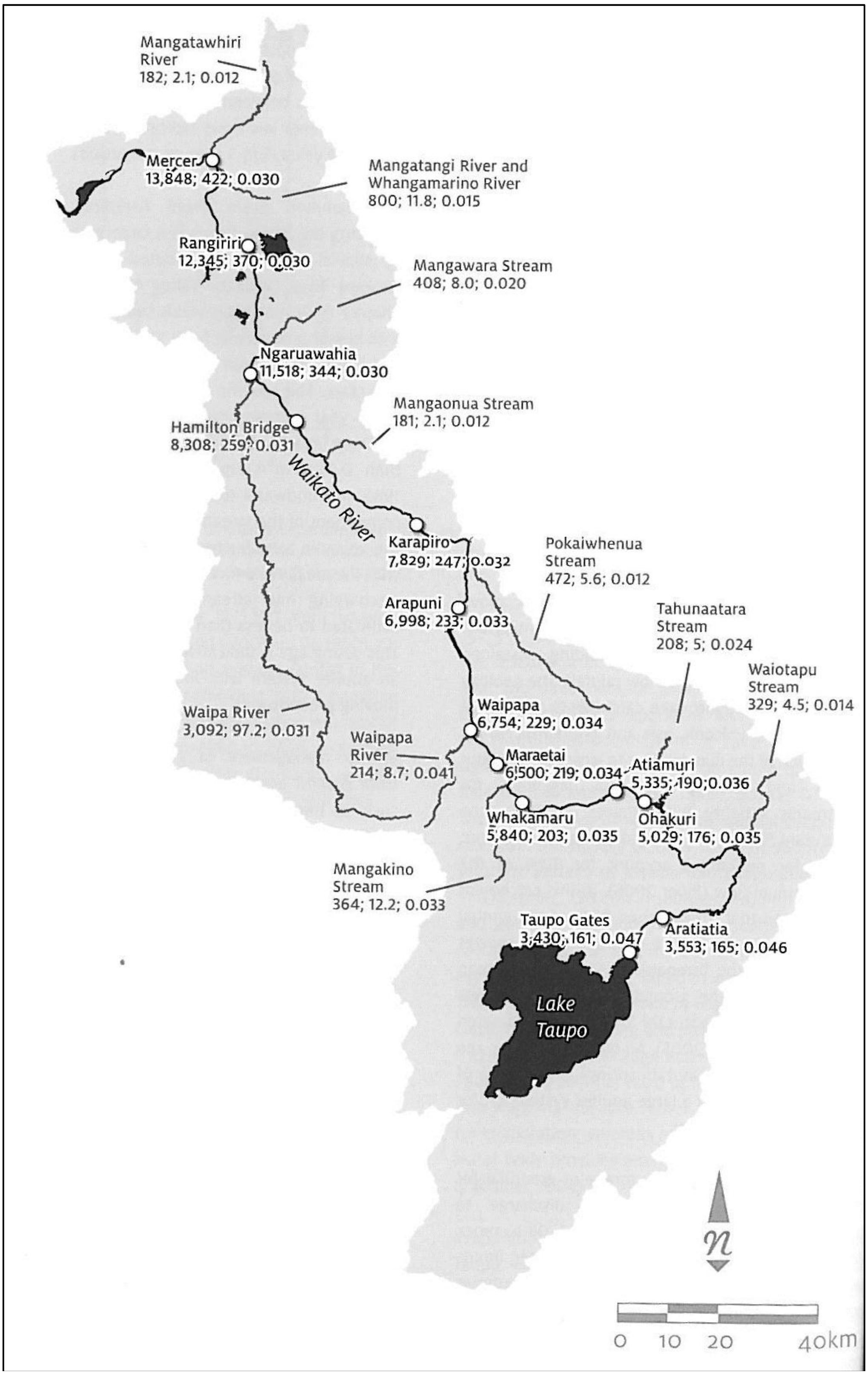


Figure 39: 500 m grid

Appendix D: Reproduction of Figure 3.2 from Collier *et. al.* (2010)



Waikato River and the major tributaries detailing in order their catchment area (km^2), average discharge (m^3/s) and specific discharge (m^3/s/km^2) over 1980 to 1998.